

The most common approach of EMG activity is to quantify the EMG signals through an assimilated integration in which the rectified signal is outlined by a smooth curve. The shape of the curve reflects the relative area at successive time points within the rectified signal. This form of integration, or mean integration, provides a visual display of the relative level of activity from the recording site at different times. The level of activity can be quantified as the total area underneath the curve or the mean amplitude of the smoothed signal. The level of EMG activity may suggest that the muscle is producing more forces or further shortening, however, muscle force or tension may not be directly related to the level of EMG activity. The closest correlation between activity and tension occurs when the muscle does not change length (Miller, 1991).

1.3.2.2 Coactivation patterns of jaw muscles during laterotrusion (Fig. 1.3-4)

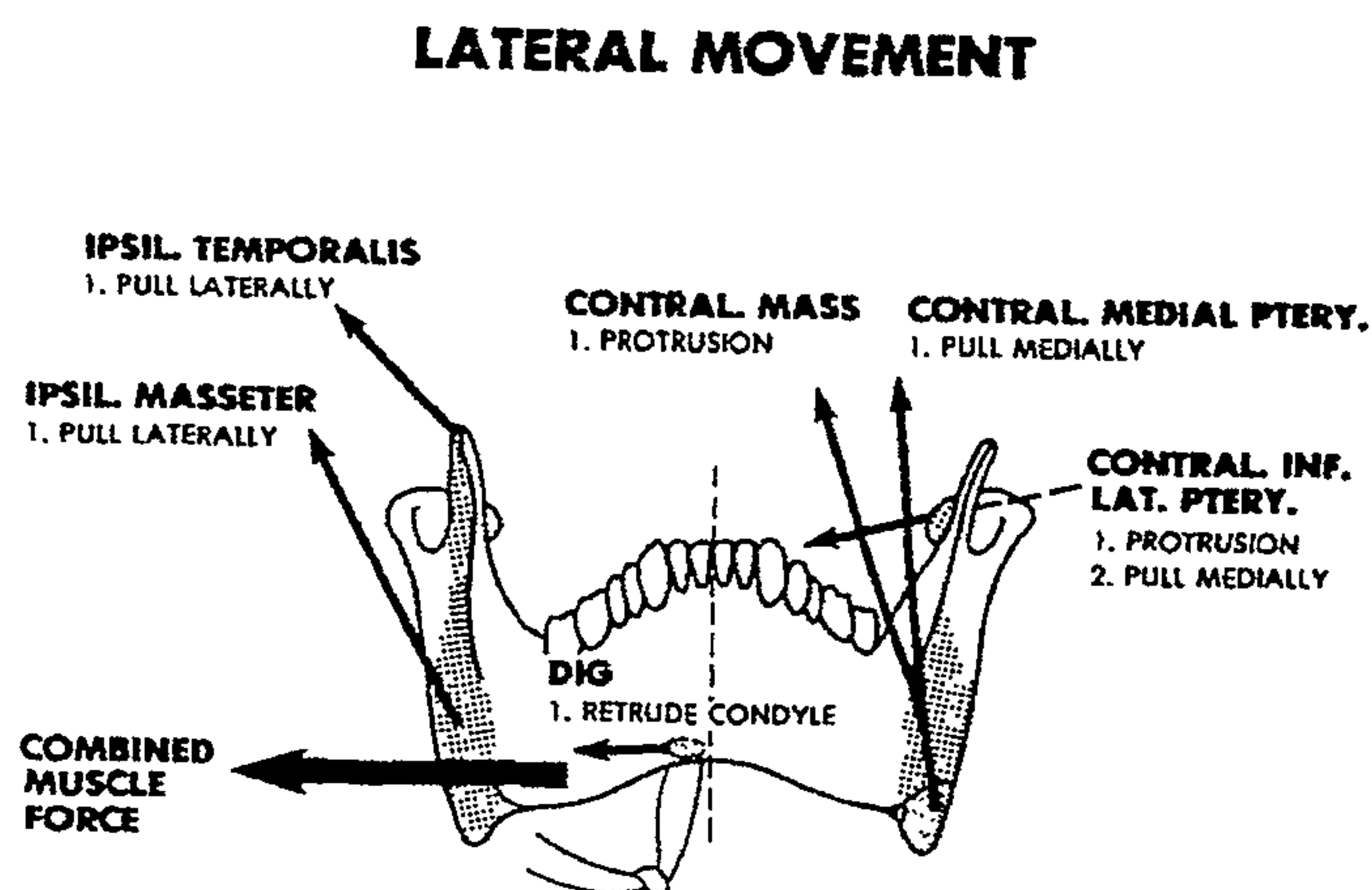


Fig. 1.3-4. Concepts of the muscles recruited in coactivation patterns to complete a laterotrusive mandibular movement. The vectors of those muscles actively recruited are shown in the frontal plane and based on EMG recordings. The thickest vector indicates the overall effect or behavioral response in which the laterotrusive movement occurs to the right (from Miller, 1991).

Anatomically, the primary muscles to move the mandible laterally and contralaterally would be the inferior lateral pterygoid and the medial pterygoid muscles. Their medio-lateral vector component appears to be important for

normal subjects to recruit even though the inferior lateral pterygoid also provides an opening vector and the medial pterygoid provides the opposite closing force vector. The suprahyoid muscle complex appears to provide some opening vector but also generates a retrusive vector. The masseter muscles are active bilaterally, suggesting that their balanced activity may serve more to stabilize the mandible from opening too much during laterotrusion and also to counteract the retrusive vectors of the suprahyoid muscles. Like the lateral and medial pterygoid muscles, the temporalis muscles are reciprocally active: the temporalis ipsilateral to the laterotrusion is active to provide a further lateral vector with some closing vector (see also Fig. 1.3-1). On the other hand, the contralateral temporalis is minimally active and usually not recruited, so that its laterotrusive vector to the ipsilateral side is not elicited. The superior head of the lateral pterygoid has been reported to be reciprocally activated during laterotrusion (Miller, 1991), although recent data suggests that this is too simplistic (Phanachet *et al.*, 2003).

1.3.2.3 Electromyographic (EMG) activity during laterotrusion

Several studies concerning the activity of jaw muscles during laterotrusion have been done (Woelfel *et al.*, 1960; Vitti and Basmajian, 1977; Mahan *et al.*, 1983; Gibbs *et al.*, 1984; Wood, 1987; Murray *et al.*, 1999; Phanachet and Murray, 2000; Phanachet *et al.*, 2001, 2002). However, most of these studies focused on whether these muscles were active or not in the lateral "position" rather than the change of the EMG pattern during lateral movement or the association between the EMG activity and mandibular movement. Furthermore, most of the studies involved with lateral pterygoid did not provide direct evidence suggesting that the recording sites were within the lateral pterygoid muscles and the relationship

between the movements and the EMG activity. Two recent studies (Murray *et al.*, 1999; Phanachet and Murray, 2000) provided EMG activity and condylar movement data during laterotrusion and CT evidence of recording site location. However, the unstandardized speed and amplitude of the movement tasks in these studies make it difficult to normalize readily the EMG activity and the condylar movement data. In addition, this lack of standardization makes it difficult to combine the data from all subjects. This could be a potential reason for the lack of correlation observed between many of the recorded jaw muscles and jaw movement. Further, there was also no information provided in these studies as the possible effects of different closing force levels and movement speeds on the activity patterns observed. In addition, the normalizing method used in these studies is not suitable for quantitatively comparing the EMG activity under different occlusal conditions in our study, unless the influence of an occlusal alteration increases as the mandible moves progressively laterally during the outgoing phase of laterotrusion or decreases as the mandible moves medially during the return phase. Therefore, a detailed study about the relationship between jaw muscle EMG activity and jaw movement as well as a new normalizing method between EMG activity and mandibular movement is needed, and are two of the aims of the present study.

Vitti and Basmajian (1977) studied the EMG activity of the anterior, middle and posterior temporalis, masseter, medial pterygoid, anterior digastric, mylohyoid and geniohyoid muscles in 29 subjects. The results during lateral movement showed that in the balancing-side jaw muscles, the medial pterygoid was markedly active in 93% of subjects, moderate activity occurred in masseter (64%),

digastric (56%), and mylohyoid (59%) muscles, slight activity was observed in 54% of geniohyoid muscles, and the temporalis was not active. Whereas, in the working-side muscles, posterior (96% of subjects), middle (72%) and anterior (71%) temporalis showed activity, and slight activity was observed in the masseter (39%) and medial pterygoid (31%) muscles.

Mahan and coworkers (1983) studied the EMG activity of the superior and inferior heads of the lateral pterygoid muscles at basic jaw positions in nine adult humans. The results suggested that the superior head was moderately active during ipsilateral movement and showed very low levels of activity in contralateral jaw movements. In contrast, the inferior head was very active in contralateral movements. However, in some subjects, the inferior and superior heads activated simultaneously, whereas, in others, these two heads exhibited reciprocal activities. The authors suggested that the electrodes for the superior head recordings were possibly placed within the inferior head in some of the subjects.

Gibbs and coworkers (1984) studied the EMG activity in 14 standardized jaw "positions" (loaded and unloaded) in 11 subjects. The superior and inferior heads of the lateral pterygoid, anterior temporalis and digastric as well as masseter muscles were recorded from the right face. During ipsilateral (right lateral) "position" (e.g. Fig. 1.3-5 a), the highest EMG activity was seen in the right anterior digastric. The right medial pterygoid showed moderate levels of activity. Moderate-to-low activity was seen in the right masseter and superior and inferior

heads of lateral pterygoid. There was also some variation in the superior head of the lateral pterygoid (some showed moderate activity, but some did not).

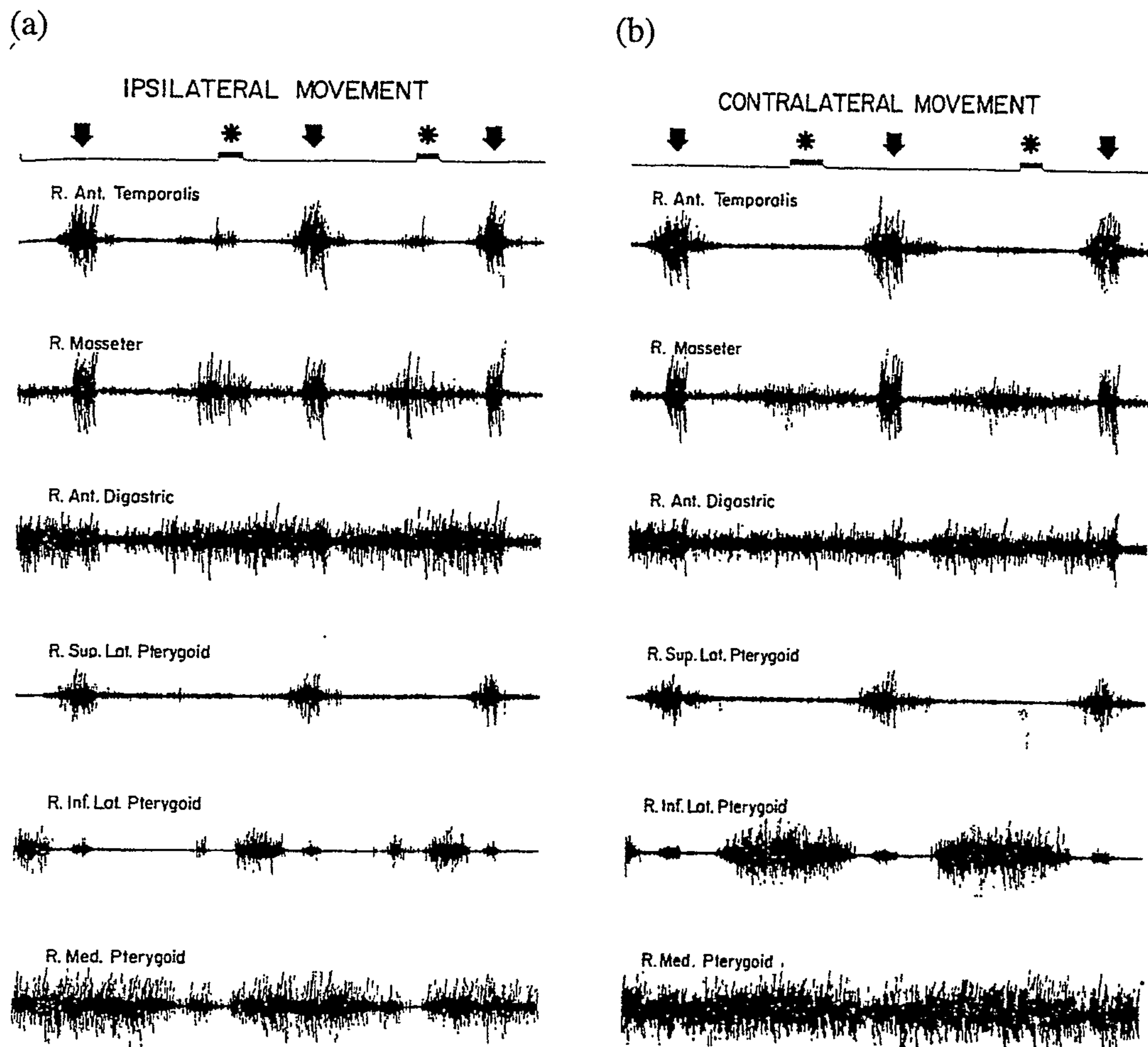


Fig. 1.3-5 (a) EMG recordings of one subject for ipsilateral (right lateral) movement (*) followed by clenching in intercuspal position (↓). Subject was atypical in that superior head of lateral pterygoid usually shows higher activity in this position. The inferior head of lateral pterygoid muscle showed considerably higher activity when some protrusion accompanied ipsilateral movement. Horizontal axis represents 17 s. (b) EMG recordings of one subject (No. 18) for contralateral movement (*) followed by clenching in intercuspal position (↓). Horizontal axis represents 18 s (from Gibbs *et al.*, 1984).

During contralateral (left) "position" (e.g. Fig. 1.3-5 b), the right inferior head of lateral pterygoid and right medial pterygoid muscles were active. The anterior digastric was moderately active, and the masseter muscle showed low-to-moderate activity. The superior head of the lateral pterygoid and anterior temporalis muscles showed low activity levels. At the end point of ipsilateral or contralateral movement, the EMG under loaded conditions (with hand pressure

opposite to the jaw movement) was equivalent to or slightly greater than the level under the unloaded condition.

There were two major limitations in these previous studies. First, in the two studies (Mahan *et al.*, 1983; Gibbs *et al.*, 1984) with the recording of lateral pterygoid, the lateral pterygoid activity during laterotrusion was variable between subjects and makes it difficult to draw conclusions as to relative activity levels. In addition, there is controversy as to the relative levels of activity between the two heads of the lateral pterygoid in other previous studies. Many studies suggested that the inferior and superior heads of the lateral pterygoid muscle act independently (Grant, 1973; McNamara, 1973; Mahan *et al.*, 1983; Gibbs *et al.*, 1984; Wood *et al.*, 1986; Hiraba *et al.*, 1995). In summary, these studies conclude that the superior head activates during closing, clenching, retrusion and ipsilateral jaw movements, whereas the inferior head activates during jaw opening, protrusion and contralateral jaw movements. However, other studies reported that both heads can become active together in some motor tasks (Sessle and Gurza, 1982; Widmalm *et al.*, 1987; Hannam and McMillan, 1994; Miller, 1991). One possible explanation for these controversial findings was that the lateral pterygoid electrodes might be misplaced in the wrong muscles, since there was no evidence provided in these studies regarding the recording sites. Another explanation was the possibility of heterogeneity in activity between different regions within the same head of lateral pterygoid muscles; that is, each head of the muscle is functionally heterogeneous. Indeed, recent evidence (Phanachet *et al.*, 2001, 2002, 2003) suggest that both heads of the lateral pterygoid muscle are functionally heterogeneous, that is, each head may consist of subcompartments,

each capable of independent activation. To address both possibilities in future studies, an electrode verifying method (e.g. Orfanos *et al.*, 1996; using computed tomography (CT) scans) is needed to make sure the electrodes are in the correct muscles and to identify the region that is being recorded.

The second limitation in these previous studies (Woelfel *et al.*, 1960; Mahan *et al.*, 1983; Gibbs *et al.*, 1984; Nielsen and Miller, 1988; van Eijden *et al.*, 1993; Vitti and Basmajian, 1977; Widmalm *et al.*, 1987, 1988; Wood, 1986; Wood, 1987) was that these studies focused on whether these muscles was active or not during a static lateral position. There was lack of detailed information about the association between the jaw movements and the EMG activity, e.g. the change in activity level throughout the laterotrusion. Such recording is essential, particularly in light of the observations of Sessle and Gurza (1982) that jaw position appeared to be an important determinant of the EMG activity in the lateral pterygoid.

Two recent studies (Murray *et al.*, 1999; Phanachet and Murray, 2000) addressed both issues using CT scans to verified electrode position and a six-degrees-of-freedom jaw-tracking device to track condylar movements. Murray and coworkers (1999) recorded the EMG activity of the superior and inferior heads of lateral pterygoid, the masseter, the anterior and posterior temporalis and submandibular muscles from the side contralateral to the movement in eight subjects. During the recordings, a six-degrees-of-freedom device was used to record the condylar movement simultaneously with the EMG recordings for later comparison. Subjects were instructed to move their jaws at a rate that was

comfortable for the individual participant at a light closing force and as far as comfortable to the side, that is contralateral to the EMG recording sites. Recording sites in the superior head and, in one subject, the inferior head of lateral pterygoid were verified by CT scans. For quantitative assessments, the condylar movement and EMG activity recordings were normalized, averaged and then assessed by using the Pearson correlation coefficient between the condylar movement and EMG recordings.

This procedure was done in the following way. For each trial, the period from the onset to the maximum displacement of condylar movement was calculated and divided into 500 data points. Then, each EMG and condylar-movement file in the same trial was quantized to these 500 data points. Data samples in the original movement or EMG file that occurred at the same time as one of the 500 data points were allocated to that data point. Where a data point occurred at a time between two consecutive data samples in the raw file, a value was calculated by linear interpolation between the data sample before and the data sample after. This procedure was done for each (i.e., X, Y and Z) axis of condylar movement and for each rectified and smoothed EMG signal in each trial in each subject. Then, averaged traces of contralateral movement and EMG activity from each jaw muscle were obtained by averaging all trials of the same jaw movement in each participant. Correlation coefficients were then calculated (multiple linear regression) on the average movement and EMG data from each participant.

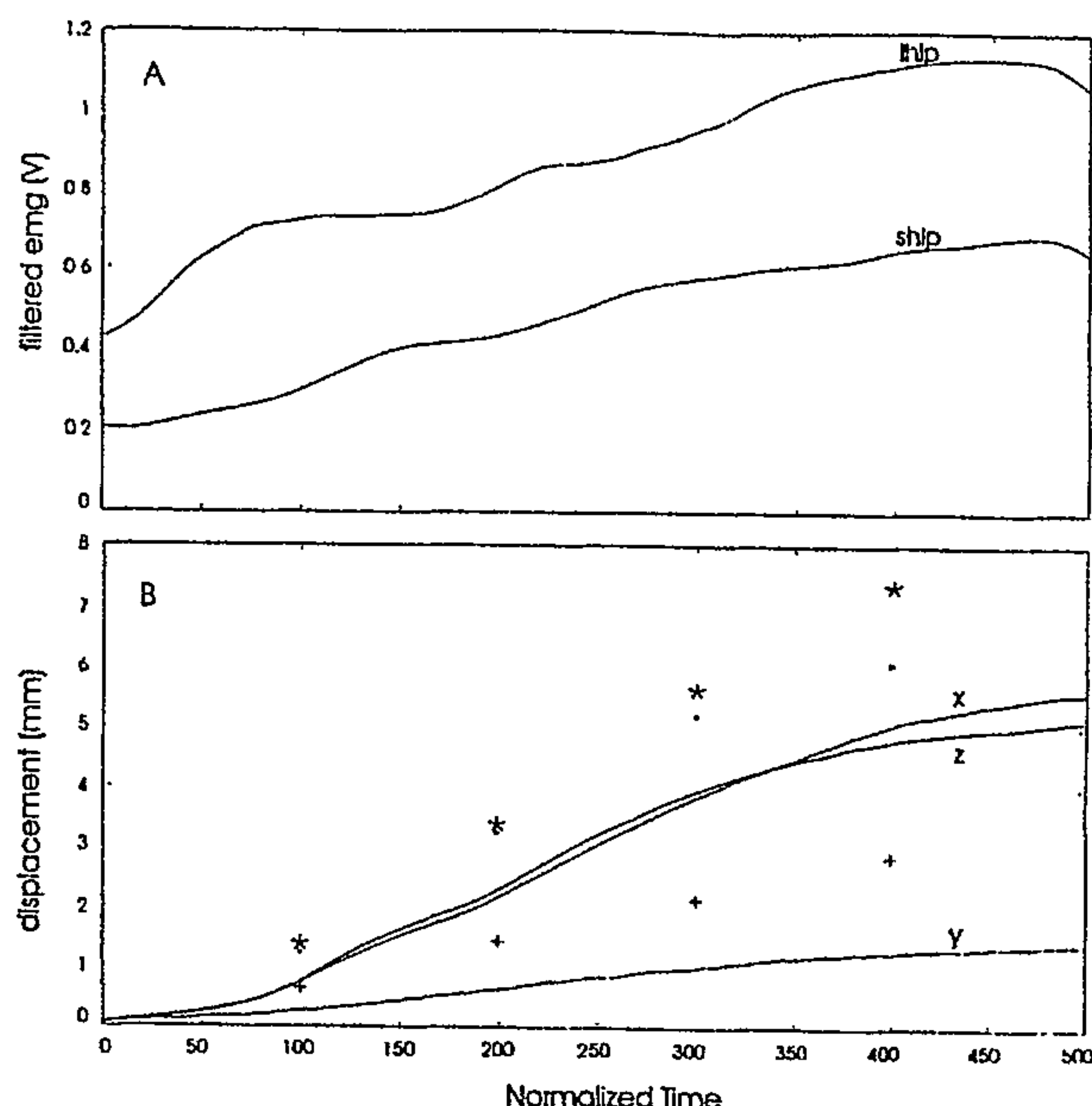


Fig. 1.3-6 Averaged plots of activity in superior (shlp) and inferior (ihlp) heads of the lateral pterygoid during contralateral jaw movement. Normalized and averaged SHLP and IHLP EMG and condylar movement data is shown for all participants during contralateral excursion (A and B). As the filtering smooths each EMG signal in a non-linear manner, the amplitudes of the traces provide an indication only of the relative levels of activity in the different jaw muscles. In the lower graph the ordinate axis refers to the displacement (mm) for display of the condylar-movement traces (from Murray *et al.*, 1999).

The results at the outgoing phase of laterotrusion suggested that in the superior and inferior heads of contralateral lateral pterygoid in each subject, there was a progressive increase in the activity in association with condylar movement during the contralateral movement (e.g. Fig. 1.3-6). Furthermore, irregularities in condylar movement, which reflected variations in the rate at which the jaw was moved, were correlated in time with prominent bursts of superior and inferior head activity. In all participants, there was a consistently high correlation coefficient between the superior and inferior head activity, and condylar displacement during the contralateral movements.

In the contralateral masseter, anterior and posterior temporal and submandibular muscles, the gradual increases in activity, that were seen in the superior and inferior heads of the lateral pterygoid in association with condylar translation and the close associations between fluctuations in EMG activity and fluctuations in condylar movement, were usually not observed. During the outgoing phase of contralateral movement, some changes (i.e. increases and/or decreases) in EMG activity were seen in some individuals, but these changes were not consistently

observed in all participants. When the data were normalized and averaged, the consistent increases in activity in association with condylar movement observed for the lateral pterygoid were not apparent for the other jaw muscles, with the possible exception of the submandibular muscles in contralateral movement (e.g. Fig. 1.3-7). The contralateral masseter, anterior and posterior temporal and submandibular muscles exhibited markedly lower and more variable correlation coefficients with condylar point movement.

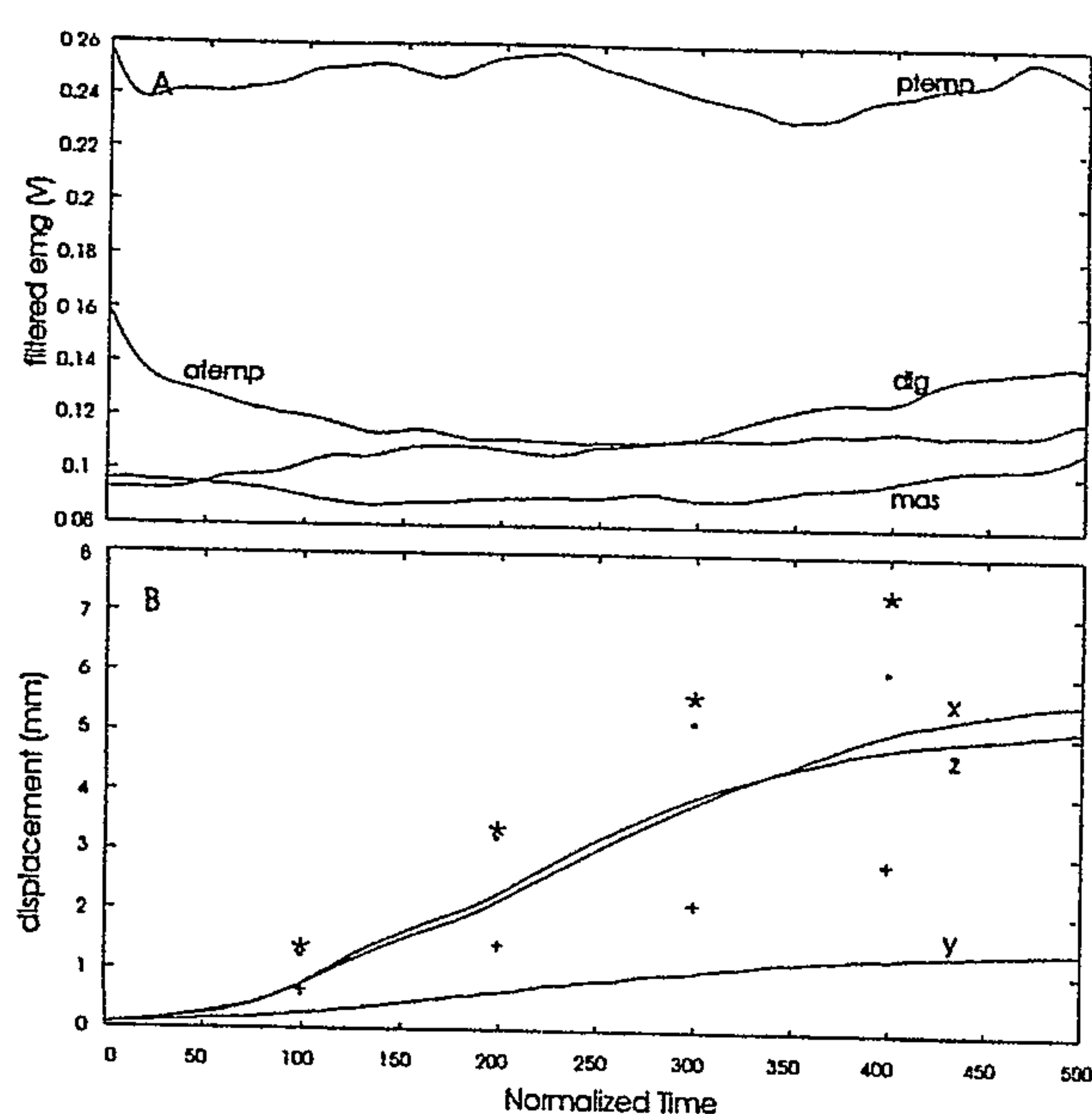


Fig. 1.3-7 Averaged plots of EMG activity and condylar movement in masseter (mas), anterior temporalis (atemp), posterior temporalis (ptemp) and anterior digastric (dig) during contralateral jaw movement (from Murray *et al.*, 1999).

According to the results, the authors suggested that the contralateral lateral pterygoid is the major jaw muscle that moves the condyle downwards and forwards during contralateral movements. The other contralateral jaw muscles recorded do not appear to make a major contribution although they did not record from the medial pterygoid muscle. The variation between subjects in the measures of correlation for these contralateral jaw muscles may reflect the different neural strategies adopted to drive the movement in individuals with different facial morphologies and skeletal muscle architectures. In addition, based on the findings of a close association between fluctuations in the EMG

activity of the superior and inferior heads and condylar movement, the authors suggested that both heads are important in the precise positioning of the condyle, and therefore the jaw, in normal movements such as mastication and speech.

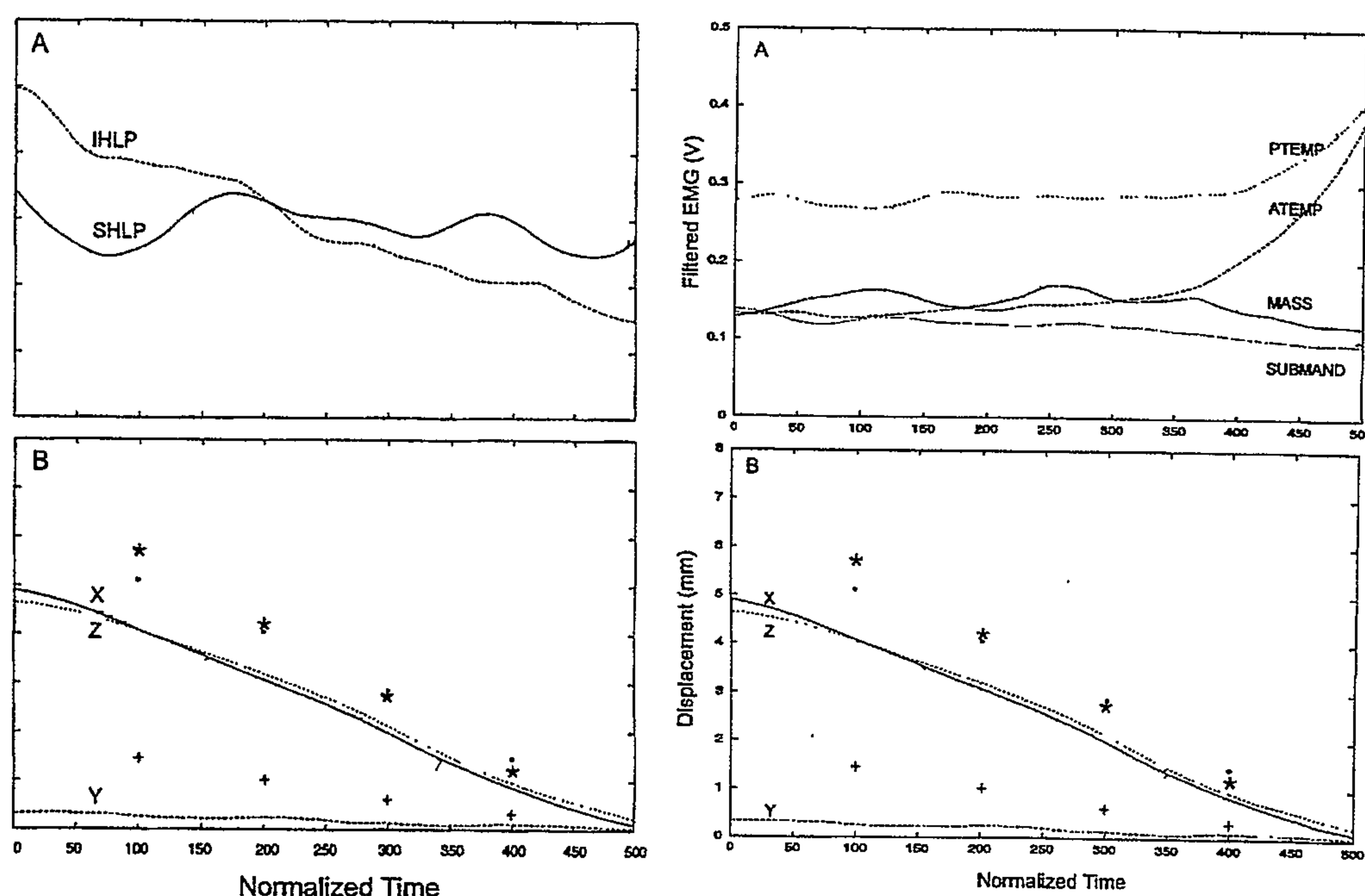


Fig. 1.3-8 Averaged plots of activity during the return phase of contralateral jaw movement (left figures) in superior (SHLP) and inferior (IHLP) heads of the lateral pterygoid and (right figures) in masseter (MASS), anterior temporalis (ATEMP), posterior temporalis (PTEMP) and submandibular muscles (SUBMAND). Normalized and averaged EMG and condylar movement data for all participants (A and B; from Phanachet and Murray, 2000).

The other study (Phanachet and Murray, 2000), with the same experimental design as Murray *et al.* (1999), in seven subjects reported the EMG activity at the return phase during contralateral jaw movement. The results showed that there was a progressive decrease in the rectified-and-smoothed inferior head of lateral pterygoid activity in relation to condylar movement during the return phase of contralateral movement in most subjects (e.g. Fig. 1.3-8). However, this pattern was not usually seen when the superior head of lateral pterygoid activity was studied in association with condylar movement. In addition, there was a high correlation coefficient between condylar displacement and the rectified and smoothed inferior head of lateral pterygoid and anterior temporalis muscle

activities during the return phase of contralateral movement, while the superior head of the lateral pterygoid, masseter and submandibular muscles presented a much lower correlation. Although there was no high correlation, the posterior temporalis tended to increase towards the end of the movement (e.g. Fig. 1.3-8).

This study suggested that the inferior head also plays an important role in condylar movement back into the glenoid fossa after a contralateral jaw movement. However, the authors suggested that the superior head does not play the same role as the inferior head in the return phases of this movement. Also, in some subjects, fluctuations in the activity of both heads closely reflected fluctuations in condylar movement, which further supports a role for lateral pterygoid in the precise control of the condyle on these return phases as previously reported in the outgoing phase (Murray *et al.*, 1999). The variation in the superior head of lateral pterygoid suggested that there are different activity patterns in lateral pterygoid between the outgoing and return phases of a contralateral movement. In addition, it is important to recognize that other jaw muscles (particularly, posterior temporalis and submandibular) as well as the superior retrodiscal ligament also are likely to control jaw movement during these return phases.

The high correlation coefficients between condylar movement during the return phase of contralateral movement and activity in the inferior head of the lateral pterygoid and the anterior temporalis muscles suggest that these muscles play an important part in controlling the movement of the condyle posteriorly, superiorly and laterally. Posterior temporalis also appeared to play an important role. The

variability between individual correlation coefficients observed in the superior head of the lateral pterygoid, masseter, and submandibular muscles suggested that these muscles do not make a consistent contribution to posterior condylar movement. The results also suggested that the contribution from the lateral pterygoid, as well as other jaw muscles, are required possibly in the role of stabilizing or controlling the movement of the condyle as it moves posteriorly and superiorly. The data suggested that the inferior head is one of the muscles controlling the movement of the condyle posteriorly and superiorly on the return phase of contralateral and protrusive jaw movement. And the data supported Wilkinson's (1988) proposal that *'the inferior lateral pterygoid muscle remains electrically active during the first half of closure. This lengthening contraction has the effect of slowly letting out the rope to control the condyle as it travels back into the fossa.'*

However, there were some issues about the normalizing methods in these two studies. First, the uncontrolled speed and amplitude of the jaw movement might cause some problem in the normalizing method. In their normalizing method, the authors divided the duration between the onset (or the offset) and maximal displacement of the condylar point in each trial into 500 data points, and then assessed the EMG activity and the condylar displacement at each data point. However, because the subjects were instructed to perform laterotrusion at a comfortable rate to a comfortable range, this might cause some variation in results after normalization and averaging. For example, at the data-point 300 from the same subject, the condylar displacement could be 3 mm in one trial, whereas it might be 4 mm in another trial and this is because of the

unstandardized tasks. This makes it very difficult to combine these data, and this is a limitation of these earlier studies.

As the authors reported, the inferior head activity was highly correlated to the condylar movements. The non-standardized nature of the tasks might also cause some problems while attempting to take specific data points for comparison across occlusal conditions in future studies, for example, the influence of occlusal alterations on jaw-muscle activity. This possible variability would become more significant while summarizing the data from different subjects, as shown in Fig. 1.3-6 and -7, due to individual differences in the definition of "comfortable range". Further, the different rates of the "comfortable speed" in movement might also have some influence on the EMG activity. Recent data demonstrate a clear influence on thresholds of single motor units of different rates of movement (Phanachet *et al.*, 2001).

Second, the use of the correlation coefficient as a measure of the association between EMG activity and movement might not be suitable for all muscles. The correlation coefficient is suitable for muscles that have a progressive and monotonic change in EMG throughout the movement, such as the lateral pterygoid muscles. However, in Fig. 1.3-7, the anterior temporalis showed a progressive decrease in the early outgoing phase of laterotrusion, and then reached a steady level at the data-point 200. In addition, in Fig. 1.3-8, the anterior and posterior temporalis showed an increase at the late return phase between data-point 350 and 500. The use of the correlation coefficient cannot show these more complex features when the entire phase was taken into

calculation. This could be the reason why the data in Phanachet and Murray (2000) did not show a high correlation coefficient between the posterior temporalis activity and condylar movement, although, the posterior temporalis has long been assumed to play an important role in the return phase of contralateral movement due to its fibre orientation (Miller, 1991). Further, the correlation coefficient may not be suitable to quantitatively compare EMG activity between conditions, such as EMG activity under different occlusal conditions as in the present study. This is because that there is lack of information whether the influence of an occlusal alteration on the EMG activity of jaw muscles increases as the mandible moves progressively laterally during the outgoing phase of laterotrusion or decreases as the mandible moves medially during the return phase. In addition, since most of the jaw-closing muscles showed a low correlation coefficient between EMG activity and condylar movement under natural tooth guidance (Murray *et al.*, 1999; Phanachet and Murray, 2000), it might be difficult to interpret the comparison of correlation coefficients between different occlusal conditions.

In addition, these two studies only reported the EMG activity of the jaw muscles contralateral to the movement side. The ipsilateral closing muscles were not recorded. Further, both studies (Murray *et al.*, 1999; Phanachet and Murray, 2000) mainly focused on the contralateral lateral pterygoid muscles during laterotrusion and the activity patterns of other jaw muscles during laterotrusion were not discussed in detail. However, a detailed understand of these muscles during laterotrusion would be needed before studying the influence of occlusal alteration on them.

Therefore, there is a need to develop a new method to standardize mandibular movement and to allow a better method for normalizing the EMG data based on time and further based on mandibular movement. In addition, a detailed study of the EMG activity of jaw muscles during laterotrusion is necessary before analyzing the influence of occlusal alteration on EMG activity.

1.3.3 Influence of an occlusal alteration on jaw-muscle activity during laterotrusion

Clark and coworkers (1999) summarized 28 studies from 1931 to 1999, and suggested that an experimental occlusal interference could induce transient local tooth pain, loosening of teeth, a slight change in postural muscle tension levels, and changes in chewing stroke patterns. However, there is limited information about the influence of a change to the occlusal schema on jaw muscle activity during laterotrusion. This section reviews the studies on the influence of an occlusal interference on jaw muscle activity during clenching at a lateral position, as well as the occlusal splint studies of EMG activity under group function and canine guidance. Then, the only study regarding the influence of occlusal alteration on jaw muscles during a laterotrusive jaw movement is reviewed.

1.3.3.1 Influence of an occlusal alteration during lateral clenching

Belser and Hannam (1985) studied the effect of altered working-side occlusal guidance on masticatory muscle activity and related jaw movement in 12 subjects with group function on the working side during laterotrusion and some molar balancing-side occlusal contacts. An artificial left canine guidance without

altering vertical dimension was constructed, as well as an overlay on the upper right first molar with an increased vertical dimension. The molar overlay simulated a working-side and non-working-side molar interference. The EMG activity of the anterior and posterior temporalis and masseter muscles were recorded with surface electrodes. Simultaneously, jaw displacement was recorded with the Kinesiograph (Myotronics Inc., Seattle, Wash.). Three sets of tests were carried out. The first set was under natural tooth guidance, and this included: maximum vertical tooth-clenching efforts in intercuspal position and prescribed right and left eccentric positions of the mandible, voluntary gliding movements to the left and right, as well as right- and left-side unilateral gum chewing. Second, with the artificial canine guidance in place, the same movements as the first set were performed. Third, after the artificial canine guidance was removed and the overlay on the upper right first molar was placed, only maximum right and left eccentric tooth clenching was performed. Only these tasks were done because the overlay could only be fabricated in combination with an increased vertical dimension.

The results of the comparison during eccentric tooth clenching showed that the working-side artificial canine guidance caused a significant reduction of muscle activity. During these two occlusal conditions (natural tooth guidance and artificial canine guidance), muscle activity fell on the ipsilateral (working) side from 53.8% {presumably of maximum voluntary contraction (MVC)} to 20.9% in the anterior temporalis muscle, from 56.3% to 32.4% in the posterior temporalis muscle, and from 26.3% to 5.5% in the masseter muscle. On the contralateral (balancing) side, muscle activity fell from 9% to 3.6% in the

anterior temporalis muscle, from 7.1% to 5.8% in the posterior temporalis muscle, and from 38.6% to 14.9% in the masseter muscle. Although there was an overall reduction in EMG activity, the relative relationships between the individual muscles remained unchanged. However, these relationships were dramatically affected during the third clenching test with the balancing-side occlusal interference. In comparison with natural occlusal conditions, the EMG activity of the two contralateral (balancing-side) temporalis muscles was significantly increased, whereas the ipsilateral (working-side) temporalis activity was considerably reduced. Both masseter muscles maintained their original level of EMG response. Electromyographic activity increased from 9% to 41.5% in the right anterior temporalis muscle, and from 7.1% to 24% in the right posterior temporalis muscle. It decreased from 53.8% to 36.3% in the left anterior temporalis muscle, and from 56.3% to 33% in the left posterior temporalis muscle. In addition, the working-side molar interference was associated with minor differences in jaw elevator muscle activity, which were concerned primarily with the working-sided (ipsilateral) masseter muscle, and the balancing-sided (contralateral) two temporalis muscles.

Baba and colleagues (1996) studied the influence of occlusal interferences on the EMG activity of the anterior and posterior temporalis and masseter muscles of 12 subjects. The EMG activity during maximal clenching in the right lateral position was recorded with surface electrodes under four occlusal conditions: natural tooth guidance, an artificial canine raiser, a working-side molar interference and a non-working-side molar interference. To estimate bilateral activity balance for each muscle pair, the asymmetry index was calculated using averaged raw EMG

data: $(\text{EMG right} - \text{EMG left}) / (\text{EMG right} + \text{EMG left}) * 100$. The results showed that the introduction of the canine raiser tended to decrease the level of EMG activity, with a significantly lower level of activity in the balancing-side masseter (contralateral to the movement) and the working-side anterior and posterior temporalis muscles. No significant change in asymmetry index could be observed for each muscle pair. Further, the initial unilateral activity with clear dominance on the working side in the anterior and posterior temporalis muscles and the bilateral activity in the masseter muscles was not changed. The working-side interference caused only minor differences in muscle activity, and only the non-working (contralateral) side masseter muscle showed a statistically significant reduction in activity. The non-working side interference, however, resulted in marked changes: the activity in the anterior and posterior temporalis muscles was decreased on the working side and increased on the non-working side. This changed the asymmetry index in the anterior and posterior temporalis muscles. Although EMG activity in the non-working side masseter muscle was reduced significantly, it did not cause a significant change in the asymmetry index.

Baba and colleagues (2000) studied the influence of occlusal interferences on the EMG activity of the anterior and posterior temporalis and masseter muscles in 12 subjects. The EMG activity during submaximal clenching (under the control of visual feedback) in the right lateral position was recorded with surface electrodes under five occlusal conditions. These included natural tooth guidance, an artificial canine raiser, a working-side molar interference and a non-working-side molar interference, as well as non-working-side contact (a combination of all

three artificial interferences). During the recordings, the sum of the fully rectified signals from the six muscles was simultaneously shown to each subject on an oscilloscope screen. Thus, it provided a force control with visual feedback at a selected level ranging from 30% to 50% of intercuspal maximal voluntary contraction. The asymmetry index was calculated and used to estimate bilateral activity balance for each muscle pair. The results showed that the masseter muscle showed the highest and bilaterally equal activity pattern irrespective of the occlusal alterations, and the posterior temporalis muscle showed the lowest activity. The two temporalis muscles showed lower activity on the left side except when the non-working-side interference was inserted.

An issue about the force controlling method in this article was the use of EMG activity as a source of visual feedback for force control. Since the hypothesis of this study and the results of the previous studies (Belser and Hannam, 1985; Baba *et al.*, 1996) suggested that the EMG activity could be changed under different occlusal conditions, the EMG activity of these muscles may not be suitable for force control reference. In addition, since the bilateral activity pattern (asymmetry index) was changed under different occlusal conditions, these might cause a change in force distribution and, thus, change the net closing force level, even if the sum of the six muscles' EMG activity remained unchanged. Furthermore, the closing force level was a factor that should be measured but not controlled, because an occlusal alteration could cause a change to the net closing force level and the force distribution from each muscle. Thus a controlled factor in any experiment should be independent of the changed factor. By controlling the force level, part of the effect of the occlusal alteration might be removed.

This could be the reason why the authors did not analyze the individual EMG-activity levels under the different occlusal conditions.

Generally, the studies of the influence of occlusal interferences on jaw muscle activity during maximal eccentric clenching suggested that occlusal interferences could cause a significant change in jaw-closing muscle activity. The working-side interference mainly caused an overall decrease in activity; whereas, the balancing-side interference could cause an increase in balancing-side temporalis activity and a decrease in working-side temporalis. Although the balancing-side exhibited more significant effects on EMG activity, there is a difficulty in fabricating this type of occlusal interference without increasing vertical dimension in the intercuspal position (Belser and Hannam, 1985). An altered vertical dimension in the intercuspal position could therefore also be an influencing factor in the studies of the effects of occlusal alteration during laterotrusion. Manns and colleagues (1981) showed a gradual decrease of EMG activity in anterior and posterior temporalis and masseter muscles with progressively increased vertical dimension from occlusal position. After a certain interocclusal distance, the activity gradually increased until maximum jaw opening. In other words, a change in vertical dimension will influence the EMG activity.

1.3.3.2 Splint studies between canine guidance and group function

Manns and colleagues (1987) studied the influence of group function and canine guidance on the surface EMG activity of the bilateral anterior temporalis and masseter muscles in six subjects. A maxillary occlusal splint was constructed

with group function during laterotrusion. Then, the splint was split into three parts at the distal end of the bilateral canines. Therefore, when the anterior part only was used, the laterotrusion could be made with canine guidance. The comparison between the EMG activity under the canine guidance and group function conditions during eccentric clenching showed a significant reduction in all muscle activity with canine guidance. The reduction in activity was higher on the ipsilateral side (to the movement) than that on the contralateral side. Statistically, the highest significance was found in the ipsilateral anterior temporalis and contralateral masseter muscles, a high significance was observed in the ipsilateral masseter muscle, and a significant difference was seen in the contralateral anterior temporalis muscle. Although, the EMG activity during laterotrusion with maximal force was recorded, and also showed a reduction with canine guidance, a detailed qualitative analysis and a quantitative comparison during the movement phases was not performed.

Borromeo and colleagues (1995) studied the effects of group function and canine guidance on masseter activity in 10 subjects. A maxillary splint adjusted to canine guidance and a mandibular splint adjusted to group function during laterotrusion were made (termed adjusted device). After all of the appropriate recordings of the adjusted device, a 1-mm-high platform of resin was added on the right second premolar region to remove the adjustment (termed unadjusted device). The results showed that during laterotrusion, there was no significant difference between canine guidance and group function. However, there was a significant reduction in masseter activity when both types of unadjusted device were used in comparison to natural tooth guidance during laterotrusion. During

clenching at the extremities of jaw position, the level of EMG activity did not alter when the different devices were in place compared with no appliance in place.

A major issue of this study (Borromeo *et al.*, 1995) was that the two occlusal guidances was constructed on two different devices. Thus, the increased vertical dimension was different. Further, the authors did not measure whether the inclination of the two devices during laterotrusion was the same or not. Therefore, there were a number of factors in this study that limit interpretation of the data.

In addition, although EMG activity during laterotrusion was recorded, simultaneous mandibular movement was not provided. The speed of laterotrusion was not standardized. This could cause a problem in normalizing the data before the comparison as individual differences in performing the lateral movement would increase the variability of the data. And the procedure to normalize the masseter data before comparison was not mentioned in the later study (Borromeo *et al.*, 1995). A detailed qualitative comparison was not performed in both studies and a quantitative comparison was not performed in the former study (Manns *et al.*, 1987).

1.3.3.3 Influence of an occlusal alteration during laterotrusion

The only paper (Soneda, 1988) that has studied the influence of an occlusal alteration on jaw muscle activity during laterotrusion and without altering vertical dimension in the intercuspal position was published in Japanese with an English abstract. According to the abstract, several maxillary canine raisers were

fabricated to change the palatal inclination. In five subjects, the activity in the bilateral masseter and posterior temporalis muscles was recorded with surface electrodes, simultaneously with an LED mandibular tracking device. The lateral gliding movements were performed with the occlusal contact on the canine raiser.

The results showed that steeper canine raisers caused a reduction of the muscle activity in comparison with the more flat guidance. The working-side posterior temporalis muscles was more active than the balancing-side posterior temporalis and bilateral masseter muscles, and the temporalis had a higher activity than the masseter during lateral grinding. This relationship remained unchanged with all canine raisers. During the return phase of the lateral gliding, the difference of the canine raiser showed no consistent change in the muscle activity. According to the subjective feelings of the participants, the canine raiser with a moderate inclination was associated with more comfort in moving the mandible, but no relationship between the EMG activity and the subjective feelings was revealed.

1.3.3.4 Summary

Generally, an occlusal alteration can alter the EMG activity of the jaw muscles during laterotrusion or clenching in a fixed lateral position. However, only temporalis and masseter muscles have been recorded in previous studies. The influence on the activity of the lateral pterygoid muscles, which are thought to play a major role during laterotrusion, has not been investigated. Further, the speed of laterotrusion in these earlier studies was not standardized, and individual differences might increase the variability in the EMG activity.

There is a need therefore to investigate further the effects of a change to the occlusion on the EMG activity of the jaw muscles, especially the lateral pterygoid muscles. A standardized task is needed to reduce the influence of individual differences. Further, the mandibular movement should be recorded to allow comparative analyses and normalization of the EMG activity throughout the lateral movement.

1.4 Conclusion of Literature review

This literature review includes the anatomy of the temporomandibular joints and jaw muscles, the mandibular and condylar movements and the muscle activity during the laterotrusion, and the effect of the occlusal alteration. Generally, previous studies have shown that an occlusal alteration could alter the mandibular and condylar path as well as muscle activity during laterotrusion or at the lateral jaw position. However, there were some issues in the previous studies that limited their conclusions.

Since the use of a single condylar point in the condylar movement studies usually cannot represent the whole movement of the condyle, a three-dimensional object, then the method for condylar point determination may increase the variability of the condylar tracings. To address these issues, a method to register the coordinates of the condylar points in the coordinate system of a six-degrees-of-freedom jaw-tracking device as well as an investigation of the accuracy of this method would be needed. Then, further investigations on the movement of the condyle as a three-dimensional object, using multiple condylar points, can be done.

In the EMG studies, there is a lack of information about the influence of an occlusal alteration on jaw muscle activity during dynamic laterotrusion and no information on the effect, if any, on lateral pterygoid EMG activity. However, before further investigation can be made on this issue, detailed information about jaw muscle activity during dynamic laterotrusion is needed.

2 Aims

The aims of this study have been divided into four stages.

- (a) First was to develop an indirect method for registering the coordinates of anatomical condylar points in the coordinate system of JAWS-3D and to test the accuracy (systematic error or the overall error) of this method.
- (b) Second was to investigate qualitatively and quantitatively the influence of an occlusal alteration on working-side condylar tracings during the outgoing and return phases of lateral jaw movements using multiple anatomical condylar points determined radiographically.
- (c) Third was to investigate the EMG activity of related jaw muscles during dynamic lateral jaw movements and to develop a new method for matching the jaw displacements and the contralateral IHLP EMG activity during dynamic laterotrusion for further quantitative comparison in aim (d).
- (d) To investigate the influence of an occlusal alteration on jaw muscle activity especially the contralateral IHLP during laterotrusion.

3. Materials and Methods:

The materials and methods section is divided into three parts. The first part is the method of indirect registration of the coordinates of condylar points with a six-degrees-of-freedom jaw tracker. Second is the investigation about the influence of the occlusal alteration on the working-side condylar movement with multiple condylar points. Third is the activity pattern of jaw muscles during three laterotrusion tasks and the influence of the occlusal alteration on the activity patterns.

3.1 Registration of anatomical condylar points in JAWS-3D system

The mandibular coordinate system of the JAWS-3D jaw-tracking device (Mesqui *et al.*, 1985; Airoidi *et al.*, 1994) was defined by three light-emitting-diodes (LEDs) that were supported on a lower triangular target frame. As direct registration of the coordinates of radiographically defined condylar points in this coordinate system was unavailable, an indirect method was needed. A fiducial-marker device was used as an interface, or an intermediate coordinate system, for the transformation of coordinates among different measuring devices: the CT scans, used to determine condyle anatomy and the fiducial marker (Fig. 3.1-1 (A)), the MicroScribe-3DX (a digitizer in three dimensions; accuracy: 0.23 mm; Immersion Corporation, San Jose, USA) that was used to digitize the fiducial marker and the LEDs on the lower target frame (Fig. 3.1-1 (B)), and the JAWS-3D. The coordinates of the condylar points and LEDs were converted into the same fiducial-marker coordinate system (Fig. 3.1-1 (C)). Then, the coordinates of the condylar points could be calculated in the JAWS-3D coordinate system (Fig.

3.1-1 (D)) for later processing of condylar movement data. The accuracy of this indirect method was investigated on a perspex model as well as on a dry skull.

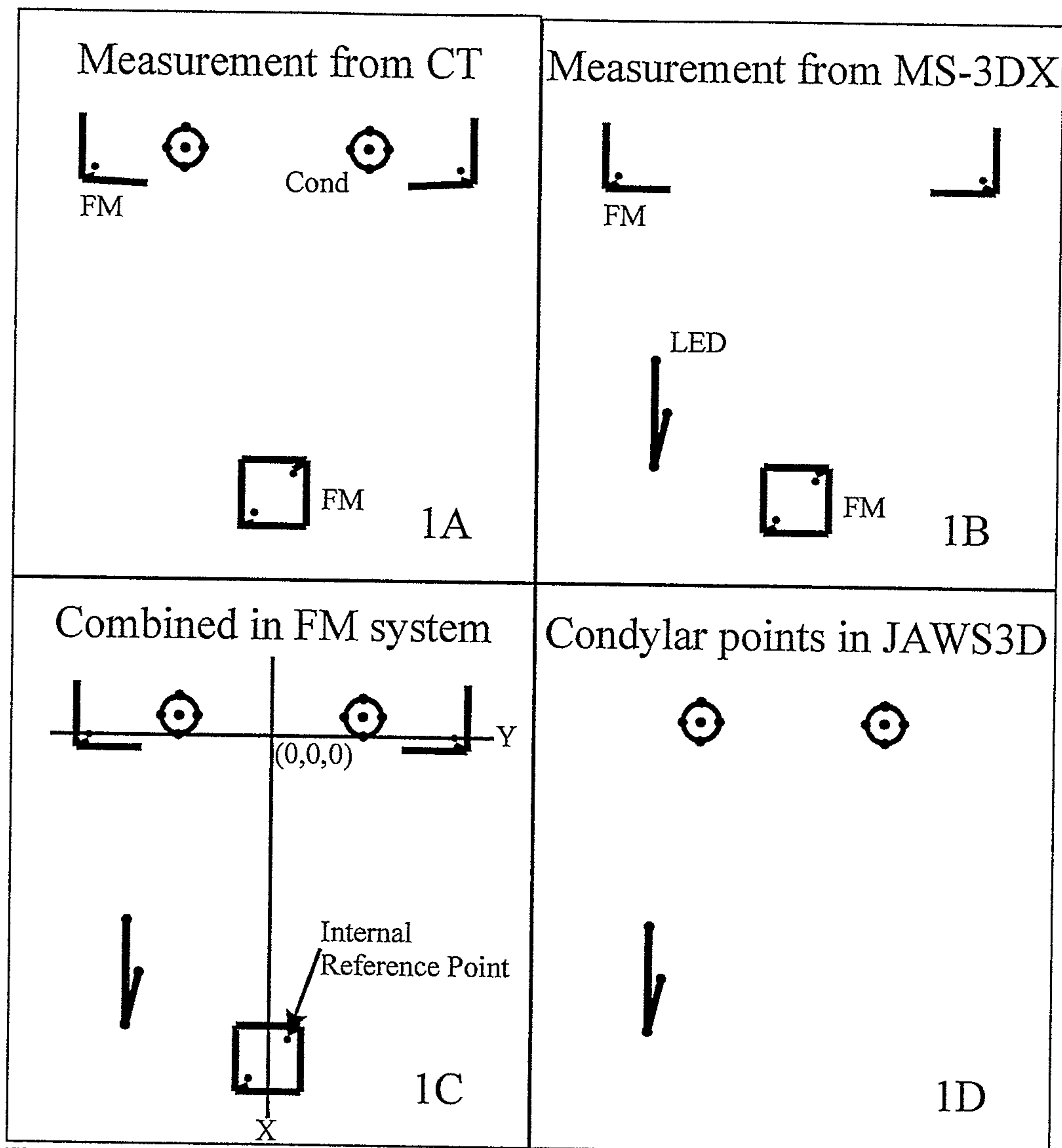


Fig. 3.1-1 Diagrammatic explanation as to how the CT scan, the MicroScribe-3DX and the fiducial marker were used to convert the coordinates of condylar points into the JAWS-3D coordinate system. (A) Measurements of condylar points and fiducial marker in the coordinate system of the CT scans. (B) Measurements of LED points and fiducial marker in the coordinate system of MicroScribe-3DX. (C) Converting data from (A) and (B) into the coordinate system of fiducial marker. (D) Calculation of the coordinates of condylar points in the coordinate system of JAWS-3D (Cond, Condylar points; FM, fiducial marker; LED, LED points on the lower target frame of JAWS-3D; X, X-axis; Y, Y-axis).

3.1.1 Fiducial marker

The CT scans and MicroScribe-3DX registered the coordinates of specific points in their own coordinate systems; therefore, the coordinates from these two measurements had to be converted into the same intermediate coordinate system

(e.g. fiducial marker) before combination. The fiducial marker contained three distributed fiducial boxes (30 mm sides): one lateral to each mandibular condyle and one anterior to the chin. The fiducial box lateral to the condyle contained three brass rods attached to the anterior and the lateral surfaces and the line of intersection of these two surfaces. The anterior box contained two sets of three brass rods: one set at the anterior and right surfaces and the line of intersection; the other set at the posterior and left surfaces and the postero-left line of intersection. These four sets of brass rods defined the coordinate systems of the fiducial marker and could be determined in both CT images and MicroScribe-3DX measurements. The brass rods were 0.3 mm diameter in the perspex model and were modified to 0.6 mm diameter in the fiducial-marker device at the dry skull experiment for better CT image results.

3.1.2 Perspex model

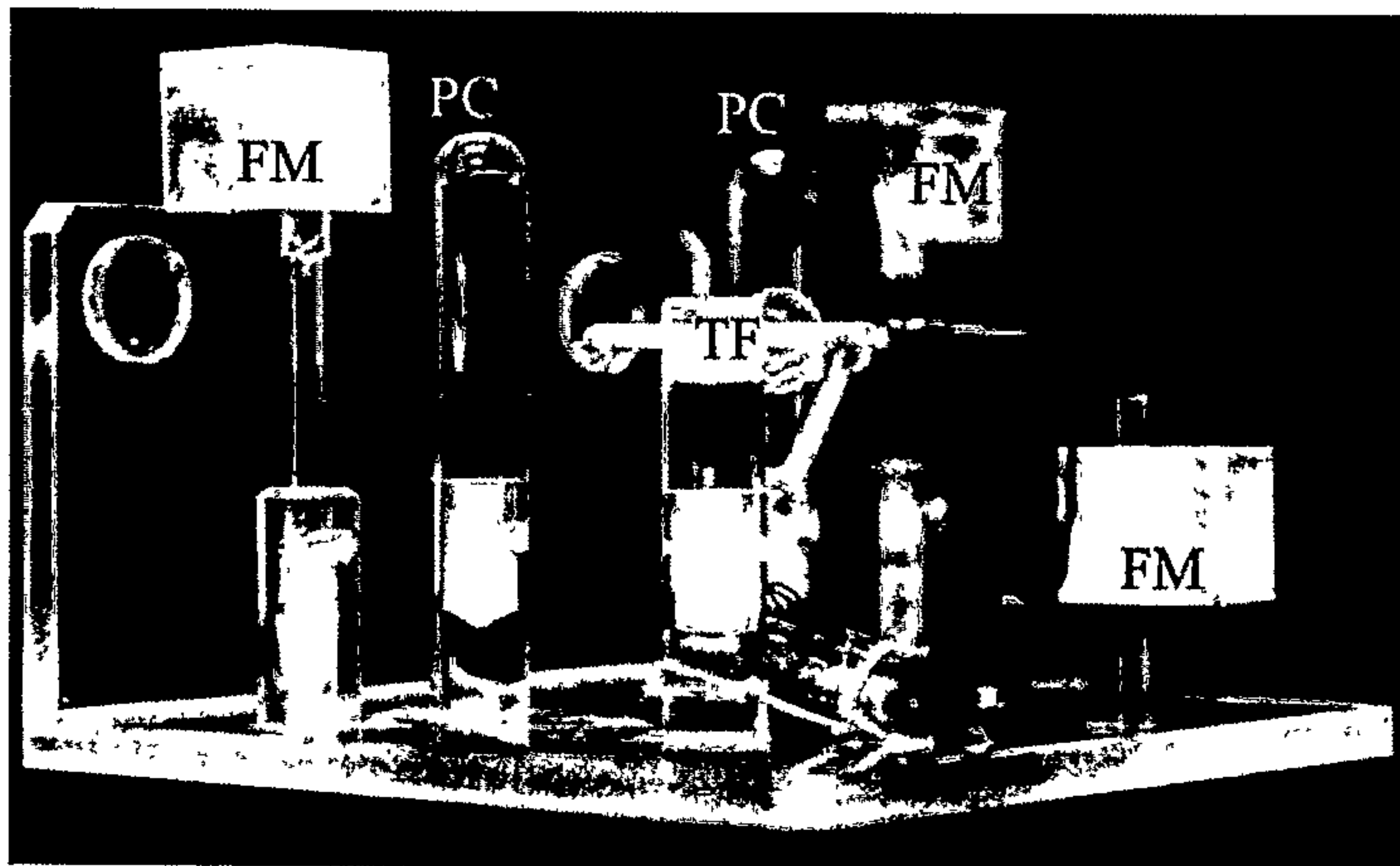


Fig. 3.1-2. Perspex model showing perspex pseudo-condyles (PC), fiducial marker (FM) and target frame (TF) at 45° view from the front and side.

A perspex model was constructed (Fig. 3.1-2). It contained two 20 mm diameter poles (representing perspex pseudo-condyles), three (bilateral to the condyles and lower anterior) fiducial-marker boxes, and a holder for the lower target frame of the JAWS-3D tracking device.

Perspex pseudo-condyle

The two 20 mm diameter poles were 100 mm apart centre to centre. The top of each pole was machined into a hemisphere. Five Gutta Percha points (Progress, Mexico, ~0.5 mm diameter) were glued to each hemisphere: one at the most superior location (S), and one each at the most anterior (A), lateral (L), posterior (P) and medial (M) locations around the circumference which was 9 mm below the most superior Gutta Percha point.

Fiducial marker

Bilateral condylar fiducial-marker boxes were located lateral to the perspex pseudo-condyles (40 mm between nearest surfaces). The anterior box was located 130 mm anterior and 70 mm below the midpoint between the bilateral boxes.

Lower target frame of JAWS-3D

The top centre of the target frame holder was 70 mm anterior, 40 mm inferior and 30 mm lateral to the right perspex pseudo-condyle. The spatial relation of the target frame to the perspex pseudo-condyles was approximately the same as its relationship to the condyles in the human subject.

3.1.3 Dry skull

The accuracy of the indirect method was also tested on one human dry skull (Fig. 3.1-3). A fiducial-marker device (modified from Krebs *et al.*, 1994), later also used for studies on living human subjects, was constructed.

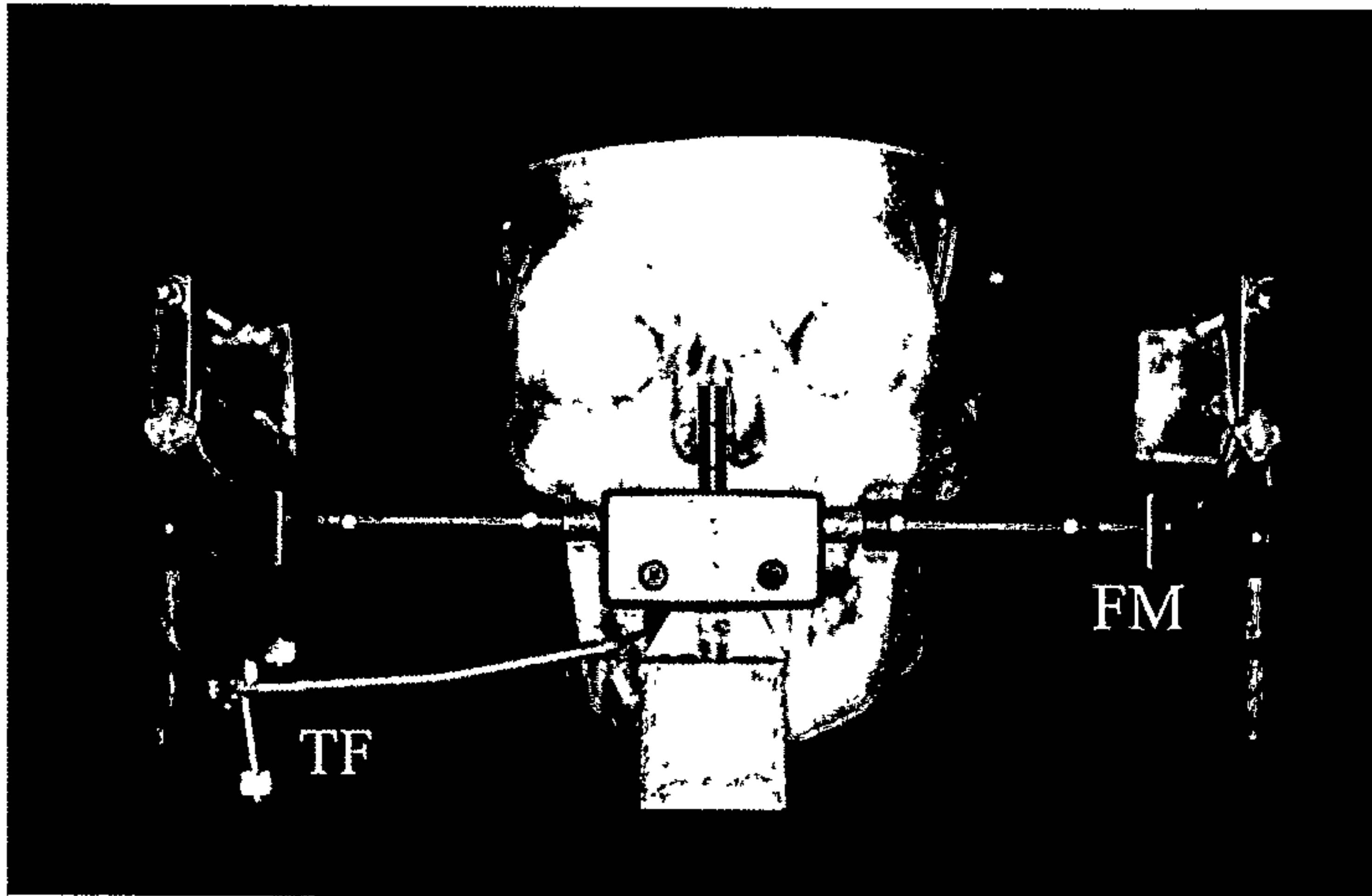


Fig. 3.1-3. Frontal-view photograph showing fiducial-marker (FM) device and target frame (TF) placed on the dry skull.

Dry skull

On each condylar head of the dry skull, five Gutta Percha points (~0.5 mm diameter) were glued: one each at the most superior (S) position, the lateral pole (L), the medial pole (M), and at about the same horizontal level as the lateral pole, one each at the most anterior (A) and most posterior (P) positions. A lower clutch supporting the lower target frame (TF in Fig. 3.1-3) of the JAWS-3D was attached to the lower right anterior teeth in a manner similar to that in human subjects.

Fiducial-marker device

The fiducial-marker device consisted of three fiducial boxes (Fig. 3.1-3) with one lateral to each condyle and one anterior to the chin. The boxes were connected by a carbon-fibre framework. An acrylic custom-made bite plate attached to the anterior part of this device allowed precise repositioning after removal.

3.1.4 Indirect measurement

The indirect method of measurement used the fiducial-marker device as a reference system that connected the coordinate systems of the MicroScribe-3DX, the CT scans and the JAWS-3D.

CT images

The aim of the CT images was to determine the three-dimensional (3D) positional relationship between the condylar Gutta Percha points and the fiducial marker in the CT coordinate system. The images were taken parallel to the Frankfort Horizontal Plane, although the method of analysis will give the correct coordinates irrespective of the orientation. On the perspex model, 22 consecutive slices through the pseudo-condylar region and 24 consecutive slices through the anterior fiducial box region were taken (1 mm thick). The brass rods of the fiducial marker and the Gutta Percha points appeared as small radiopaque dots on the CT images. The CT images were then transformed into TIF format to allow measurement of the coordinates of each dot in Microsoft® Paint. The resolution (i.e. field of view divided by the number of elements) of the CT images was approximately 0.67 mm per pixel (345 mm/512 pixel) in the antero-posterior and medio-lateral axes and 1 mm per slice in the supero-inferior axis. The CT images were a superimposition of all the structures within the 1-mm thickness.

To reduce the radiation dose, an investigation was made of the influence of reducing the number of CT images on the accuracy with which the indirect condylar points could be determined. From the 46 CT images (22 condylar images + 24 anterior images) of the perspex model, two sets of images were

selected. One set (12 + 6) consisted of 12 consecutive images that covered the whole perspex pseudo-condylar head and six images that were arbitrarily selected from the anterior images but at 2 mm intervals. The other set (12 + 5) had the same images as the 12 + 6 set except the lowest of the six anterior images. There was little difference in accuracy among these three data sets (22 + 24, 12 + 6, and 12 + 5) of CT images. So, on the dry skull, it was sufficient to take 12 consecutive slices through the condylar head and five slices (2 mm apart) through the anterior fiducial box region. Each slice was 1 mm thick.

MicroScribe-3DX measurement

The aim of the MicroScribe-3DX measurement was to determine the positional relationship between the target frame LEDs and the brass rods of the fiducial marker in the MicroScribe-3DX coordinate system. MicroScribe-3DX is a 3D digitizer that registers in its coordinate system the 3D coordinates of any point.

On the fiducial boxes of the perspex model and fiducial-marker device, four points on each brass rod were arbitrarily preselected at 8 mm intervals (a total of 48 points). An indentation (~0.2 mm in dimension) at each point on the brass rod was made. The 3D coordinates of these 48 points were determined in sequence with the MicroScribe-3DX and repeated 25 times. On the perspex model and dry skull with the fiducial-marker device in position, a set of MicroScribe-3DX measurements was also made in sequence and this was repeated 25 times. The regions digitized were the centres of each of the three LEDs (termed LED points) and, of the 48, six widely distributed preselected points: the highest and lowest points on the right surface and the lowest point on the anterior surface of the

anterior fiducial box and the same three points on the right box. The tip of the MicroScribe-3DX was positioned by hand as close as possible to the centre of each LED.

The reason for performing measurements of 48 fiducial marker points in the first instance and measurements of six preselected points and LED points in the second was to reproduce the procedure to be used later during experiments with living subjects. The registration of 48 points as well as the LED points in the same measurement would take so long that a living subject would be unlikely to maintain a fixed position throughout. However, by registering separately, we could fix the fiducial-marker device itself firmly on the table and measure the 48 points before the experiments to allow calculation of the fiducial-marker coordinate system. During the experiments on human subjects, we only need to measure the six preselected points and three LED points to transform the LED points into this fiducial-marker coordinate system.

To test how accurately the fiducial-marker device could be placed back on the skull, a set of MicroScribe-3DX measurements was obtained on the dry skull and fiducial-marker device after removing and repositioning the fiducial-marker device. Measurements were repeated five times. This procedure was repeated three times.

Calculation of condylar point coordinates in JAWS-3D coordinate system
with the fiducial marker

As noted before, the fiducial marker acts as an interface between the coordinate systems of the CT scanner, the MicroScribe-3DX, and the JAWS-3D. The fiducial marker defined a transient coordinate system for combining CT scans and MicroScribe-3DX measurements. Then, the coordinates of condylar points could be converted into the coordinate system of JAWS-3D.

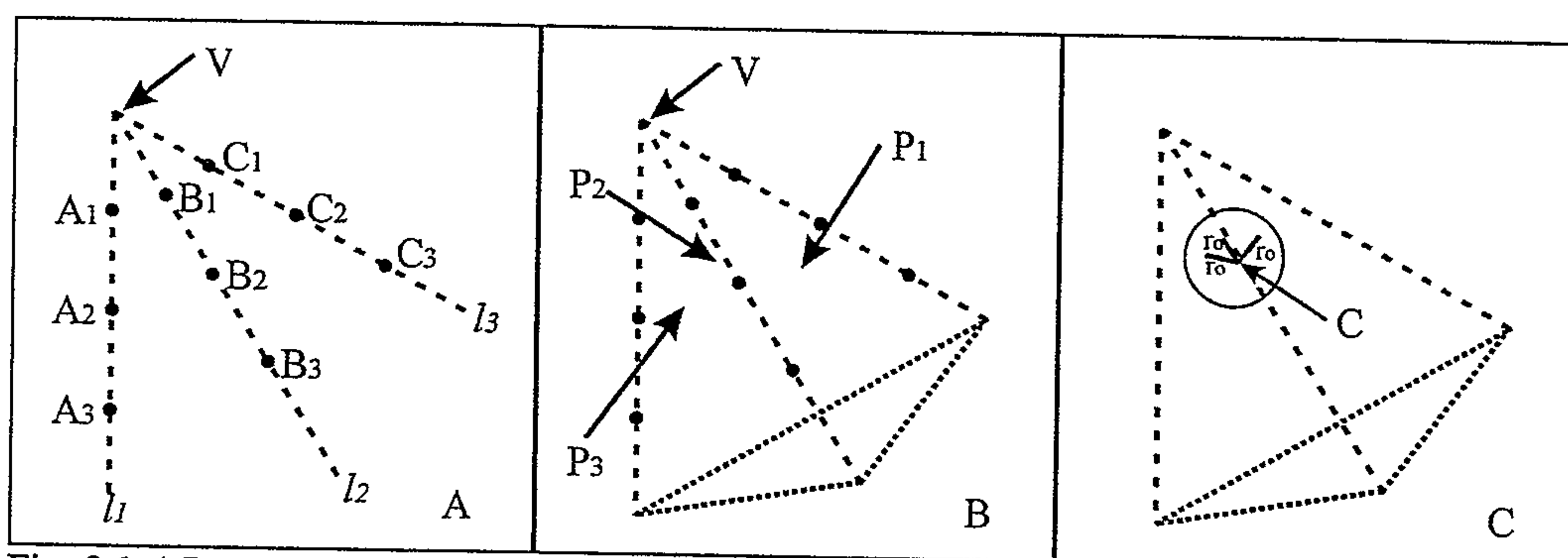


Fig. 3.1-4 Internal reference points. (A) Points measured from the brass rods are denoted A_1-A_3 , B_1-B_3 and C_1-C_3 . Lines l_1 , l_2 and l_3 are constructed through them and intersect at the vertex reference point V. (B) Planes are drawn through two sets points, e.g. P_1 through B_1-B_3 and C_1-C_3 . The three planes theoretically intersect at the vertex V. (C) A sphere of radius r_0 inscribed within the three planes, i.e. equidistant from the three planes, defines the internal centre reference point C.

In the CT images, each brass dot provides the coordinates of one point in the brass rod. With several dots on the same rod, the line defining the position of the rod in space can be determined. In Fig. 3.1-4 (A), the dots A_1-A_3 define the line l_1 , the dots B_1-B_3 define l_2 and the dots C_1-C_3 define l_3 .

In principle these three lines should have a common point of intersection at the vertex V of the box. In practice, measurement errors will cause the lines to be slightly skew and they will fail to meet at a point. This problem can be overcome by fitting three planes to the points. In Fig. 3.1-4 (B), plane P_1 is fitted through the points B_1-B_3 and C_1-C_3 , plane P_2 through C_1-C_3 and A_1-A_3 and plane P_3

through A_1 - A_3 and B_1 - B_3 . Three planes always intersect in a unique point and this determines the vertex V of the box. However, the lines (or planes) must be extrapolated outwards from the set of data points in order to find the vertex. This is a source of error and makes the vertex a poor choice as a reference point. Extrapolation errors can be avoided by choosing an internal point close to the centre of gravity of the points A_1 - A_3 , B_1 - B_3 and C_1 - C_3 as the reference point. We took this to be a point equidistant from the three planes, i.e. the centre of the sphere, of radius r_0 , which touches the three planes, P_1 , P_2 and P_3 internally. This is the point C in Fig. 3.1-4 (C). A series of values was tried and the results showed that taking the radius r_0 as 3.5 mm minimizes the variance of the estimates. Altogether there are four centre reference points (two lateral, two anterior; Fig. 3.1-1 (C)).

The same procedure was applied to determine the four reference points in the fiducial-marker coordinate system from the MicroScribe-3DX measurements of the 48 points on the rods. Since the CT images locate the centres of the rods and the MicroScribe-3DX measurements are taken at the sides, the locations of the CT centres have to be offset to be consistent with the MicroScribe-3DX centres. The effect was immediately apparent in the derived separation of the four centres. The offsets can be ignored for the perspex model (with 0.3 mm rods) but are required for the dry skull (with 0.6 mm rods). The coordinates of the condylar points could then be transformed into the coordinate system of the fiducial marker defined by matching the positions of the four reference points.

Furthermore, by matching the six points selected from the 48, the coordinates of the LED points could also be transformed into the coordinate system of the fiducial marker. Since all the condylar points and the LED points were now in the same fiducial-marker coordinate system, the positional relationships between all points could be determined.

Finally, the coordinates of the condylar points in the JAWS-3D system could be generated since that system is defined by the LED points of the lower target frame.

3.1.5 Direct measurement

A direct measurement between the condylar point coordinates in relation to LED coordinates was done using MicroScribe-3DX. On the perspex model and the dry skull, the position of 10 condylar points and the LED points was measured in sequence and repeated 25 times. Then, the coordinates of the condylar points were re-calculated in the coordinate system of the JAWS-3D. These data were then compared arithmetically with the data from the indirect measurements.

3.2 Influence of an occlusal alteration on working side condylar movement

3.2.1 Subjects

Thirteen healthy volunteers (age 19 – 29 years (mean $\pm$ SD: 21.5 $\pm$ 2.8); six males and seven females) were selected from the dental students of the University of Sydney. The selection criteria included: (a) a complete dentition (range 24-32 teeth) with normal occlusion and tooth alignment, (b) minimal tooth wear, (c) good periodontal health and (d) free of signs and symptoms of temporomandibular disorders, neuromuscular disorders or other pain conditions (for criteria, see Klineberg, 1991b). A clinical assessment included history and comprehensive examination involving palpation of jaw joint and cervical and masticatory muscles, measurement of the range of mandibular movements and an occlusal assessment. All subjects were fully informed and all experimental procedures were approved by the Western Sydney Area Health Service Human Ethics Committee and the Human Ethics Committee of the University of Sydney. In one of the 13 subjects, there was a head movement during the CT scans recording, and this was recognized later during the data analyzing, therefore, the data of this subject were excluded.

3.2.2 Recording of condylar and mid-incisor point movement

Condylar and lower mid-incisor point (MIPT) movements were recorded with an opto-electronic jaw-tracking system (JAWS-3D, Metropoly AG, Zurich, Switzerland, sampling rate = 67/s) which registered the motion of the mandible with six-degrees-of-freedom in real time. The tracings of any point on the mandible could be calculated after recording. During all recordings, the participants sat in an upright position without head support. The system used

three, one-dimensional opto-sensors (resolution: 0.07 mm) to measure the spatial locations of six light-emitting-diodes (LEDs) mounted on two light-weight, plastic, triangular target frames (~2 g ea.) positioned on the side of the face near the area of the temporomandibular joint (TMJ) (Fig. 3.2-1). One target frame was attached to the maxilla and the other to the mandible by custom-made metal clutches. These clutches were designed to interfere minimally with normal lip movement, they allowed full lip seal on closure and were free of occlusal contact. The maxillary target frame followed the motion of the cranium and the mandibular target frame followed the motion of the mandible and the cranium. The target frames were positioned parallel to the sagittal plane with the longest side of each frame parallel to the Frankfort Horizontal Plane. The coordinates of any point of interest on the mandible could be registered with a preselection pointer of JAWS-3D or input manually. Motion of both the cranium and the mandible were recorded with six degrees of freedom. Thus, the pure motion of the mandibular points (after the cranial movements were subtracted) could be calculated in the coordinate system, parallel to the anatomical planes (the Frankfort Horizontal Plane, the sagittal plane and the frontal plane). The coordinate system X-axis was antero-posterior (the posterior direction was positive), Y-axis was left-right (the right direction was positive) and Z-axis was supero-inferior (the superior direction was positive). The starting location of each mandibular point was set to be the (0,0,0) point of each tracing.

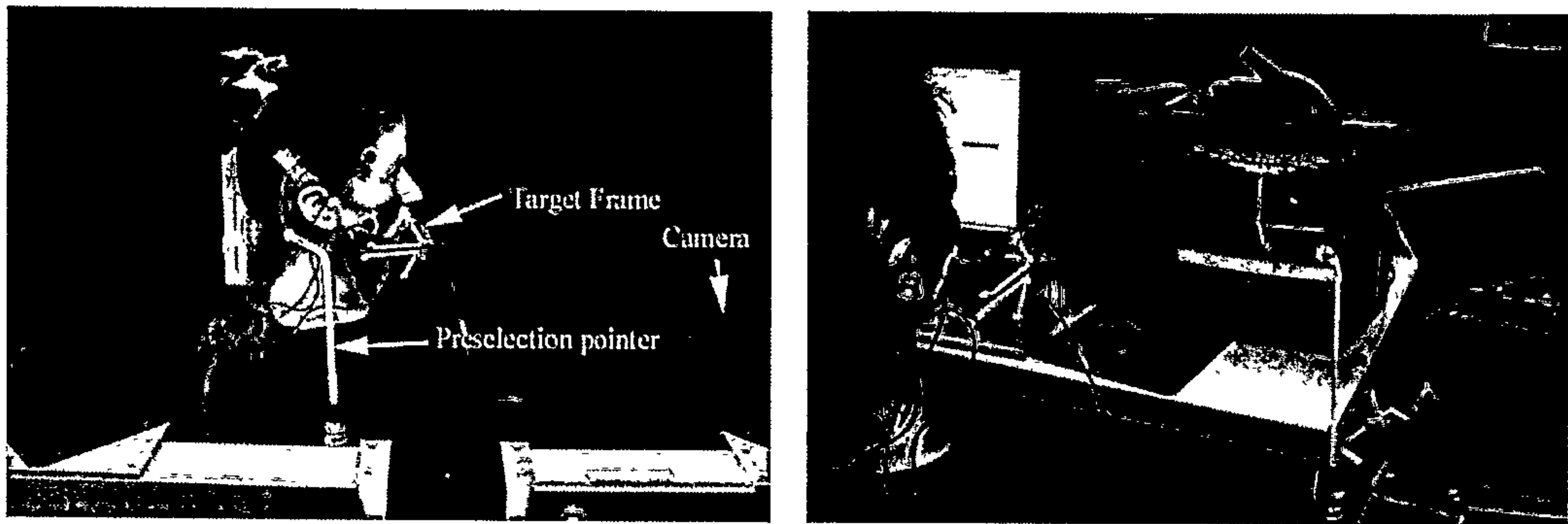


Fig. 3.2-1 JAWS-3D set-up.

The mid-incisor point (MIPT) and five condylar points were selected as reference points:

- (A) the MIPT was the mid-point between the incisal edges of the mandibular left and right first incisors and was registered by the preselection pointer of the JAWS-3D. This point was selected to represent the movement of the lower incisors. The trajectory of this point was displayed on the video screen of the JAWS-3D system in real time during the recordings to standardize the lateral movement by providing visual-feedback.
- (B) The five condylar points included the most superior point (S), the lateral (L) and medial (M) poles, and, at about the same horizontal level of the lateral pole, the most anterior (A) and most posterior (P) points of the working-side condylar head. This should provide a good image for movement of the working-side condylar head. The tracings of these condylar points were calculated off-line.

The coordinates of the condylar points in the coordinate system of JAWS-3D were determined using MicroScribe-3DX and CT scans as previously described in Section 3.1.

Before the jaw-movement recording, a MicroScribe-3DX measurement of six preselected fiducial marker points and three LED points of the lower target frame were registered in sequence and were repeated continuously five times. If the lower clutch was dislocated during the recording, it was first recemented and an additional MicroScribe-3DX measurement would be done to calculate the new coordinates of condylar points. The reason was that the positional relationship between the condylar points and lower target frame might be changed due to the difficulty of cementing the clutch back to exactly the same position. After the end of the recordings, a set of 17-19 slices (12-14 around the condylar head region and 5 anterior to the chin) was taken as previously described in Section 3.1 to measure the relationship between the fiducial marker and the condylar points.

3.2.3 Clutches and occlusal alteration

Upper and lower impressions and a face-bow transfer records were taken from each subject. The casts were articulated on a semi-adjustable articulator (Denar Mk II, Denar Corporation, California, USA). The wax patterns of an overlay (for occlusal alteration) and the retention part of the upper and lower clutches were made in blue inlay wax and then invested and cast in titanium alloy.

Clutches

The clutches included three major components: (a) the retention part, (b) the connection part, and (c) the supporting part for the target frame of JAWS-3D (Fig. 3.2-2). The titanium retention part covered the labial surfaces of the anterior teeth and had a short rod that extended extra-orally. The design of this part did

not cause any interference to tooth contact in maximal intercuspal position and during all jaw movements. The connection part was made in aluminum tube (inner diameter ~1.5 mm). On one end, it was cemented to the short rod of the retention part, whereas the other end was connected to a brass rod that supported the target frame. At the outer third, the tube was cut into two parts and reconnected with a 2-mm separation and fixed with self-cure acrylic resin. This reduced interference (or noise) in the EMG recordings from the JAWS-3D signals. The brass rod fitted into a hole of the target frame. At the outer third of the rod, a flat surface was ground so that a screw could be locked onto the surface to prevent the rotation of the target frame along the rod.

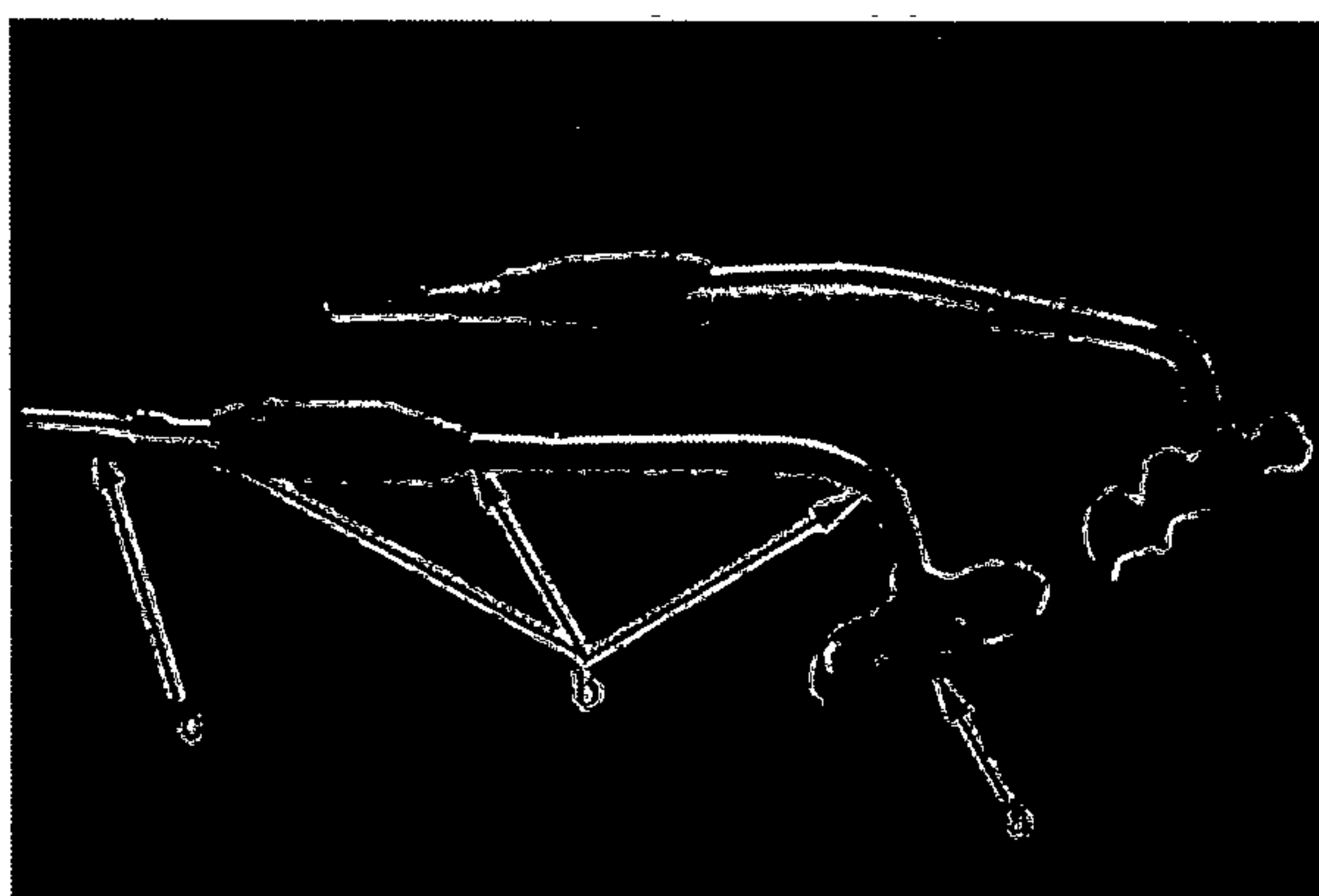


Fig. 3.2-2 Upper and lower clutches: (a) the retention part (b) the connection part, and (c) the supporting part for the target frame of JAWS-3D.

Occlusal alteration

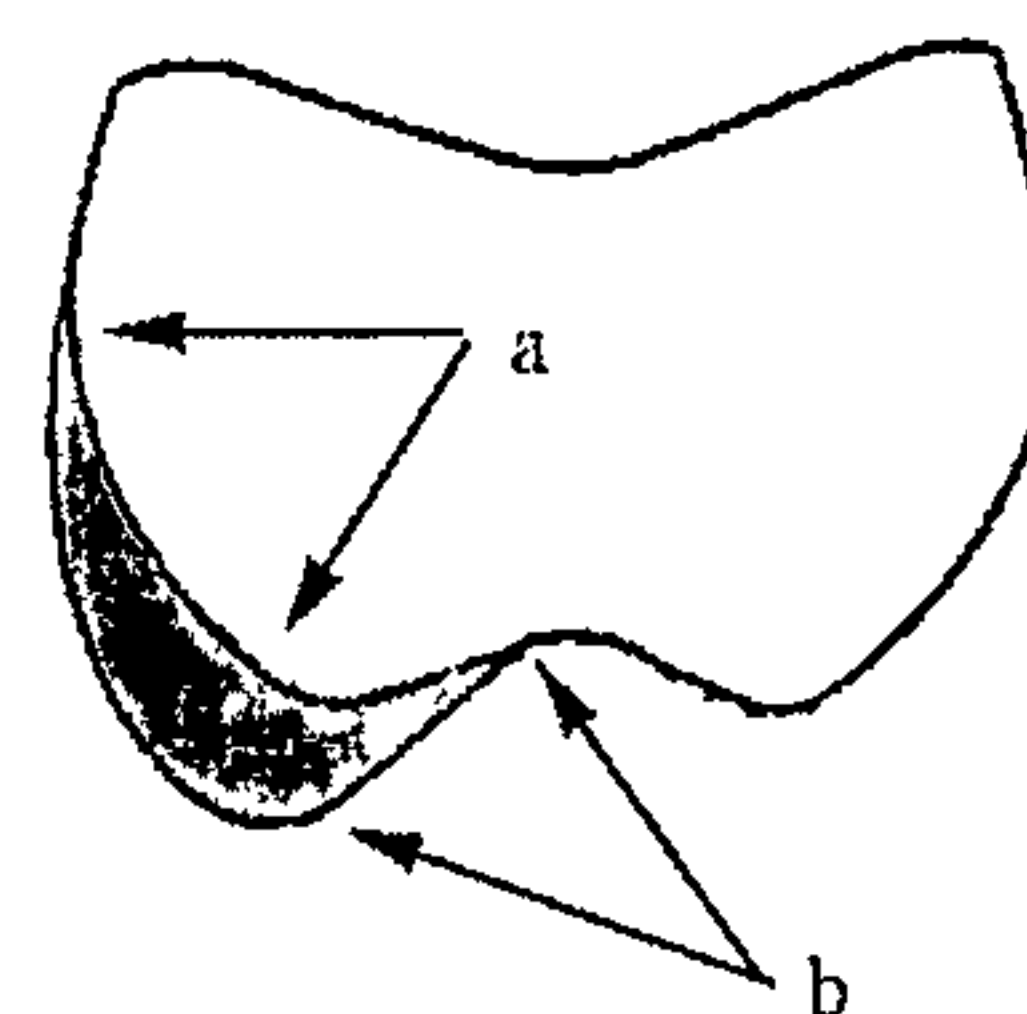


Fig 3.2-3 The design and location of the overlay: (a) the retention part and (b) the interference part.

An overlay was cemented onto the upper first molar of the working side to alter the occlusion. The overlay contained two parts: (a) the retention part and (b) the interference part (Fig. 3.2-3).

The retention part covered the buccal surfaces of three upper posterior teeth to provide retention, and the interference part covered the mesiobuccal cusp of the upper first molar to change the tooth guidance during lateral movements. In the maximal intercuspal position, the overlay did not cause any interference, therefore, the vertical dimension and the occlusal contact location remained the same as those of natural tooth contact (Fig 3.2-4 a and b). In 11 subjects, the lingual inclination of the interference part was 10 degrees steeper than that of the natural tooth guidance (either canine guidance or group function). In one of the 11 subjects, the data was excluded later during data analysis, and this is because of the head movement during CT scans recordings. Therefore, this overlay guided the mandible and discluded all other teeth during laterotrusion to the same side as the overlay (Fig 3.2-4 c and d). Any alteration in the anterior or posterior direction of the natural tooth guidance during laterotrusion was minimized by adjusting and matching the path of laterotrusion under natural and overlay guidance while preparing the wax pattern on the articulator.

The overlay as well as the clutches were first adjusted and fitted on the articulator and later were tried in the mouth for final adjustment prior to the recording session. The surface of the overlay was then polished to allow smooth tooth contact during laterotrusion. A dental floss was tied onto the overlay to prevent accidental dropping and swallowing by the subjects. This floss was fixed

with adhesive wax onto the buccal (or labial) surfaces of the anterior teeth to prevent interference with the experiments as shown in Fig. 3.2-4 b.

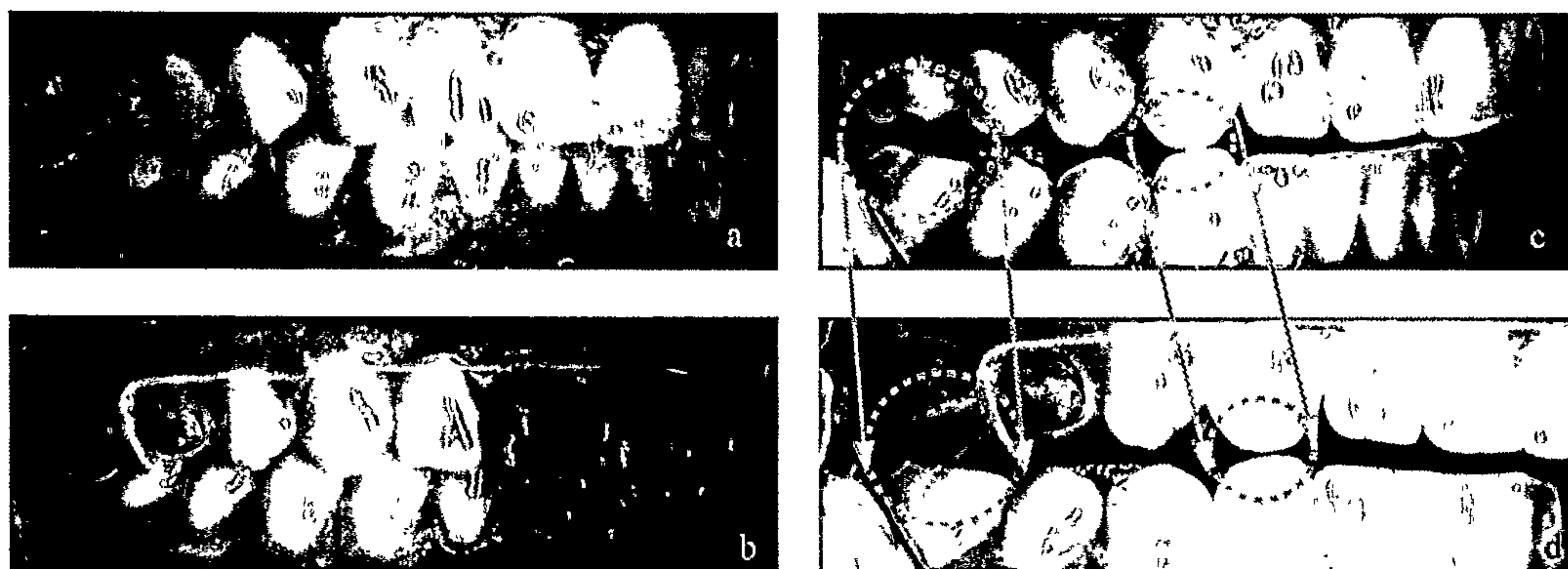


Fig 3.2-4 The effect of the overlay: (a) maximal intercuspal position without overlay; (b) maximal intercuspal position with overlay; there was no interference to maximum intercuspation; (c) laterotrusion under natural tooth guidance; the contact was on the canine area; (d) laterotrusion under overlay guidance; the contact was on the overlay.

In two subjects, there was space available for a steeper inclination, therefore, an additional overlay was constructed with a lingual inclination 20° steeper than that of the natural tooth guidance. However, in another two subjects there was no space for any overlay with an inclination steeper than that of the original guidance. Therefore, in one of these two subjects, a sham overlay was constructed. The sham overlay only had the retention component and did not cause any interference in intercuspal position and during lateral movement. In the other subject, an overlay was constructed with an increase in vertical dimension in the intercuspal position, and the inclination of the overlay guidance was 10° less than that of the natural tooth guidance during lateral movement.

3.2.4 *Jaw movements and experimental conditions*

10 trials of lateral movement to the same side of the occlusal alteration were repeated under the sequence of three (or four, if there was a second overlay) conditions:

- (a) control 1 condition,

- (b) occlusal alteration (OA) condition,
- (c) occlusal alteration 2 (OA2; if present) condition,
- and (d) control 2 condition.

The control 1 condition was performed before the overlay was placed, so the lateral movements were carried out under natural tooth guidance. The occlusal alteration condition was recorded immediately after the placement of the overlay (or the sham overlay in one subject) that discluded all other teeth during laterotrusion. In the three subjects with a second overlay (20° steeper), another set of 10 trials of lateral movement were recorded under the influence of the second overlay (as the occlusal alteration 2 condition). The control 2 condition was performed after the removal of the overlay, and therefore, the occlusal scheme was returned to the original tooth guidance. The control 2 condition was performed immediately after the occlusal alteration (or the occlusal alteration 2) condition. There was an interval of approximately 30 seconds between each trial of recording. During the recordings of the lateral movements, subjects were instructed to maintain a minimal force required to keep the teeth together.

Each trial of lateral movement included five phases:

- (a) *intercuspal position 1 (IP1) phase*: 2.6 s;
- (b) *outgoing phase*: 1.9 mm/s; movement to the same side as the overlay;
- (c) *holding phase*: 2.6 s; the jaw was hold in a position approximately 6 mm away from the intercuspal position;
- (d) *return phase*: 1.9 mm/s; return to the intercuspal position;
- (e) *intercuspal position 2 (IP2) phase*: 2.6 s.

instructed to move the lower jaw laterally under the guidance of teeth or overlay, and therefore the tracings of the MIPT dot might curve slightly. The target LEDs stopped at the last selected LED (normally the fifth LED, which was about 5 mm away from the intercuspal position) for 2 s to hold the mandible in the position close to edge-to-edge position. Then, the selected last LED flashed again, and the target LEDs sequentially illuminated back and stopped at the first LED (at the intercuspal position) for 2 s. The LEDs were controlled by scripts written in Spike 2 software (Cambridge Electronic Design, Cambridge, UK, CED) and run on the CED system. At the beginning of each trial, the CED system sent a signal to both the target LEDs and the JAWS-3D to synchronize the LED illumination and the JAWS-3D recordings.

3.2.5 Data analysis

For qualitative and quantitative assessment of the condylar head tracings, the MIPT displacements in 3D from the intercuspal position were used to standardize the comparison. The MIPT displacements in 3D from the intercuspal position was defined as the total displacements of the MIPT along the X-axis, Y-axis, and Z-axis from the maximum intercuspatation. The formula of calculation is shown as follow:

$$D_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2}$$

The x_0 , y_0 and z_0 represents the MIPT location in X-axis, Y-axis, and Z-axis, respectively, at the maximum intercuspatation. The x_i , y_i and z_i represents the MIPT new location in X-axis, Y-axis, and Z-axis, respectively, at any arbitrarily selected time within a tracing, and D_i is the MIPT displacement in 3D at the same time. From each tracing, the time, at which $D_i = 1, 2, 3$ and so on (mm),

was selected and determined at the outgoing and return phases. After matching the time in the files for the MIPT tracing and for the condylar point tracing, the displacements of each condylar point from the starting position could be found and standardized by the MIPT displacements. A computer program (see Appendix I) was written to perform this procedure.

3.2.5.1 Qualitative assessment of the MIPT and condylar-head tracings

For qualitative assessment of the MIPT and condylar head tracings, each trial of the lateral movements was projected and plotted into three different planes (frontal, horizontal and sagittal planes) as well as two different phases (outgoing and return phases).

MIPT tracings

The tracings of each trial of MIPT movement were projected and plotted into three planes and two phases. By superimposition of the tracings of one trial arbitrarily selected from each condition, the differences among *Control 1*, *Occlusal Alteration*, *Occlusal Alteration 2* and *Control 2* conditions could be qualitatively assessed (of which the results were not shown in the Results section).

Condylar head tracings

The influence of the occlusal alteration on condylar movements was qualitatively assessed by the superimpositioning of the movements of a simplified outline of the condylar head from one trial arbitrarily selected from each of the three (or four) conditions.

First, in each plane, the radiographically-defined condylar points were projected and plotted based on their positional relationships in the starting intercuspal position. In the frontal plane, the most superior condylar point and the lateral and the medial poles of the condylar head were projected. In the horizontal plane, the most anterior and the most posterior condylar points and the lateral and the medial poles of the condylar head were projected. In the sagittal plane, the most superior, the most anterior and the most posterior condylar points were also projected. Lines between the selected condylar points were plotted to provide a simple outline of the condylar head. Therefore, a triangle was projected and plotted in the frontal as well as the sagittal planes and a quadrilateral in the horizontal plane.

Second, in each trial, the displacements of each condylar point were calculated at each mm of MIPT displacement from the intercuspal position as mentioned previously. Then, in each plane, a second, third, fourth, and so on, projected triangle (or quadrilateral) could be drawn based on the displacements of the condylar points at the selected displacement(s) of MIPT. The trajectories of the movements of the condylar points at the outgoing or return phases could also be drawn.

Finally, by superimposing one trial arbitrarily selected from each condition, the influence of the occlusal alteration on the working-side condylar movements could be qualitatively assessed. From each subject, five trials from 10 trials of each condition were arbitrarily selected and compared.

3.2.5.2 Quantitative assessment of the tracings of the condylar points

With the tracings of multiple radiographically defined points of the working-side condylar head, the quantitative assessment of the influence of an occlusal alteration on the working-side condylar head during lateral movement could be separated into two parts: (a) the displacements of each condylar point, and (b) the rotation of the condyle. From each subject, the mean values of 10 trials under each condition were calculated. General Linear Model Repeated Measures with Bonferroni adjustment for multiple comparisons was used for statistical comparison at the significance level of 0.05.

Displacements of each condylar point

First, in each trial, the time at which MIPT reached each mm of its displacement from the intercuspal position was determined. Second, after matching the time in the files for the MIPT tracing and for the condylar point tracing, the displacements of each condylar point from the starting position could be found. Then, the condylar displacements were statistically compared at the 3rd and 5th mm of mid-incisor displacement. At the 5th mm of mid-incisor displacement, the mandibular displacement at the working-side first molar region was about 2.5 mm and this approximates the regular molar cusp tip-to-cusp tip position during lateral movement.

Rotation of the working-side condyle

When an object performs a three-dimensional translation, the amount of translation along each axis is independent to each other. For example, the two-

dimensional model, in Fig. 3.2-6 A, showed that when point A moved to the new position A', the amount of translation along each axis remains the same no matter which axis was first calculated. But this is not the case when an object performs a three-dimensional rotation. For example, the rotation angle calculated about the X-axis is defined as angle ϕ , about the Y-axis is as angle θ , and about the Z-axis is as angle γ . The angle ϕ_1 , θ_1 and γ_1 (calculated in the order of X-, Y- and Z-axes) would be different to the angle ϕ_2 , θ_2 and γ_2 (calculated in the order of Z-, Y- and X-axes), respectively, despite the fact that these values were calculated from the same movement of the same object. Therefore, the calculated amount of rotation along each axis was dependent on the other two angles, and could not be discussed separately.

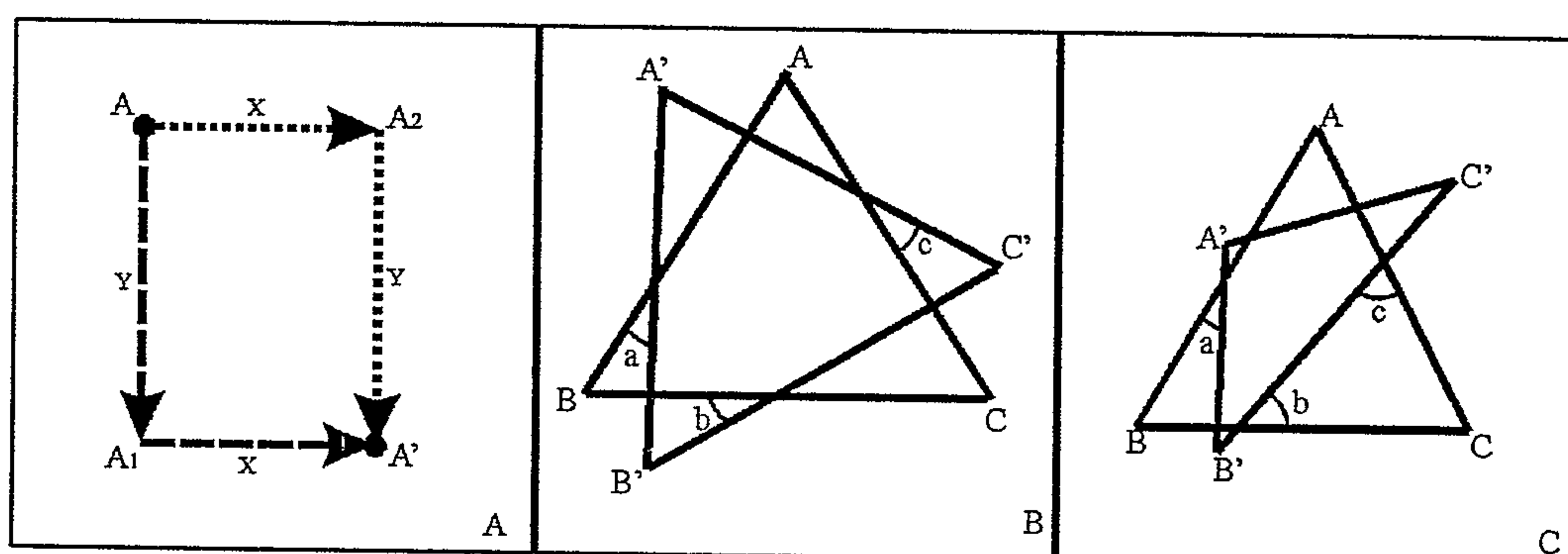


Fig. 3.2-6 Diagrammatic explanation of the difficulty of separately calculating rotation angle along each axis after three-dimensional rotation. (A) The independence of the translation. When point A moves to the new position A', the amount of translation along each axis remains the same, irrespective of which axis that was calculated first. (B) After an object ABC rotates around an axis perpendicular to a plane, the projection of this object shows a uniform angle of rotation (eg., angle $a = b = c$). (C) After an object rotated three-dimensionally, the projection of this object on one plane shows different angles of rotation (calculated between the two positions of two arbitrary points) to each other (eg., angle $a \neq b \neq c$). Therefore, there is no representative rotation angle in this plane.

In addition, unlike one-dimensional rotation, the projection of an object on a single plane would not show a representative angle of rotation after a three-dimensional rotation. For example, in Fig. 3.2-6 B, after an one-dimensional rotation from ABC to A'B'C', the projection of the object on the plane perpendicular to the rotatory axis showed a uniform angle of rotation. The angle

a between line AB and A'B', the angle b between line BC and B'C' and the angle c between line AC and A'C' were similar to each other. Therefore, in the symmetrical movement of the mandible (e.g. opening-closing), the angle could be calculated along the axis perpendicular to the sagittal plane. However, the lateral movement of the mandible involves three-dimensional rotation. As in Fig. 3.2-6 C, after a three-dimensional rotation, the projection of this object on an arbitrary plane shows different angles of rotation (calculated between the two positions of two arbitrary points) to each other. Therefore, there was no representative angle along the axis perpendicular to the projected plane.

However, when the angles of rotation were very small, we could use the approximate value in the formula (for detail, see Appendix II) used to calculate the angle of rotation. Then, we could obtain the results that were independent to the order of rotation. In other words, the rotation angle calculated in the order of X-axis (ϕ_1), Y-axis (θ_1), and Z-axis (γ_1) would be very close to the order of Z-axis (γ_2), Y-axis (θ_2) and X-axis (ϕ_2) (e.g. $\phi_1 = \phi_2$; $\theta_1 = \theta_2$; $\gamma_1 = \gamma_2$).

Angles of rotation	Errors caused by approximation
1°	0.01°
2°	0.04°
3°	0.08°
5°	0.24°
8°	0.65°
10°	1.1°
12°	2.5°

Table 3.2-1 The errors caused by using approximate values in the angle calculation at different angles of rotation.

When the measurement error was not taken into account, the error, yielded in the calculation of rotation angles based on this formula (provided by A/Prof. C. Durrant, see Appendix II) with approximate values, was about 1% for angles of 1°, 2.5% for angles of 5° and 10% for angles of 10° due to the use of

approximation (Table. 3.2-1). Therefore, a macro (Appendix II) in MicroSoft® Excel could be written to calculate the approximate angle of rotation along the axis perpendicular to each plane. Fig. 3.2-7 defines the orientation of the reference axes and the rotation angles. The angle at each mm of MIPT displacements was calculated for further comparison. Again, the angles at the 3rd and 5th mm of displacements were selected for statistical comparison.

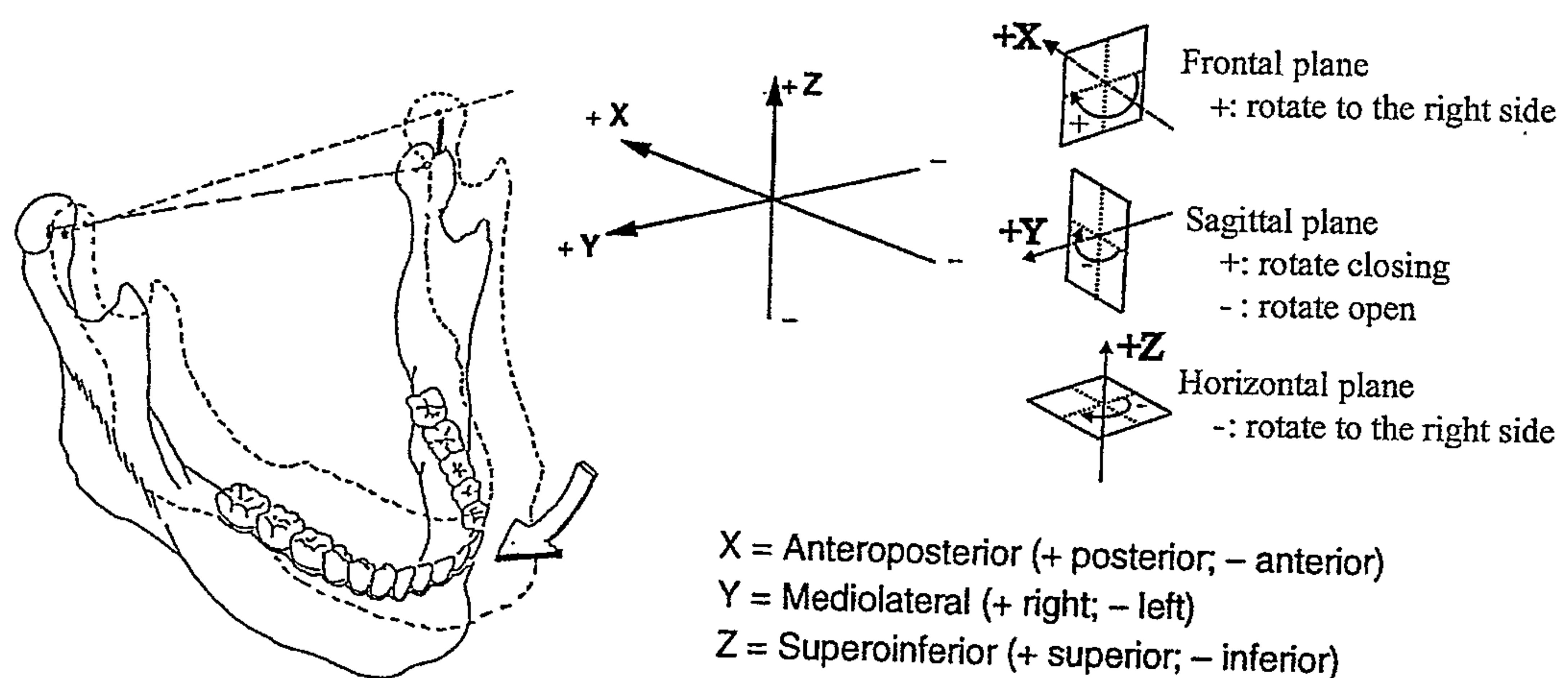


Fig. 3.2-7 Reference planes and the orientation of the reference axes and rotation angles (modified from: Lundeen *et al.*, 1978).

3.3 Influence of an occlusal alteration on the EMG activity of jaw muscles

3.3.1 Subjects

Sixteen healthy volunteers (age 18 – 29 years (mean $\pm$ SD: 21.5 $\pm$ 2.6); eight males and eight females) were selected from the dental students of the University of Sydney. These 16 included the same 13 subjects described in 3.2.1. The selection criteria have been described in Section 3.2.1. All subjects gave informed consent and all experimental procedures were approved by the Western Sydney Area Health Service Human Ethics Committee and the Human Ethics Committee of the University of Sydney. The following summarizes methods relating principally to the EMG recordings. Other methodological aspects are detailed in Section 3.2.1.

3.3.2 Recording of mid-incisor point movement and visual feedback

During all recordings, the participants sat in an upright position without head support. Lower mid-incisor point (MIPT) movements were recorded with an opto-electronic jaw-tracking system (JAWS-3D, for details see Section 3.2.2). The trajectory of this point was displayed on the video screen of the JAWS-3D system in real time during the recordings to standardize the movement tasks by providing visual-feedback (for details, see Section 3.2.4). The visual-feedback device was a linear bank of LEDs controlled by scripts written in Spike 2 software (Cambridge Electronic Design, Cambridge, UK, CED) and ran on the CED system. At the beginning of each trial, the CED system sent a signal to both the target LEDs and the JAWS-3D to synchronize the EMG activity recordings (CED system), the LED illumination and the JAWS-3D recordings.

3.3.3 EMG recording, electrode placement and verification

Electromyographic (EMG) activity was amplified by an isolated bioelectric amplifier (SA Instrumentation Co., San Diego, USA) and then recorded by the micro1401 from Cambridge Electronic Design (CED; Cambridge, UK) for off-line analysis. The sampling rate was approximately 10,000 samples/s and the bandwidth was 100 – 10 kHz. A modification on this device was performed to reduce the background noise by replacing the original connection wires with shielded wires. However, due to this modification, a maximum of seven (originally eight) channels was available during each experiment.

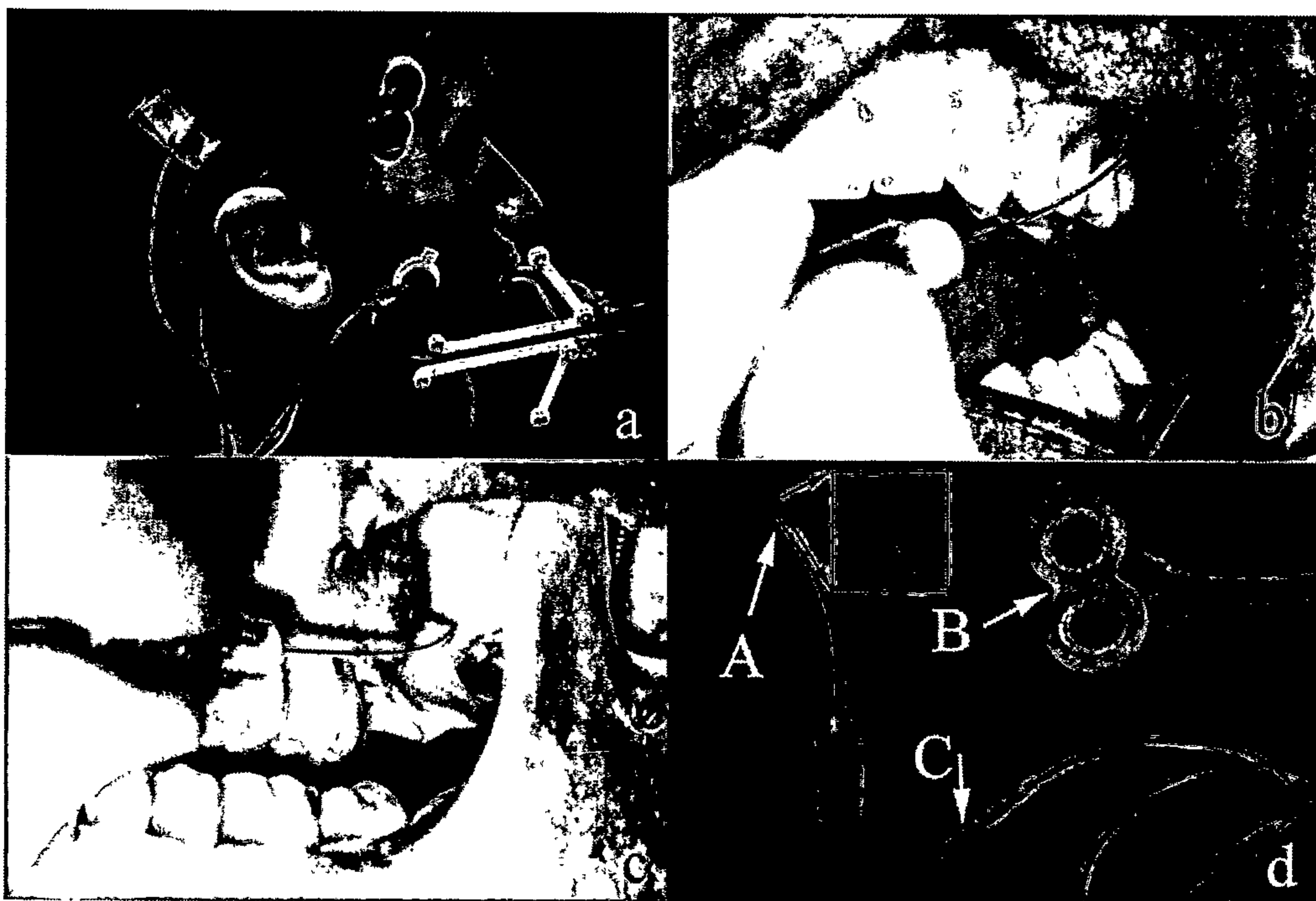


Fig. 3.3-1 Electrode placement. (a) Right posterior temporalis (bipolar hook electrodes), as well as anterior temporalis, masseter, and anterior digastric (bipolar surface electrodes) muscles. (b) Intra-oral approach for the inferior head of the lateral pterygoid muscle. (c) Intra-oral approach on dried skull; the tip of the needle contacts the lateral pterygoid plate. (d) Electrodes: (A) pre-curved spinal needle with a pair of Teflon-coated stainless-steel wires. The wires were bent back over the bevel of the needle ~2 mm in one wire and ~4 mm in the other from its tip; (B) surface electrodes; and (C) hook electrode.

The EMG activity of the contralateral (to the overlay) inferior head of lateral pterygoid (IHLP; with intra-muscular electrodes), bilateral posterior temporalis (bipolar hook electrodes; Fig. 3.3-1 (d) C) as well as bilateral anterior temporalis,

masseter and submandibular muscles (silver/silver chloride surface electrodes; Fig. 3.3-1 (d) B) muscles were recorded (Fig. 3.3-1 (a)). Since a maximum of seven muscles only could be recorded simultaneously, in the first six experiments, EMG activity was recorded from the bilateral anterior temporalis, masseter and submandibular muscles. In the next three recordings, the EMG activity was recorded from the contralateral IHLP and masseter as well as ipsilateral anterior and posterior temporalis, masseter and submandibular muscles. In these subjects, no change in activity was observed in the bilateral submandibular muscles due to the occlusal alteration, therefore, in the remaining recordings, the contralateral IHLP and bilateral anterior and posterior temporalis as well as masseter muscles were recorded.

The contralateral IHLP was recorded with bipolar Teflon-coated stainless-steel wire electrodes. An intra-oral approach (modified from Wood et al., 1986) was used (Fig. 3.3-1 (b)). The intra-oral approach involved placement via a pre-curved 25-G spinal needle that was inserted through the oral mucosa above the second molar tooth with the lower jaw slightly opened (about 10–15 mm) and shifted to the needle insertion side. Therefore, the position and the length of the lateral pterygoid during electrode placement would be reasonably close to that during movement recordings to avoid possible electrode displacement during recording. The needle was advanced in an upward, medial and posterior direction until the needle contacted the lateral surface of lateral pterygoid plate (Fig. 3.3-1 (c)). The needle was then withdrawn, leaving the wires in place. The first 2 mm of the Teflon coating at the tip of the electrodes was removed for multiple motor-unit EMG recordings. One electrode was bent back over the bevel of the needle

2-mm from the tip and the other was bent back 4-mm from the tip (Fig. 3.3-1 (d) A).

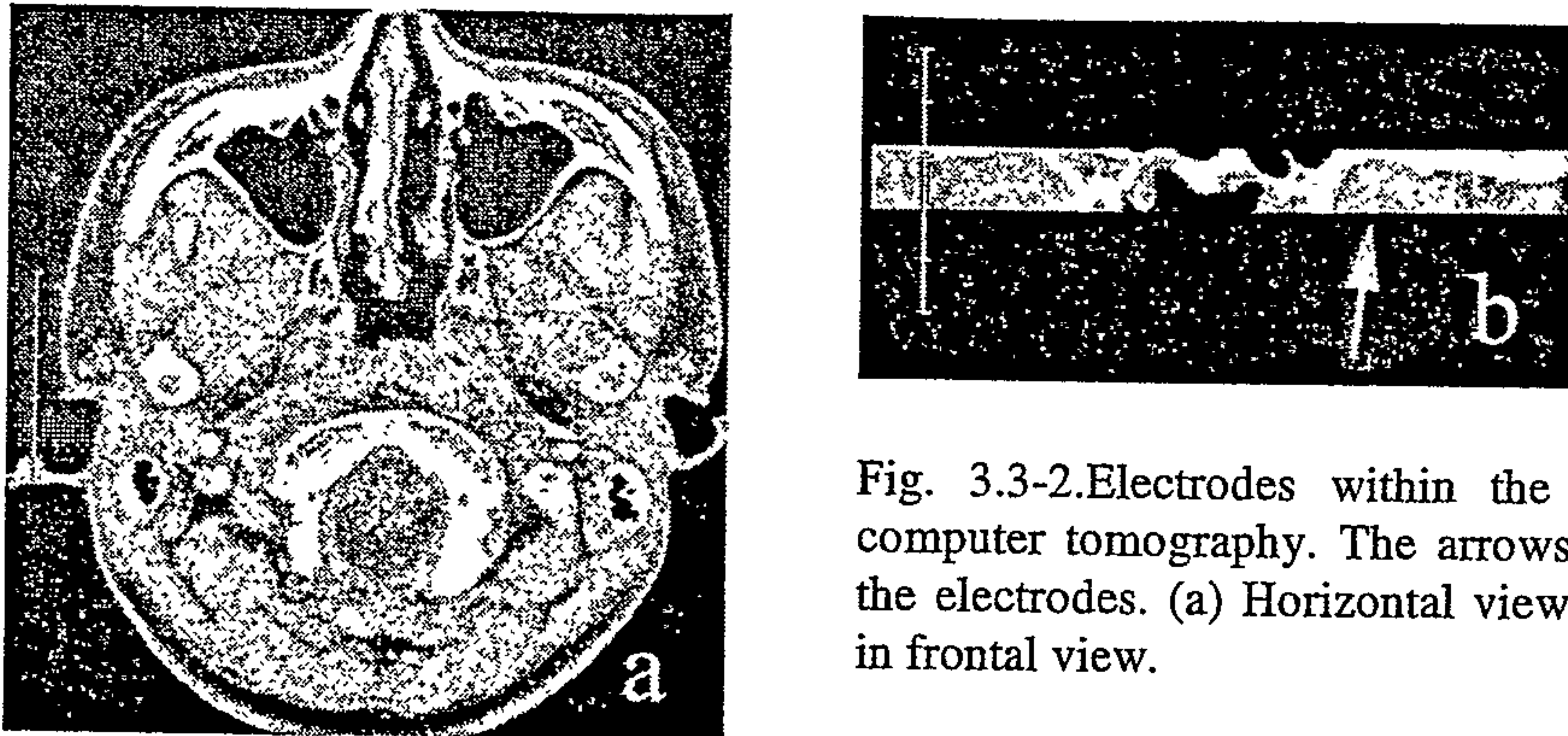


Fig. 3.3-2. Electrodes within the IHLP verified by computer tomography. The arrows indicate the tip of the electrodes. (a) Horizontal view; (b) reconstruction in frontal view.

At the end of each experiment, computer tomography scans (at 1-mm thickness) were made parallel to the Frankfort Horizontal Plane. These scans together with the reconstructed images in the frontal plane were used to verify and confirm the location of the electrodes within the IHLP (eg. Fig. 3.3-2 (a) and (b)).

3.3.4 Occlusal alteration

Upper and lower impressions as well as face-bow transfer records were taken from each subject for preparing clutches and the overlay (for details, see Section 3.2.3). The overlay was cemented onto the upper first molar of the working side to alter the occlusion. In 14 subjects, the lingual inclination of the overlay was 10° steeper than that of the natural tooth guidance (either canine guidance or group function). Therefore, this overlay guided the mandible and discluded all other teeth during laterotrusion to the same side as the overlay. This overlay did not cause any interference at intercuspal position.

In another two subjects, there was no space for any overlay with an inclination steeper than that of the original guidance. Therefore, in these two subjects, a sham overlay was constructed. The sham overlay covered the buccal surfaces

only of the posterior teeth and did not cause any interference in intercuspal position and during lateral movement. In one of the two subjects with the sham overlay, an additional overlay was made and caused an increase in vertical dimension in intercuspal position, and the inclination of the overlay guidance was 10° less than that of the natural tooth guidance during lateral movement.

3.3.5 Jaw movements and experimental conditions

Four movement tasks were repeated under the sequence of:

- (a) lateral movement with low closing force to maintain tooth contact at slow speed (10 trials) to the same side of the occlusal alteration (14 subjects plus two with sham overlay and one (of the two) with increased vertical dimension); or,
- (b) protrusion with low closing force to maintain tooth contact (5 trials) at slow speed (13 subjects plus one with sham overlay);
- (c) lateral movement with low closing force to maintain tooth contact at fast speed (about triple the speed of the movement (a), 10 trials, five subjects plus one with sham overlay);
- (d) lateral movement with high closing force at slow speed (10 trials): subjects were instructed to maintain low closing force during the IP1 and IP2 phases and to perform lateral movement at the highest closing force within comfortable range during the outgoing, holding and return phases (14 subjects plus two with sham overlay).

These movement tasks were repeated under the sequence of three conditions:

- (a) control 1 (before occlusal alteration); or,

- (b) occlusal alteration (OA) (immediately after the placement of the overlay or the sham overlay);
- (c) control 2 (immediately after the removal of the overlay).

Each trial (which lasts a duration of approximately 10 - 14 s) of the movement tasks included five phases:

- (a) intercuspal position 1 (IP1) phase: the first 2.6 s (2.15 s in the fast laterotrusion) when the mandible was in the intercuspal position;
- (b) outgoing phase: the period that the target LEDs were sequentially illuminated outward and required jaw tracking; 1.9 mm/s for the slow speed and 5.2 mm/s for the fast speed;
- (c) holding phase: 2.6 s (2.15 s in the fast laterotrusion); the jaw was hold in a position approximately 6 mm away from the intercuspal position;
- (d) return phase: the period over which the target LEDs were sequentially illuminated backward (same speed as outgoing phase);
- (e) intercuspal position 2 (IP2) phase: the last 2.6 s (2.15 s in the fast laterotrusion) when the mandible was back at the intercuspal position.

3.3.6 Data analysis

The EMG activity of each trial was re-sampled to ~2,500 samples/s by deleting three of every four data samples. A computer program was written for processing the output EMG files (see Appendix III). The files were then rectified and smoothed with a digital filter [Butterworth filter (Vaughan, 1982); cut-off: 2 Hz] and the amplitude of the output is expressed in arbitrary units derived from the analogue to digital converter. In addition, the MIPT movement along each of the

three axes was smoothed (five-point moving average applied 10 times). The EMG activity at three laterotrusion tasks under control 1 condition was qualitatively and quantitatively assessed to describe the activity of jaw muscles during lateral movements. Then, the effect of the occlusal alteration on jaw muscles was qualitatively and quantitatively investigated by comparing the EMG activity between three occlusal conditions.

3.3.6.1 EMG activity of the jaw muscles during lateral movement tasks

The EMG activity at the three laterotrusion tasks under the control 1 condition were investigated based on the timing and the amount of the MIPT movement. The investigation based on the timing included the raw data, the overall pattern, the normalized EMG activity of the entire phase, and the onset and offset times. The contralateral IHLP activity during the outgoing and return phases was further normalized and calculated at each mm of MIPT movement.

Normalization and comparison based on the timing

The raw EMG activity and MIPT movement of each trial were plotted against time (X-axis: time; Y-axis: amplitude of the EMG activity and MIPT movement) for the first qualitative assessment of jaw muscle activity during laterotrusion (e.g. Fig. 4.3-1). Because the speed, timing and amplitude of the MIPT movement were standardized and controlled by the visual feedback, the overall pattern of EMG activity in each subject could be assessed by averaging the EMG activity of 10 trials of the rectified and smoothed EMG data at each sampling time. For example, in each subject, the first EMG sample (from the start of the recording) from 10 trials of the same movement was averaged, then the second, third and,

etc. Therefore, the average EMG activity of 10 trials in each subject could be plotted (e.g. Fig. 4.3-2). Computer programs were written for this processing (see Appendix IV). In some figures (e.g. Fig. 4.3-6), average EMG activity from different subjects was superimposed to show different relative patterns. However, because the recorded amplitude of the EMG activity varied between subjects, the EMG activity from different subjects was multiplied and subtracted by different arbitrary amounts to match the EMG level at IP1 phase for display purposes. Therefore, the overall pattern, related to the IP1 level, of each muscle from different subjects could be shown in the same figure.

For the quantitative assessment, the areas underneath the rectified and smoothed EMG activity of each trial were calculated at each of the five phases and then normalized by the duration of each phase. Computer programs were written for this calculation process (see Appendix V). To compare the effect of force and speed alteration, the mean EMG activity of 10 trials from all subjects was statistically compared between slow laterotrusion at two closing force levels as well as between slow and fast laterotrusion at low closing force with paired-samples t-test. Statistical significance was taken at $p < 0.05$.

In addition, the *onset* and *offset* of the EMG activity and MIPT movement of each trial was determined. Computer programs were written for this calculation process (see Appendix VI). The *onset* of the increase (or decrease) in EMG activity of each trial was defined as the time when the amplitude of EMG activity were beyond the range of the mean plus (or minus, respectively) two standard deviations of the muscle activity during the first second of the IP1 phase of each

trial. The onset of the MIPT three-dimensional movement was also calculated based on the same criteria. The *offset* was defined as the time when the amplitude of EMG activity and MIPT movement returned to within the range of the mean plus/minus two standard deviations of muscle activity and MIPT movement, respectively, at the first second of each trial. Then the onset and offset time difference between the EMG activity and the MIPT movement was calculated by subtracting the onset and the offset of MIPT movement with the onset and the offset time of the EMG activity in each trial, respectively. To compare the effect of force and speed alteration, the mean onset and offset time difference of 10 trials was statistically compared between slow laterotrusion at two closing force levels as well as between slow and fast laterotrusion at low closing force with paired-samples t-test with the statistical significance at $p < 0.05$.

IHLP activity at each mm of MIPT movement

Although visual feedback was used to standardize the movements, there was still some fluctuation in the timing and the speed of the movements between each trial. Therefore, a further normalization of the IHLP EMG activity at the selected amplitude of the MIPT displacement was made. The amplitude of MIPT displacement from intercuspal position was defined as the three-dimensional distance between the starting MIPT location and the MIPT location. Two normalizing methods were used.

In the first normalizing method (Fig. 3.3-3), the time when MIPT was 0.5 mm away (then 1.5, 2.5, 3.5 mm and so on) from the intercuspal position in each trial at the outgoing and return phases was determined. After matching the time in the

JAWS-3D and the IHLP data files, the IHLP activity at the first mm of MIPT displacement was calculated as the area (e.g. gray area (B) at the outgoing phase and (C) at the return phase in Fig. 3.3.3) under the rectified and smoothed IHLP activity between the time at 0.5 mm and at 1.5 mm of the MIPT displacement of the same trial. The second mm was between the 1.5 and 2.5 mm, and so on. Because of slight variation between trials, the duration between 0.5 and 1.5 mm (as well as between the 1.5 and the 2.5 mm, and so on) were different between trials. Therefore, the EMG activity at the first mm was divided by the duration of the time between the 0.5 and the 1.5 mm of MIPT displacement for normalization as well as in other ranges.

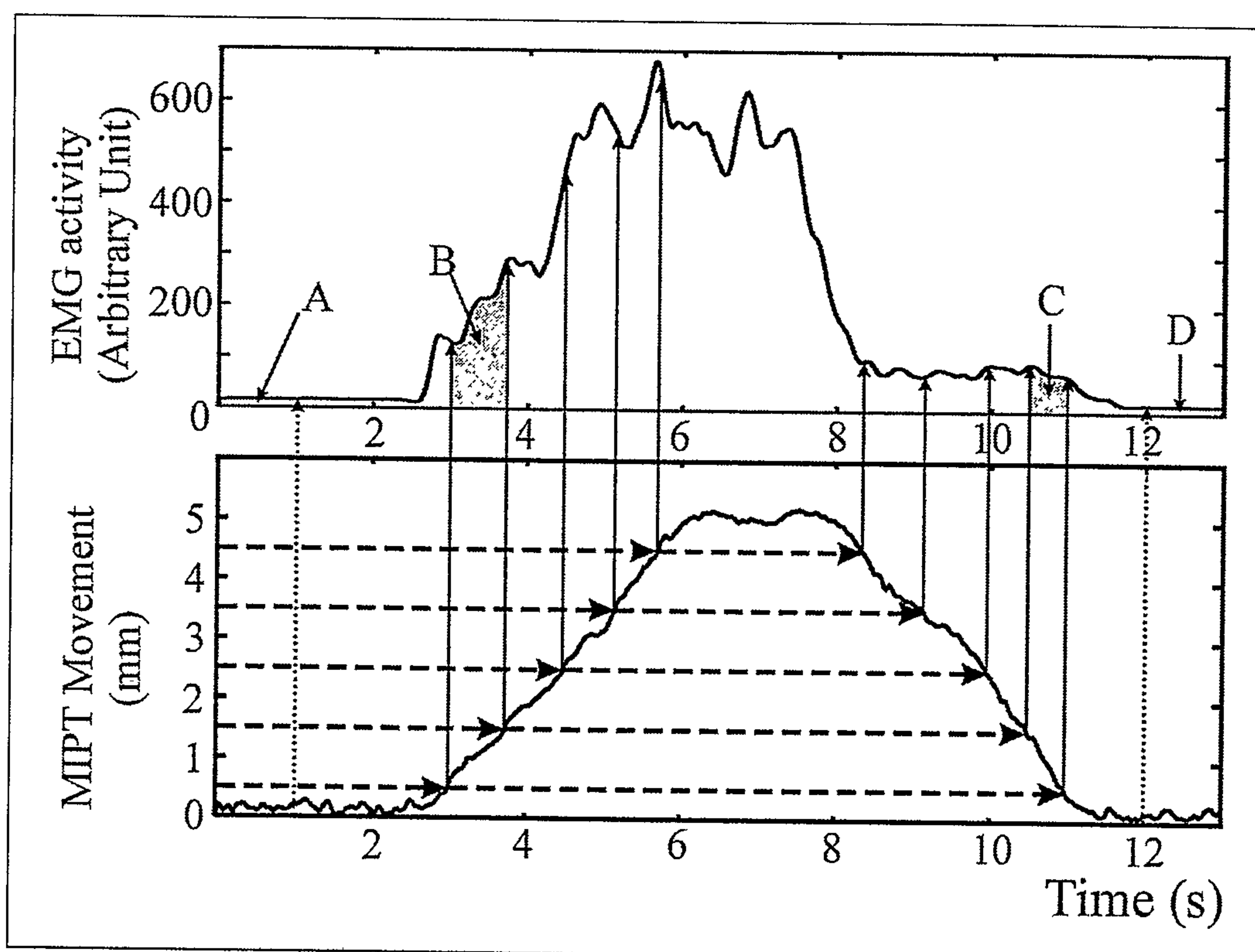


Fig. 3.3-3 Example of normalizing method 1. Gray area (A) and (B) were the EMG activity at 0 mm and around 1 mm, respectively, of the MIPT displacement from the intercusp position at the outgoing phase. Gray area (C) and (D) were the EMG activity around 1 mm and at 0 mm, respectively, of the MIPT displacement from the intercusp position at the return phase.

The IHLP activity at 0 mm of the MIPT displacement during the outgoing phase was defined as the area under the curve of IHLP activity (gray area (A) in Fig.

3.3-3) within the first second of each trial or before the MIPT reached 0.5-mm displacement (whichever reached first), divided by the duration. The IHLP activity at 0 mm during the return phase was defined as the area under the curve of IHLP activity (gray area (D) in Fig. 3.3-3) within the last second of each trial divided by one second. A computer program was written for this calculation process (see Appendix VII).

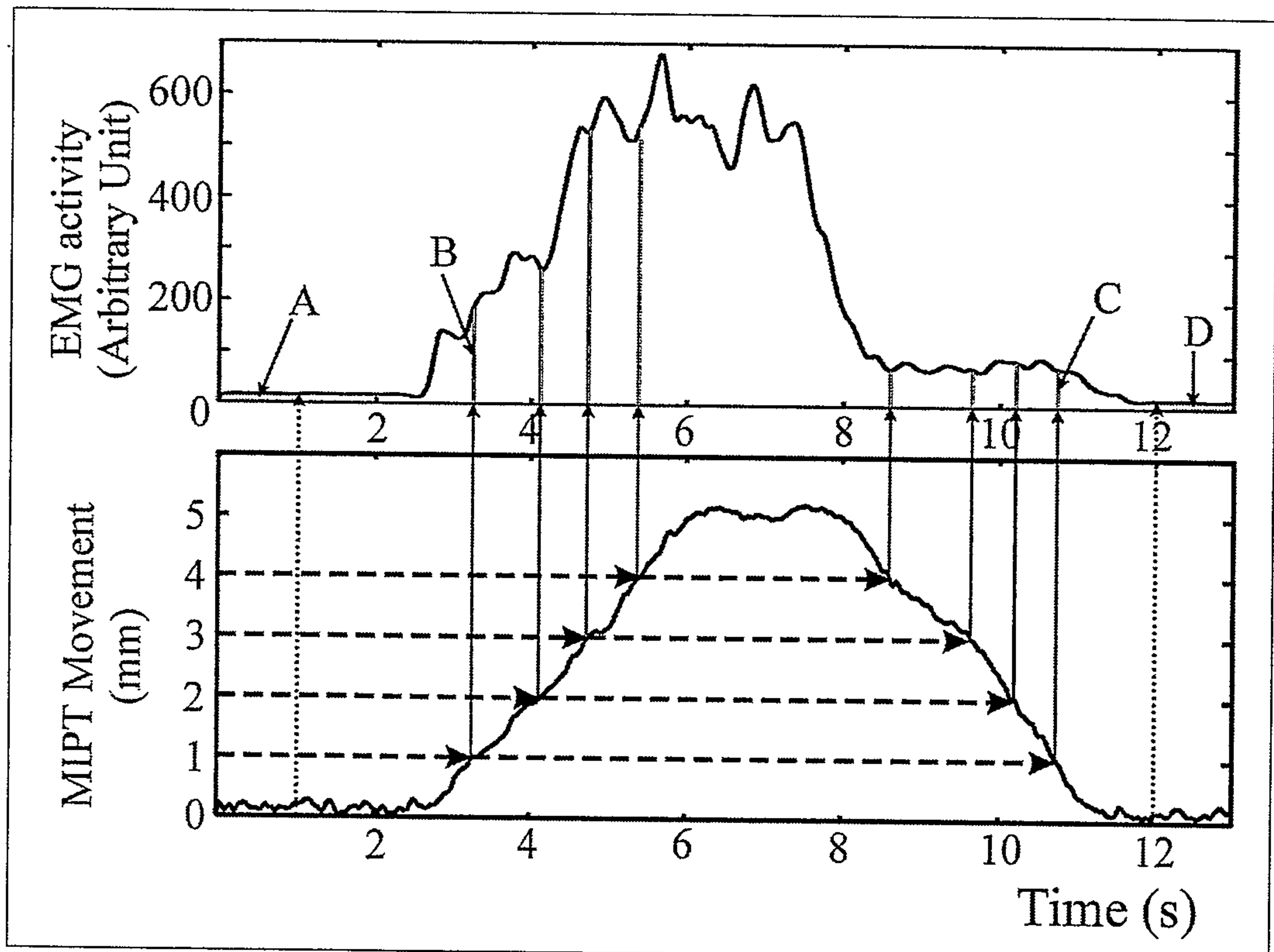


Fig. 3.3-4 Example of normalizing method 2. Gray area (A) and (B) were the EMG activity at 0 mm and around 1 mm, respectively, of the MIPT displacement from the intercuspal position at the outgoing phase. Gray area (C) and (D) were the EMG activity around 1 mm and at 0 mm, respectively, of the MIPT displacement from the intercuspal position at the return phase.

In the second normalizing method (Fig. 3.3-4), the time when the MIPT was 1.0 mm away (then 2.0, 3.0, 4.0 mm and so on) from the intercuspal position in each trial at the outgoing and return phases was determined. After matching the time of the JAWS-3D and IHLP data files, the IHLP activity at the first mm of MIPT displacement was calculated as the areas under 100 samples of the rectified and smoothed IHLP activity around the time of the 1.0 mm of MIPT displacement of

the same trial (50 samples before, and 50 samples after; e.g. Fig. 3.3-4 gray area (B) and (C)). This was then divided by the duration of 100 samples (~0.04 second).

The IHLP activity at 0 mm of the MIPT displacement during the outgoing phase was defined as the area under the curve of IHLP activity (gray area (A) in fig. 3.3-4) within the first second of each trial or before MIPT reached 1.0-mm displacement (whichever reached first), divided by the duration. The IHLP activity at 0 mm during the return phase was defined as the area under the curve of IHLP activity (gray area (D) in fig. 3.3-4) within the last second of each trial divided by one second. A computer program was written for this calculation process (see Appendix VIII).

In both methods, the IHLP at each mm of MIPT displacement away from intercuspal position was plotted in all subjects for qualitative assessment. To compare the effect of force and speed alteration, the mean EMG activity of 10 trials at the 3rd mm away from intercuspal position was statistically compared between slow laterotrusion at two closing force levels as well as between slow and fast laterotrusion at low closing force with paired-samples t-test. Statistical significance was taken at $p < 0.05$. The 3rd mm was used as this amount of lateral displacement was considered to be within the power phase of the chewing cycle.

3.3.6.2 Influence of occlusal alteration on jaw muscles

The investigation of the influence of the occlusal alteration on jaw muscle activity included an overall comparison and a comparison within each subject. From 13 subjects with protrusion recordings, the data from 10 subjects were included for the comparison based on the inclusion criteria that the overlay altered the occlusion during laterotrusion but not during protrusion.

The overall comparison included the mean EMG activity of an entire phase (i.e. outgoing, holding or return), the mean contralateral IHLP activity at the 3rd mm of MIPT displacement at the outgoing and return phases, and the onset and offset time difference between contralateral IHLP and MIPT movement. From each subject, the mean values of the 10 trials under each condition were calculated. These mean values were compared using General Linear Model Repeated Measures with statistical significance taken at $p < 0.05$.

In each subject, a qualitative and quantitative comparison was performed. For the qualitative comparison, the average EMG activity (overall pattern, of which the results were not shown in the Results section) and the average contralateral IHLP activity at each mm of MIPT displacement of all trials under each condition were plotted and superimposed. For the quantitative comparison, the EMG activity of entire phases and the contralateral IHLP at each mm of MIPT displacement was calculated from each trial. Then, the data of all trials in the same subject was compared between the three occlusal conditions using one-way ANOVA with Bonferroni Post Hoc Multiple Comparison with statistical significance taken at $p < 0.05$.

To investigate the effect of the occlusal alteration, three criteria were used. In criterion 1, only the result between the control 1 and occlusal alteration condition was taken into consideration. It was considered as significantly higher, or lower, when the EMG activity under the occlusal alteration condition was significantly higher, or lower, than that under the control 1 condition. In criterion 2, the control 2 result was also taken into consideration. The occlusal alteration data had to be higher, or lower, than those of both control conditions, and there must be a statistically significant difference between the control 1 and the occlusal alteration data. Criterion 3 was similar to the criterion 2, but there should also be a statistically significant difference between the control 2 and the occlusal alteration results.

4 Results

The Results section is divided into three major parts. The first part is the accuracy of the indirect registration of the coordinates of condylar points with a six-degrees-of-freedom jaw tracker. Second is the influence of the occlusal alteration on the working-side condylar movement with multiple condylar points. Third is the activity pattern of jaw muscles during three laterotrusion tasks and the results of the influence of the occlusal alteration on the activity patterns.

4.1 Registration of anatomical condylar points in JAWS-3D system

4.1.1 Direct and indirect method comparison on perspex model

Table 4.1-1 shows a comparison between the 3D coordinates of the condylar points calculated from the direct and indirect measurements on the perspex model. The direct measurements were repeated 25 times. The standard deviation (SD) of the condylar coordinates in the JAWS-3D coordinate system was better than 0.3 mm for the right points but rose to 0.7 mm for the left points, which are contralateral to the JAWS-3D recording side. In the indirect method, the SD of 25 repeated measurements of fiducial marker points and LED points in the MicroScribe-3DX coordinate system were better than 0.15 mm. The internal reference centres of the fiducial-marker coordinate system had a SD of 0.06 mm. After transferring into the fiducial-marker coordinate system, the SD of the LED points' coordinates was better than 0.25 mm. However, the indirect condylar measurements were derived from a single CT scan; therefore, the SD of condylar coordinates in the JAWS-3D coordinate system was not available.

Condylar point	Data	X-coordinate	Y-coordinate	Z-coordinate
R-S	Direct	-53.71	-181.54	121.65
	Indirect	-52.84	-181.63	121.52
R-A	Direct	-54.95	-190.82	112.64
	Indirect	-54.06	-190.23	112.43
R-L	Direct	-63.17	-180.48	112.90
	Indirect	-62.19	-180.25	113.01
R-P	Direct	-52.61	-172.35	112.55
	Indirect	-51.90	-172.82	112.62
R-M	Direct	-44.68	-182.95	112.52
	Indirect	-44.79	-182.74	112.53
L-S	Direct	45.18	-186.58	122.34
	Indirect	45.91	-186.94	121.23
L-A	Direct	44.39	-195.96	112.75
	Indirect	44.99	-196.08	112.63
L-L	Direct	54.59	-187.93	112.70
	Indirect	54.14	-187.90	112.74
L-P	Direct	46.30	-177.73	112.50
	Indirect	46.48	-178.61	112.32
L-M	Direct	36.39	-185.95	112.52
	Indirect	37.36	-186.29	112.72

Table 4.1-1 3D coordinates (mm) of condylar points on the perspex model from direct and indirect measurements. R-: Right side; L-: left side; S: most superior point; A: most anterior point; L: most lateral point; P: most posterior point; M: most medial point. Data processed by A/Prof. C. Durrant.

Condylar point	X-coordinate	Y-coordinate	Z-coordinate
R-S	-0.87	+0.09	+0.13
R-A	-0.89	-0.59	+0.21
R-L	-0.98	-0.13	-0.11
R-P	-0.71	+0.47	-0.07
R-M	+0.11	-0.21	-0.01
Average of absolute difference	0.71	0.30	0.11
L-S	-0.73	+0.36	+1.11
L-A	-0.60	+0.12	+0.12
L-L	+0.45	-0.03	-0.04
L-P	-0.18	+0.88	+0.18
L-M	-0.97	+0.34	-0.20
Average of absolute difference	0.59	0.35	0.33

Table 4.1-2 Differences (mm) between data from direct and indirect measurements on the perspex model. R-: Right side; L-: left side; S: most superior point; A: most anterior point; L: most lateral point; P: most posterior point; M: most medial point. Data processed by A/Prof. C. Durrant.

Table 4.1-2 shows the differences between the direct and indirect measurements for each coordinate. The overall accuracy of the indirect measurement on the perspex model was ~0.5 mm for all points in every axis except the left most superior point, which was contralateral to the JAWS-3D recording site.

4.1.2 Number of computer tomography (CT) images required

The comparison of the discrepancies among condylar-point coordinates calculated from the three sets of perspex model CT images showed that reducing the number of CT images from 22 and 24 to 12 and 6 produced a maximum change of less than 0.1 mm in the derived coordinates. A further reduction to 12 and 5 images produced an additional change of no more than 0.02 mm. Therefore, a set of 12 condylar continuous slices and five chin slices (2 mm apart) appears sufficient for condylar-point determination with an acceptable reproducibility and were later used in the assessment on the dry skull.

4.1.3 Direct and indirect method comparison on dry skull

The comparison between the condylar-point coordinates calculated from the direct and indirect measurements on the dry skull is shown in Tables 4.1-3 and 4.1-4. As for the perspex model, the discrepancies between the direct and indirect measurement were ~0.5 mm in all axes for all locations. In the direct measurements, the SD of condylar coordinates in the JAWS-3D coordinate system was better than 0.4 mm on the right side and rose to 0.6 mm on the left side. With the indirect method, the SD of fiducial marker points' and LED points' measurements in the MicroScribe-3DX coordinate system was less than 0.16 mm. The internal reference centres of the fiducial-marker coordinate system

had a SD of 0.07 mm. After transferring into the fiducial-marker coordinate system, the SD of the LED points' coordinates was better than 0.3 mm.

Condylar point	Data	X-coordinate	Y-coordinate	Z-coordinate
R-S	Direct	51.72	-187.70	29.15
	Indirect	51.50	-187.17	28.83
R-A	Direct	59.03	-191.81	34.92
	Indirect	59.02	-190.90	34.48
R-L	Direct	62.02	-189.82	34.81
	Indirect	61.46	-189.13	34.66
R-P	Direct	48.52	-183.79	32.09
	Indirect	48.40	-183.68	31.36
R-M	Direct	45.39	-185.99	33.17
	Indirect	45.28	-185.97	33.14
L-S	Direct	-30.40	-201.14	25.64
	Indirect	-30.83	-201.19	25.86
L-A	Direct	-34.39	-207.35	30.65
	Indirect	-34.92	-206.85	30.95
L-L	Direct	-39.53	-207.09	30.67
	Indirect	-39.73	-206.85	30.95
L-P	Direct	-28.00	-196.63	29.68
	Indirect	-28.70	-196.53	29.66
L-M	Direct	-24.00	-198.14	30.68
	Indirect	-24.37	-198.24	30.76

Table 4.1-3 3D coordinates (mm) of condylar points on the dry skull from direct and indirect measurements. R-: Right side; L-: left side; S: most superior point; A: most anterior point; L: most lateral point; P: most posterior point; M: most medial point. Data processed by A/Prof. C. Durrant.

Condylar point	X-coordinate	Y-coordinate	Z-coordinate
R-S	-0.22	+0.53	-0.32
R-A	-0.01	+0.91	-0.44
R-L	-0.56	+0.69	-0.15
R-P	-0.12	+0.11	-0.73
R-M	-0.11	+0.02	-0.03
Average of absolute difference	0.20	0.45	0.33
L-S	-0.43	-0.05	+0.22
L-A	-0.53	+0.50	+0.30
L-L	-0.20	+0.24	+0.28
L-P	-0.70	+0.10	-0.02
L-M	-0.37	-0.10	+0.08
Average of absolute difference	0.45	0.20	0.18

Table 4.1-4 Differences (mm) between data from direct and indirect measurements on the dry skull. Data processed by A/Prof. C. Durrant.

4.1.4 Fiducial-marker device repositioning

Table 4.1-5 lists the coordinates of the three LED points in fiducial-marker coordinate system calculated from the set of 25 repeated MicroScribe-3DX measurements (a) and the additional three sets of five repeated measurements (b, c, d). The maximum discrepancies were ~0.5 mm. This error will be part of the error of the indirect method (< 1 mm) on the dry skull in this experiment.

Marker point	File	X coordinate		Y coordinate		Z coordinate	
			Max. Diff.		Max. Diff.		Max. Diff.
LED 1	a	112.48	0.25	-277.01	0.47	84.17	0.54
	b	112.47		-277.01		84.27	
	c	112.71		-277.22		83.83	
	d	112.46		-276.75		84.37	
LED 2	a	101.78	0.74	-217.73	0.44	86.79	0.20
	b	101.81		-217.62		86.81	
	c	102.45		-217.92		86.99	
	d	101.71		-217.48		86.93	
LED 3	a	108.01	0.75	-263.50	0.75	110.91	0.51
	b	107.89		-263.31		110.96	
	c	108.48		-263.81		110.76	
	d	107.73		-263.06		111.27	

Table 4.1-5 Comparison (mm) between measurements after fiducial-marker device removal and reposition. a: the set of 25 measurements; b, c and d: a set of five measurements each after repositioning the fiducial-marker device on three separate occasions. LEDs 1, 2 and 3 are the three LED points. Max. Diff.: maximum difference between files a, b, c and d. Data processed by A/Prof. C. Durrant.

4.2 Influence of an occlusal alteration on working-side condylar movement

4.2.1 Outgoing phase during laterotrusion

In summary, the working-side condylar path under the occlusal alteration was anterior and inferior to that under the control 1 condition at the same amount of MIPT displacement during the outgoing laterotrusion, with a statistically significant difference at the 3rd and 5th mm of MIPT displacement. The occlusal alteration also significantly changed all three rotatory angles at both MIPT displacements, except for the rotation angle along the Y-axis at the 3rd mm of MIPT displacement. There was no significant difference in the displacement and rotation along each axis between the two control conditions. The selection of the condylar referencing points had a significant influence in quantitative comparisons of the effects of the occlusal alteration between the five condylar points, however, all five points under the occlusal alteration had significantly more anterior and inferior paths than those under the control 1 condition.

4.2.1.1 Condylar path projections

Fig. 4.2-1 shows an example from one subject's condylar path, projected onto each plane, during a single trial of laterotrusion under the control 1 and occlusal alteration conditions. The black triangles (or quadrilateral) show the starting position (i.e. at intercuspal position) of the working-side condyle, indicated by the arrow. The red triangles (or quadrilaterals) with solid lines indicate the projected condylar position at the 2nd, 4th and 6th mm of MIPT displacement away from the intercuspal position during the outgoing phase under the occlusal alteration. The blue triangles (or quadrilaterals) with dashed lines indicate the condylar position under the control 1 condition. In this subject, the working-side

condylar head showed a more inferior path under the occlusal alteration than that under the control 1 condition. And the difference between the two conditions increased as the MIPT moved further away from the intercusp position.

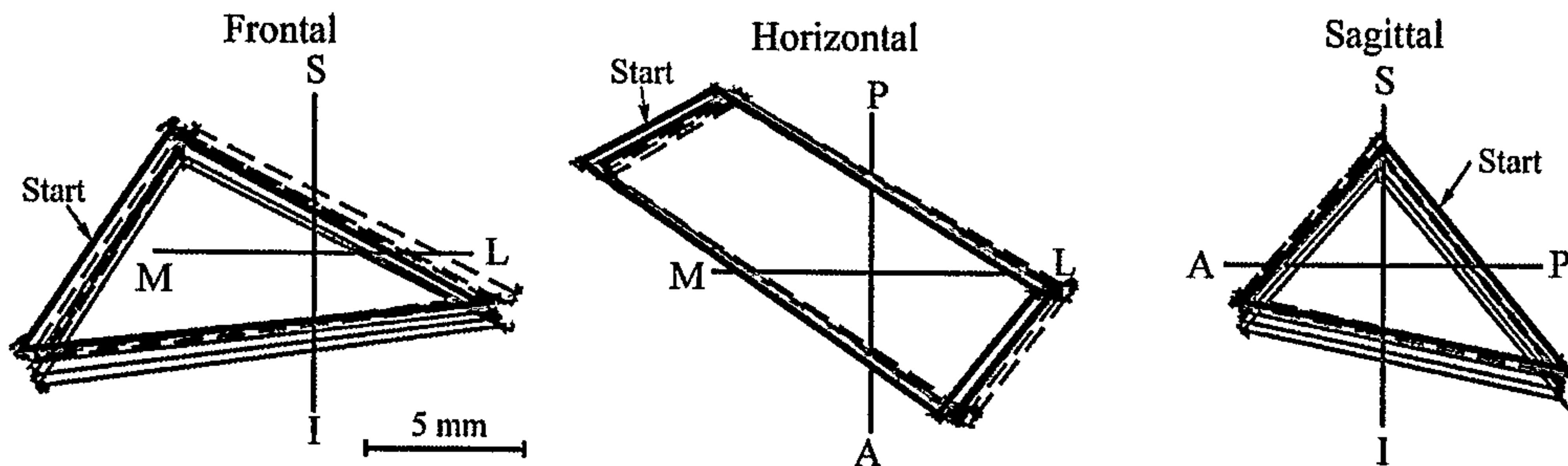


Fig. 4.2-1 The influence of the occlusal alteration on the projected working-side condylar path during outgoing laterotrusion in each plane. Black triangles (or quadrilateral) indicate the starting position of the condyle. The red triangles (or quadrilaterals) with solid lines show the condylar path under the occlusal alteration, whereas the blue ones with the dashed lines show that under the control 1 condition. A: anterior direction; I: inferior direction; L: lateral direction; M; medial direction; P: posterior direction; S: superior direction. Program for figure plotting was provided by C. Johnson.

4.2.1.2 *The influence of an occlusal alteration on the condylar translatory movements*

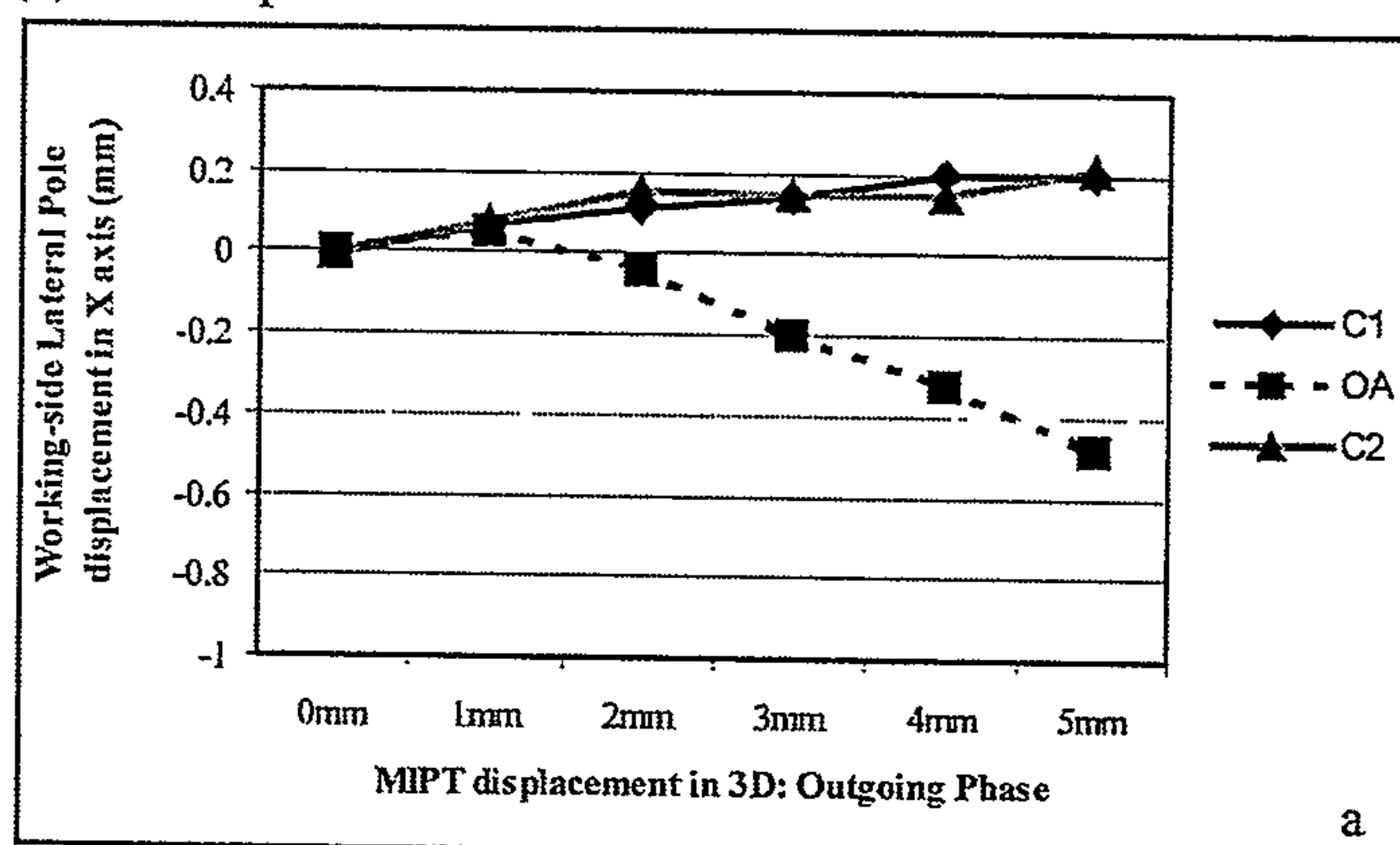
Antero-posterior displacement (X-axis)

Generally, the occlusal alteration caused a more anterior condylar path than that under the control 1 condition during outgoing laterotrusion, with statistically significant differences at the 3rd and 5th mm of the MIPT displacement (Table 4.2-1). The condylar path under the occlusal alteration was also significantly anterior to that under the control 2 condition in all condylar points at both MIPT displacements except for the most superior and the most posterior points and the medial pole at the 3rd mm of MPT displacement. There was no significant difference between both control conditions.

The difference between the occlusal alteration and both control conditions was larger at the 5th mm of MIPT displacement than that at the 3rd mm. In eight of 10

subjects, the difference between the occlusal alteration condition and both control conditions increased as the MIPT moved progressively further away from the intercusp position (e.g. Fig. 4.2-2 a).

(a) Lateral pole



(b) Medial pole

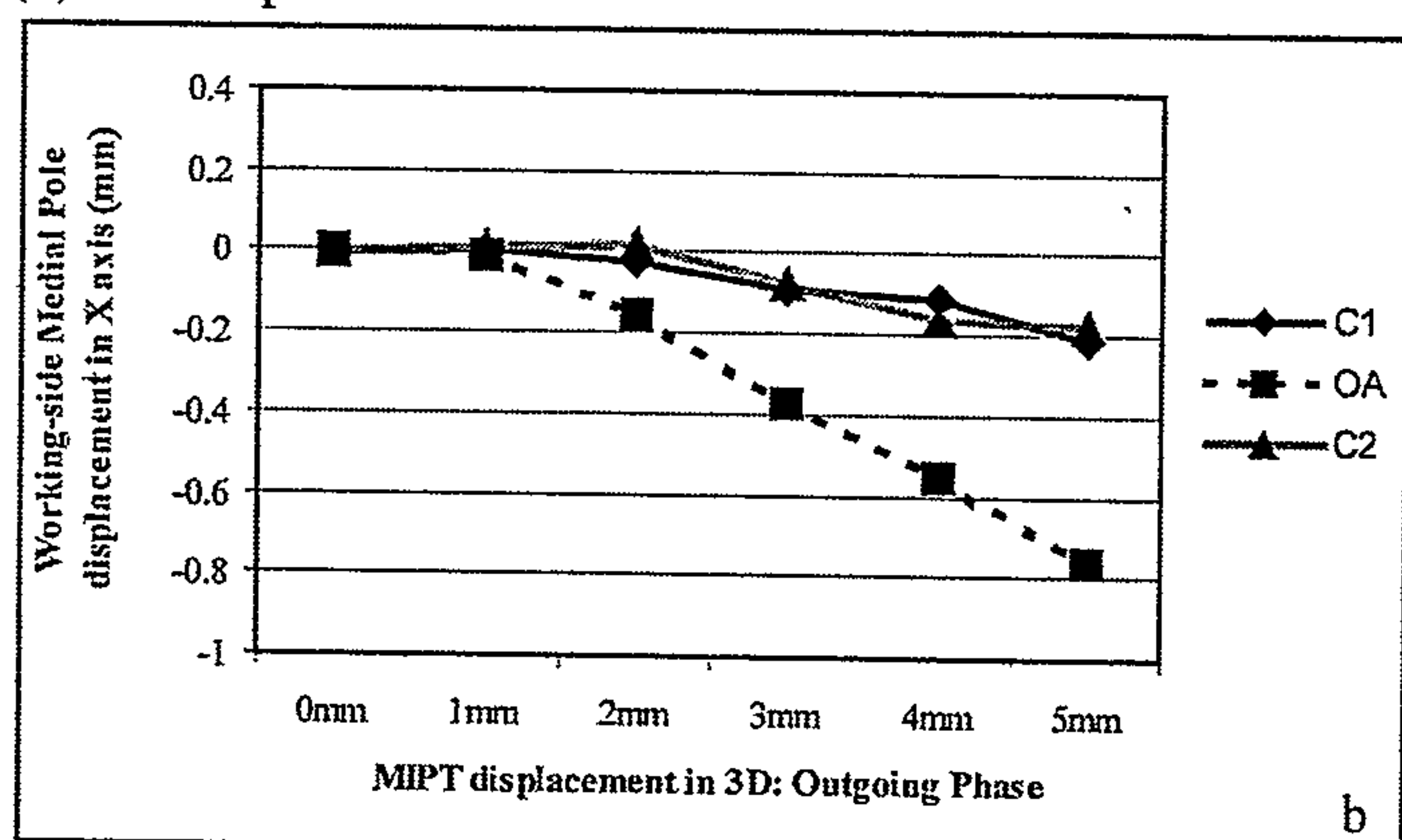


Fig. 4.2-2 An example of the condylar movement of the lateral pole (a) and medial pole (b) in X-axis under the three occlusal conditions at each mm of MIPT displacement. Each data point is the average of 10 trials. Positive values indicate that the condyle position was posterior to the starting position. C1: the control 1 condition; OA: the occlusal alteration condition; C2: the control 2 condition.

There was a slight variation between different condylar points. For example, in two subjects, under the control conditions, the lateral pole of the working-side condyle moved posteriorly, whereas the medial pole moved anteriorly. And both poles moved anteriorly under the occlusal alteration (e.g. Fig. 4.2-2 a and b). Thus, the selection of the condylar points could cause a difference in the qualitative assessment of the influence of the occlusal alteration on the working-side condylar path.

(a) Displacement (mm) at the 3rd mm of MIPT displacement from the intercusp position

	Axis	X			Y			Z		
		C1	OA	C2	C1	OA	C2	C1	OA	C2
L	Condition									
	Mean $\pm$ SD	0.09 $\pm$ 0.21	-0.12 $\pm$ 0.18	0.10 $\pm$ 0.28	0.50 $\pm$ 0.27	0.37 $\pm$ 0.30	0.47 $\pm$ 0.22	-0.07 $\pm$ 0.22	-0.39 $\pm$ 0.24	-0.04 $\pm$ 0.27
	Pairwise	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2
	p	0.012	0.836	0.033	0.085	0.301	0.154	0.002	0.595	0.011
A	Condition									
	Mean $\pm$ SD	0.02 $\pm$ 0.20	-0.17 $\pm$ 0.16	0.03 $\pm$ 0.27	0.53 $\pm$ 0.28	0.39 $\pm$ 0.30	0.50 $\pm$ 0.22	-0.19 $\pm$ 0.22	-0.51 $\pm$ 0.24	-0.16 $\pm$ 0.28
	Pairwise	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2
	p	0.020	0.960	0.050	0.072	0.305	0.122	0.002	0.538	0.011
S	Condition									
	Mean $\pm$ SD	-0.07 $\pm$ 0.20	-0.26 $\pm$ 0.17	-0.08 $\pm$ 0.27	0.37 $\pm$ 0.29	0.25 $\pm$ 0.25	0.37 $\pm$ 0.29	-0.20 $\pm$ 0.21	-0.48 $\pm$ 0.21	-0.15 $\pm$ 0.28
	Pairwise	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2
	p	0.026	0.867	0.081	0.120	0.980	0.030	0.003	0.411	0.012
P	Condition									
	Mean $\pm$ SD	-0.03 $\pm$ 0.20	-0.21 $\pm$ 0.17	-0.03 $\pm$ 0.28	0.41 $\pm$ 0.27	0.30 $\pm$ 0.31	0.38 $\pm$ 0.21	-0.17 $\pm$ 0.22	-0.45 $\pm$ 0.24	-0.14 $\pm$ 0.30
	Pairwise	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2
	p	0.028	0.942	0.062	0.145	0.231	0.278	0.005	0.600	0.023
M	Condition									
	Mean $\pm$ SD	-0.10 $\pm$ 0.20	-0.26 $\pm$ 0.17	-0.10 $\pm$ 0.27	0.44 $\pm$ 0.28	0.33 $\pm$ 0.31	0.41 $\pm$ 0.22	-0.30 $\pm$ 0.21	-0.57 $\pm$ 0.22	-0.26 $\pm$ 0.30
	Pairwise	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2
	p	0.042	0.960	0.091	0.118	0.227	0.231	0.004	0.543	0.018

Table 4.2-1 The overall quantitative comparison of the working-side-condylar-point displacement in each axis between the three conditions at the (a) 3rd and (b) 5th mm of MIPT displacement from the intercusp position during outgoing laterotrusion from all ten subjects with the first overlay. The mean and standard deviation, from all subjects, of the condylar-point displacement in each axis under each condition is displayed. The far left column indicates the condylar points [L: the lateral pole of the working-side condylar head; A: the most anterior point; S: the most superior point; P: the most posterior point; M: the medial pole]. In the third and fourth rows of the condylar point, the results of the pairwise comparison (General Linear Models with Repeated Measures) between the mean displacement in each axis of the three conditions were displayed. The cells marked with gray color indicate that there is a statistically significant difference ($p < 0.05$). The results of the five condylar points are aligned based on the medio-lateral position of each point. C1: the control 1 condition; OA: the occlusal alteration condition; C2: the control 2 condition.

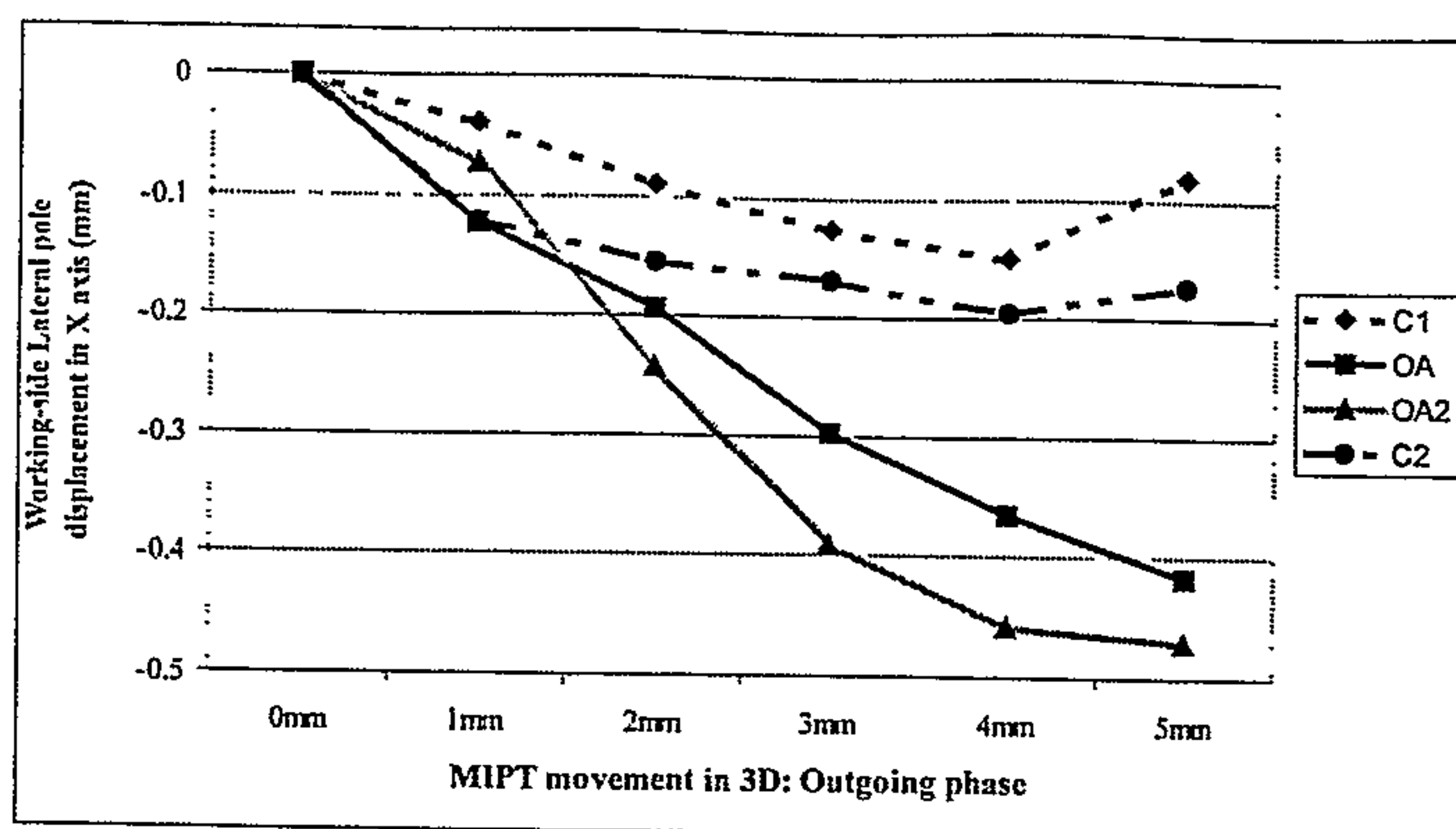


Fig. 4.2-3 An example of the condylar movement under the occlusal alteration and control conditions at each mm of MIPT displacement. Each data point is the average of 10 trials. Positive values indicate that the condyle position was posterior to the starting position. C1: the control 1 condition; OA: the occlusal alteration condition; OA2: the occlusal alteration 2 condition with a steeper overlay; C2: the control 2 condition.

In the two subjects with a second overlay, there was suggestive evidence that the difference between the occlusal alteration and control conditions increased where the inclination increased. For example, in Fig. 4.2-3, the condylar path of the lateral pole was more anterior under the first occlusal alteration (OA) than that under both control conditions. The condylar path under the second overlay (OA2) was more anterior than that under the first overlay at the 2nd, 3rd, 4th and 5th mm of MIPT displacement. Although the difference was within the error of the system, the data are suggestive that steeper inclines result in greater effects on magnitude of condylar movement. In the subject with the shallower overlay, which increased vertical dimension and caused a shallower (10° less) inclination during laterotrusion, the working-side condyle moved anteriorly under the control conditions and less anteriorly under the occlusal alteration. In the subject with the sham overlay, there was no significant difference between the occlusal alteration and control 1 conditions.

Medial-Lateral displacement (Y-axis)

Generally, all working-side condylar points moved toward the lateral direction during the outgoing laterotrusion under the three occlusal conditions. However,

for all 10 subjects, there was no statistically significant difference between the three conditions at both MIPT displacements in all points, except for the most superior point at the 3rd mm of the MIPT displacement (Table 4.2-1).

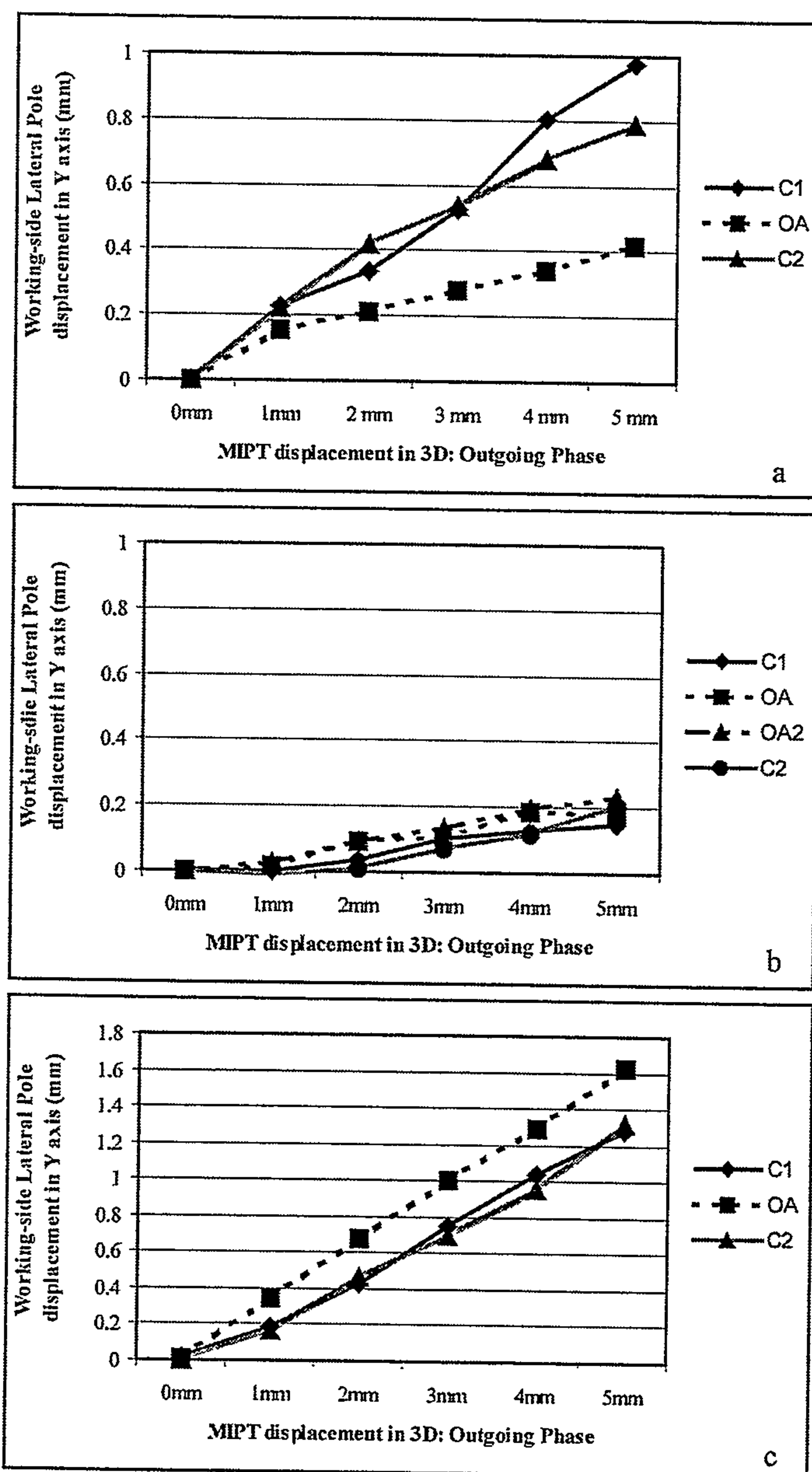


Fig. 4.2-4 Three examples (a, b and c) of the condylar movement in Y-axis under the occlusal alteration and control conditions at each mm of MIPT displacement. Each data point is the average of 10 trials. Positive values indicate that the condyle position was lateral to the starting position. C1: the control 1 condition; OA: the occlusal alteration condition; OA2: the occlusal alteration 2 condition with a steeper overlay (in b); C2: the control 2 condition.

Qualitatively, in five (of 10) subjects, the occlusal alteration caused a less lateral movement than that under the control conditions (e.g. Fig. 4.2-4 a). In four subjects, the occlusal alteration did not change the lateral displacement (e.g. Fig. 4.2-4 b). In one subject, the occlusal alteration caused an increase in lateral

displacement of the working side condylar head (e.g. Fig. 4.2-4 c). In the subject with the shallower overlay and the subject with the sham overlay, there was no difference between the occlusal alteration and control conditions.

Supero-inferior displacement (Z-axis)

Table 4.2-1 shows that the occlusal alteration caused a more inferior condylar path during the outgoing laterotrusion, with significant differences between the occlusal alteration and the both control conditions at all points at both MIPT displacements. There was no significant difference between the control conditions. The difference between the occlusal alteration condition and both control conditions increased as the MIPT displaced progressively further from the intercusp position (e.g. Fig. 4.2-5 a) in all 10 subjects.

(a) Lateral pole

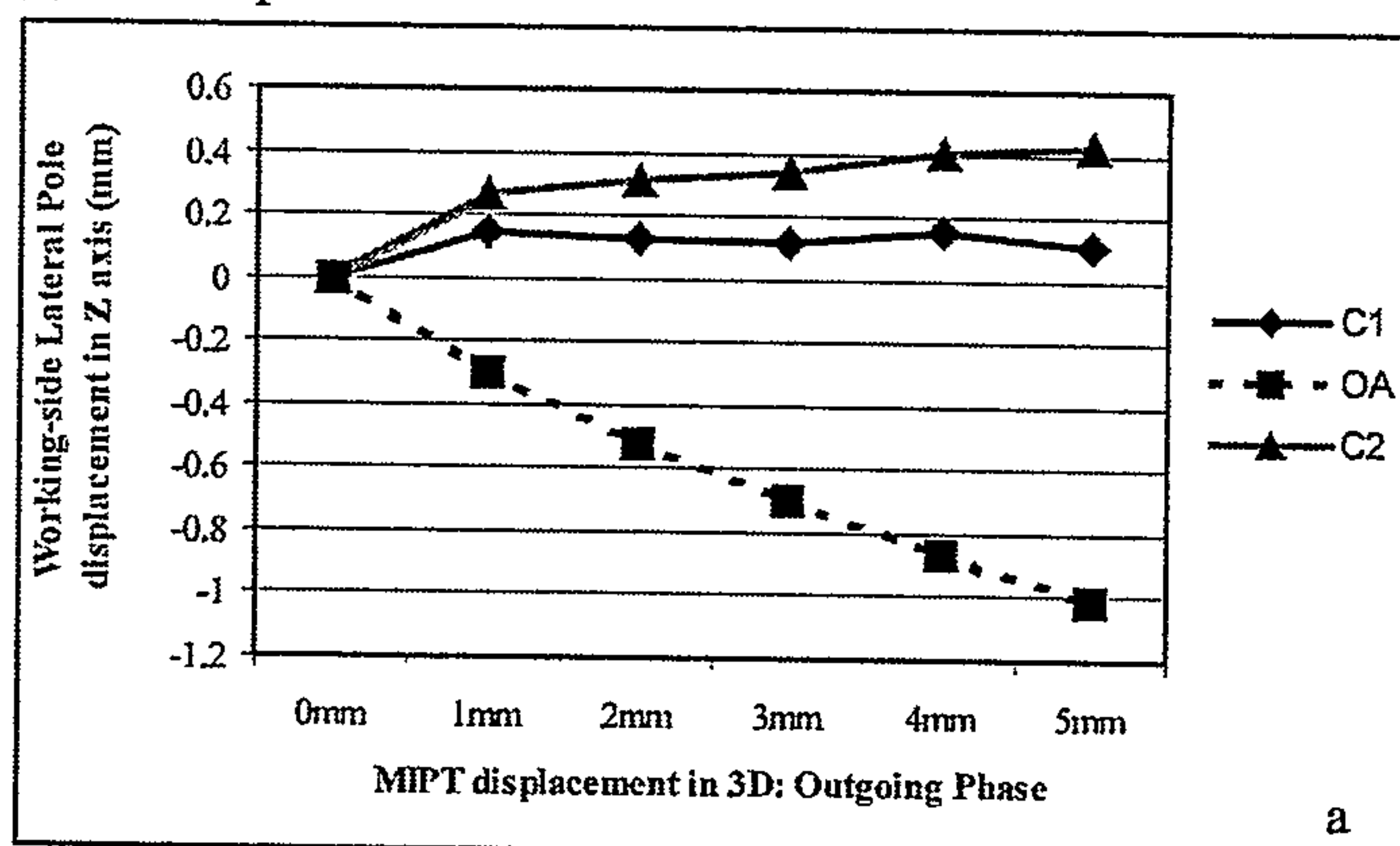
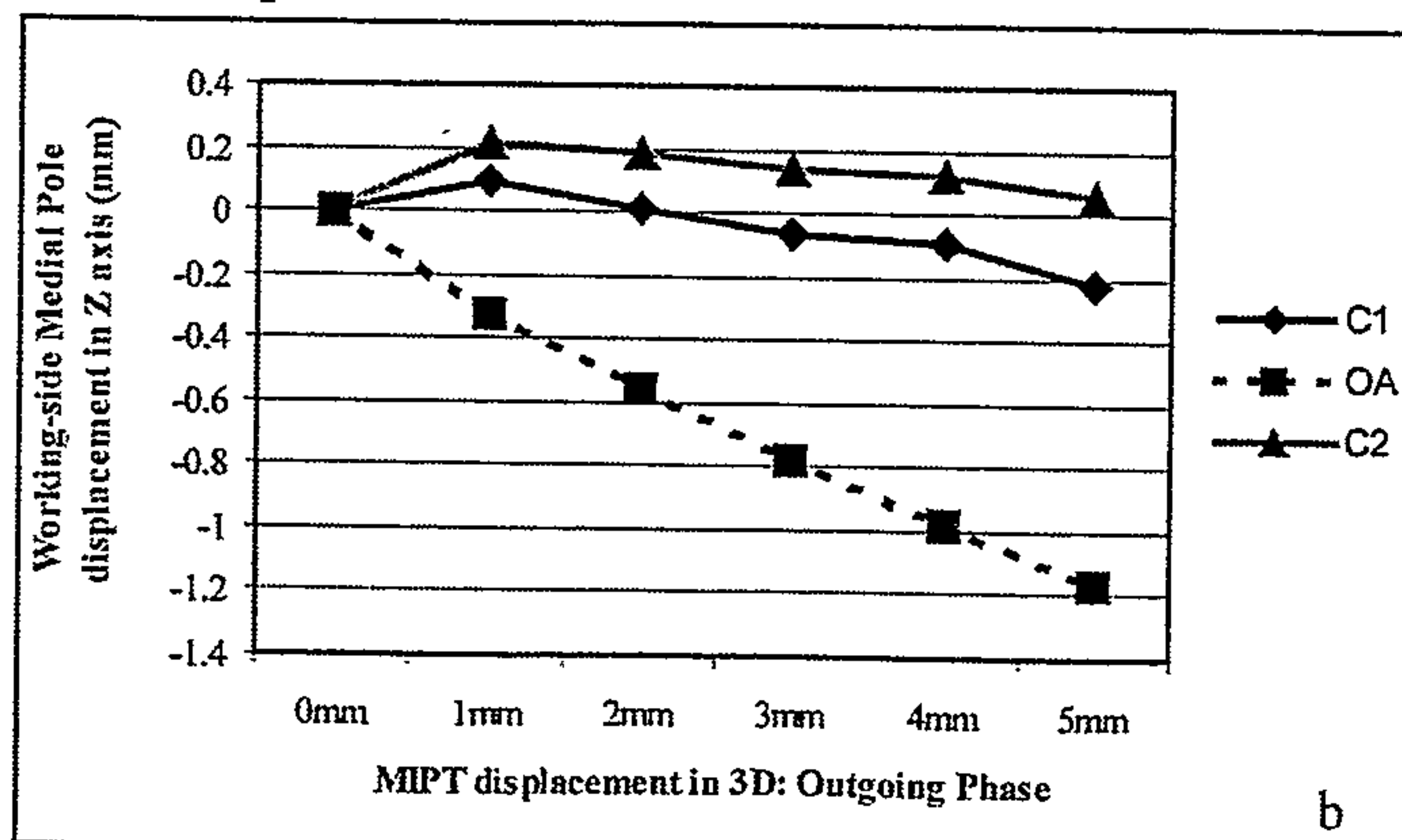


Fig. 4.2-5 An example of the condylar movement of the lateral pole (a) and medial pole (b) in Z-axis under the three occlusal conditions at each mm of MIPT displacement. Each data point is the average of 10 trials. Positive values indicate that the condyle position was inferior to the starting position. C1: the control 1 condition; OA: the occlusal alteration condition; C2: the control 2 condition.

(b) Medial pole



Qualitatively, the occlusal alteration could also change the movement direction supero-inferiorly. During the outgoing laterotrusion, the working condyle moved superiorly in three subjects under the control conditions, and inferiorly under the occlusal alteration conditions (e.g. Fig. 4.2-5 a). In the remaining seven subjects, the working-side condyle moved inferiorly under the three occlusal conditions. However, in two of the three subjects who showed a change in the movement direction supero-inferiorly, there was a slight variation between different condylar points. For example, in these two subjects, while both medial and lateral poles moved initially superiorly, the medial pole then moved inferiorly under the three occlusal conditions, whereas the lateral pole moved superiorly or remained at the same superoinferior level under the control conditions but moved inferiorly under the occlusal alteration (e.g. Fig. 4.2-5). Therefore, the selection of the condylar points could cause a difference in the qualitative assessment of the influence of the occlusal alteration on the working-side condylar path.

In the two subjects with a second overlay, the difference in the Z-axis between the occlusal alteration and control conditions qualitatively increased, although no statistical analysis was done. For example, in Fig. 4.2-6, the condylar path was more inferior under the first occlusal alteration than that under both control conditions. The condylar path under the second overlay was more inferior than that under the first overlay. In the subject with the shallower overlay, the working-side condyle moved less inferiorly under the occlusal alteration than that under the control conditions. In the subject with the sham overlay, there was no difference between the occlusal alteration and control conditions.

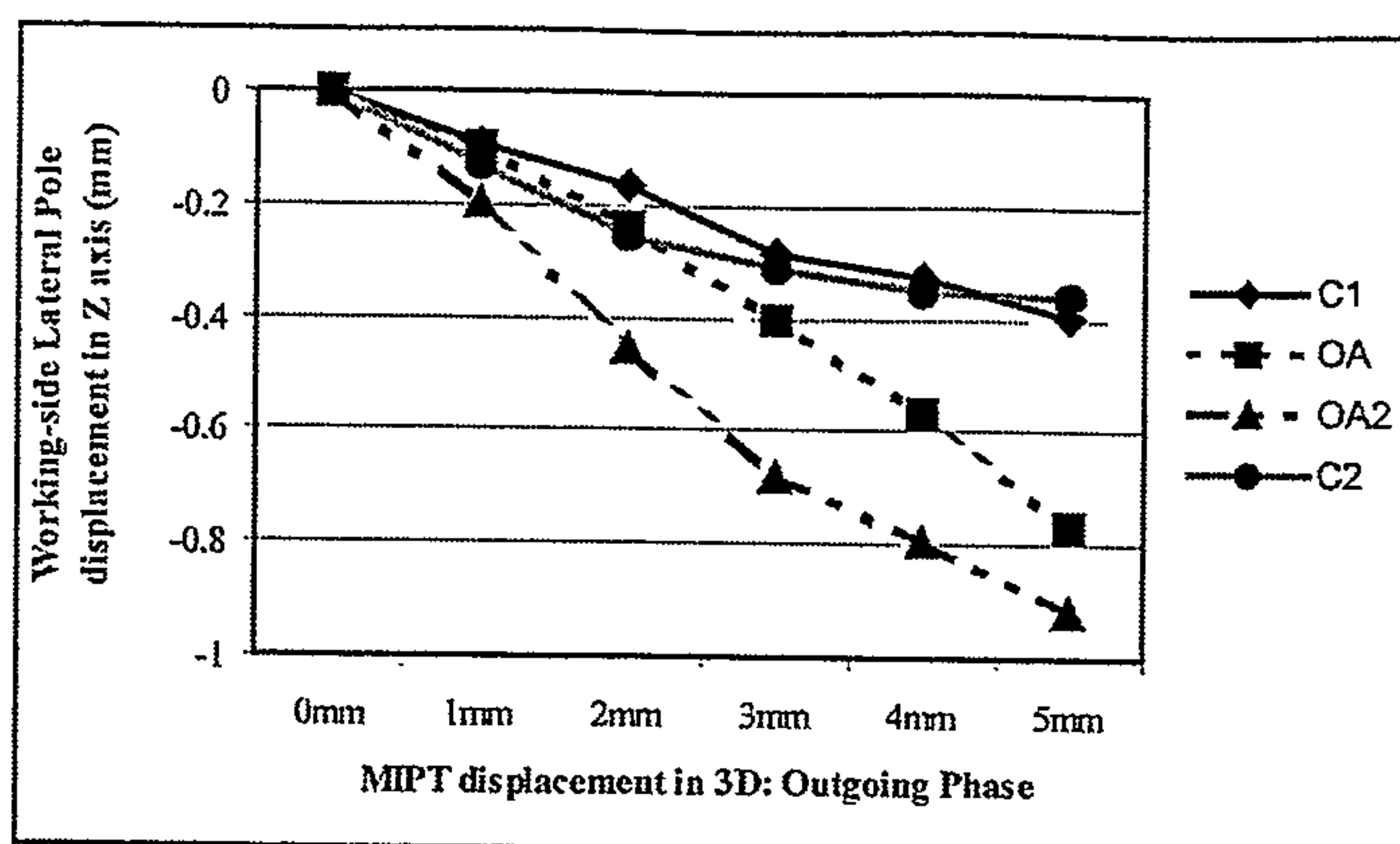


Fig. 4.2-6 An example of the condylar movement under the occlusal alteration and control conditions at each mm of MIPT displacement. Each data point is the average of 10 trials. Negative values indicate that the condyle position was inferior to the starting position. C1: the control 1 condition; OA: the occlusal alteration condition; OA2: the occlusal alteration 2 condition with a steeper overlay; C2: the control 2 condition.

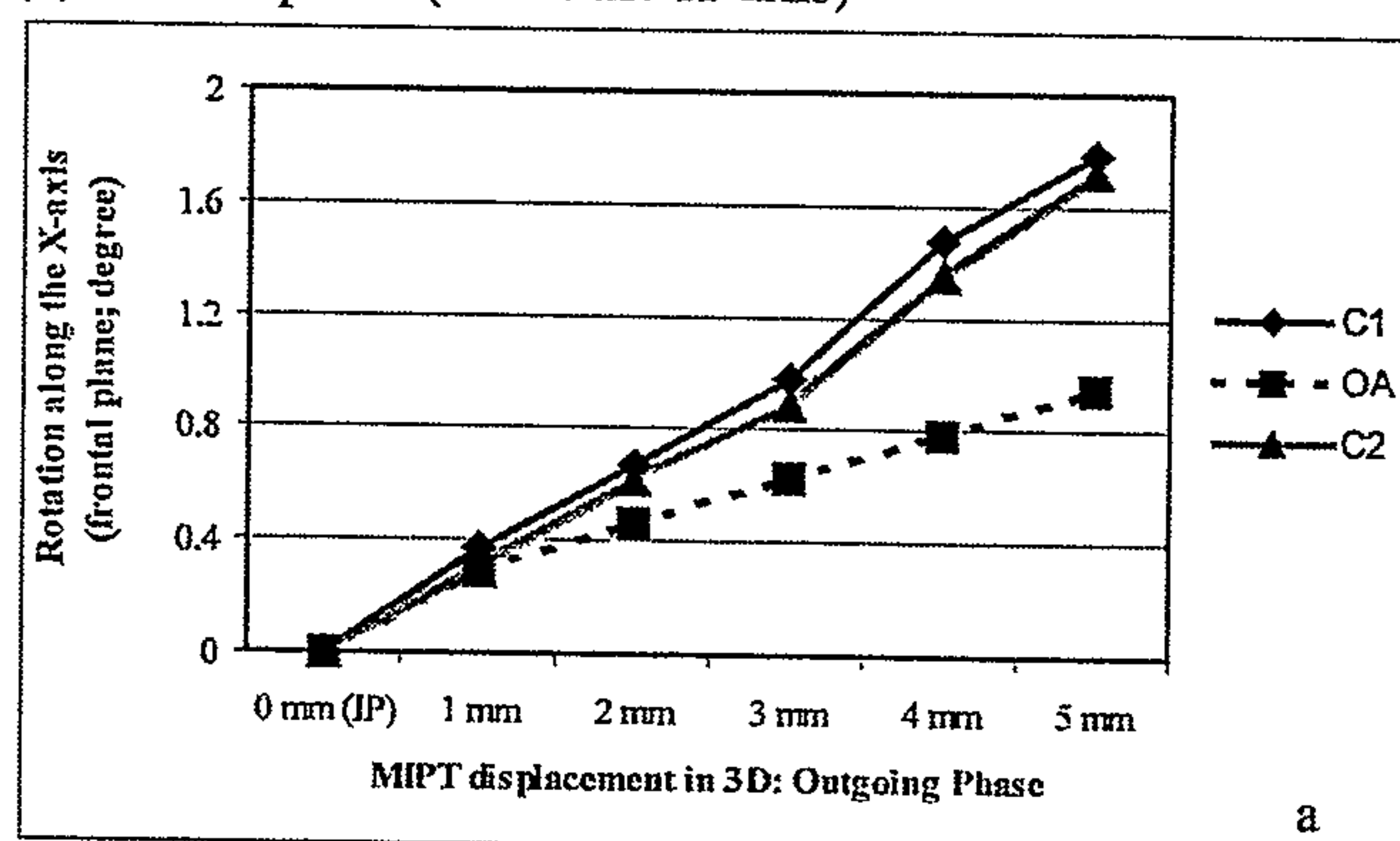
4.2.1.3 The influence of an occlusal alteration on the rotatory movements

In all 10 subjects, the occlusal alteration caused a reduction in the rotation angle (in absolute value) in the frontal plane (i.e. about the X-axis; e.g. Fig. 4.2-7 a) and horizontal plane (i.e. about the Z-axis; e.g. Fig. 4.2-7 c) compared with those under the control conditions during the outgoing laterotrusion. From 10 subjects, the overall statistical comparison showed a significant difference between the occlusal alteration and both control conditions at both MIPT displacements (Table 4.2-2). There was no significant difference between the two control conditions. The absolute value of the difference between the occlusal alteration and control conditions increased as the MIPT was further away from the intercuspal position. The occlusal alteration did not change the direction of rotation in the frontal and horizontal planes.

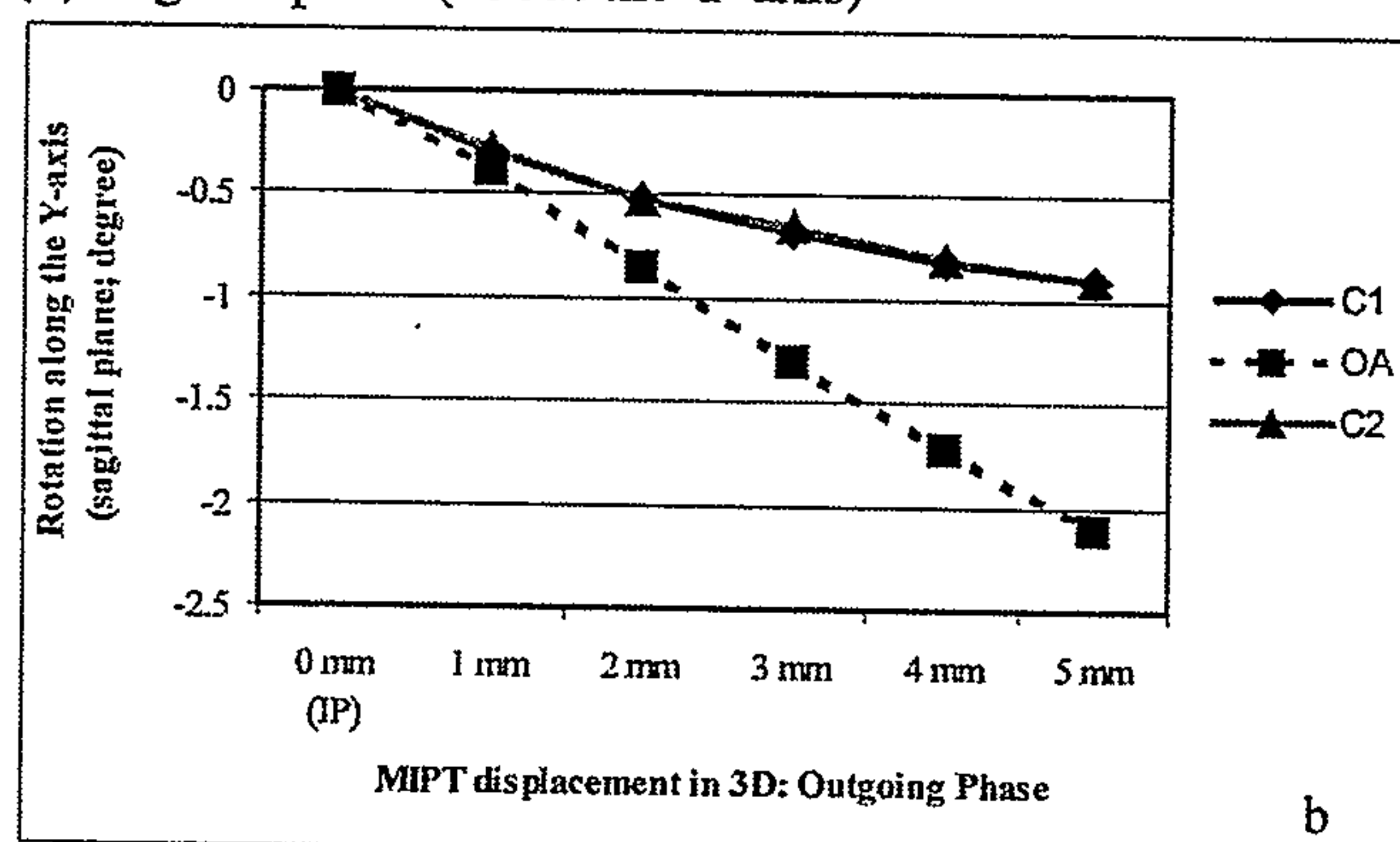
In the sagittal plane, the mandible rotated (about the Y-axis) open during the outgoing laterotrusion in nine subjects. From all 10 subjects, the occlusal alteration caused a significantly larger (in absolute values) opening angle than those under control conditions at the 5th mm of MIPT displacement. There was no significant difference between the two control conditions. Qualitatively, the

occlusal alteration caused a further opening rotation in eight of these nine subjects (e.g. Fig. 4.2-7 b), but a less opening rotation in one subject. In the other subject, the mandible rotated in the closing direction during the outgoing laterotrusion, and the occlusal alteration caused a larger angle of closing rotation.

(a) Frontal plane (about the X-axis)



(b) Sagittal plane (about the Y-axis)



(c) Horizontal plane (about the Z-axis)

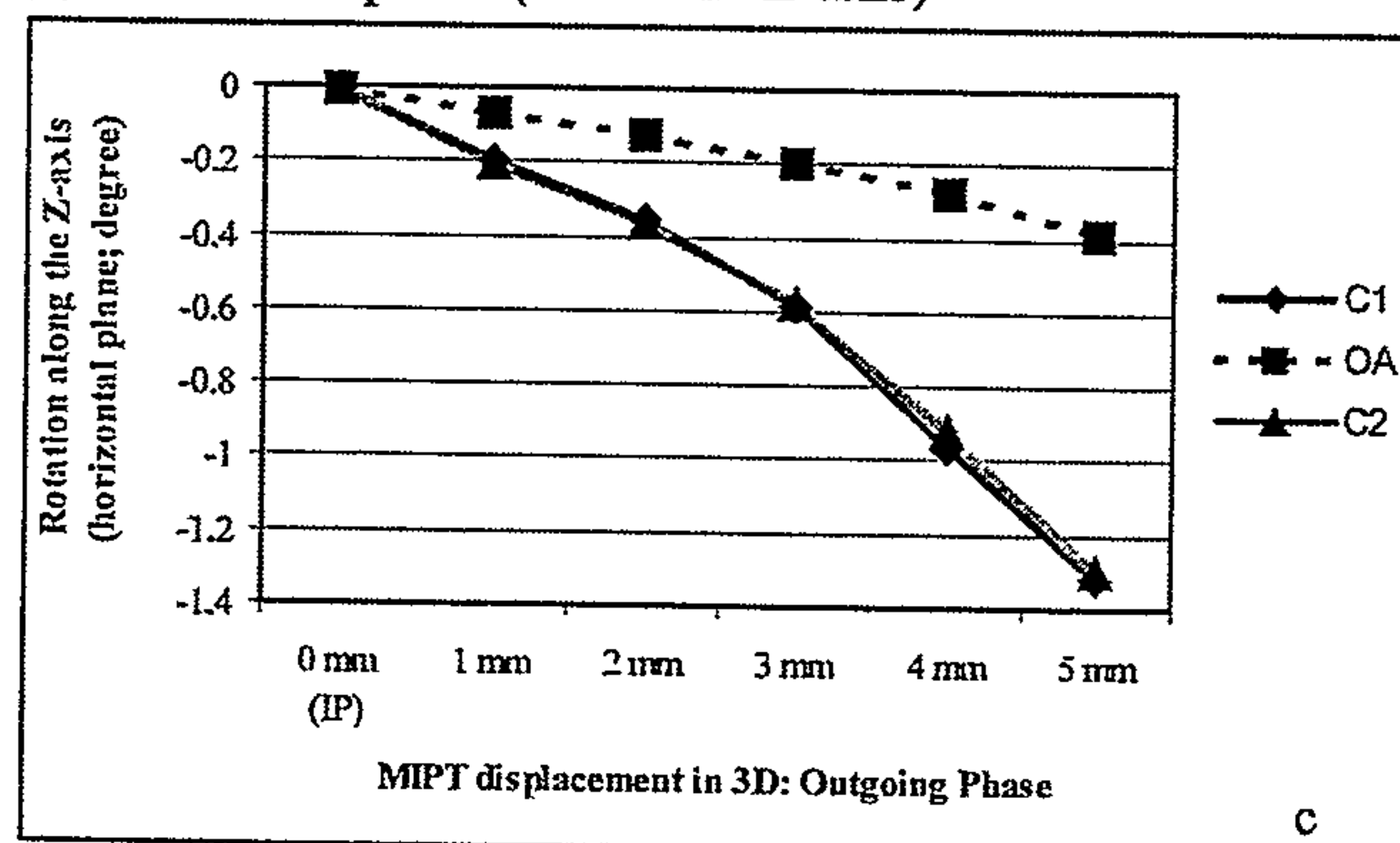


Fig. 4.2-7 An example of the influence of occlusal alteration on the rotation of the mandible at each mm of MIPT displacement during outgoing laterotrusion in the frontal (a), sagittal (b) and horizontal (c) planes. Each data point is the average of 10 trials. Positive values in the frontal plane (i.e. about the X-axis) indicate that the mandible is rotating to the right side (working side). Negative values in the sagittal plane (i.e. about the Y-axis) indicate that the mandible is rotating open. Negative values in the horizontal plane (i.e. about the Z-axis) indicate that the mandible is rotating to the right side. See Fig. 3.2-7 for details. C1: the control 1 condition; OA: the occlusal alteration condition; C2: the control 2 condition.

In the two subjects with a second overlay, the difference in rotation angle between the occlusal alteration and control conditions increased with the steeper overlay, although no statistical analysis was done. In the subject with the shallower overlay, the occlusal alteration caused a larger rotation angle in the

horizontal plane, and there was no change in the frontal and sagittal planes. In the subject with the sham overlay, there was no change in all three rotatory angles due to the occlusal alteration.

(a) 3rd mm of MIPT displacement

	3 rd mm MIPT displacement			
Rotation (°) about X-axis	Condition	C1	OA	C2
	Mean ± SD	0.88 ± 0.19	0.73 ± 0.33	0.88 ± 0.23
	Pairwise p	C1_OA 0.038	C1_C2 0.817	OA_C2 0.029
Rotation (°) about Y-axis	Condition	C1	OA	C2
	Mean ± SD	-0.55 ± 0.33	-0.65 ± 0.37	-0.53 ± 0.40
	Pairwise p	C1_OA 0.159	C1_C2 0.748	OA_C2 0.181
Rotation (°) about Z-axis	Condition	C1	OA	C2
	Mean ± SD	-0.62 ± 0.15	-0.46 ± 0.22	-0.65 ± 0.16
	Pairwise p	C1_OA 0.007	C1_C2 0.062	OA_C2 0.003

(b) 5th mm of MIPT displacement

	5 th mm MIPT displacement			
Rotation (°) about X-axis	Condition	C1	OA	C2
	Mean ± SD	1.49 ± 0.30	1.09 ± 0.51	1.46 ± 0.37
	Pairwise p	C1_OA 0.004	C1_C2 0.525	OA_C2 0.004
Rotation (°) about Y-axis	Condition	C1	OA	C2
	Mean ± SD	-0.72 ± 0.51	-1.05 ± 0.70	-0.71 ± 0.64
	Pairwise p	C1_OA 0.041	C1_C2 0.755	OA_C2 0.034
Rotation (°) about Z-axis	Condition	C1	OA	C2
	Mean ± SD	-1.19 ± 0.27	-0.80 ± 0.35	-1.21 ± 0.21
	Pairwise p	C1_OA 0.012	C1_C2 0.431	OA_C2 0.003

Table 4.2-2 The influence of the occlusal alteration on the mandibular rotatory angle about the X-axis (frontal plane), Y-axis (sagittal plane) and Z-axis (horizontal plane) at the (a) 3rd and (b) 5th mm of MIPT displacement during outgoing laterotrusion. The mean and standard deviation (in degrees) of the mandibular rotation under each condition is displayed. Positive values in the frontal plane (i.e. about the X-axis) indicate that the mandible is rotating to the right side (working side). Negative values in the sagittal plane (i.e. about the Y-axis) indicate that the mandible is rotating open. Negative values in the horizontal plane (i.e. about the Z-axis) indicate that the mandible is rotating to the right side. See Fig. 3.2-7 for details. In the third and fourth rows of each axis, the results of the pairwise comparison (General Linear Models with Repeated Measures) between the mean rotation angle about each axis under the three conditions are displayed. The cells marked with gray color indicate that there is a statistically significant difference ($p < 0.05$). C1: the control 1 condition; OA: the occlusal alteration condition; C2: the control 2 condition.

4.2.1.4 The influence of reference point selection

During the outgoing laterotrusion, the results of the overall statistical comparison regarding the influence of occlusal alteration on the working condylar path, was very similar among the five condylar points. All five points exhibited a significantly more anterior and inferior path under the occlusal alteration than that under the control 1 condition. However, the pairwise comparison between the occlusal alteration and control 2 conditions showed a slight variation among the different condylar referencing points at the 3rd mm of MIPT displacement. The medial points (the medial pole and the most superior and posterior points) did not show a significant difference between these two conditions in the X-axis as they did for the lateral points (the lateral pole and the most anterior point).

In addition, the influence of the occlusal alteration on the amount of the condylar-point displacement was significantly influenced by the selection of the condylar points. The General Linear Models with Repeated Measures (Table 4.2-3) showed that the difference between the condylar displacement under the control 1 and occlusal alteration conditions at the lateral pole and the most anterior point were significantly different to those at the most posterior point and the medial pole in all axis.

Furthermore, in the qualitative comparison, as mentioned in Section 4.2.1.2, there was a slight variation in the influence of occlusal alteration on changing movement direction in some subjects.

(A) X-axis (antero-posterior)

	L	A	S	P	M
Diff.	-0.21	-0.19	-0.19	-0.18	-0.16
L		0.031	0.233	0.012	0.007
A			0.692	0.034	0.009
S				0.823	0.363
P					0.016

(B) Y-axis (medial-lateral)

	L	A	S	P	M
Diff.	-0.13	-0.14	-0.12	-0.11	-0.12
L		0.052	0.081	0.027	0.033
A			0.030	0.014	0.011
S				0.522	0.735
P					0.111

(C) Z-axis (supero-inferior)

	L	A	S	P	M
Diff.	-0.32	-0.32	-0.28	-0.28	-0.27
L		0.363	0.058	0.014	0.011
A			0.070	0.027	0.016
S				0.677	0.321
P					0.440

Table. 4.2-3 The effect of condylar-points' selection on the difference of condylar displacement along each axis between the control 1 and occlusal alteration conditions at the 3rd mm of the MIPT displacement during the outgoing phase of laterotrusion. The second row of each table shows the mean difference (Diff.; in mm) between the condylar displacement under the control 1 and occlusal alteration conditions in each axis from all 10 subjects. Then the displacement difference at each point was compared with other points using General Linear Models with Repeated Measures. The third to sixth rows show the p values of the pairwise comparison. The gray cells indicate that there was a significant difference between the two points ($p < 0.05$). L: the lateral pole; A: the most anterior point; S: the most superior point; P: the most posterior point; M: the medial pole.

4.2.2 Return phase during laterotrusion

In summary, the influence of the occlusal alteration on the working-side condylar path during the return phase of laterotrusion was very similar to that during the outgoing phase, despite that, according to our results, the condylar path during the return phase was different to that during the outgoing phase. The working-side condylar path under the occlusal alteration was anterior and inferior to that under the control conditions at the same amount of MIPT displacement during the return phase of laterotrusion, with a statistically significant difference at most of the condylar points. The occlusal alteration also significantly changed all three rotatory angles, except for the rotation angle along the Y-axis at the 3rd mm of MIPT displacement. There was no significant difference in the displacement and rotation along each axis between the two control conditions, except for the condylar displacement in the Z-axis at the 3rd mm of MIPT displacement away from the intercuspal position. The qualitative assessment showed that in most subjects the condylar displacement in the Z-axis under the control 2 condition was superior to the control 1 condition and the control 1 was superior to the occlusal alteration condition. The selection of the condylar referencing points had an effect on the results of the statistical comparison between the working-side condylar path under the occlusal alteration and control conditions.

4.2.2.1 Condylar path projections

Fig. 4.2-8 shows an example from one subject's projected working-side condylar path of a single trial during the return phase of laterotrusion under the control 1 and occlusal alteration conditions. The black triangles (or quadrilaterals) show the end position (i.e. at return to intercuspal position) of the working-side

condyle, indicated by the arrow, under the control 1 (with dotted lines) and occlusal alteration (with solid lines) conditions. The red triangles (or quadrilaterals) with solid lines indicate the projected condylar positions at the 2nd, 4th and 6th mm of MIPT displacement away from the intercusp position during the return phase under the occlusal alteration. The blue triangles (or quadrilaterals) with dashed lines indicate the condylar position under the control 1 condition. In this subject, the working-side condylar head showed a more inferior path under the occlusal alteration than that under the control 1 condition. And the difference between the two conditions increased as the MIPT moved further away from the intercusp position.

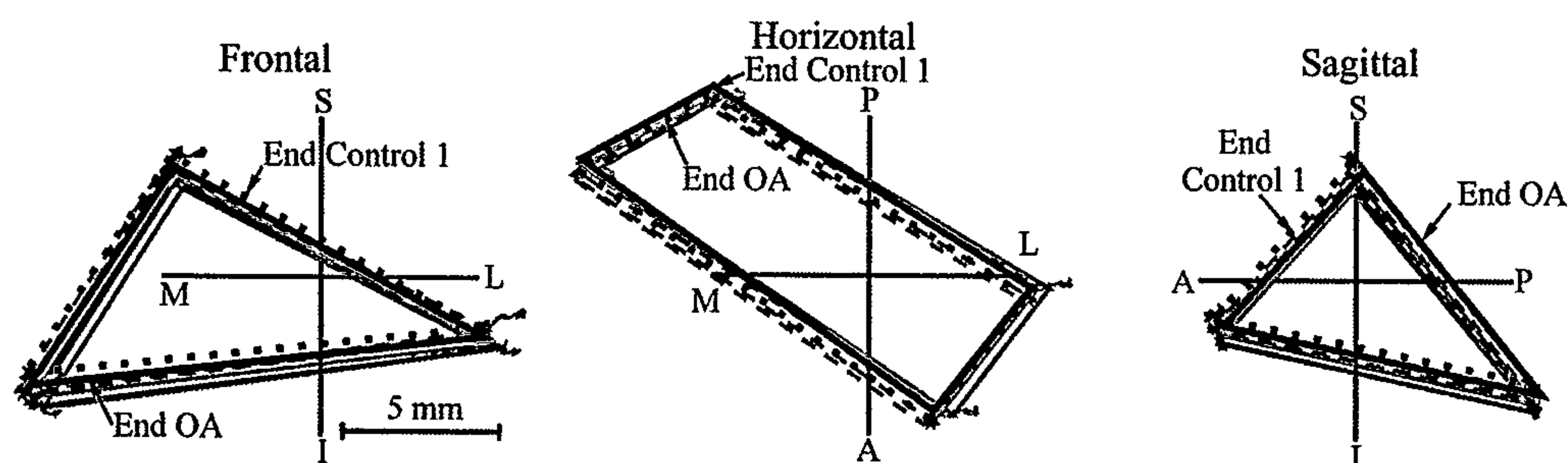


Fig. 4.2-8 The influence of the occlusal alteration on the projected working-side condylar path in each plane during the return phase of laterotrusion. Black triangles (or quadrilaterals) indicate the end position of the condyle under the control 1 (with dotted lines) and occlusal alteration (OA; with solid lines) conditions. The red triangles (or quadrilaterals) with solid lines show the condylar path under the occlusal alteration, whereas the blue ones with the dashed lines show that under the control 1 condition. A: anterior direction; I: inferior direction; L: lateral direction; M: medial direction; P: posterior direction; S: superior direction.

4.2.2.2 The influence of an occlusal alteration on the condylar translatory movements

Antero-posterior displacement (X-axis)

During the return phase of laterotrusion, the working-side condylar path under the occlusal alteration was statistically significantly anterior to that under the control conditions in all condylar points at both MIPT displacements (Table 4.2-4). These results were very similar to those during the outgoing phase, despite that,

qualitatively during the return phase in all 10 subjects, the condylar displacement in the X-axis was different to that during the outgoing laterotrusion under the same condition at the same amount of MIPT displacement from the intercusp position (e.g. Fig. 4.2-9). There was no significant difference between the control conditions on the return phase. In addition, in the only subject in whom the condylar path under the occlusal alteration was posterior to that under the control conditions during the outgoing laterotrusion (for details, see Section 4.2.1.2), the condylar path was anterior to that under the control conditions during the return phase of laterotrusion (e.g. Fig. 4.2-9). During the return phase, the difference between the condylar path under the three occlusal conditions decreased when the MIPT returned progressively toward the intercusp position in six of 10 subjects.

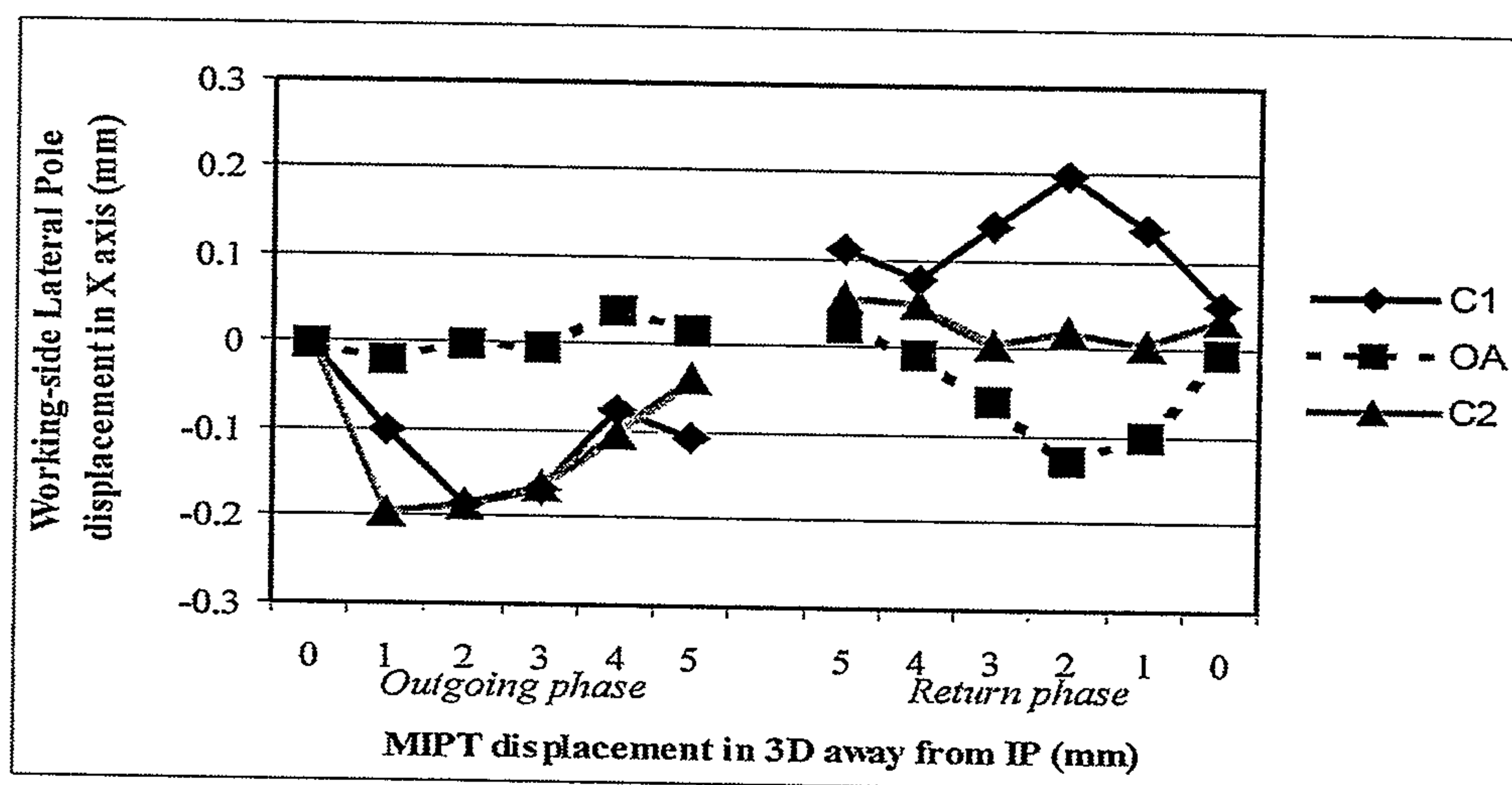


Fig. 4.2-9 An example of the condylar movement of the lateral pole in the X-axis under the three occlusal conditions at each mm of MIPT displacement away from the intercusp position (IP). Each data point is the average of 10 trials. Positive values indicate that the condyle position was posterior to the starting position. C1: the control 1 condition; OA: the occlusal alteration condition; C2: the control 2 condition.

(a) Displacement (mm) at the 3rd mm of MIPT displacement from the intercusp position

	Axis	X			Y			Z		
		C1	OA	C2	C1	OA	C2	C1	OA	C2
L	Condition									
	Mean $\pm$ SD	-0.02 $\pm$ 0.46	-0.24 $\pm$ 0.40	0.07 $\pm$ 0.32	0.22 $\pm$ 0.36	0.24 $\pm$ 0.44	0.30 $\pm$ 0.39	-0.18 $\pm$ 0.36	-0.46 $\pm$ 0.33	0.03 $\pm$ 0.26
	Pairwise	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2
A	p	0.004	0.265	0.007	0.702	0.169	0.347	0.032	0.016	0.001
	Condition									
	Mean $\pm$ SD	-0.09 $\pm$ 0.43	-0.27 $\pm$ 0.33	0.00 $\pm$ 0.31	0.25 $\pm$ 0.38	0.26 $\pm$ 0.45	0.33 $\pm$ 0.41	-0.30 $\pm$ 0.33	-0.57 $\pm$ 0.31	-0.12 $\pm$ 0.25
S	Pairwise	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2
	p	0.022	0.257	0.009	0.852	0.172	0.283	0.036	0.038	0.002
P	Condition									
	Mean $\pm$ SD	-0.19 $\pm$ 0.42	-0.38 $\pm$ 0.37	-0.11 $\pm$ 0.31	0.11 $\pm$ 0.39	0.14 $\pm$ 0.46	0.23 $\pm$ 0.47	-0.32 $\pm$ 0.34	-0.54 $\pm$ 0.32	-0.12 $\pm$ 0.25
	Pairwise	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2
M	p	0.008	0.334	0.019	0.543	0.112	0.151	0.063	0.024	0.002
	Condition									
	Mean $\pm$ SD	-0.15 $\pm$ 0.42	-0.33 $\pm$ 0.36	-0.07 $\pm$ 0.31	0.15 $\pm$ 0.36	0.19 $\pm$ 0.44	0.23 $\pm$ 0.37	-0.30 $\pm$ 0.36	-0.51 $\pm$ 0.36	-0.10 $\pm$ 0.28
	Pairwise	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2
	p	0.010	0.292	0.014	0.500	0.214	0.555	0.072	0.040	0.003
	Condition									
	Mean $\pm$ SD	-0.22 $\pm$ 0.40	-0.39 $\pm$ 0.36	-0.13 $\pm$ 0.29	0.18 $\pm$ 0.37	0.20 $\pm$ 0.44	0.25 $\pm$ 0.38	-0.42 $\pm$ 0.34	-0.63 $\pm$ 0.33	-0.27 $\pm$ 0.33
	Pairwise	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2	C1 OA	C1 C2	OA C2
	p	0.015	0.246	0.017	0.608	0.218	0.481	0.075	0.119	0.008

Table 4.2-4 The overall quantitative comparison of the working-side-condylar-point displacement in each axis between the three conditions at the (a) 3rd and (b) 5th mm of MIPT displacement from the intercusp position during the return phase of laterotrusion from all 10 subjects with the first overlay. The mean and standard deviation, from all subjects, of the condylar-point displacement in each axis under each condition is displayed. The far left column indicates the condylar points [L: the lateral pole of the working-side condylar head; A: the most anterior point; S: the most superior point; P: the most posterior point; M: the medial pole]. In the third and fourth rows of the condylar point, the results of the pairwise comparison (General Linear Models with Repeated Measures) between the mean displacement in each axis of the three conditions were displayed. The cells marked with gray color indicate that there is a statistically significant difference ($p < 0.05$). The results of the five condylar points are aligned based on the medio-lateral position of each point. C1: the control 1 condition; OA: the occlusal alteration condition; C2: the control 2 condition.

(b) Displacement (mm) at the 5th mm of MIPT displacement from the interscusp position

	Axis	X			Y			Z		
		CI	OA	C2	CI	OA	C2	CI	OA	C2
L	Condition									
	Mean $\pm$ SD	0.05 $\pm$ 0.56	-0.34 $\pm$ 0.54	0.16 $\pm$ 0.45	0.37 $\pm$ 0.64	0.44 $\pm$ 0.58	0.55 $\pm$ 0.56	-0.24 $\pm$ 0.44	-0.72 $\pm$ 0.49	-0.08 $\pm$ 0.40
	Pairwise	CI OA	CI C2	OA C2	CI OA	CI C2	OA C2	CI OA	CI C2	OA C2
A	p	0.008	0.174	0.005	0.638	0.105	0.243	0.002	0.136	0.001
	Condition	CI	OA	C2	CI	OA	C2	CI	OA	C2
	Mean $\pm$ SD	-0.08 $\pm$ 0.53	-0.41 $\pm$ 0.47	0.03 $\pm$ 0.43	0.54 $\pm$ 0.57	0.48 $\pm$ 0.59	0.61 $\pm$ 0.59	-0.43 $\pm$ 0.41	-0.90 $\pm$ 0.46	-0.27 $\pm$ 0.38
S	Pairwise	CI OA	CI C2	OA C2	CI OA	CI C2	OA C2	CI OA	CI C2	OA C2
	p	0.018	0.180	0.008	0.605	0.235	0.194	0.002	0.103	0.001
	Condition	CI	OA	C2	CI	OA	C2	CI	OA	C2
P	Mean $\pm$ SD	-0.24 $\pm$ 0.52	-0.56 $\pm$ 0.46	-0.14 $\pm$ 0.42	0.30 $\pm$ 0.55	0.29 $\pm$ 0.56	0.42 $\pm$ 0.65	-0.47 $\pm$ 0.40	-0.84 $\pm$ 0.43	-0.29 $\pm$ 0.34
	Pairwise	CI OA	CI C2	OA C2	CI OA	CI C2	OA C2	CI OA	CI C2	OA C2
	p	0.004	0.208	0.006	0.933	0.196	0.160	0.006	0.530	0.001
M	Condition	CI	OA	C2	CI	OA	C2	CI	OA	C2
	Mean $\pm$ SD	-0.20 $\pm$ 0.52	-0.50 $\pm$ 0.51	-0.09 $\pm$ 0.43	0.35 $\pm$ 0.51	0.35 $\pm$ 0.54	0.42 $\pm$ 0.51	-0.45 $\pm$ 0.42	-0.78 $\pm$ 0.52	-0.29 $\pm$ 0.39
	Pairwise	CI OA	CI C2	OA C2	CI OA	CI C2	OA C2	CI OA	CI C2	OA C2
	p	0.015	0.185	0.010	0.972	0.251	0.441	0.017	0.117	0.005
	Condition	CI	OA	C2	CI	OA	C2	CI	OA	C2
	Mean $\pm$ SD	-0.32 $\pm$ 0.49	-0.60 $\pm$ 0.49	-0.21 $\pm$ 0.41	0.39 $\pm$ 0.54	0.38 $\pm$ 0.56	0.47 $\pm$ 0.54	-0.64 $\pm$ 0.39	-0.98 $\pm$ 0.45	-0.51 $\pm$ 0.33
	Pairwise	CI OA	CI C2	OA C2	CI OA	CI C2	OA C2	CI OA	CI C2	OA C2
	p	0.023	0.180	0.015	0.882	0.251	0.348	0.010	0.195	0.001

Table 4.2-4 (continued)

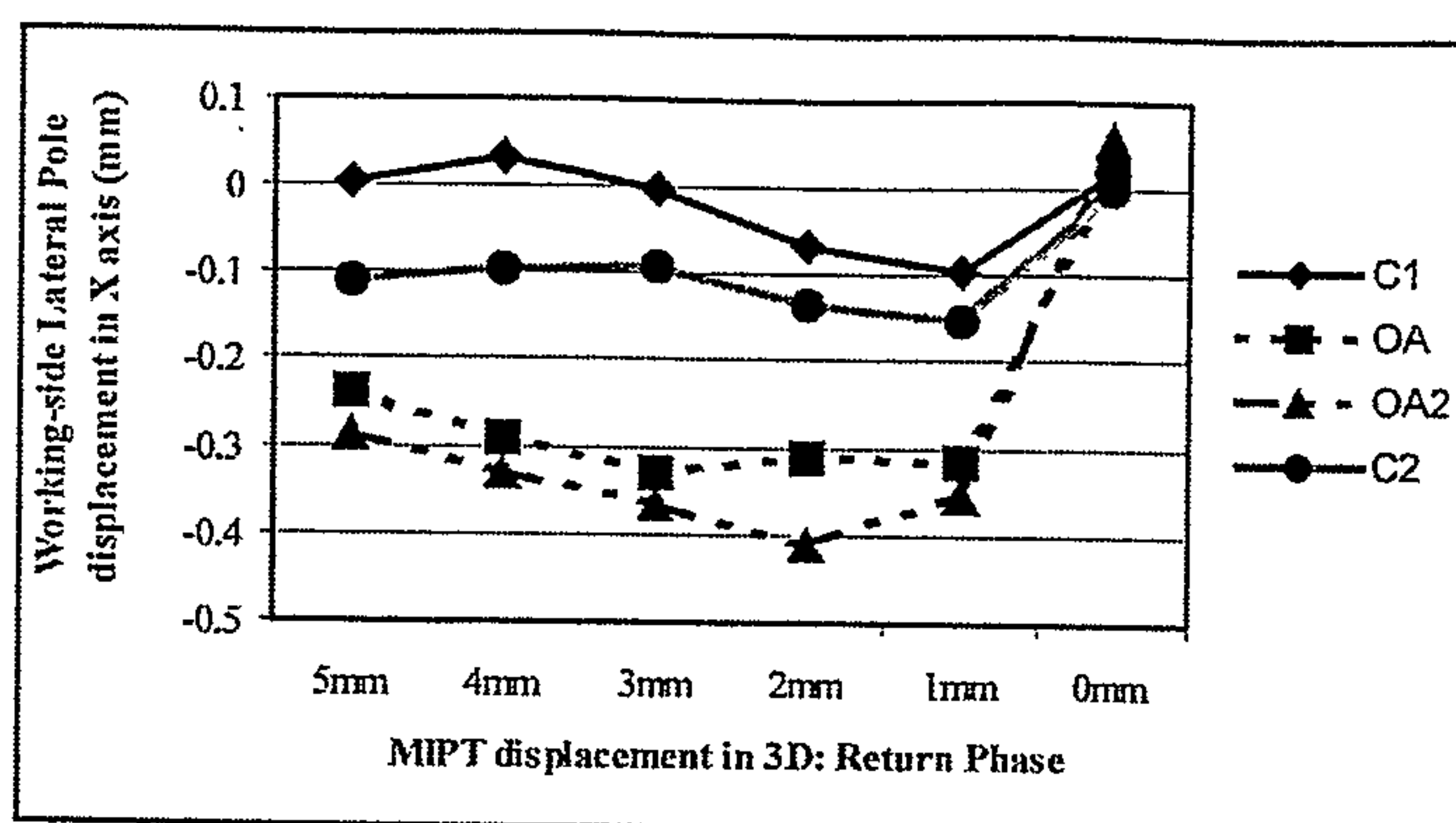


Fig. 4.2-10 An example of the condylar movement under the occlusal alteration and control conditions at each mm of MIPT displacement. Each data point is the average of 10 trials. Positive values indicate that the condyle position was posterior to the starting position. C1: the control 1 condition; OA: the occlusal alteration condition; OA2: the occlusal alteration 2 condition with a steeper overlay; C2: the control 2 condition.

In the two subjects with a second overlay, the working-side condylar path under the first overlay was anterior to those under the control conditions, and the data showed suggestive evidence that, under the second (steeper) overlay, the working-side condylar path was further anterior to that under the first overlay (e.g. Fig. 4.2-10). In the subject with the shallower overlay, the condylar path was posterior to that under the control conditions. In the sham overlay subject, there was no difference between the three conditions.

Medial-lateral displacement (Y-axis)

Table 4.3-4 shows that there was no significant difference in the condylar displacement in the medial-lateral direction between the three occlusal conditions at both MIPT displacements. Qualitatively, the influence of the occlusal alteration of the working-side condylar path during the return phase was similar to that during the outgoing phase at the same mm of MIPT displacement away from the intercusp position, in all except one subject. Under the occlusal alteration, four (of five during the outgoing phase) subjects showed a less lateral path, four (of four during the outgoing phase) showed no change in lateral displacement, and one showed a more lateral path during both the outgoing and return phases. In the

only exception, the condylar path under the occlusal alteration was less lateral to that under the control conditions during the outgoing phase, however, there was no difference during the return phase (e.g. Fig. 4.2-11). In the sham overlay subject, the occlusal alteration did not change the condylar path.

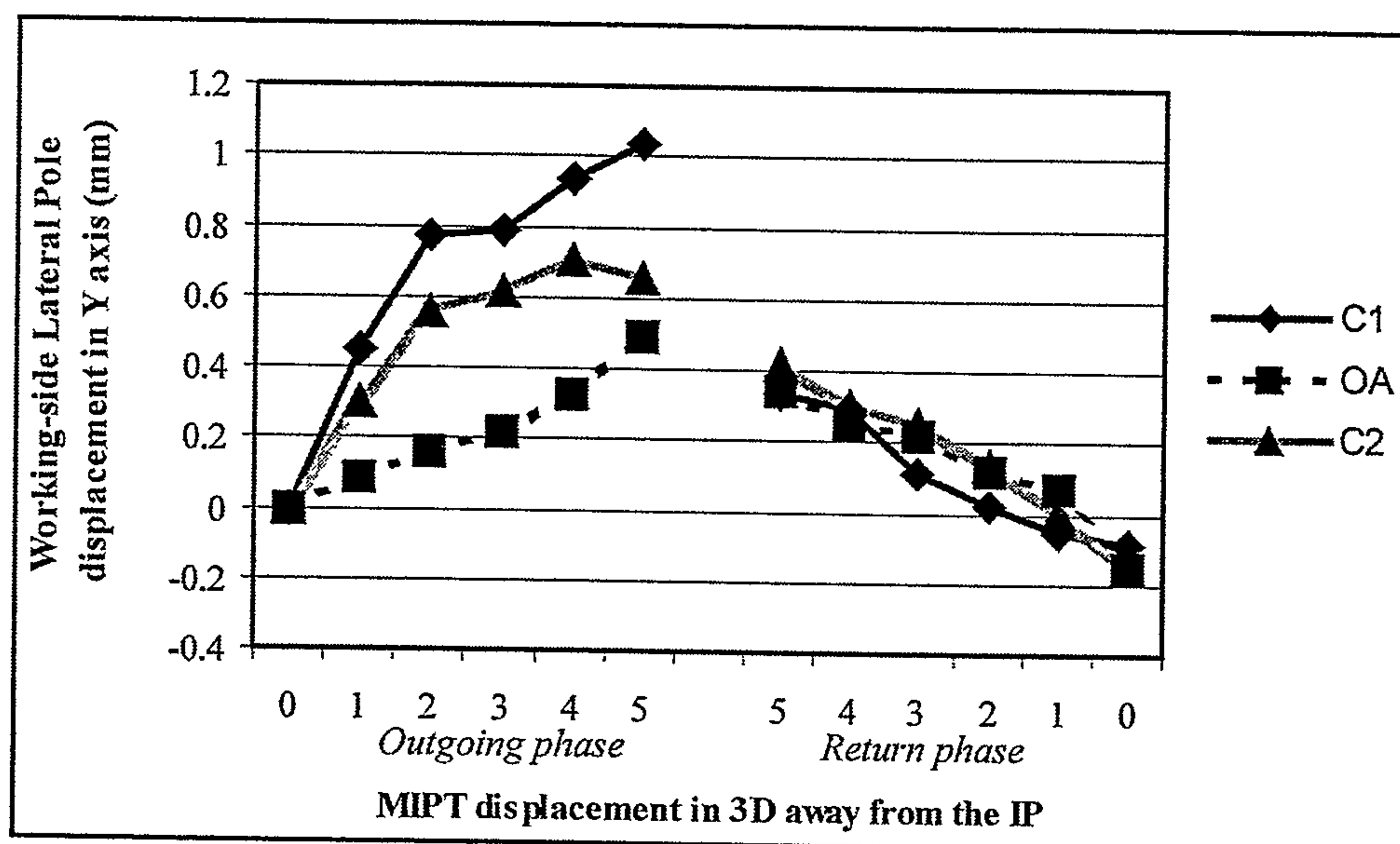


Fig. 4.2-11 An example of the condylar movement of the lateral pole in the Y-axis under the three occlusal conditions at each mm of MIPT displacement away from the intercusp position (IP). Each data point is the average of 10 trials. Positive values indicate that the condyle position was lateral to the starting position. C1: the control 1 condition; OA: the occlusal alteration condition; C2: the control 2 condition.

Supero-inferior displacement (Z-axis)

Table 4.2-4 shows that the occlusal alteration resulted in a working-side condylar path that was inferior to that under the control 1 condition at the 3rd and 5th mm MIPT displacement during the return phase. At the 5th mm of MIPT displacement during the return phase, the result was similar to that during the outgoing phase, that is the occlusal alteration caused a significantly more inferior condylar path compared with both control conditions and there was no significant difference between the control 1 and 2 conditions. However, at the 3rd mm of MIPT displacement, the results were significantly influenced by the selection of the condylar reference points. Although all the condylar points under the occlusal

alteration showed a path inferior to that under the control conditions, only the laterally positioned points (the lateral pole and the most anterior point) showed a statistically significant difference. Whereas, the more medially positioned points (the most superior and posterior points and the medial pole) did not show a significant difference. Furthermore, after the removal of overlay, the working-side condylar path under the control 2 condition was superior to that under the control 1 condition, with statistically significant difference between the two conditions in all condylar points except the medial pole. Thus, it indicates the possibility that other factors may also be involved in influencing the working side condylar path.

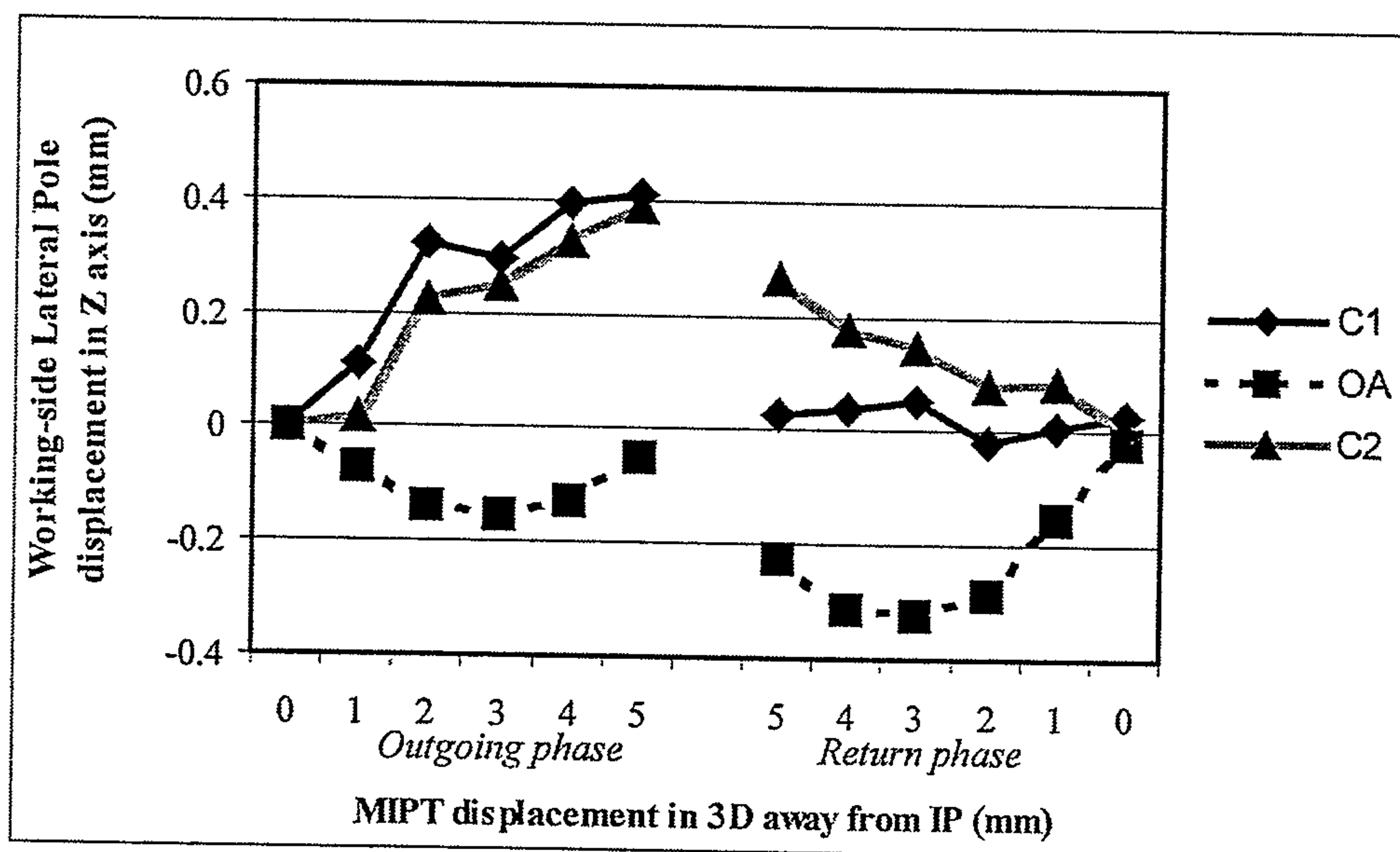


Fig. 4.2-12 An example of the condylar movement of the lateral pole in the Z-axis under the three occlusal conditions at each mm of MIPT displacement away from the intercuspal position (IP). Each data point is the average of 10 trials. Positive values indicate that the condyle position was superior to the starting position. C1: the control 1 condition; OA: the occlusal alteration condition; C2: the control 2 condition.

Qualitatively, as in the X- and Y-axes, the condylar path in the Z-axis during the return phase was different to that at the outgoing phase (e.g. Fig. 4.2-12). However, the working-side condylar paths under the occlusal alteration were inferior to those under both control conditions, during the outgoing and return

phases (e.g. Fig. 4.2-12 and 4.2-13). In seven (of 10) subjects, the working side condylar path in the Z-axis under the control 2 condition not only returned toward the control 1 level but also was superior to that under the control 1 condition. In three subjects, the condylar displacement in the Z-axis under the control 2 condition was about the same as or slightly inferior to that under the control 1 condition (e.g. Fig. 4.2-13). The difference between the condylar displacement in the Z-axis under the occlusal alteration and control conditions decreased while the MIPT returned progressively toward the intercuspal position, in all except one subject.

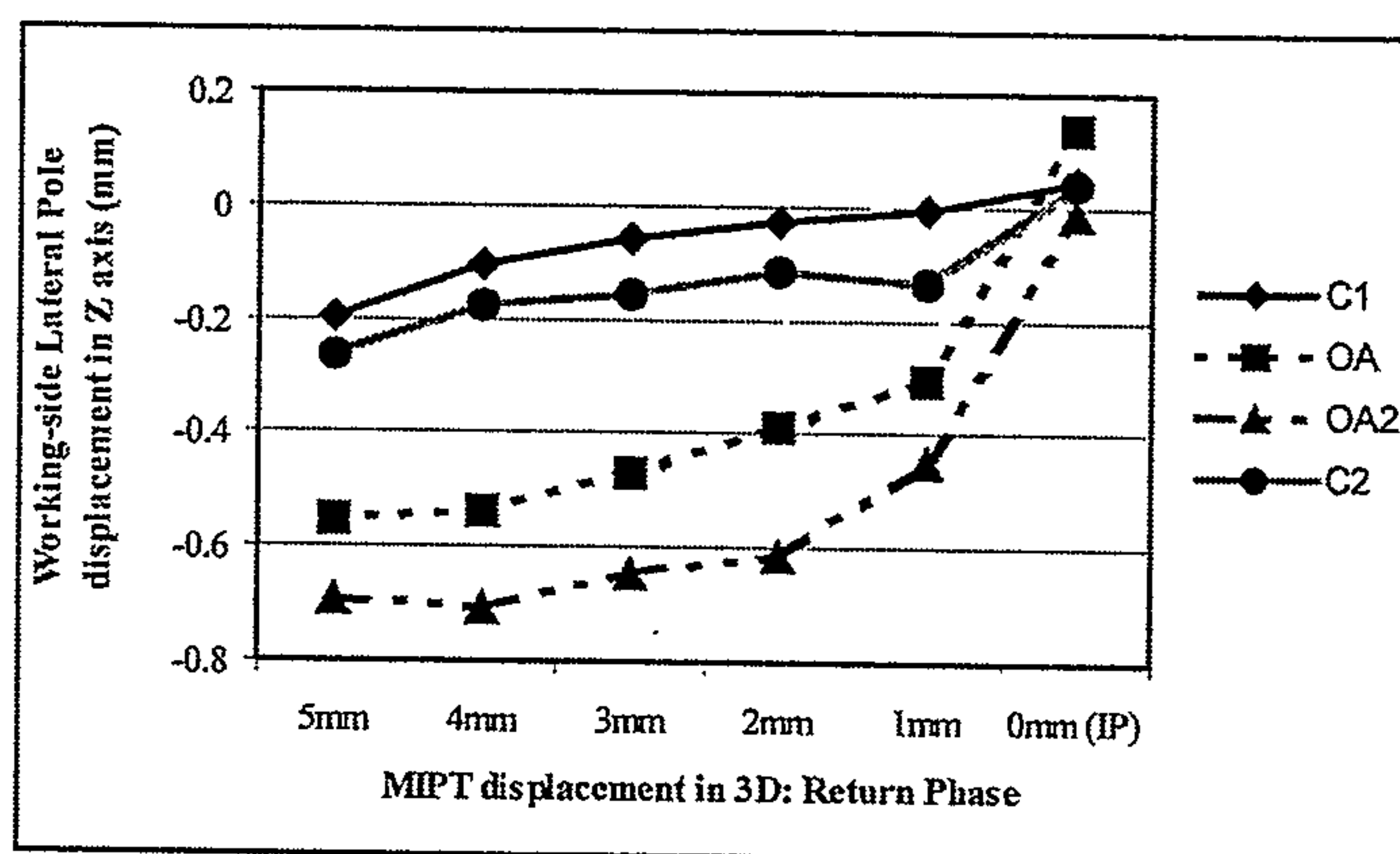


Fig. 4.2-13 An example of the condylar displacement in the Z-axis under the occlusal alteration and control conditions at each mm of MIPT displacement. Each data point is the average of 10 trials. Positive values indicate that the condyle position was superior to the starting position. C1: the control 1 condition; OA: the occlusal alteration condition; OA2: the occlusal alteration 2 condition with a steeper overlay; C2: the control 2 condition.

In the two subjects with a second overlay, the working-side condylar path under the first overlay was inferior to those under the control conditions, and that under the second (steeper) overlay, was further inferior to that under the first overlay (e.g. Fig. 4.2-13), although no statistical analysis was done. In the subject with the shallower overlay, the condylar path was superior to that under the control conditions. In the sham overlay subject, there was no difference between the three conditions.

4.2.2.3 The influence of an occlusal alteration on the rotatory movements

(a) 3rd mm of MIPT displacement

	3 rd mm MIPT displacement			
Rotation (°) about X-axis	Condition	C1	OA	C2
	Mean ± SD	0.92 ± 0.26	0.72 ± 0.35	0.88 ± 0.27
	Pairwise p	C1_OA 0.005	C1_C2 0.103	OA_C2 0.016
Rotation (°) about Y-axis	Condition	C1	OA	C2
	Mean ± SD	-0.49 ± 0.42	-0.60 ± 0.44	-0.53 ± 0.45
	Pairwise p	C1_OA 0.214	C1_C2 0.434	OA_C2 0.442
Rotation (°) about Z-axis	Condition	C1	OA	C2
	Mean ± SD	-0.63 ± 0.24	-0.48 ± 0.25	-0.69 ± 0.17
	Pairwise p	C1_OA 0.040	C1_C2 0.148	OA_C2 0.001

(b) 5th mm of MIPT displacement

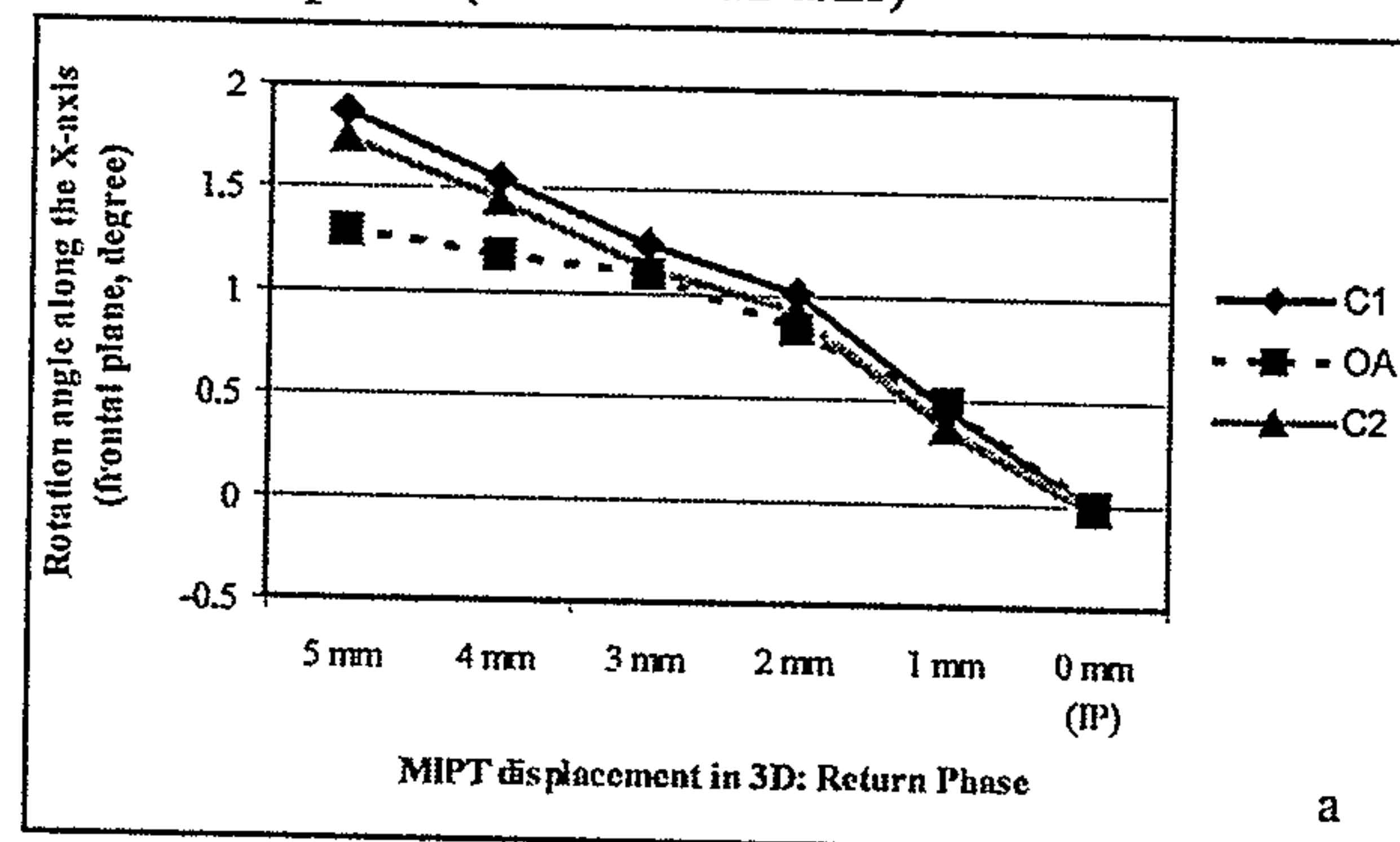
	5 th mm MIPT displacement			
Rotation (°) about X-axis	Condition	C1	OA	C2
	Mean ± SD	1.51 ± 0.37	1.11 ± 0.51	1.48 ± 0.42
	Pairwise p	C1_OA 0.001	C1_C2 0.362	OA_C2 0.002
Rotation (°) about Y-axis	Condition	C1	OA	C2
	Mean ± SD	-0.68 ± 0.63	-1.03 ± 0.72	-0.68 ± 0.66
	Pairwise p	C1_OA 0.037	C1_C2 0.984	OA_C2 0.024
Rotation (°) about Z-axis	Condition	C1	OA	C2
	Mean ± SD	-1.20 ± 0.34	-0.83 ± 0.36	-1.23 ± 0.27
	Pairwise p	C1_OA 0.004	C1_C2 0.293	OA_C2 0.002

Table 4.2-5 The influence of the occlusal alteration on the mandibular rotatory angle about the X-axis (frontal plane), Y-axis (sagittal plane) and Z-axis (horizontal plane) at the (a) 3rd and (b) 5th mm of MIPT displacement during the return phase of laterotrusion. The mean and standard deviation of the rotation under each condition is displayed. Positive values in the frontal plane (i.e. about the X-axis) indicate that the mandible is rotating to the right side (working side). Negative values in the sagittal plane (i.e. about the Y-axis) indicate that the mandible is rotating open. Negative values in the horizontal plane (i.e. about the Z-axis) indicate that the mandible is rotating to the right side. See Fig. 3.2-7 for details. In the third and fourth rows of each axis, the results of the pairwise comparison (General Linear Models with Repeated Measures) between the mean rotating angle along each axis under the three conditions are displayed. The cells marked with gray color indicate that there is a statistically significant difference ($p < 0.05$). C1: the control 1 condition; OA: the occlusal alteration condition; C2: the control 2 condition.

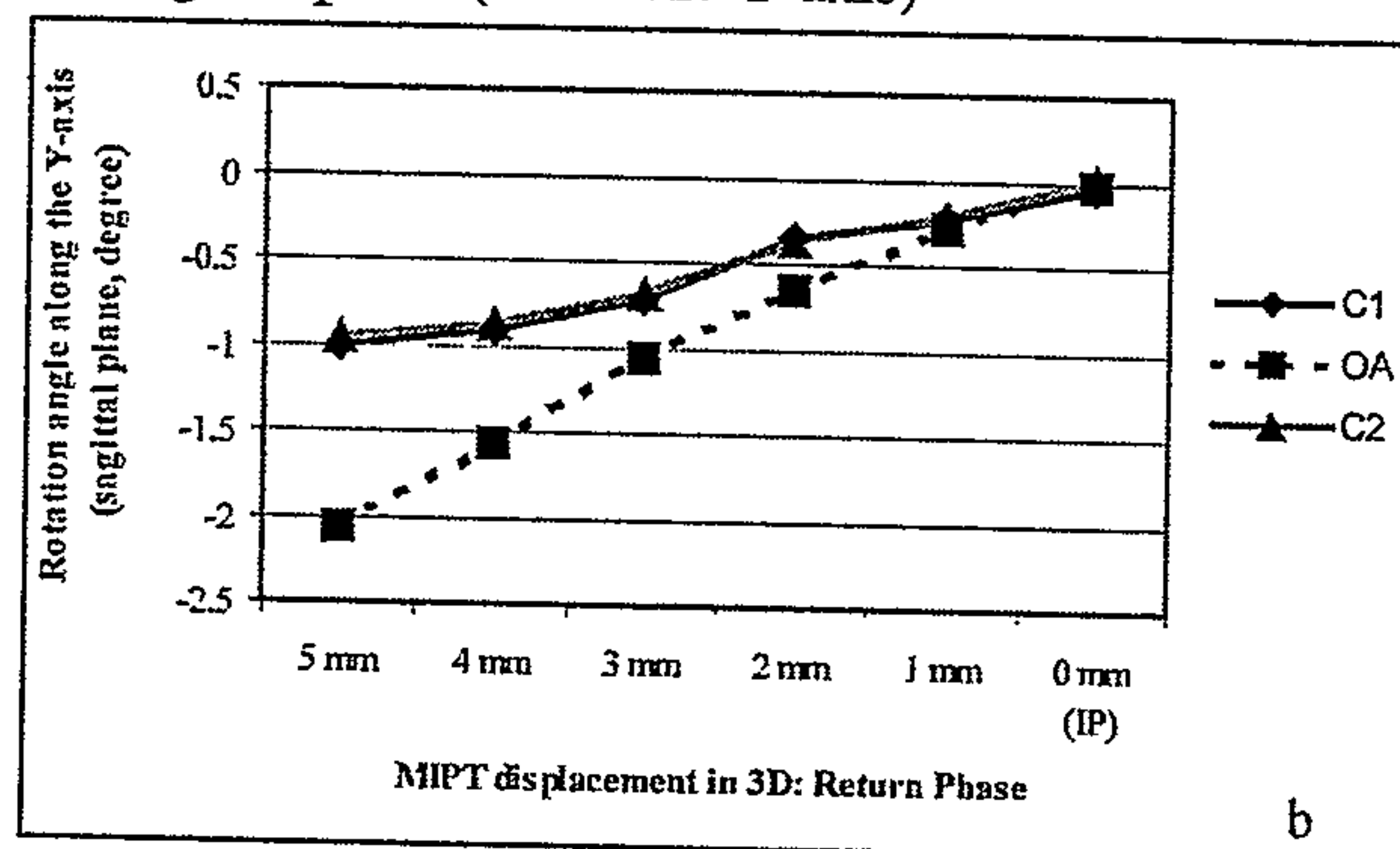
In all 10 subjects, the mandibular rotation angle returned toward zero during the return phase of laterotrusion. At both MIPT displacements, the mandibular rotation angle under the occlusal alteration was significantly less (in absolute value) in the frontal plane (i.e. about the X-axis; e.g. Fig. 4.2-14 (a)) and

horizontal plane (i.e. about the Z-axis; e.g. Fig. 4.2-14 (c)) than those under the control conditions (Table 4.2-5). There was no significant difference between the control conditions. The difference between the occlusal alteration and control conditions during the return phase decreased while the MIPT returned progressively toward the intercuspal position.

(a) Frontal plane (about the X-axis)



(b) Sagittal plane (about the Y-axis)



(c) Horizontal plane (about the Z-axis)

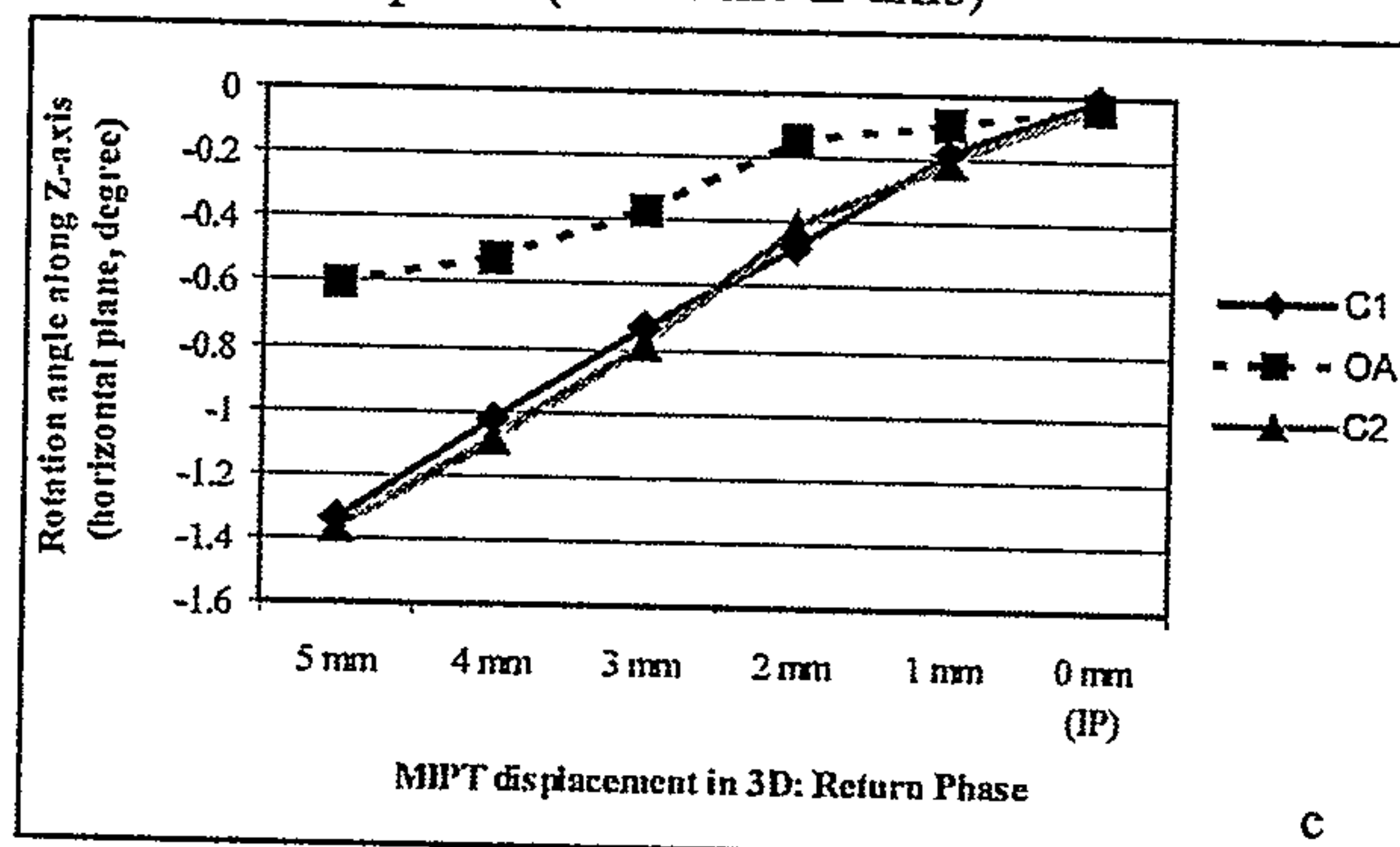


Fig. 4.2-14 An example of the influence of occlusal alteration on the rotation of the mandible at each mm of MIPT displacement during the return phase of laterotrusion in the frontal (a), sagittal (b) and horizontal (c) planes. Each data point is the average of 10 trials. Positive values in the frontal plane (i.e. about the X-axis) indicate that the mandible is rotating to the right side (working side). Negative values in the sagittal plane (i.e. about the Y-axis) indicate that the mandible is rotating open. Negative values in the horizontal plane (i.e. about the Z-axis) indicate that the mandible is rotating to the right side. See Fig. 3.2-7 for details. C1: the control 1 condition; OA: the occlusal alteration condition; C2: the control 2 condition.

In the sagittal plane, the mandibular rotation angle (about the Y-axis) returned from rotated open towards zero during the return phase of laterotrusion in eight (of nine during the outgoing phase) subjects. Table 4.2-5 (b) shows that the occlusal alteration caused an increase (in absolute value) in the rotation angle

about the Y-axis with a significant difference at the 5th mm of MIPT displacement. There was no significant difference between the control conditions. Individually, at the same amount of MIPT displacement, the angle under the occlusal alteration was larger (in absolute value) than that under the control conditions in seven of these eight subjects (e.g. Fig. 4.2-14 b), but less in one subject. In the only exception of the nine subjects (as shown in Fig. 4.2-15), the mandible rotated open slightly during the outgoing phase, but during the return phase the mandibular rotation returned to zero from a rotated-closed angle under the control conditions. Under the occlusal alteration, the angle of opening rotation was larger (in absolute value) than that under the control conditions during the outgoing phase, and the mandibular rotation angle about the Y-axis returned from rotated open towards zero during the return phase (Fig. 4.2-15). In the remaining one (other than the nine subjects), the mandible returned from a rotated closing angle towards zero (see Fig. 3.2-7), and the angle under the occlusal alteration was less (in absolute value) than that under the control conditions.

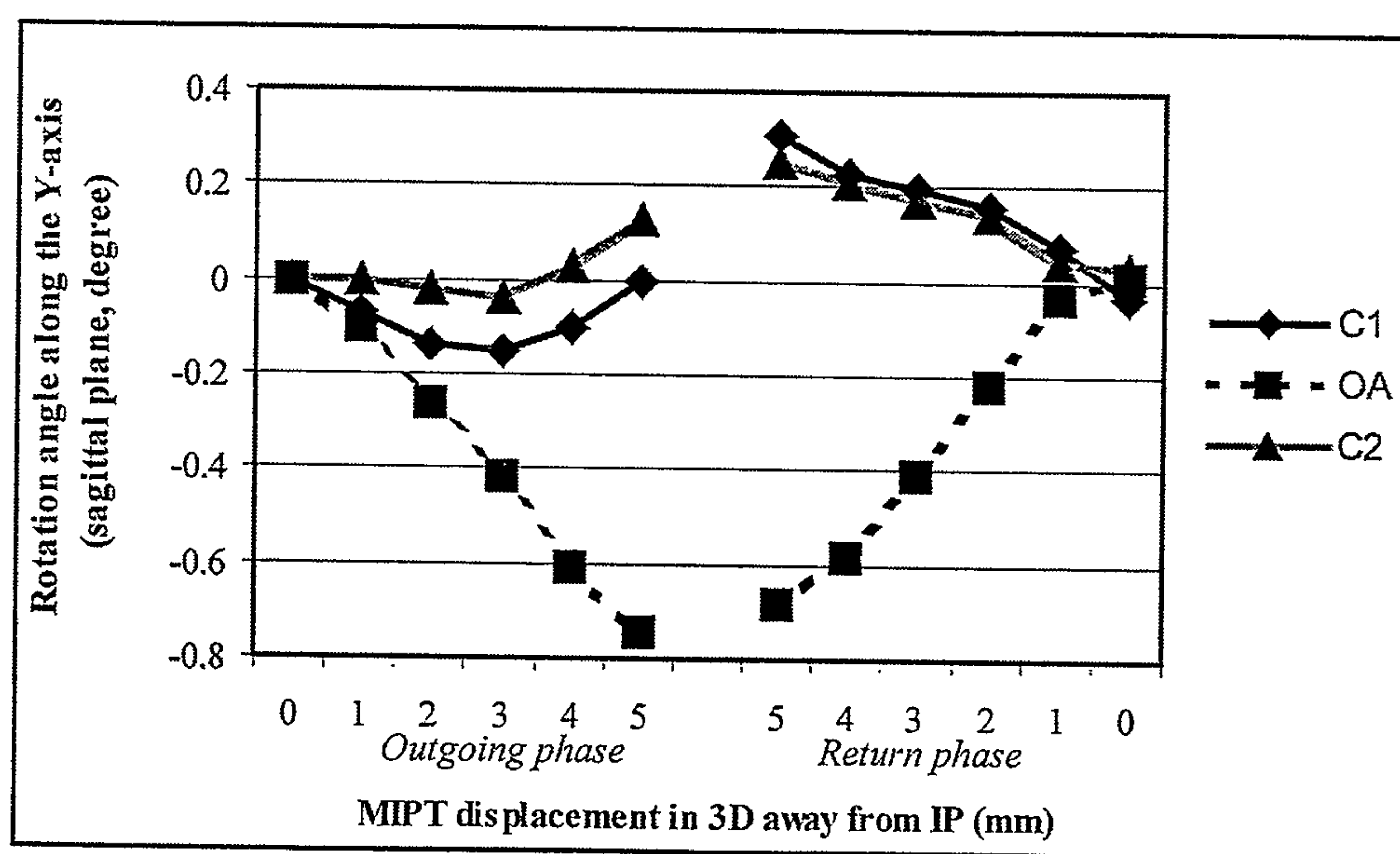


Fig. 4.2-15 An example from one subject of the influence of occlusal alteration on the rotation of the mandible about the Y-axis (the sagittal plane) at each mm of MIPT displacement during laterotrusion. Each data point is the average of 10 trials. Negative values indicate that the mandible is rotating open. See Fig. 3.2-7 for details. C1: the control 1 condition; OA: the occlusal alteration condition; C2: the control 2 condition.

In the two subjects with a second overlay, the difference in rotation angle between the occlusal alteration and control conditions increased with the steeper overlay during the return phase. In the subject with the shallower overlay, the occlusal alteration caused a larger rotation angle in the horizontal plane, and there was no change in the frontal and sagittal planes. In the subject with the sham overlay, there was no change in all three rotatory angles due to the occlusal alteration.

4.2.2.4 The influence of reference point selection

During the return phase of laterotrusion, the results of the overall statistical comparison regarding the influence of the occlusal alteration on the working condylar path, could be significantly influenced by the selection of the condylar reference points. In Table 4.2-4 (a), the pairwise comparison in the Z-axis showed that only the laterally positioned points (the lateral pole and the most anterior point) showed statistically significant differences between the control 1 and occlusal alteration conditions, and between the occlusal alteration and control 2 conditions. Whereas, the medially positioned points (the most superior and posterior points and the medial pole) did not show significant differences between control 1 and occlusal alteration conditions. Furthermore, the medial pole did not show a significant difference between the two control conditions as did the other four condylar points.

4.3 EMG activity of the jaw muscles

4.3.1 EMG activity of the jaw muscles during laterotrusive tasks

4.3.1.1 Laterotrusion with low closing force at slow speed

In general, the IHLP contralateral to the direction of jaw movement exhibited a clear increase in EMG activity throughout the outgoing, holding and return phases of the movement. The contralateral anterior and posterior temporalis usually showed a decrease during eccentric phases, and the activity in the other closing muscles was more variable between subjects. Representative data from one trial in one subject is shown in Fig. 4.3-1.

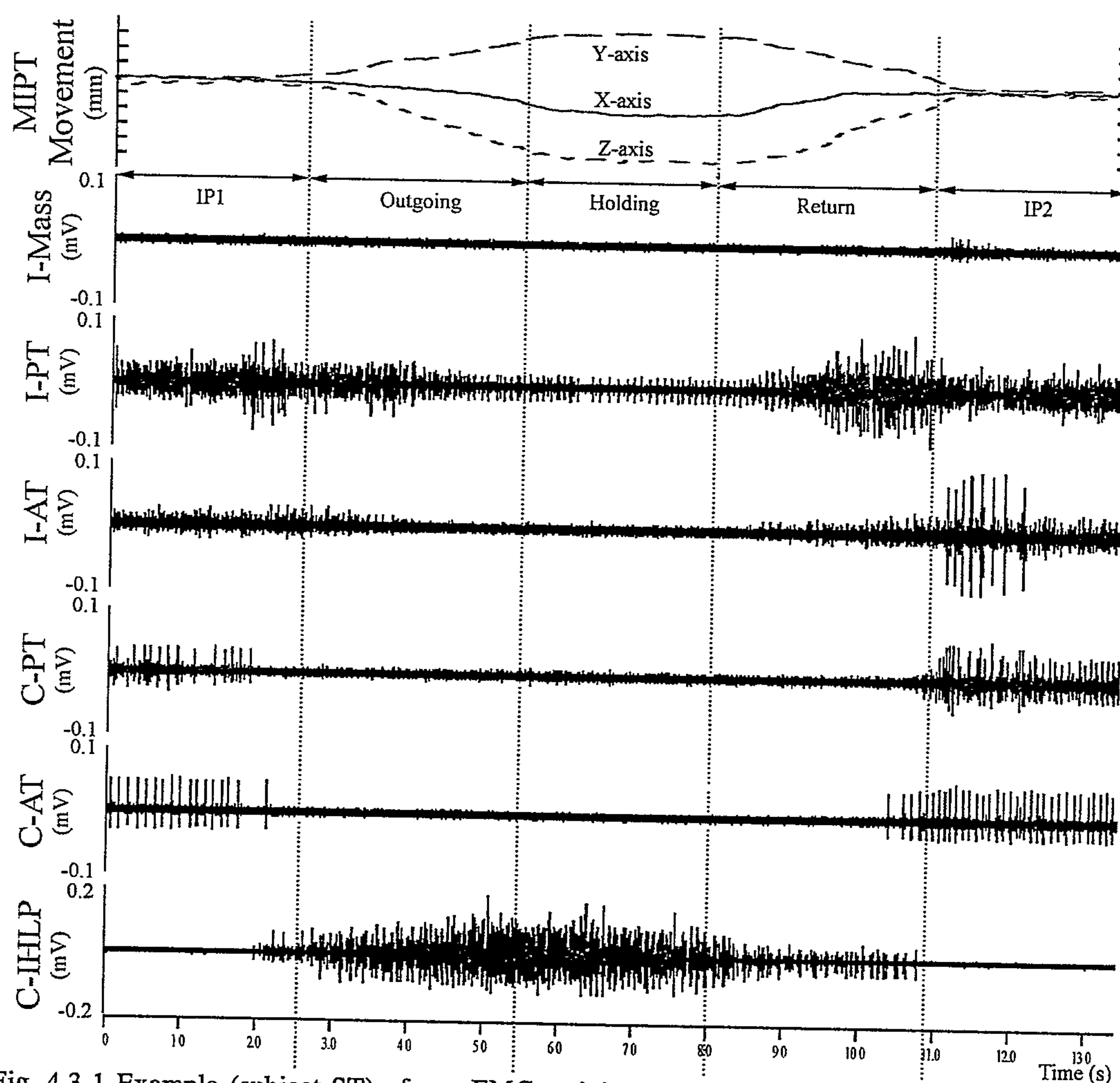


Fig. 4.3-1 Example (subject ST) of raw EMG activity and mid-incisor point (MIPT) movement during laterotrusion with low force to maintain tooth contact at slow speed. The four vertical dotted lines separate the five phases indicated by the visual-feedback device. The contralateral masseter was not available due to technical difficulties in this recording. C-: contralateral to the movement side; I-: ipsilateral to the movement side; IHLP: inferior head of lateral pterygoid muscle; AT: anterior temporalis; PT: posterior temporalis; Mass: masseter.

Contralateral inferior head of the lateral pterygoid muscles

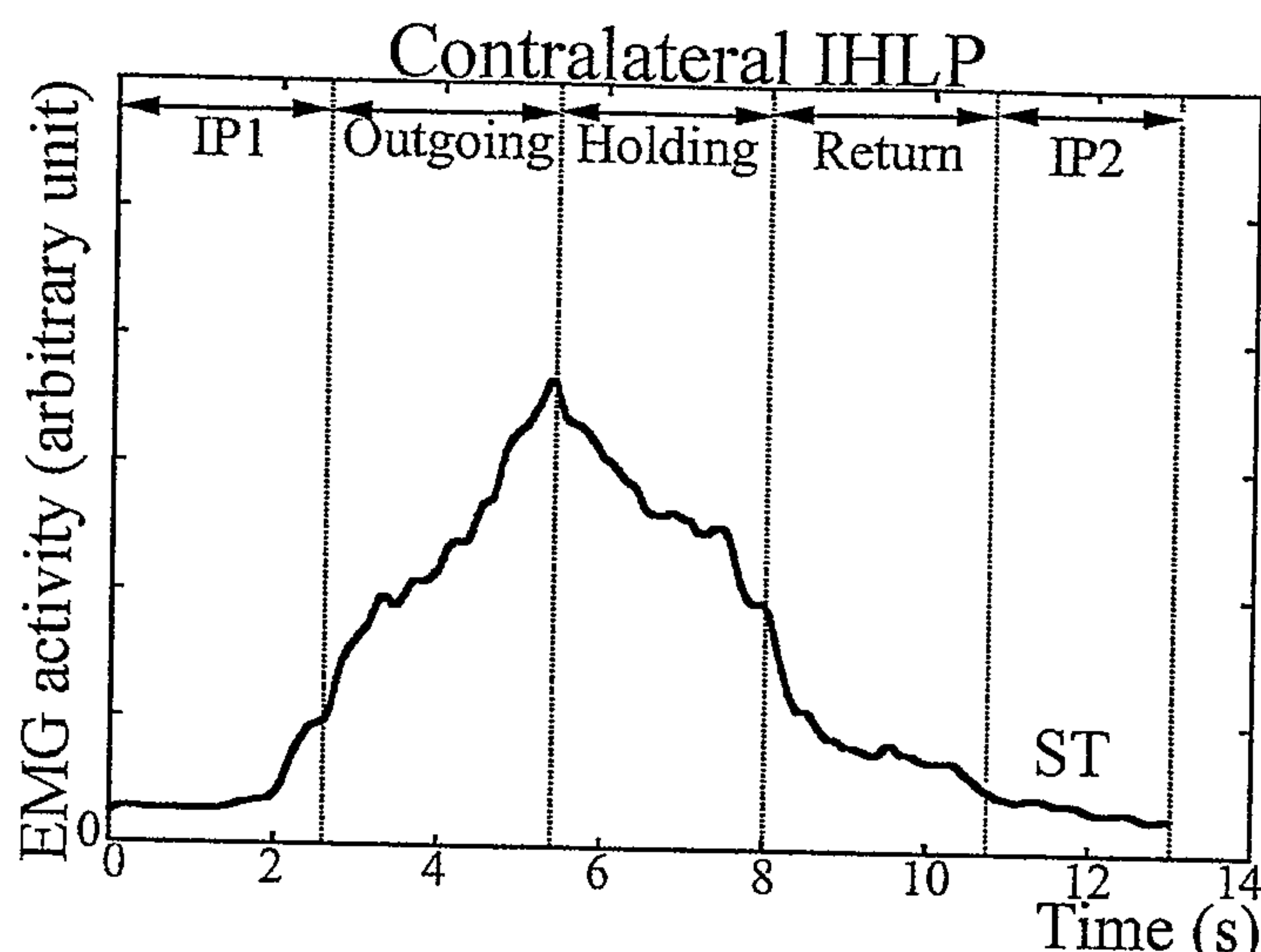


Fig. 4.3-2 Example (subject ST) of average contralateral IHLP activity of 10 trials after being rectified and smoothed.

The qualitative assessment of 10 subjects indicated that there was no active motor unit in the contralateral IHLP recorded at the intercuspal position (for example, see Fig. 4.3-1 and 4.3-2). The EMG activity gradually increased in the outgoing phase, and reached its peak usually by the early one-third of the holding phase. Then, the EMG activity gradually decreased. Between the late one-third of the holding phase and the early one-third of the return phase, there was a rapid decrease in the contralateral IHLP activity, except in two subjects, which was then followed by a slower decrease during the remainder of the return phase. No motor unit was recorded after returning back to intercuspal position. The slight increase in activity in the early IP2 phase (e.g. Fig. 4.3-2) reflected the fact that some subjects did not return completely to intercuspal position by the end of the return phase defined by the visual-feedback targets.

Subject	Onset	Offset
01	0.33	1.02
02	0.56	0.19
03	0.30	1.07
04	0.64	0.16
05	0.13	0.32
06	-0.41	0.21
07	0.40	-0.20
08	0.38	0.52
09	0.05	1.36
10	-0.85	2.63
Mean $\pm$ SD	0.15 $\pm$ 0.46	0.73 $\pm$ 0.83

Table 4.3-1 The difference (s) between the onset of MIPT movement and IHLP activity in each subject, and corresponding values for offset, that is after return to intercuspal position. Positive values indicate that the onset (or the offset) of the IHLP activity was earlier than that of MIPT three-dimensional movement.

In each subject, the difference of the onset (as well as the offset) in each trial between the MIPT three-dimensional displacement and IHLP activity was calculated arithmetically. Table 4.3-1 shows the average values of 10 trials in each subject. The results showed that the onset, and the offset, of IHLP was earlier than that of the MIPT displacement except in two subjects, and in one subject, respectively. This means that IHLP activity usually commenced before the start of the movement and ceased before the end of the movement.

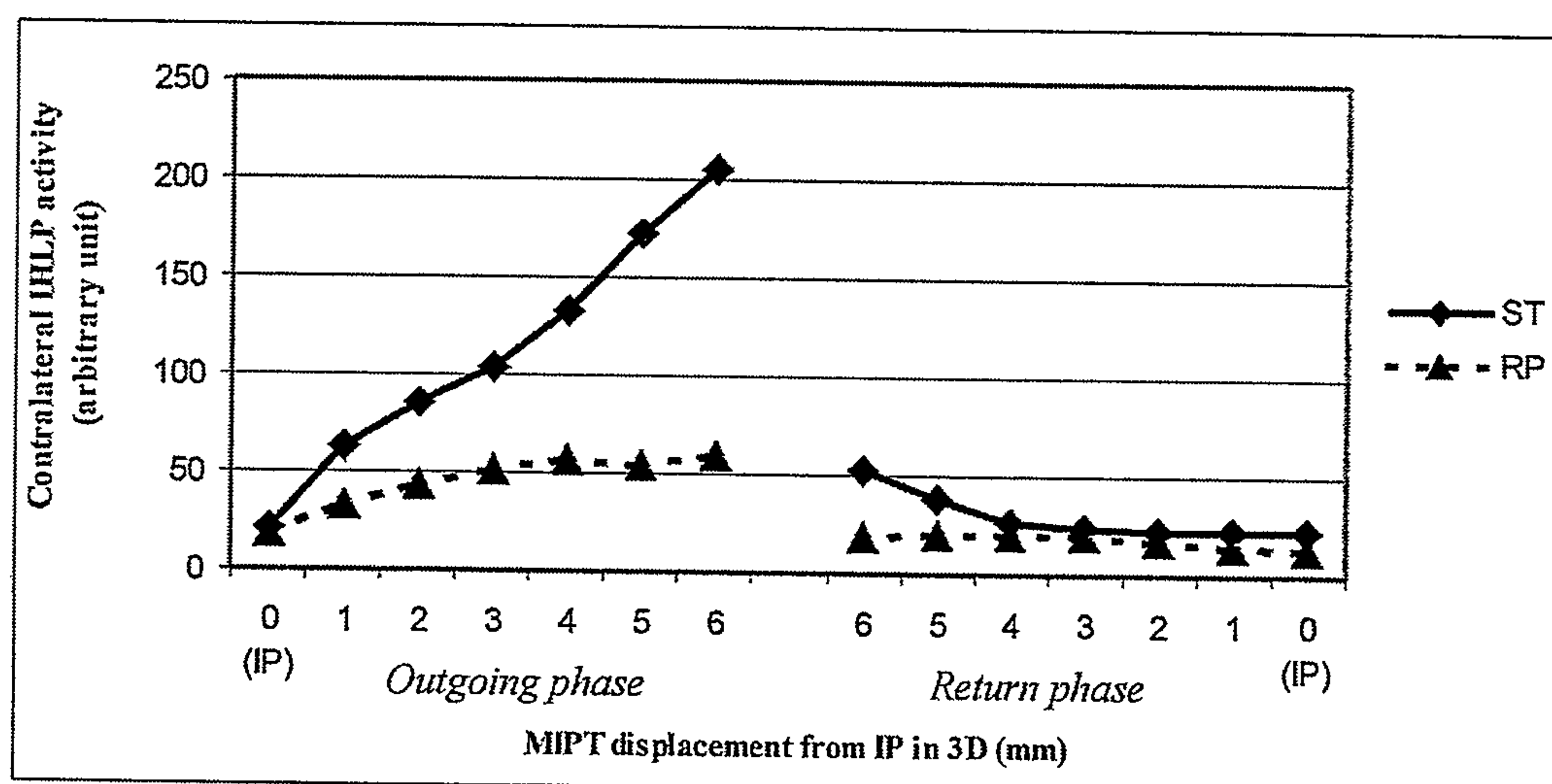


Fig. 4.3-3 Two examples (subjects ST and RP) of IHLP after being normalized with MIPT movement during outgoing phase and return phase. IP: intercuspal position; 3D: three-dimensions.

After being normalized with respect to MIPT displacement, six (of 10) subjects showed a steady increase in the IHLP activity while the MIPT moved continuously outward (e.g. Fig. 4.3-3, subject ST). Whereas, the other four subjects showed an increase and then reached a plateau around the 3rd mm of the displacement during the outgoing phase (e.g. Fig. 4.3-3, subject RP). In eight (of 10) subjects, CT scans were used to verify the location of the electrodes within the IHLP, and no association was found between the location of the electrodes and these two patterns of IHLP activity. The IHLP activity at the beginning of the return phase was less than half of the activity at the end of outgoing phase in all subjects. At the return phase, the IHLP activity showed a gradual decrease (e.g. Fig. 4.3-3, subjects ST and RP).

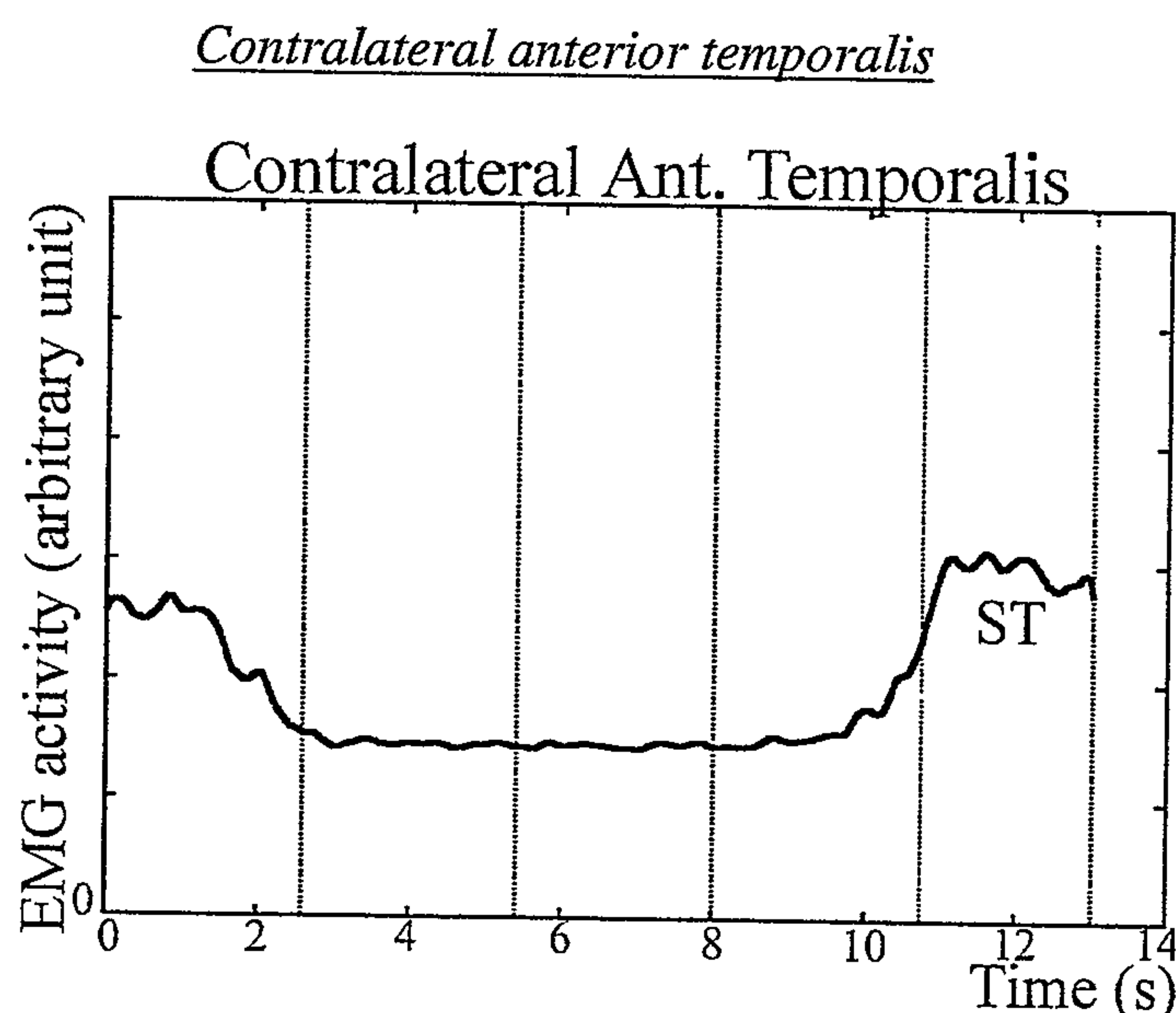


Fig. 4.3-4 Example (subject ST) of average contralateral anterior temporalis activity of 10 trials after being rectified and smoothed.

In 11 (of 12 whose contralateral anterior temporalis was recorded) subjects, there was a decrease in contralateral anterior temporalis at the late one-third of the IP1 phase and the early one-third of the outgoing phase, then the activity reached a steady level slightly below that at the intercuspal position. In the other subject, the activity stayed at the same level as the intercuspal position throughout the

entire trial. In the 11 subjects, EMG remained steady at the remaining two-thirds of outgoing phase, the whole holding phase, and the early half of the return phase. Then, there was a rapid increase in activity during the second half of the return phase and the early one-third of the IP2 phase to a level higher than that at the intercuspal position in all subjects except one. In this subject, the rapid increase started at the late holding phase and then there was a slight decrease but the activity level at the end of the IP2 phase was still higher than that at the IP1 phase. Fig. 4.3-1 and 4.3-4 show an example of the activity of the contralateral anterior temporalis typical of the 11 subjects.

Although a calculation of the onset and offset time of the bilateral anterior and posterior temporalis, masseter, as well as submandibular muscles was made in all subjects, the SD was frequently more than 2 s in each subject, because these muscles did not show a clear EMG pattern as the IHLP did and the EMG activity passed the mean ± 2 SD lines several times during laterotrusion in each trial. And in some muscles, there was no uniform pattern of activity between subjects. Therefore, the onset and offset of these muscles will not be presented.

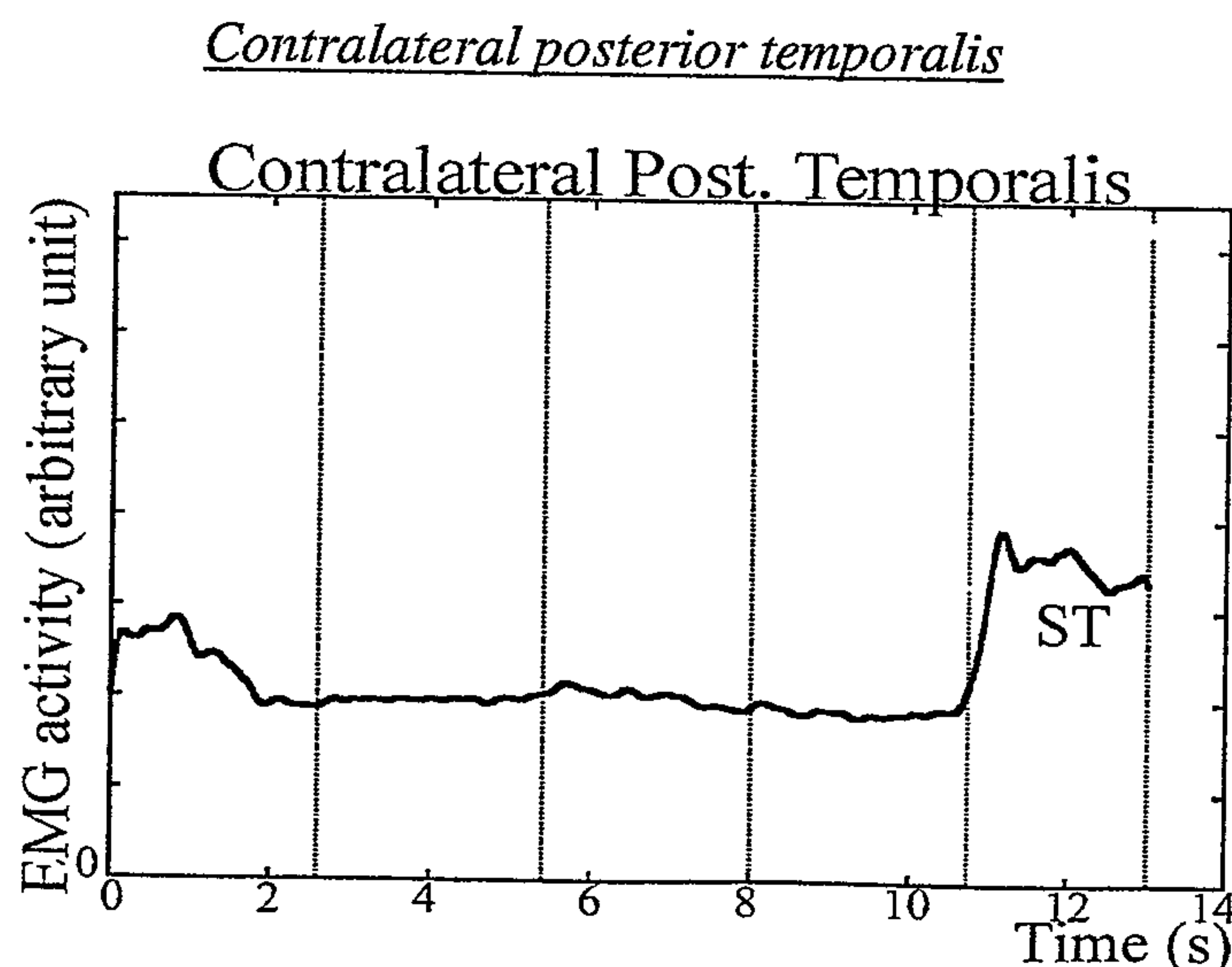


Fig. 4.3-5 Example (subject ST) of average contralateral posterior temporalis activity of 10 trials after being rectified and smoothed.

Six (of seven) subjects showed a similar pattern to the contralateral anterior temporalis: a decrease followed by a steady level in activity (i.e. Fig. 4.3-1 and 4.3-5). Whereas in the other subject, who was the same subject as singled out for the contralateral anterior temporalis above, the EMG activity remained at the same level as the IP1 phase. All the subjects showed a rapid increase at the late one-third of the return phase and the early one-third of the IP2 phase to a level higher than that at the IP1 phase. Then, there was a slight decrease but the activity level at the end of the IP2 phase was still higher than that at the IP1 phase.

Contralateral masseter

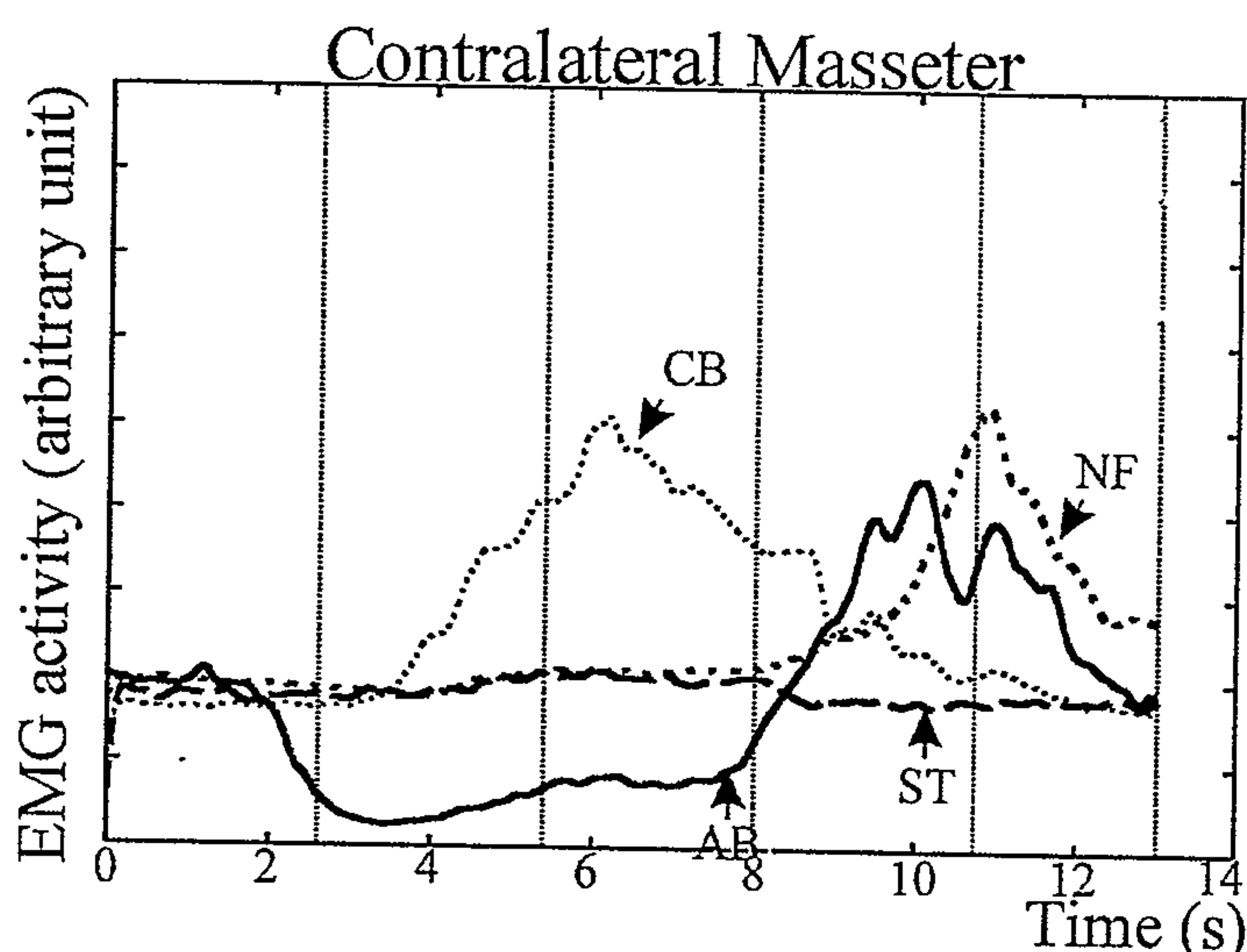


Fig. 4.3-6 Four examples (subjects ST, AB, NF and CB) of average contralateral masseter activity of 10 trials after being rectified and smoothed. Note that the amplitudes of the different subjects may be scaled differently (see Methods).

The activity of the contralateral masseter was variable. Only two (of 16) subjects showed the same pattern as the contralateral anterior and posterior temporalis muscles (e.g. Fig. 4.3-6, subject AB). Four subjects exhibited masseter activity that remained at the same level during the whole movement (e.g. Fig. 4.3-6, subject ST). Five subjects exhibited activity that gradually increased at the outgoing phase, reached a peak at the holding phase, and then gradually decreased (e.g. Fig. 4.3-6, subject CB). Five subjects exhibited masseter activity

that remained at the same activity level until the holding or the return phase when the EMG started to increase and reached its peak around the beginning of the IP2 phase (e.g. Fig. 4.3-6, subject NF).

Contralateral submandibular muscles

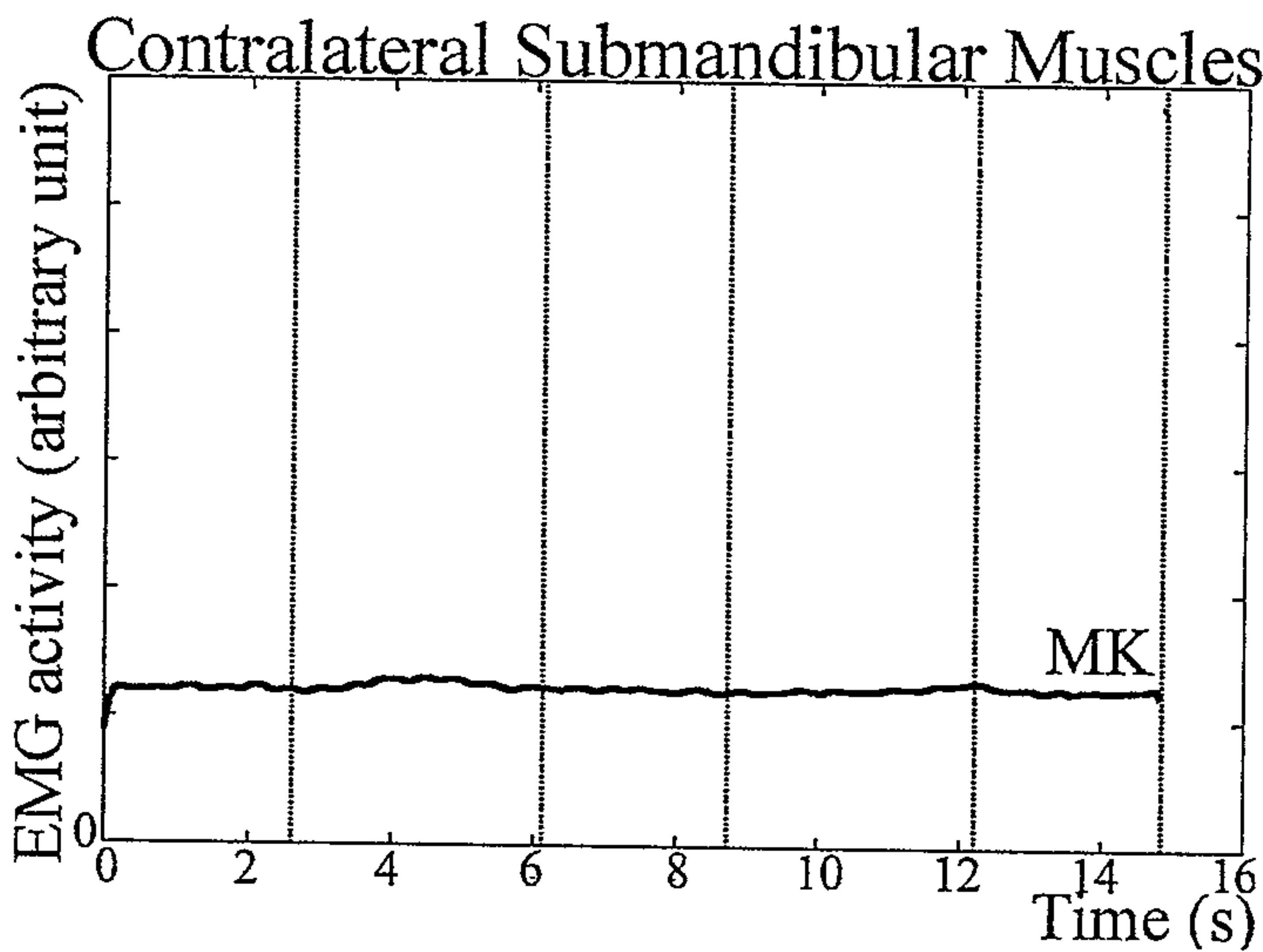


Fig. 4.3-7 Example (subject MK) of average contralateral submandibular muscles' activity of 10 trials after being rectified and smoothed.

In all six subjects whose contralateral submandibular muscles were recorded, the submandibular muscles stayed at the same level of activity through the movement (e.g. Fig. 4.3-7).

Ipsilateral anterior temporalis

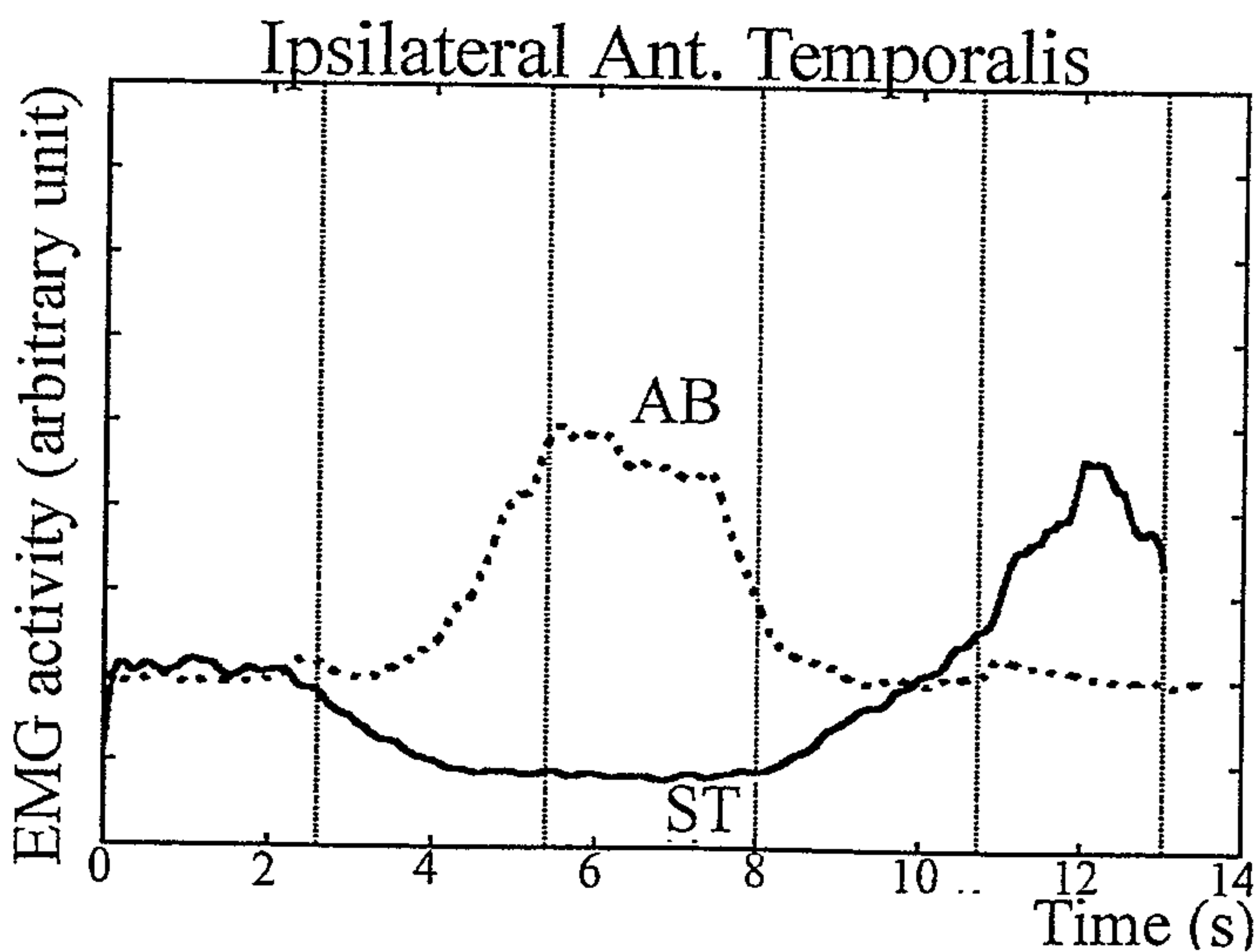


Fig. 4.3-8 Examples (subjects ST and AB) of average ipsilateral anterior temporalis activity of 10 trials after being rectified and smoothed. Note that the amplitudes of the different subjects may be scaled differently (see Methods).

In seven (of 16) subjects, the ipsilateral anterior temporalis showed a similar pattern to the contralateral anterior and posterior temporalis muscles: a decrease followed by a steady level in activity and then an increase at the second half of the return phase (i.e. Fig. 4.3-1 and 4.3-8, subject ST). The remaining nine subjects showed an increase at the outgoing phase with a peak at the holding phase, and then a decrease in activity (i.e. Fig. 4.3-8, subject AB); five of these nine subjects had a secondary increase at the return phase with the peak at the beginning of the IP2 phase.

Ipsilateral posterior temporalis

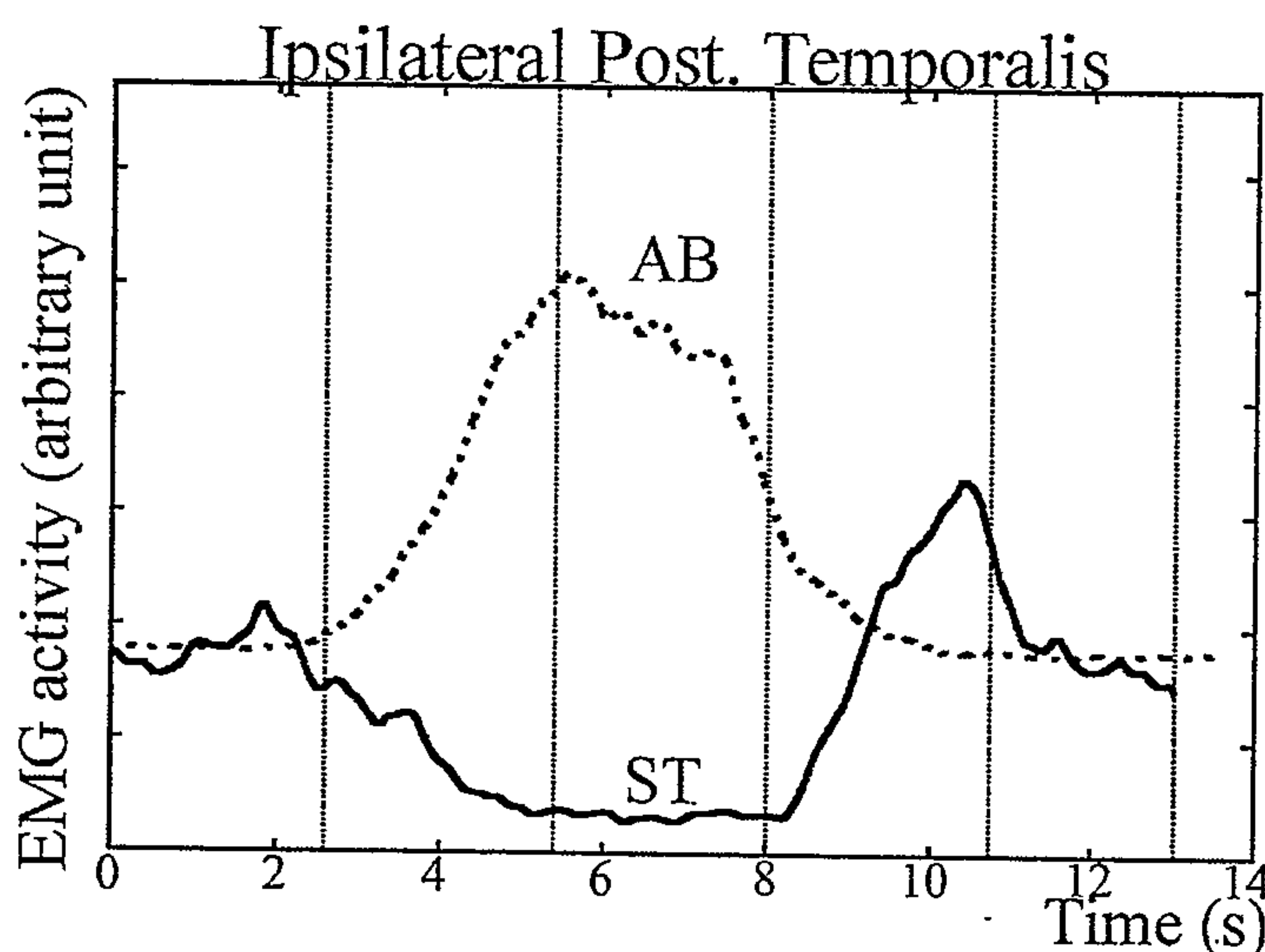


Fig. 4.3-9 Examples (subjects ST and AB) of average ipsilateral posterior temporalis activity of 10 trials after being rectified and smoothed. Note that the amplitudes of the different subjects may be scaled differently (see Methods).

Generally, in nine subjects with both the ipsilateral anterior and posterior temporalis recordings available, the activity pattern of the ipsilateral posterior temporalis was similar to the ipsilateral anterior temporalis in the same subject. Fig. 4.3-9 shows the two patterns of ipsilateral posterior temporalis from the same subjects as in Fig. 4.3-8.

Ipsilateral masseter

The activity of the ipsilateral masseter was also variable. Nine (of 15) subjects exhibited activity that gradually increased at the outgoing phase, reached a peak

at the holding phase, and then gradually decreased (e.g. Fig. 4.3-10, subject CB); seven of these nine subjects had a secondary increase at the return phase (e.g. Fig. 4.3-10, subject KS) or the activity at IP2 phase was higher than that at IP1 phase. Six subjects exhibited activity that remained at the same activity level until the beginning of the return phase when the EMG started to increase and reached its peak around the beginning of the IP2 phase (e.g. Fig. 4.3-1 and 4.3-10, subject ST).

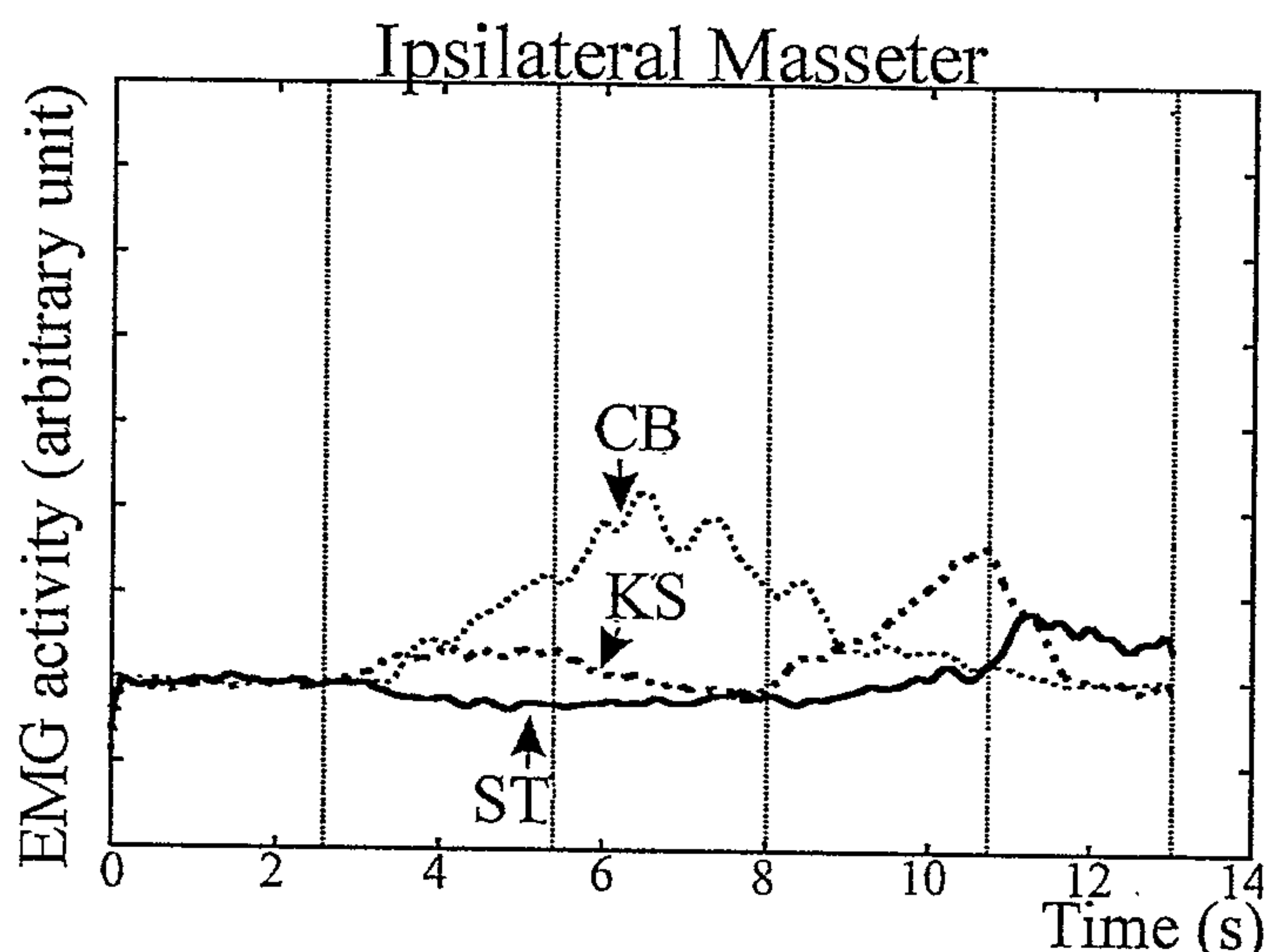


Fig. 4.3-10 Three examples (subjects ST, CB and KS) of average ipsilateral masseter activity of 10 trials after being rectified and smoothed. Note that the amplitudes of the different subjects may be scaled differently (see Methods).

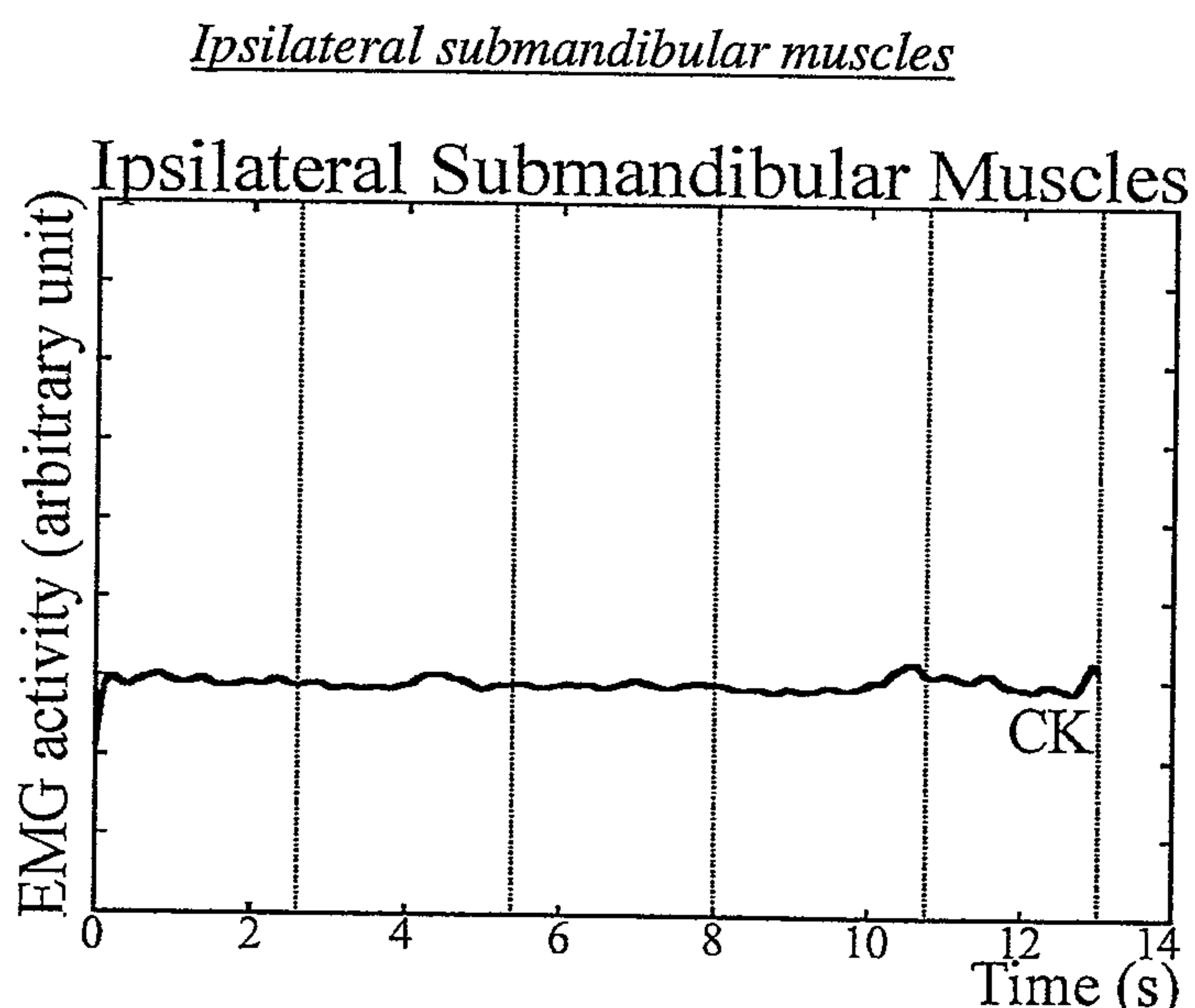


Fig. 4.3-11 Example (subject CK) of average ipsilateral submandibular muscles' activity of 10 trials after being rectified and smoothed.

In seven (of eight) subjects, the ipsilateral submandibular muscles remained at the same level of activity through the lateral movement (e.g. Fig.4.3-11).

4.3.1.2 Laterotrusion with high closing force at slow speed

Generally during slow laterotrusion, the overall pattern of EMG activity of jaw muscles at the high closing force was similar to that at the low closing force, except for the bilateral masseter and ipsilateral anterior temporalis. The increase in closing force was associated with a significantly higher activity in contralateral IHLP and bilateral anterior temporalis and masseter muscles. Representative data from one trial in one subject is shown in Fig. 4.3-12.

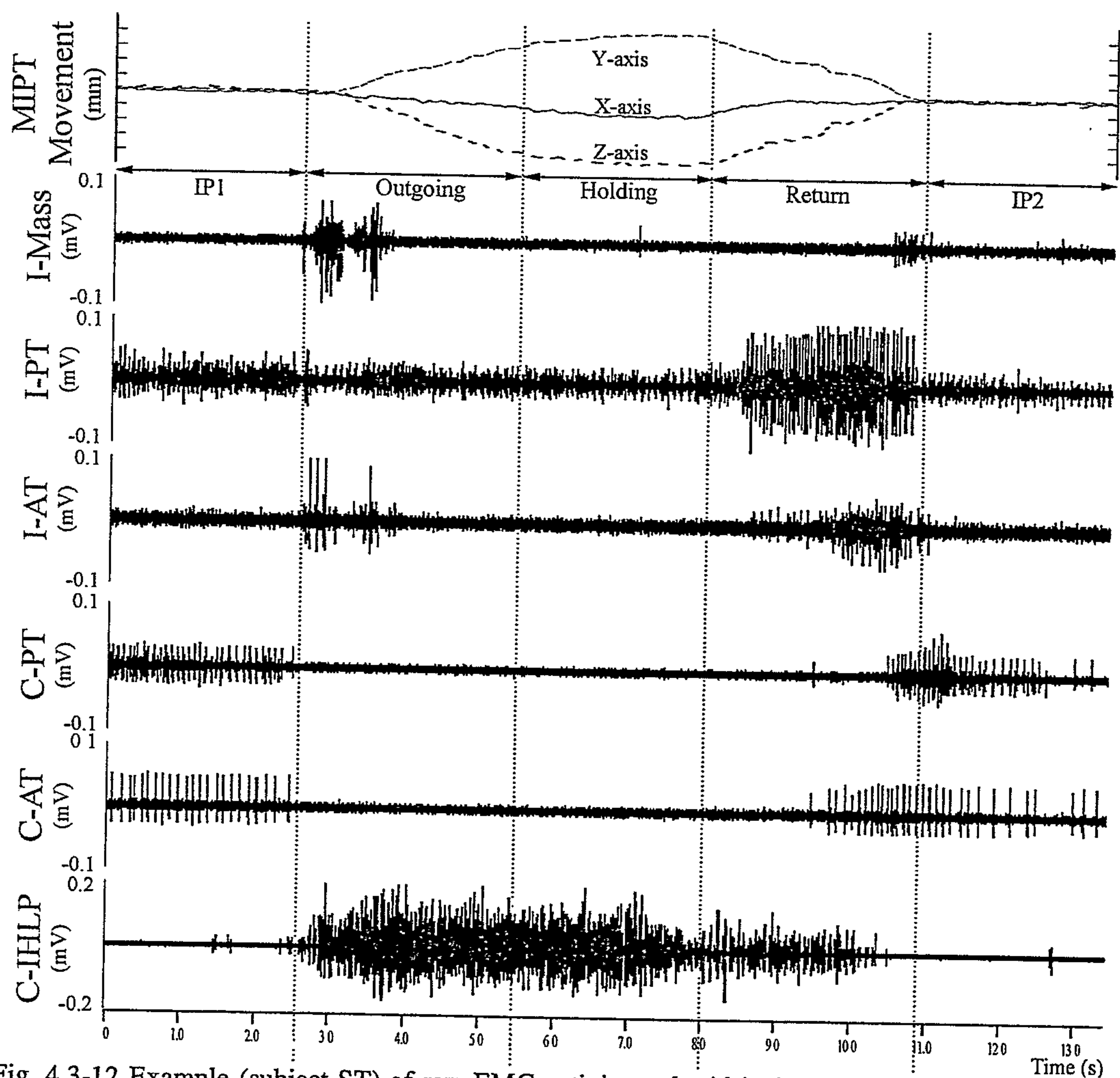


Fig. 4.3-12 Example (subject ST) of raw EMG activity and mid-incisor point (MIPT) movement during laterotrusion with high closing force at slow speed from the same subject as in Fig. 4.3-1. The four vertical dotted lines separate the five phases indicated by the visual-feedback device. The contralateral masseter was not available due to technical difficulties in this recording. C-: contralateral to the movement side; I-: ipsilateral to the movement side; IHLP: inferior head of lateral pterygoid muscle; AT: anterior temporalis; PT: posterior temporalis; Mass: masseter.

Contralateral inferior head of the lateral pterygoid muscles

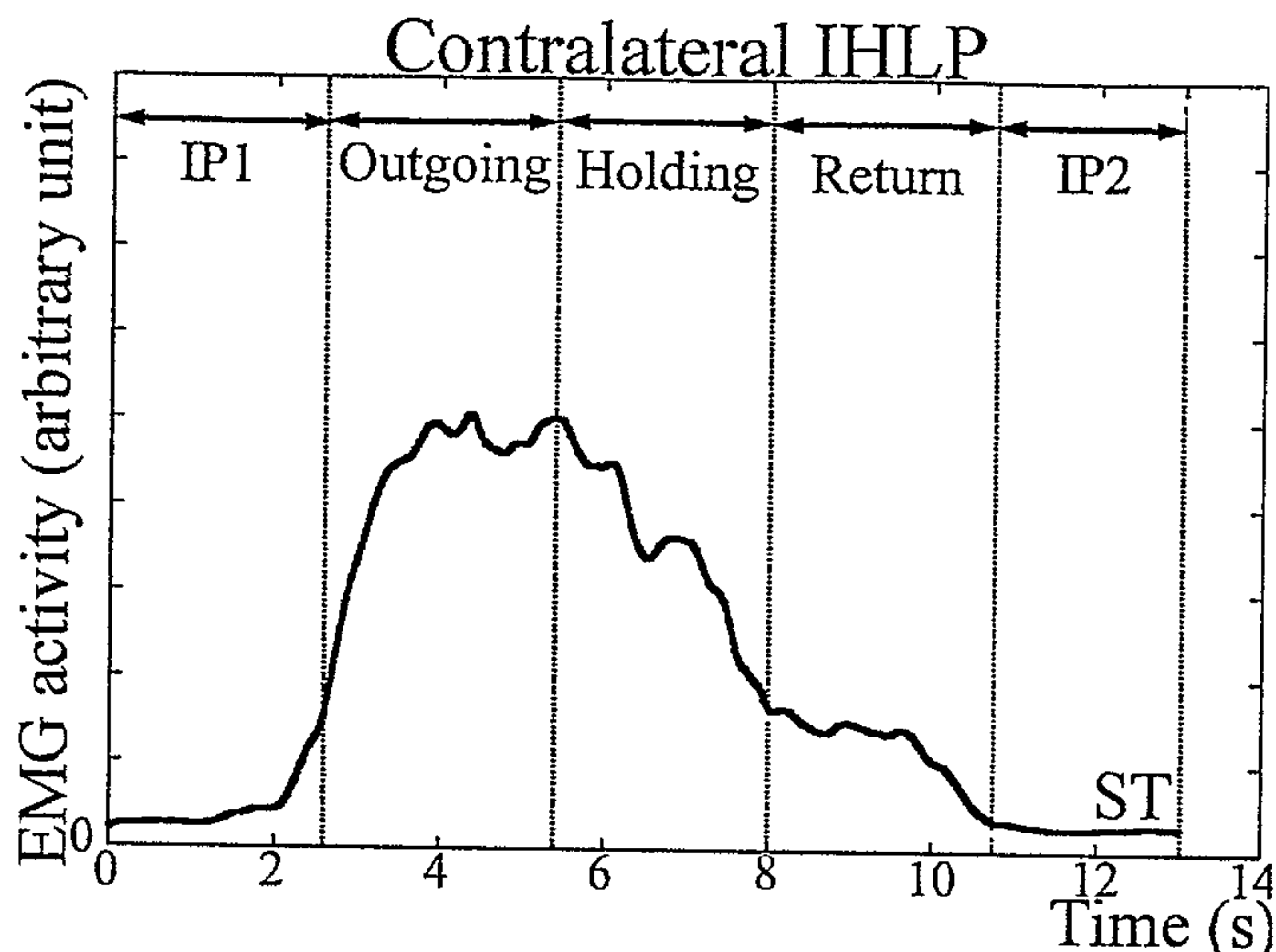


Fig. 4.3-13 Example (subject ST) of average contralateral IHLP activity of 10 trials after being rectified and smoothed.

The overall pattern of the contralateral IHLP activity (e.g. Fig. 4.3-12 and 4.3-13) during laterotrusion at high closing force was similar to the pattern of IHLP activity during lateral movement with low force (e.g. Fig. 4.3-1 and 4.3-2). Thus, an increase was observed at the outgoing phase, a peak near the holding phase, then a decrease in activity and a return to the IP1 level at the IP2 phase. However, the increase in EMG activity at the outgoing phase was qualitatively more rapid than that with low force. The activity during the return phase was also higher than that with low force. Furthermore, some trials showed a secondary increase during the return phase (e.g. Fig. 4.3-12).

The normalized IHLP activity of three (of 10) subjects showed a change from a steady increase (at low force level) to a rapid increase during the first 1 – 3 mm and then a plateau during the remainder of the outgoing phase (at high closing force level) (e.g. Fig. 4.3-14). Therefore, only three subjects (instead of six subjects at low closing force) showed a steady increase in the IHLP activity while the MIPT moved continuously outward at high closing force. Whereas, the remaining seven subjects showed a rapid increase followed by a plateau. In eight

(of 10) subjects, CT scans were used to verify the location of the electrodes within the IHLP, and no association was found between the location of the electrodes and these three patterns of IHLP activity. The mean IHLP activity from all subjects at the 3rd mm away from intercuspal position at high closing force was statistically significantly higher than that at low closing force during the outgoing and the return phases.

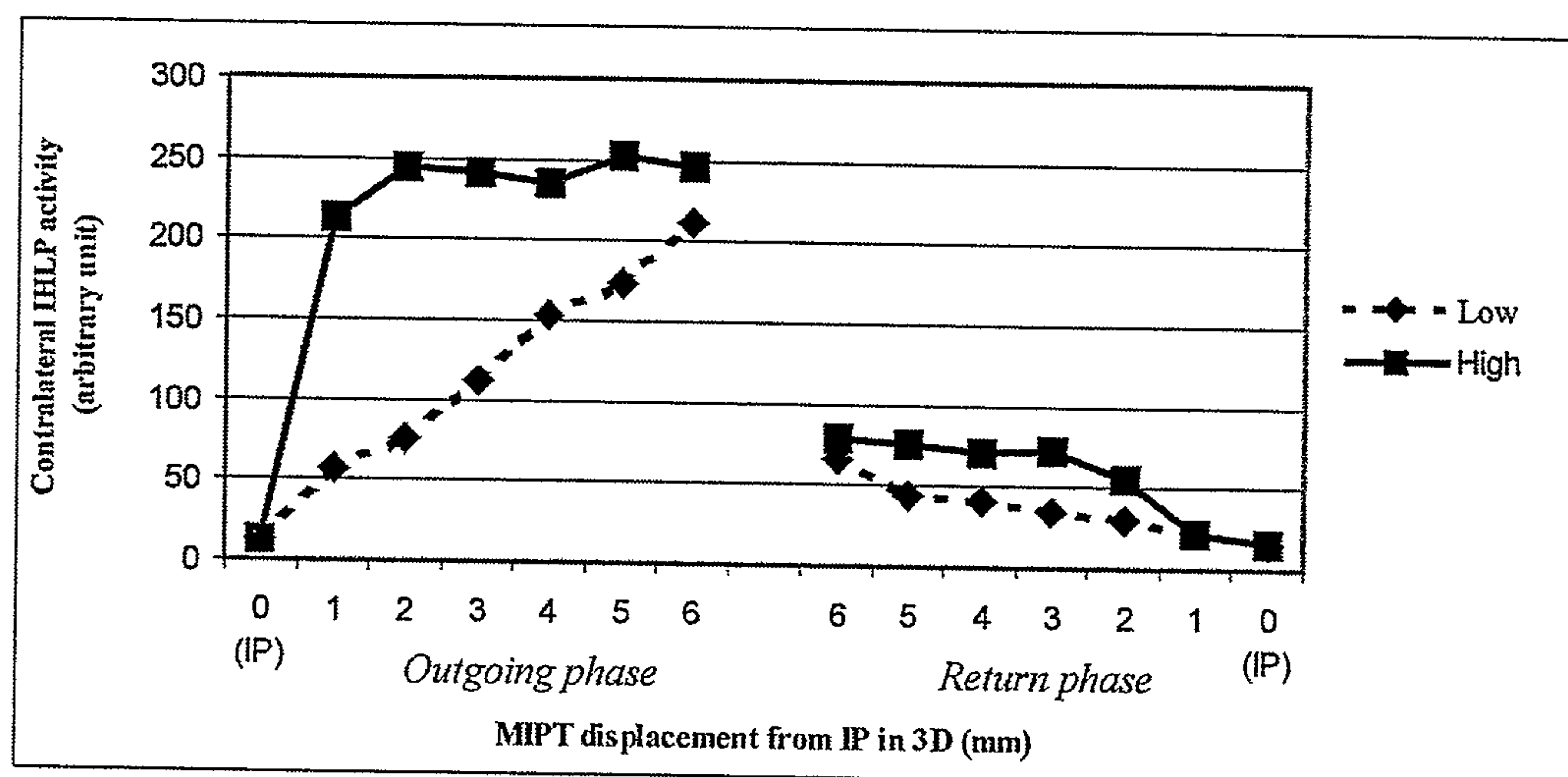


Fig. 4.3-14 Example (subject ST) of IHLP after being normalized with MIPT movement during the outgoing and the return phases at low and high closing force levels in the same subject. IP: intercuspal position; 3D: three-dimensions.

Subject	Onset		Offset	
	Low force	High force	Low force	High force
01	0.33	0.01	1.02	0.79
02	0.56	0.69	0.19	-0.15
03	0.30	0.23	1.07	0.24
04	0.64	0.53	0.16	0.11
05	0.13	-0.18	0.32	-0.10
06	-0.41	0.50	0.21	0.96
07	0.40	0.63	-0.20	-0.01
08	0.38	0.91	0.52	0.11
09	0.05	0.37	1.36	2.66
10	-0.85	0.62	2.63	1.45
Mean $\pm$ SD	0.15 $\pm$ 0.46	0.43 $\pm$ 0.33	0.73 $\pm$ 0.83	0.61 $\pm$ 0.89

Table 4.3-2 The difference (in s) of the onset and offset time between the MIPT movement and the IHLP activity in each subject at two closing force levels: low force to maintain tooth contact and high closing force at subject's comfortable range. Positive values indicate that the onset (or the offset) of the IHLP activity was earlier than that of MIPT three-dimensional movement.

Table 4.3-2 shows the average arithmetical difference of the onset and the offset times between MIPT movement and IHLP activity at two closing force levels. There was no statistically significant difference in onset and offset times between the two force levels.

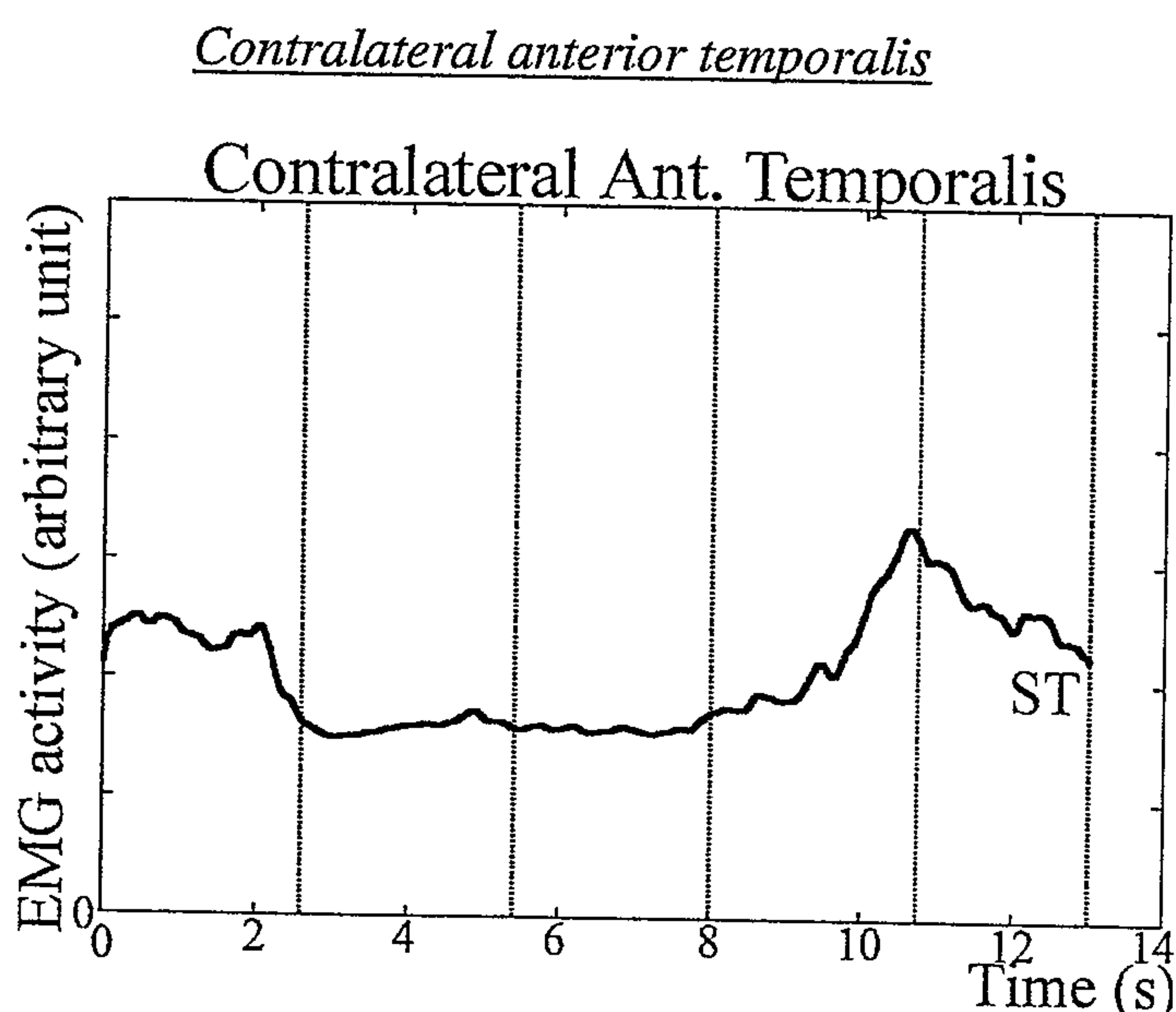


Fig. 4.3-15 Example (subject ST) of average contralateral anterior temporalis activity of 10 trials after being rectified and smoothed.

In all 10 subjects, the overall pattern of the contralateral anterior temporalis at the high closing force was similar to that at the low force (e.g. Fig. 4.3-4 and 4.3-15). The mean activity at the high closing force was statistically higher than that at the low closing force during the outgoing, holding and return phases.

Contralateral posterior temporalis

In all seven subjects, the overall pattern of the contralateral posterior temporalis at the high closing force was similar to that at the low force (e.g. Fig. 4.3-5 and 4.3-16). Six of the seven subjects showed a lower activity at high closing force than that at low closing force during the outgoing and holding phases (three subjects during the return phase). This was the only muscle (of the nine muscles recorded) that more than half of the subjects showed a lower activity during the

outgoing and holding phases at the high closing force. However, no statistically significant difference was found between the two force levels.

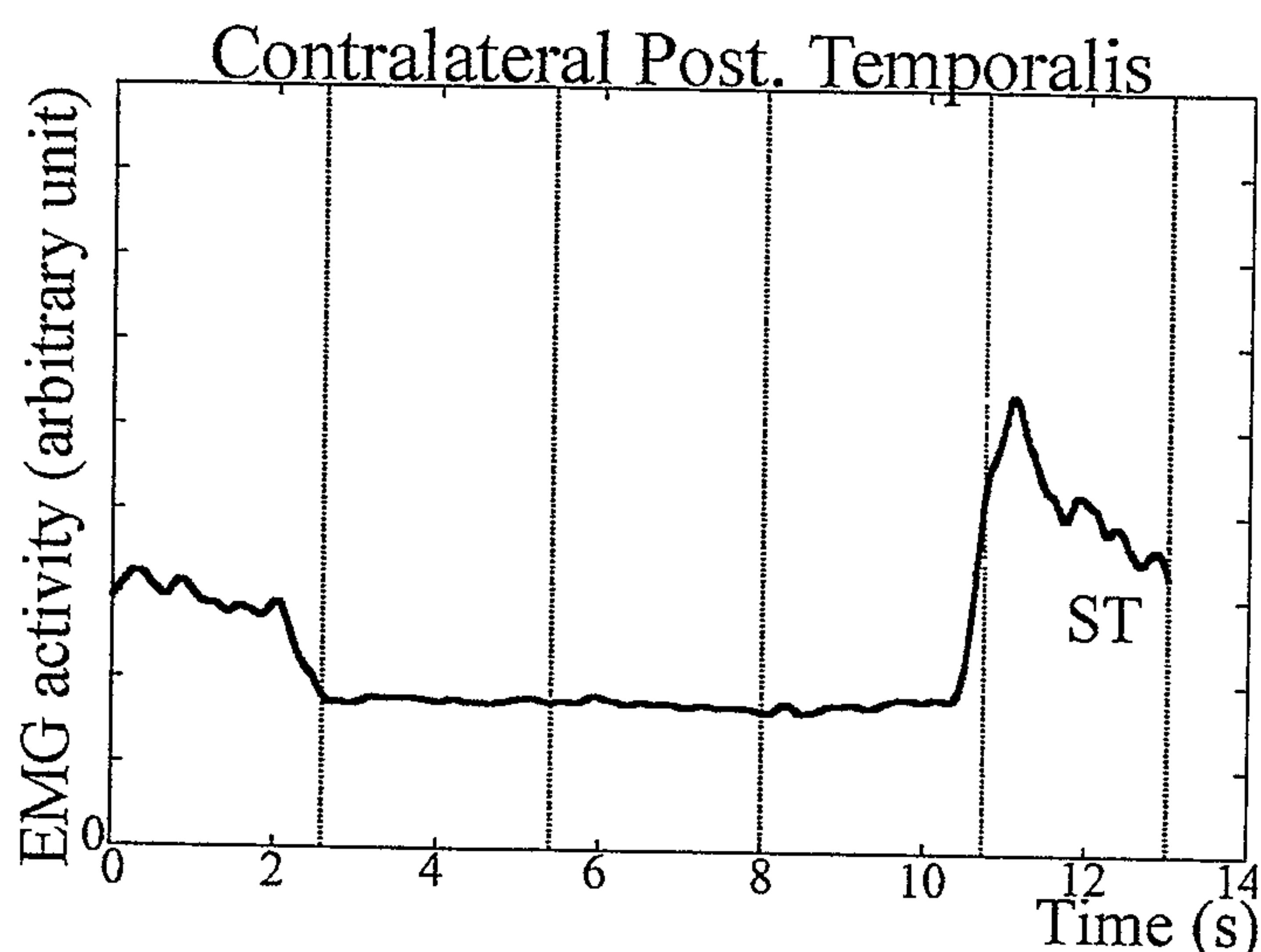


Fig. 4.3-16 Example (subject ST) of average contralateral posterior temporalis activity of 10 trials after being rectified and smoothed.

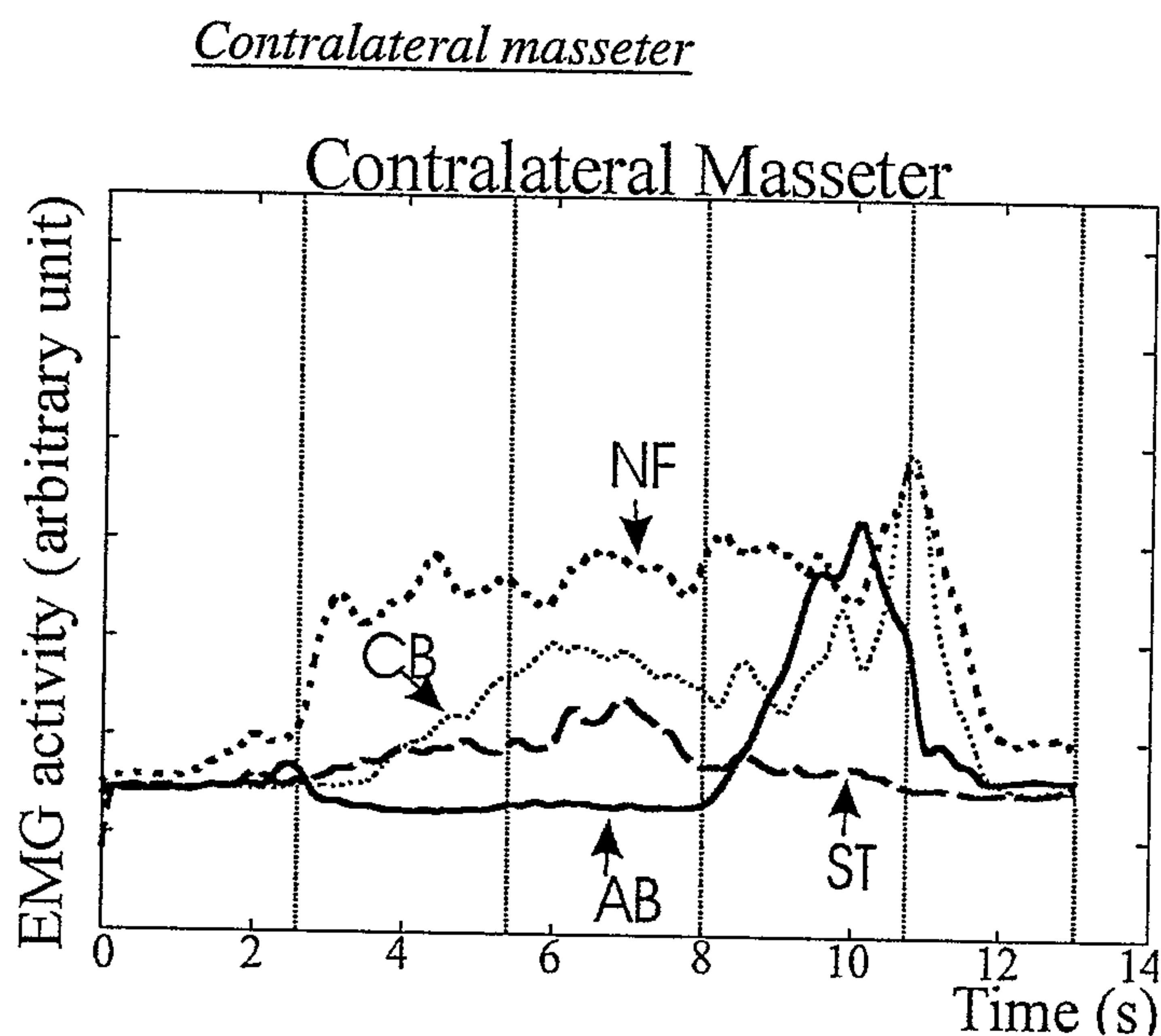


Fig. 4.3-17 Four examples (subjects ST, AB, NF and CB) of average contralateral masseter activity of 10 trials after being rectified and smoothed. Note that the amplitudes of the different subjects may be scaled differently (see Methods).

The overall pattern of the contralateral masseter activity could be changed by the alteration of the closing force in some subjects, and the change was toward an increase in activity during lateral movement at the high closing force. For example, in Fig. 4.3-6 and 4.3-17, the activity in subject ST changed from no change through the movement to an increase during the outgoing phase, followed by a decrease. Subject NF activity changed from an increase at the beginning of

the return phase and reaching a peak at the beginning of the IP2 phase, to a rapid increase at the beginning of the movement with high force, and returned towards the activity level at IP1. In subject CB, there was a secondary increase at the return phase at the high closing force level. In subject AB, although the overall pattern was similar at the two force levels, the activity at the high closing force level was much higher during the return phase. The mean EMG activity of the contralateral masseter at the high closing force was statistically higher than that at the low closing force at each of the outgoing, holding and return phases.

Contralateral submandibular muscles

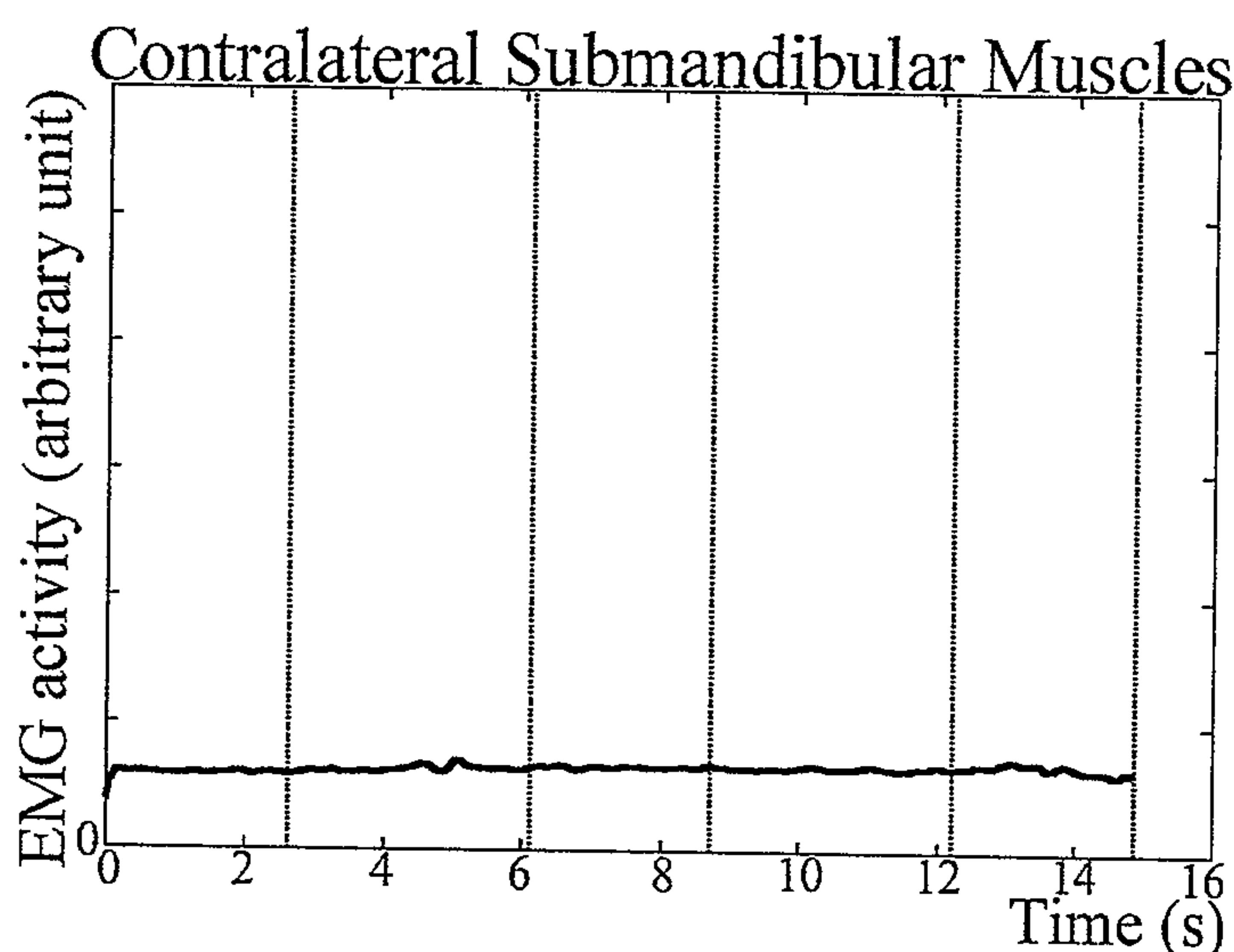


Fig. 4.3-18 Example (subject MK) of average contralateral submandibular muscle activity of 10 trials after being rectified and smoothed.

The overall pattern of the contralateral submandibular muscles' activity during lateral movement was not changed by the alteration of closing force level (e.g. Fig. 4.3-7 and 4.3-18). There was no statistical difference between the two force levels during the outgoing, holding and the return phases.

Ipsilateral anterior temporalis

As for the contralateral masseter muscle, the overall pattern of the ipsilateral anterior temporalis activity might be changed by the alteration of the closing force in some subjects. For example, in Fig. 4.3-8 and 4.3-19, subjects ST and AB showed a burst in activity at the late IP1 phase or the early outgoing phase due to the alteration of the closing force level. The other subjects, who showed a similar pattern (that is a decrease during the outgoing phase) as the subject ST in Fig. 4.3-8, showed a burst at the early outgoing phase or an increase in activity during the outgoing phase at the high closing force level. The mean activity of the ipsilateral anterior temporalis at the high closing force was statistically higher than that at the low closing force at the outgoing, holding and return phases.

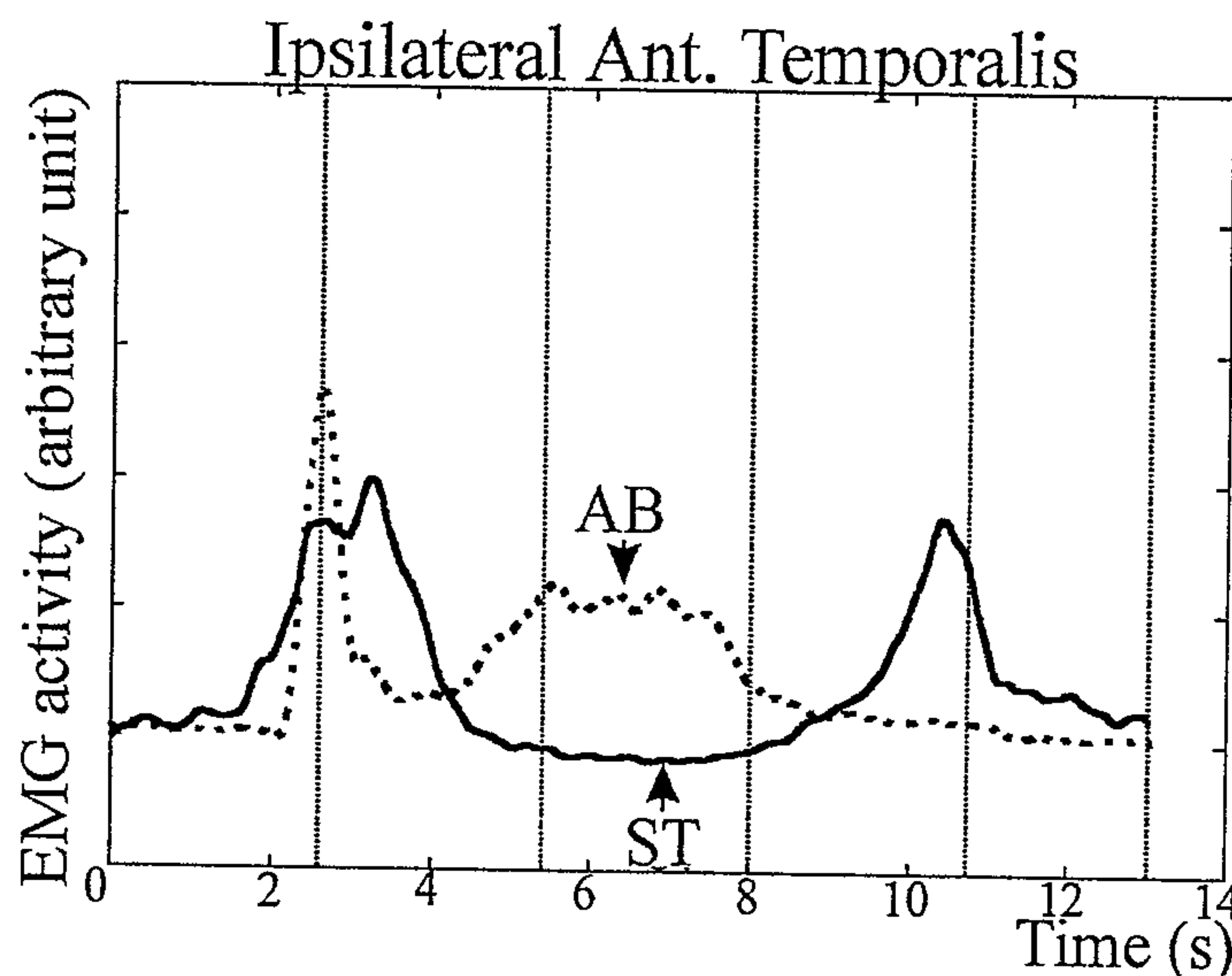


Fig. 4.3-19 Two examples (subjects ST and AB) of average ipsilateral anterior temporalis activity of 10 trials after being rectified and smoothed. Note that the amplitudes of the different subjects may be scaled differently (see Methods).

Ipsilateral posterior temporalis

The overall pattern of the ipsilateral posterior temporalis muscles was not changed due to the alteration of the closing force (e.g. Fig. 4.3-9 and 4.3-20, subject ST and AB) except in one (of nine) subject. Unlike the activity at the low closing force (e.g. Fig. 4.3-8 and 4.3-9), the overall pattern of the ipsilateral anterior and posterior temporalis could be different to each other at high closing

force (e.g. Fig. 4.3-19 and 4.3-20, subject ST and AB) due to the alteration of the ipsilateral anterior temporalis activity pattern. For the ipsilateral posterior temporalis, there was no statistical difference between the two force levels during the outgoing, holding and return phases.

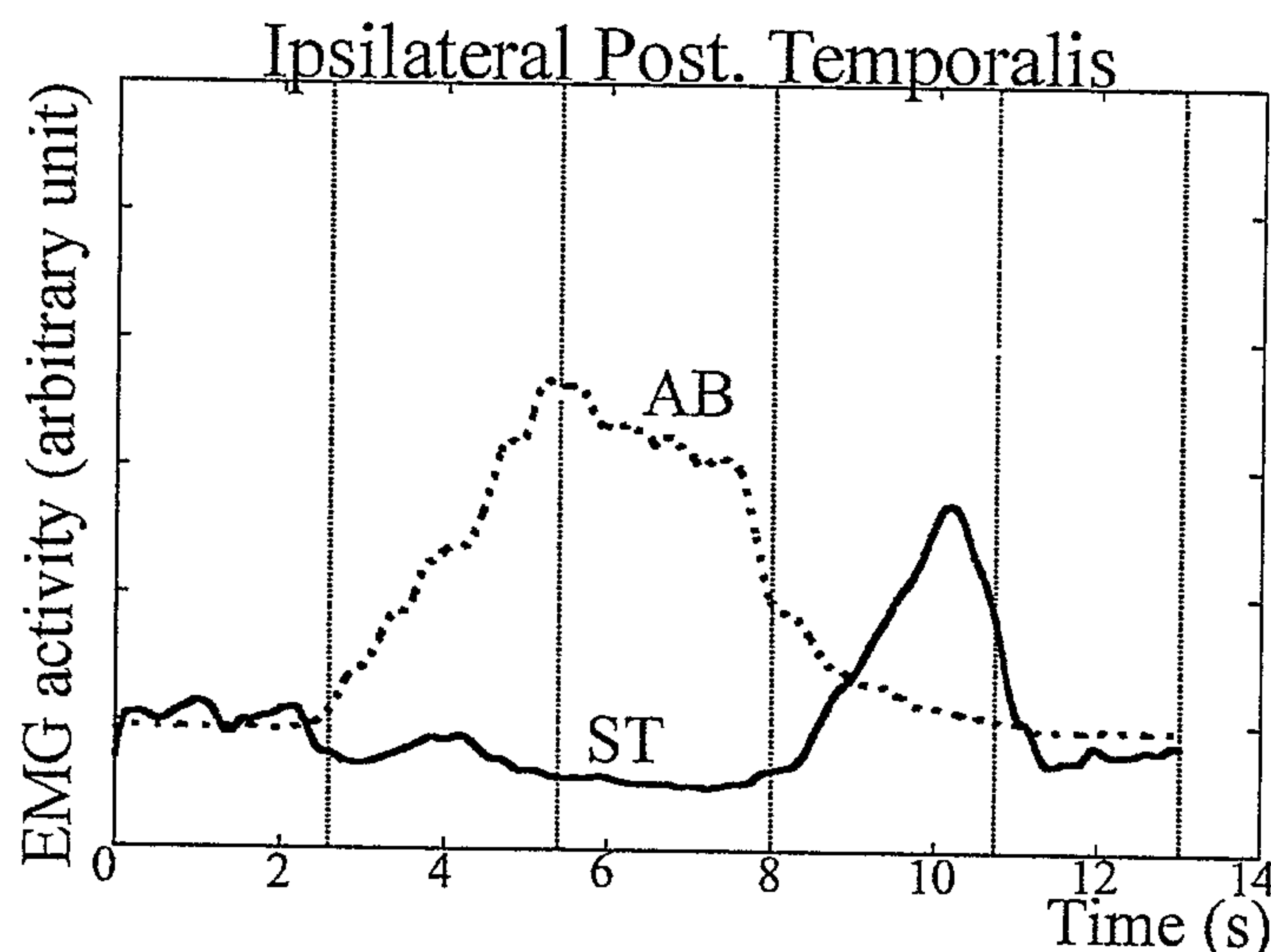


Fig. 4.3-20 Two examples (subjects ST and AB) of average ipsilateral posterior temporalis activity of 10 trials after being rectified and smoothed. Note that the amplitudes of the different subjects may be scaled differently (see Methods).

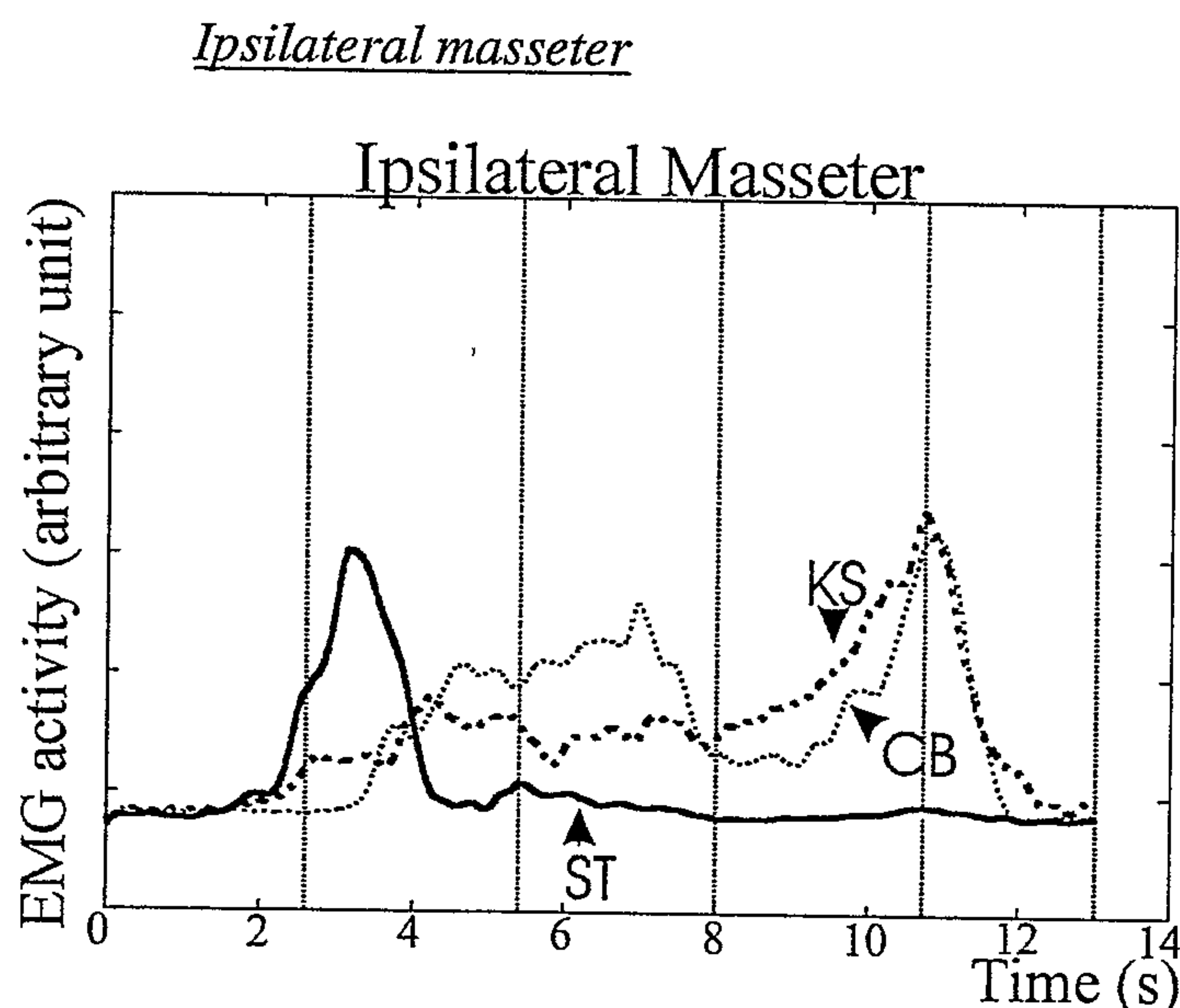


Fig. 4.3-21 Three examples (subjects ST, CB and KS) of average ipsilateral masseter activity of 10 trials after being rectified and smoothed. Note that the amplitudes of the different subjects may be scaled differently (see Methods).

The overall pattern of the ipsilateral masseter activity could be changed by the alteration of the closing force in some subjects, and the change was toward a higher activity during lateral movement at the high closing force. For example, in Fig. 4.3-10 and 4.3-21, the activity of subject CB and KS maintained at a high

activity level over a longer period than that at the low closing force. Subject ST showed a burst of activity at the early outgoing phase which was about the same time as in the ipsilateral anterior temporalis muscles (Fig. 4.3-19). The mean activity of the ipsilateral masseter from all subjects at the high closing force was statistically higher than that at the low closing force at the outgoing, holding and return phases.

Ipsilateral submandibular muscles

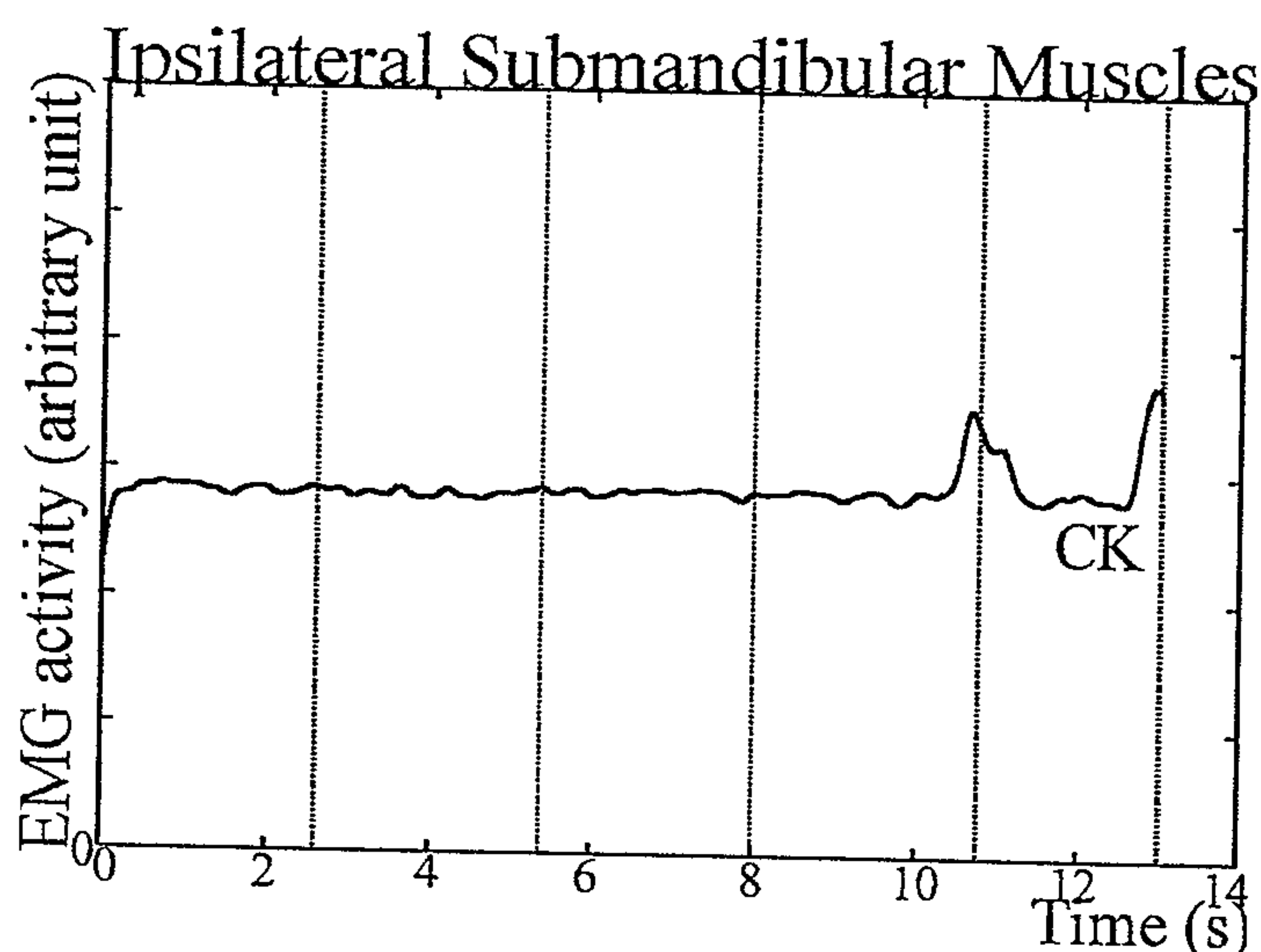


Fig. 4.3-22 Example (subject CK) of average ipsilateral submandibular muscle activity of 10 trials after being rectified and smoothed. This subject is the same subject as in Fig. 4.3-11.

The overall pattern of the ipsilateral submandibular muscles activity during lateral movement was not changed by the alteration of closing force level (e.g. Fig. 4.3-11 and 4.3-22). There was no statistical difference between two force levels during the outgoing, holding and return phases.

4.3.1.3 Laterotrusion with low closing force at fast speed

Generally, the overall pattern of EMG activity of the jaw muscles during fast laterotrusion was similar to that during slow laterotrusion. The change from slow laterotrusion to fast laterotrusion did not significantly alter the mean activity of the jaw muscles except for the contralateral IHLP at the outgoing phase (a significantly higher activity) and the return phase (a significantly lower activity) as well as the contralateral anterior temporalis at the outgoing phase (a significantly lower activity). Representative data from one trial in one subject is shown in Fig. 4.3-23.

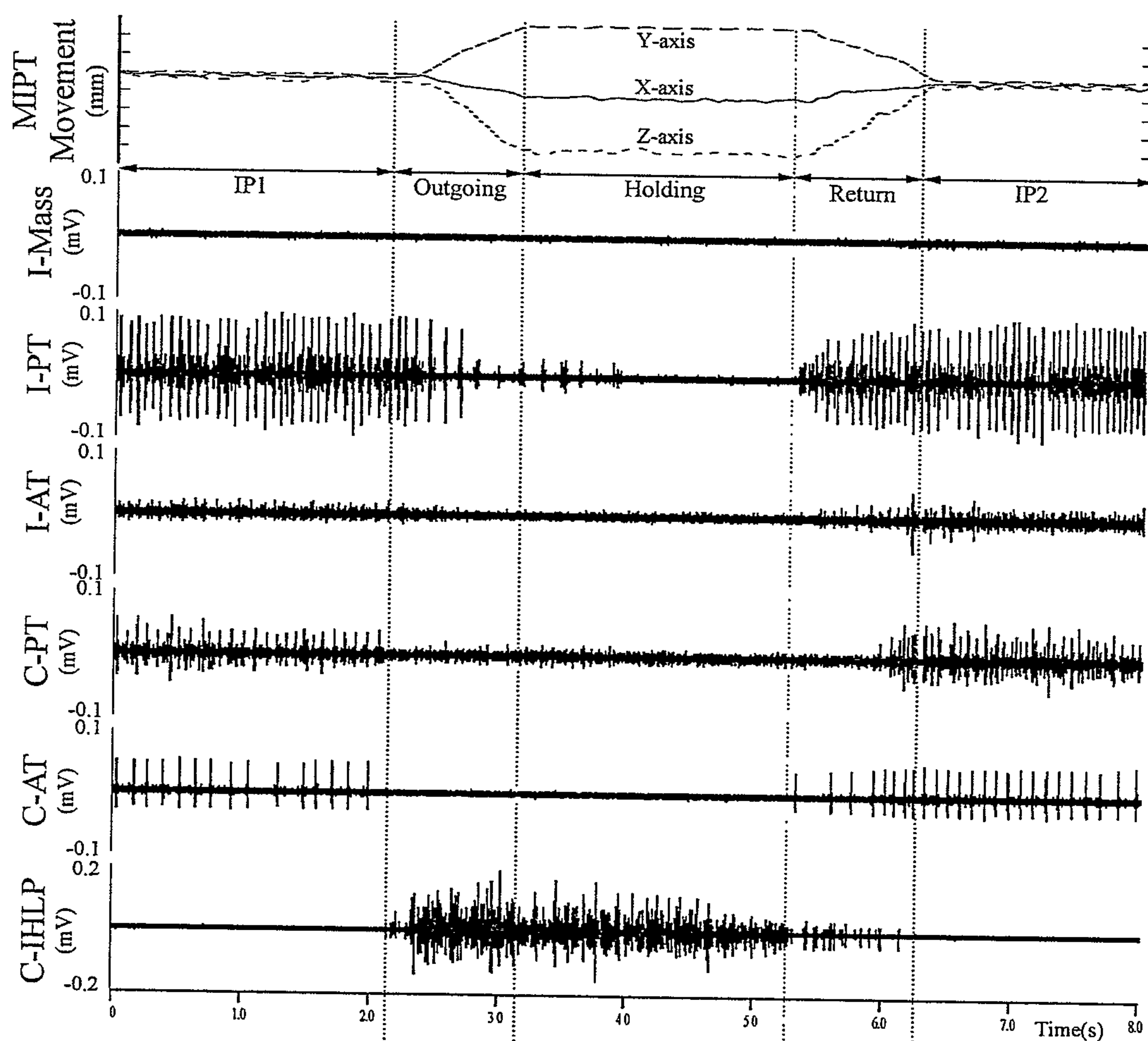


Fig. 4.3-23 Example (subject ST) of raw EMG activity and mid-incisor point (MIPT) movement during laterotrusion with low closing force at fast speed from the same subject as in Fig. 4.3-1. The four vertical dotted lines separate the five phases indicated by the visual-feedback device. The contralateral masseter was not available due to technical difficulties in this recording. C-: contralateral to the movement side; I-: ipsilateral to the movement side; IHLP: inferior head of lateral pterygoid muscle; AT: anterior temporalis; PT: posterior temporalis; Mass: masseter.

Contralateral inferior head of the lateral pterygoid muscles

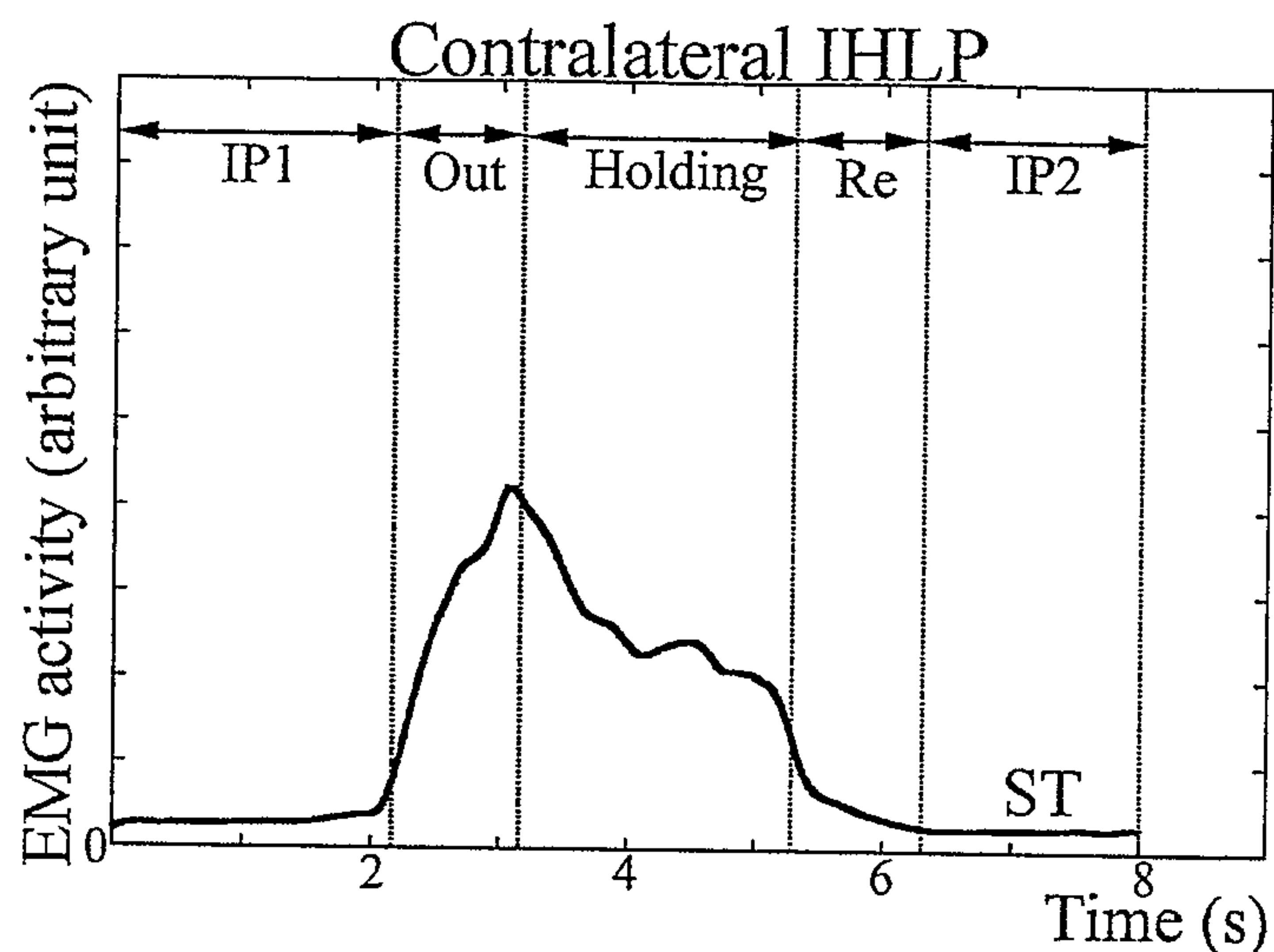


Fig. 4.3-24 Example (subject ST) of average contralateral IHLP activity of 10 trials after being rectified and smoothed.

The overall pattern of the contralateral IHLP at fast lateral movement was similar to that at the slow speed (e.g. Fig. 4.3-2 and Fig. 4.3-24). The activity pattern of contralateral IHLP, normalized with MIPT movement, was not changed by the alteration of speed in all five subjects (e.g. Fig. 4.3-25). But the mean IHLP activity from all subjects was higher during the outgoing phase and lower during the return phase at the fast speed (Fig. 4.3-25) with a statistically significant difference at the 3rd mm of MIPT displacement from IP in both phases.

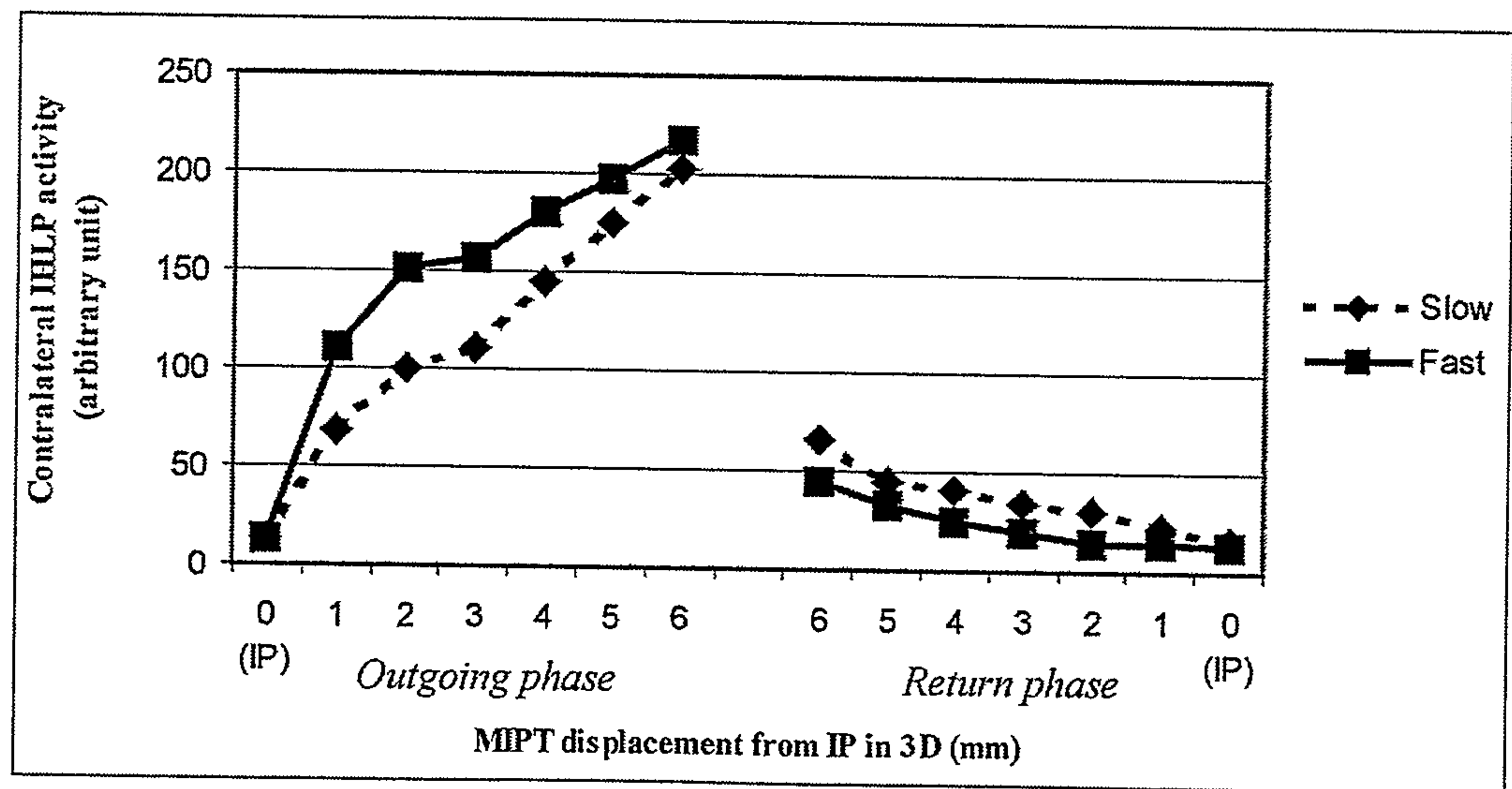


Fig. 4.3-25 Example (subject ST) of contralateral IHLP after being normalized with MIPT movement during outgoing and return phases under two speeds at low closing force in the same subject. This subject is the same subject as in Fig. 4.3-1 and 4.3-23. IP: intercuspal position; 3D: three-dimensions.

Subject	Onset		Offset	
	Slow speed	Fast speed	Slow speed	Fast speed
01	0.33	0.21	1.02	0.45
02	0.56	0.41	0.19	-0.24
03	0.30	0.20	1.07	0.56
04	0.64	0.45	0.16	0.31
05	0.13	0.13	0.32	-0.34
Mean $\pm$ SD	0.39 $\pm$ 0.21	0.28 $\pm$ 0.14	0.55 $\pm$ 0.45	0.15 $\pm$ 0.41

Table 4.3-3 The difference (s) of the onset and offset time between the MIPT movement and the IHLP activity in each subject at two laterotrusive speeds at low force to maintain tooth contact. Positive values indicate that the onset (or the offset) of the IHLP activity was earlier than that of MIPT three-dimensional movement.

In five subjects where both low- and fast-speed recordings were available (Table 4.3-3), the arithmetical difference of the onset, as well as the offset, between the contralateral IHLP and the MIPT movement at the slow speed was statistically larger than those values at the fast speed.

Contralateral anterior and posterior temporalis and masseter muscles

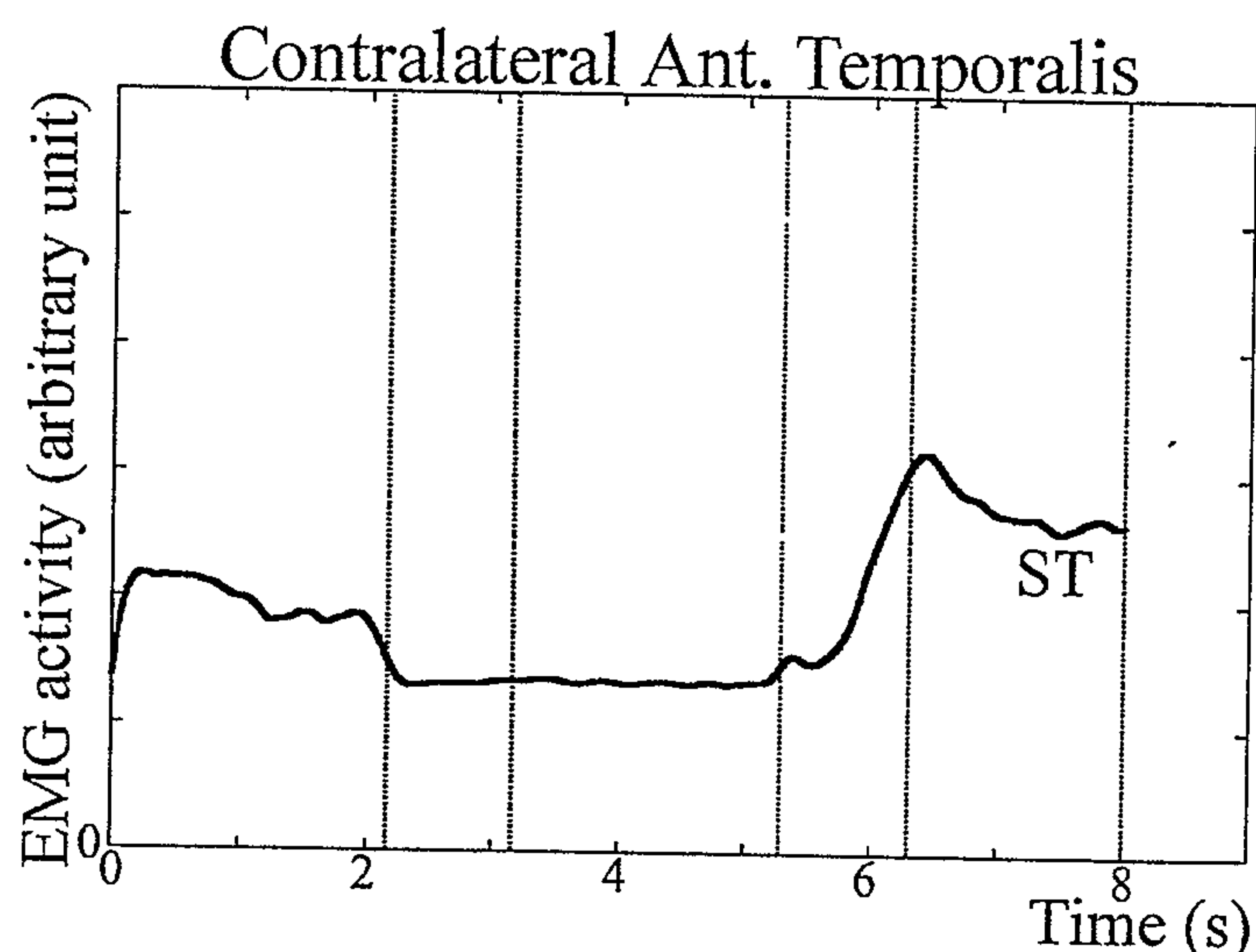


Fig. 4.3-26 Example (subject ST) of average contralateral anterior temporalis activity of 10 trials after being rectified and smoothed.

The overall pattern of the contralateral anterior and posterior temporalis as well as masseter muscles at fast lateral movement was similar to that at the slow speed (e.g. Fig. 4.3-4 and -26; Fig. 4.3-5 and -27; Fig. 4.3-6 and -28). There was no statistically significant difference in mean EMG activity between the laterotrusion under two speeds except the contralateral anterior temporalis at the

outgoing phase showed a significantly lower activity at the fast speed of lateral movement.

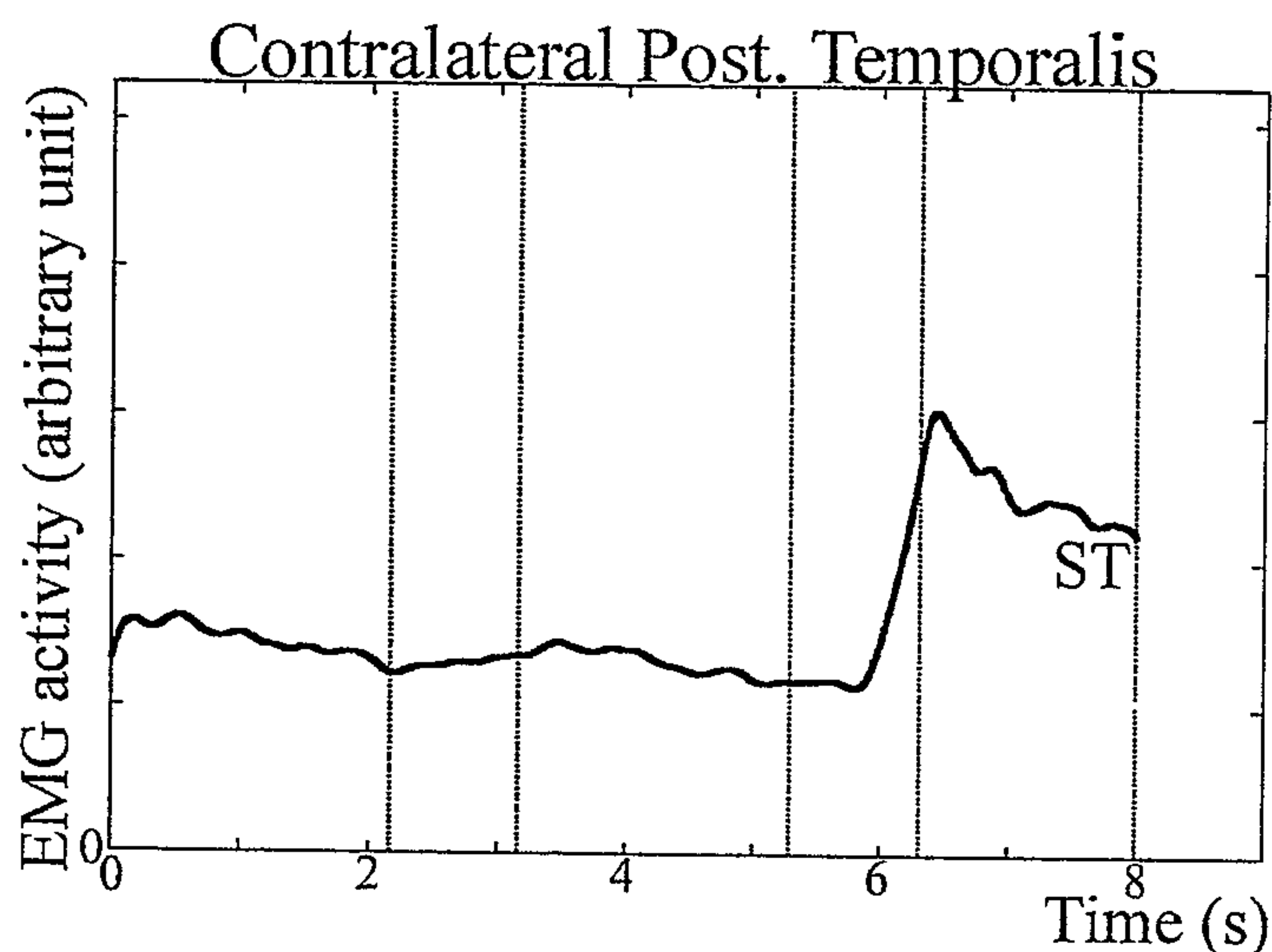


Fig. 4.3-27 Example (subject ST) of average contralateral posterior temporalis activity of 10 trials after being rectified and smoothed.

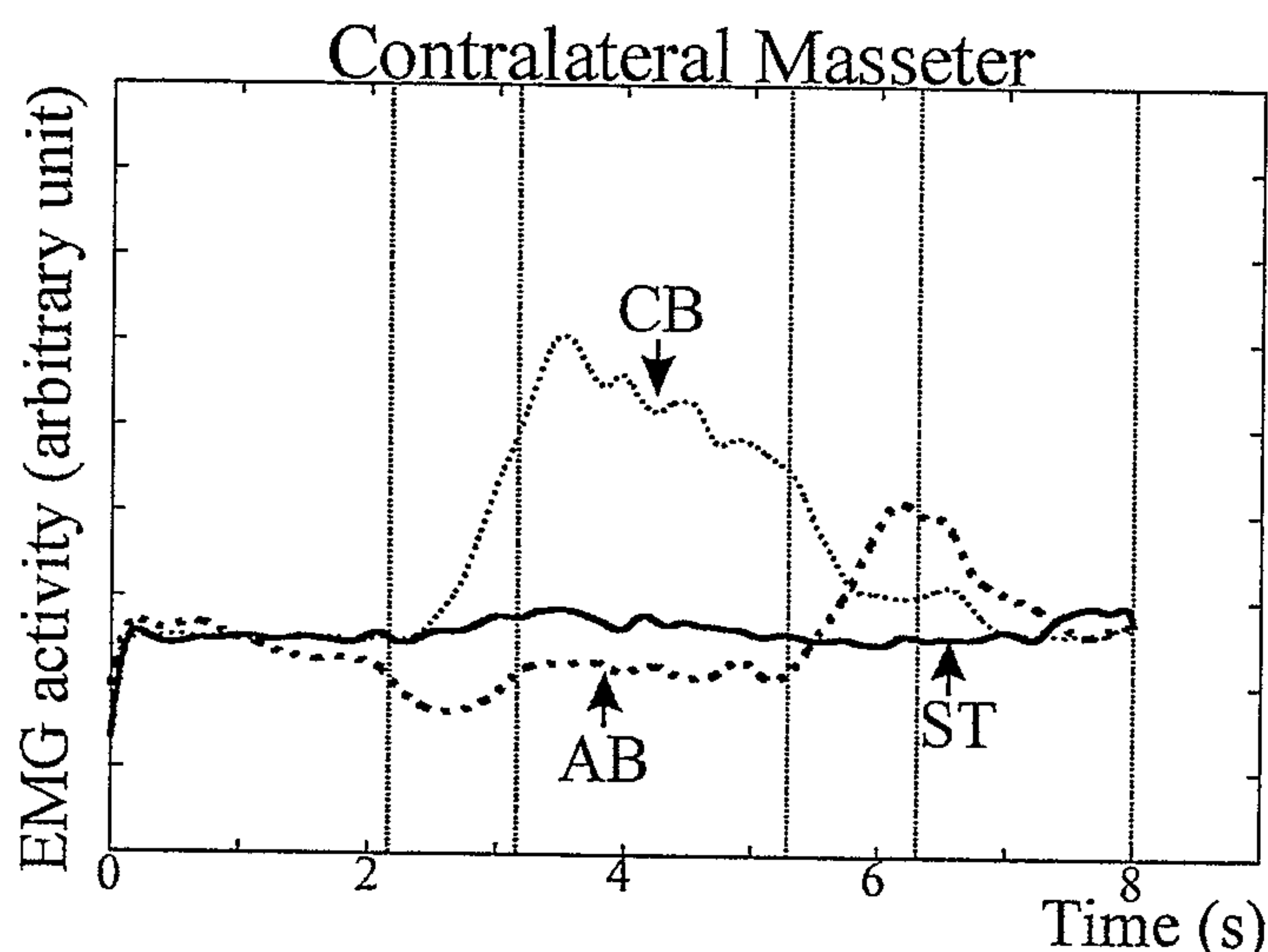


Fig. 4.3-28 Three examples (subjects ST, AB and CB) of average contralateral masseter activity of 10 trials after being rectified and smoothed. Note that the amplitudes of the different subjects may be scaled differently (see Methods).

Ipsilateral anterior and posterior temporalis and masseter muscles

The overall pattern of the ipsilateral anterior and posterior temporalis as well as masseter muscles at the fast lateral movement was similar to that at the slow speed (e.g. Fig. 4.3-8 and -29; Fig. 4.3-9 and -30; Fig. 4.3-10 and -31). There was no statistically significant difference between the laterotrusion under the two speeds during the outgoing, holding and return phases.

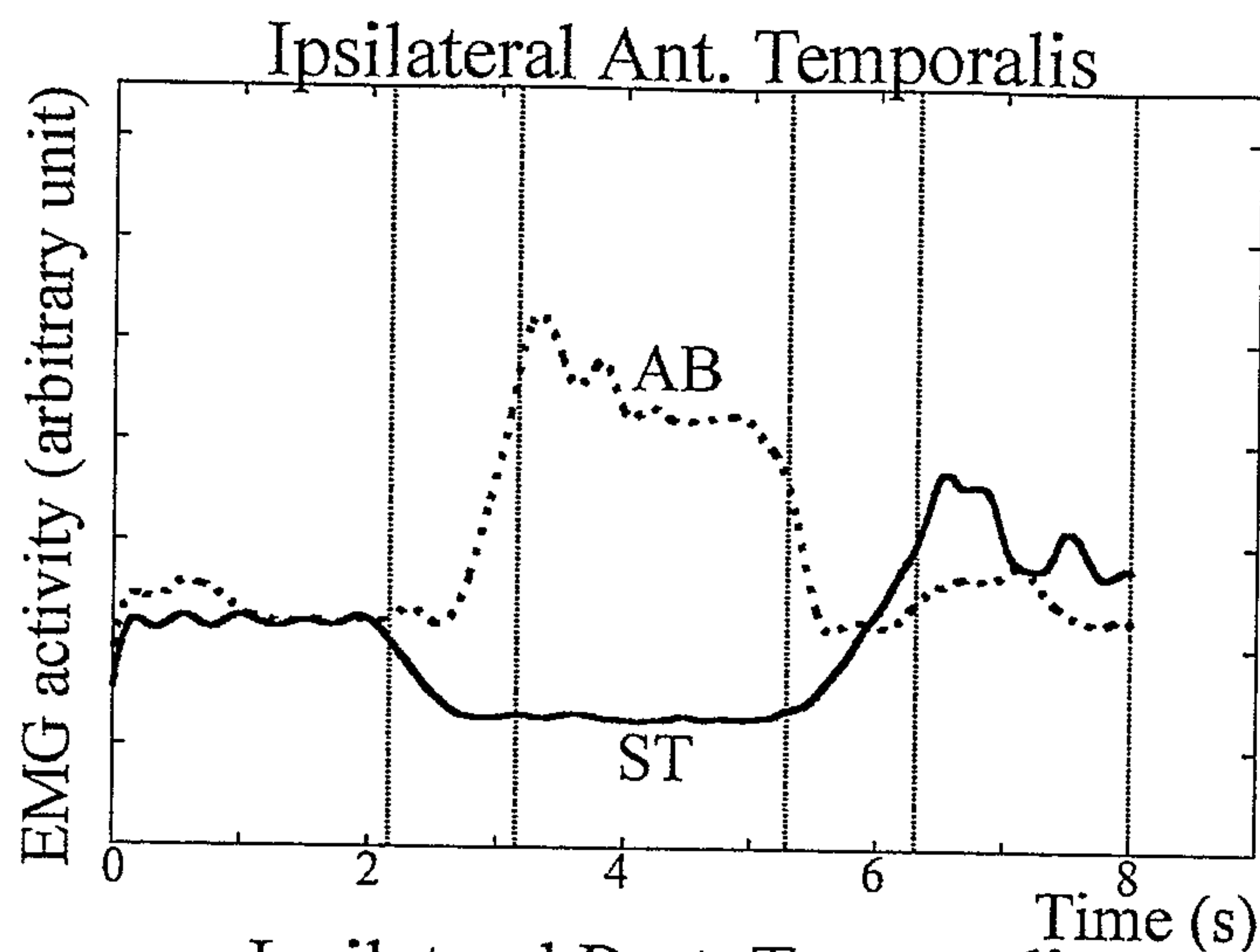


Fig. 4.3-29 Two examples (subjects ST and AB) of average ipsilateral anterior temporalis activity of 10 trials after being rectified and smoothed. Note that the amplitudes of the different subjects may be scaled differently (see Methods).

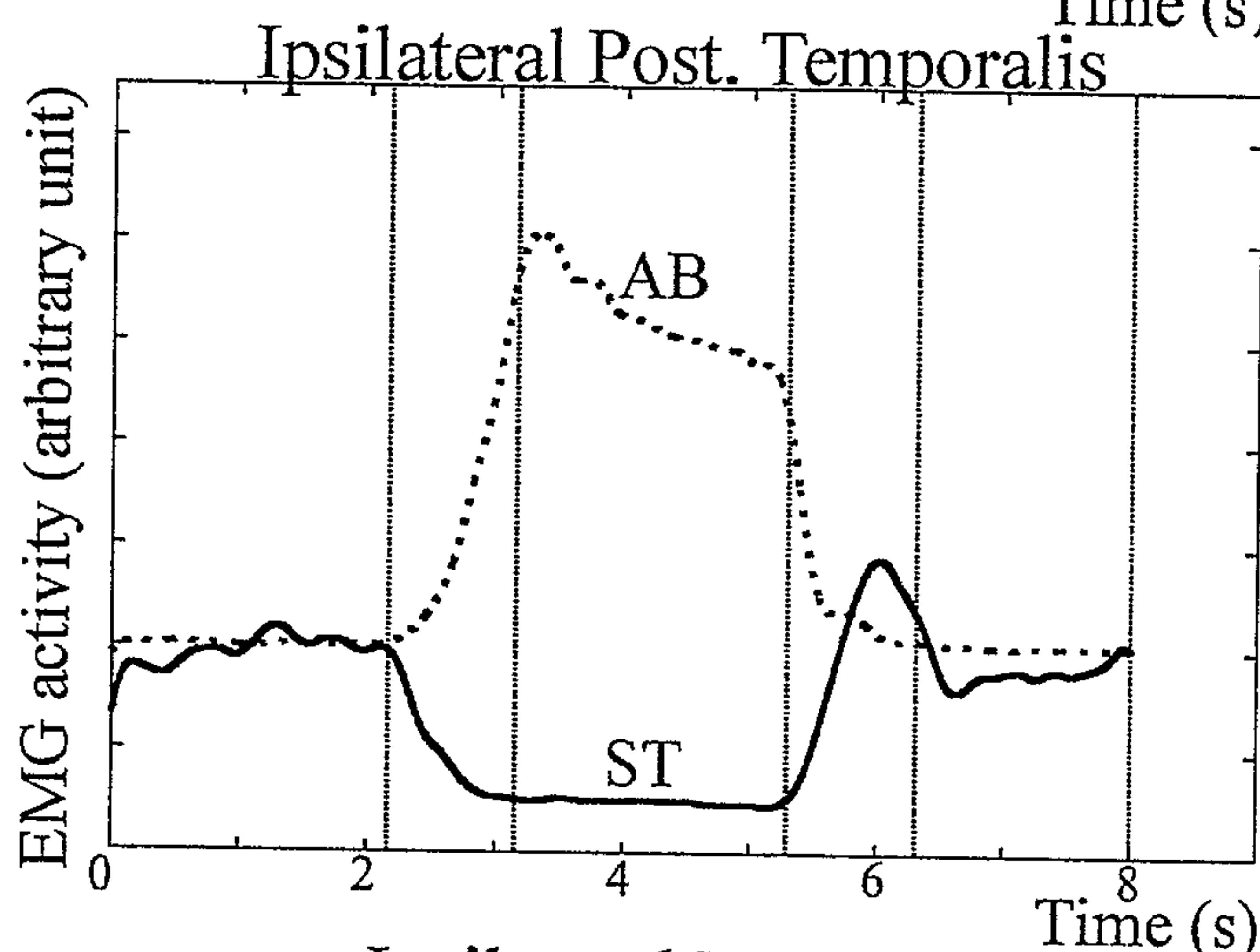


Fig. 4.3-30 Two examples (subjects ST and AB) of average ipsilateral posterior temporalis activity of 10 trials after being rectified and smoothed. Note that the amplitudes of the different subjects may be scaled differently (see Methods).

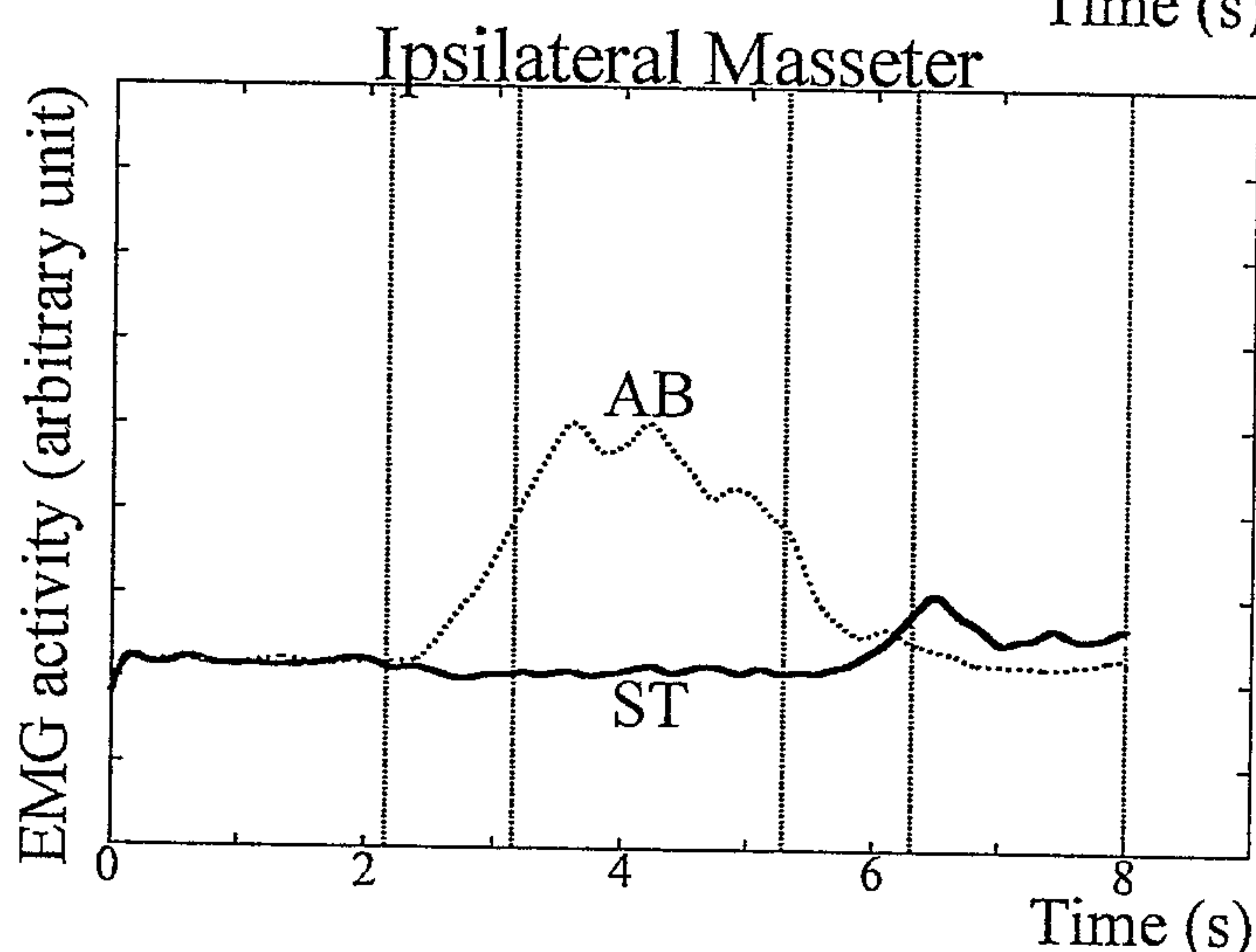


Fig. 4.3-31 Two examples (subjects ST and CB) of average ipsilateral masseter activity of 10 trials after being rectified and smoothed. Note that the amplitudes of the different subjects may be scaled differently (see Methods).

4.3.1.4 Difficulty of repeating same movement task

The MIPT movement in Fig. 4.3-1 and 4.3-12 started at different times although they were under the guidance of the same visual-feedback sequence. Such a difference could also be observed in two consecutive trials of the same

movement task. In addition, there was also slight variation in amplitude and velocity between two consecutive trials of the same movement task in the same subject.

4.3.1.5 Comparison between two normalizing methods matching with MIPT

The results of the pattern of the average EMG activity of the two normalizing methods matching with MIPT movement were very close to each other. However, as shown in Fig. 4.3-32, the data distribution of the second normalizing method (i.e. mean value of 100 EMG activity samples) was more variable than that of the first method (i.e. mean value of EMG activity between each mm of MIPT movement). Nonetheless the pattern of the average EMG activity of the 11 trials shows a gradual decrease in both methods.

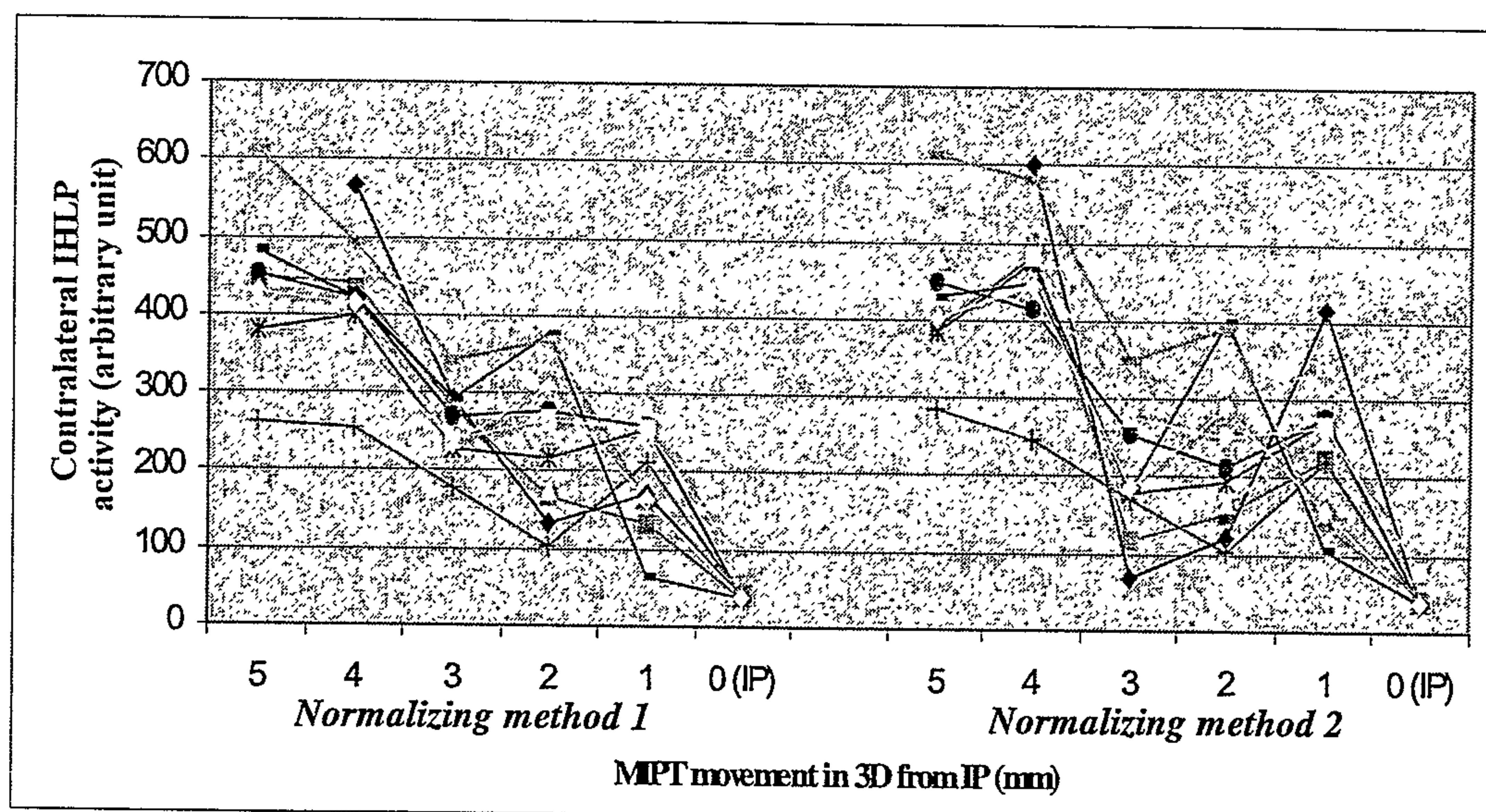


Fig. 4.3-32 Example of the comparison between two normalizing methods from subject CB at the return phase. The data for both methods 1 and 2 are from the same 11 trials.