4.3.3 Qualitative assessments of form of condylar point traces for open-close movement

This next step showed that the general form of the different condylar point traces within a subject were not necessarily the same. Indeed, a considerable variability was identified in the following qualitative assessment of the condylar point tracings. In only four of the 44 subjects were the arbitrary point traces similar in form within a subject, while 27 subjects exhibited direction changes and 13 exhibited cross-overs. The representative tracings from 16 subjects in Figures 14 and 15 were classified as: similar in form (Figure 14, subject A; Figure 15, subject G), exhibiting cross-over differences (Figure 14, subjects B, F, H; Figure 15, subjects B, C, H), and exhibiting direction changes (Figure 14, subjects C, D, E, G; Figure 15, subjects A, D, E, F).

The variability of the traces may be understood when the arbitrary points are correctly oriented to each other in the sagittal plane, and this is shown for the 16 subjects in Figures 14 and 15. The individual traces for the four subjects in Figures 11 and 12 correspond to subjects A, B and C in Figure 14, and subject F in Figure 15 respectively. Changes in form and dimension of the tracings of the arbitrary points, as described above, may be interpreted as movement of an arbitrary condylar square (ACS, second overlay to Figures 14 and 15). For example, the ACS in subject A of Figure 14 moved downwards and forwards and the final positioning of the ACS at maximum opening not only indicates that the ACS has translated in both horizontal and vertical axes but also indicates quite a different orientation of the ACS to that at the beginning of opening. It is also apparent that for a single open-close movement in different subjects, the movements of each ACS are not the same. That is, there is considerable variability in the downwards and forwards component of movement and in the final positioning of the ACS from a standard starting position. In the 2
subjects in which the condylar points were radiographically determined (see below) there was also variability between the pathways of each anatomical point during the open-close movement (see Figure 16). This too may be better understood when the anatomical points are correctly orientated to each other in the sagittal and horizontal planes as shown in Figure 20 C and D.

4.3.4 Relationship between condylar rotation and anterior translation of a condylar point

The variability between different arbitrary points can only be explained in terms of rotation in the region of the condyle during open-close movements. It was then determined whether the variability observed between different condylar points within a subject was also apparent when the relation between rotation and translation was examined at each arbitrary condylar point.

Figures 17, 18 and 19 show graphs of anterior condylar translation as a function of condylar rotation for a representative group of six subjects. None of the subjects in these figures, nor the entire subject group, displayed graphs of rotation and translation that were identical between different arbitrary points. Furthermore, there was considerable variation between the subjects. For the 44 subjects, condylar rotation for an open-close movement varied between 19.3-44.0° (mean±SD: 31.5±6.1°), and anterior condylar translation varied between 1.3-25.4 mm (11.1±4.3 mm). The maximum condylar rotation showed good correlation with maximum mandibular opening as measured at the MIPT (r=0.79).

Seven subjects demonstrated a near linear relationship between condylar rotation and translation for each arbitrary condylar point (eg. Figure 17 A-E) with the ratio of maximum anterior condylar translation to maximum condylar rotation ranging between 0.09-0.47 mm/° (mean±SD:
0.29±0.11 mm°). The ratio of anterior condylar translation to condylar rotation varied between 0.07-0.59 mm°/° (0.35±0.11 mm°/°) for the entire group of 44 subjects. A variable relationship between condylar rotation and translation was observed in 37 subjects. Of these subjects, 24 demonstrated an S shaped graph (e.g., Figure 17 F-J; see methods), which indicates that during jaw opening, condylar rotation occurred with little or no anterior translation at the beginning of opening, that condylar rotation and translation occurred concurrently during mid-opening, and that rotation predominated at the end of opening.

Although there were clear differences between subjects, within a subject, the graphs of condylar rotation and anterior condylar translation for the primary and surrounding points were, in general, similar in form, although they varied in size (eg. Figures 17, 18 and 19). The range of the ratio of anterior condylar translation to condylar rotation between each subject's arbitrary condylar points was 0.05-0.13 mm°/° (mean±SD: 0.10±0.02 mm°/°) for the subject group. This means that on average, the anterior translations of a subject's arbitrary condylar points will vary, with respect to that subject's other arbitrary condylar points, by 0.10 mm for every degree the condyle, and hence mandible, is rotated open.
Figure 17, Figure 18, and Figure 19 Anterior translation/rotation graphs
In each figure, graphs of anterior translation of arbitrary condylar point (ordinate axis) are plotted against sagittal plane rotation (abscissa axis).

A,F Primary condylar point for 2 different subjects.
B,G
C,H Surrounding arbitrary condylar points for the 2 different subjects.
D,I
E,J

$10^\circ$ or 10 mm
Figure 20 Comparison of anatomic and arbitrary point pathways for open-close movement

Sagittal views of pathways of anatomic and arbitrary condylar points in correct spatial relationship to each other for an open-close mandibular movement for the two subjects.

Overlay: Corresponding sagittal plane ACS and anatomical triangle for the two subjects. A shape is plotted each 300 ms.

A, B  Arbitrary points of Subject 1 and 2 respectively
C,D  Anatomical points of Subject 1 and 2 respectively. NB. Pathway of terminal hinge axis point is inferior most trace in both subjects

(to the right of page is anterior; to the bottom of page is inferior).

Total length of horizontal or vertical axis: 15 mm.
4.3.5 Pathways of radiographically determined condylar points for an open-close movement

In the two subjects in which the pathways of the radiographically determined condylar points were plotted, the general features identified above for the arbitrarily defined condylar point tracings were also apparent in the anatomical points. The sagittal pathway for the radiographically determined most anterior, posterior and superior condylar points, and the medial and lateral poles for 2 subjects are shown in Figure 16 (see also Figure 5). Marked variation was seen between the 2 subjects and within each subject for the anatomical condylar point movements. The maximum difference between the maximum horizontal translations of the five anatomical condylar points was 6.8 mm for Subject 1, and 4.2 mm for Subject 2, and for the arbitrary condylar points the variation was 5.3 mm for Subject 1 and 1.4 mm for Subject 2. The maximum difference between the maximum vertical translations of the 3 condylar points was 2.2 mm for Subject 1, and 3.1 mm for Subject 2, and for the arbitrary points the variation was 0.6 mm for Subject 1 and 2.2 mm for Subject 2. In comparing the pathways qualitatively, Subject 1 was categorised into the 'direction changes' group and subject 2 categorised into the 'cross-over differences' group. In Figure 20 the sagittal plane pathways for the condylar points were correctly oriented with respect to each other. This figure shows the relationship of a hinge axis point and pathway to the selected anatomical points. For both subjects the hinge axis lies inferior to the anatomical condylar points, in the region of the condylar neck. The overlay to Figure 20 shows that the ACS and sagittal plane anatomical triangles both follow similar anterior and inferior paths in each subject. It can be seen that the hinge axis pathway does not describe the motion of the anatomical condylar triangle for either of the two subjects.
4.3.6 Excursive movements

These data suggest that the tracings of a single condylar point are not a valid indicator of condylar movement during open-close mandibular movements. The aim of the next part of the study was to determine whether the tracings of a single condylar point accurately indicate condylar movement during excursive jaw movements.

4.3.6.1 Lateral movement: Working side or ipsilateral condyle

Figures 21, 22 and 23 show the sagittal and horizontal plane views of the movement of the primary (lateral) condylar point during mandibular movement to the ipsilateral side for 12 representative subjects. These tracings indicate the direction and displacement of the condylar point. The first overlays show the pathways of the surrounding arbitrary condylar points in the sagittal and horizontal planes, and the second overlays show the movement of the subjects' sagittal ACS and horizontal ACS; a square is plotted every 300 ms during the movement. The maximum overall displacement of the horizontal ACS varied between 1.0-4.0 mm (mean±SD: 2.0±0.7 mm; see Figure 27), and the maximum displacement of the sagittal ACS varied between 0.7-4.3 mm (1.5±0.7 mm). Because of the small movements of the working side ACS, maximum displacement values in each plane only were determined and not individual displacements along each axis.

The general direction of the movement of the ACS corresponded to the direction of the movement of the primary condylar point although the direction of the movement was more easily discernible on the diagrams of the ACS. However, within a subject the movement of each corner of the
horizontal ACS was usually different to the other three corners. For example, in Subject C/G of Figure 21, the anterior-left corner (trace G) showed the smallest displacement of the four corners and the movement was directed laterally with a small posterior component. The anterior right corner of this subject's ACS moved laterally also, but was directed more posteriorly than the anterior-left corner. The posterior corners of the ACS showed the greatest displacement in a postero-lateral direction.

Between subjects, there was variability in the direction of movement of the ACS. In 32 subjects (73%) the movement was upwards, backwards and laterally directed, in 8 subjects (18%) the movement was downwards, forwards and laterally directed, and in 4 subjects (9%) the movement was downwards, backwards and laterally directed (see Figure 24 B). No other movement patterns were present in the subject group, that is, no ACS moved upwards, forwards and laterally, and none moved medially, and in all subjects some bodily movement of the ACS was displayed.

An assessment was made of the magnitude of lateral displacement of the ACS in the subject group. It was assumed that the lateral displacement of the corner showing the smallest movement would reflect the amount of lateral translation (ie. Bennett movement) of the condyle. This lateral translation was present in all subjects and varied between 0.5-3.5 mm (mean±SD: 1.4±0.7 mm; Figure 25 A). It was most evident in subject C/G in Figure 23 who showed a lateral displacement of 3.5 mm of
Figures 21, Figure 22 and Figure 23: Arbitrary condylar points' pathways for ipsilateral movement

A-D  Sagittal view of the pathways of the primary condylar point on the ipsilateral side in 12 subjects during a working side mandibular movement (to the right of page is anterior; to the bottom of page is inferior).
E-H  Horizontal view of pathways during same movements as in A-D.
(to the right of page is subject's left side; to the bottom of the page is anterior)

1st Overlay:
A-D  Sagittal view of arbitrary points' pathways
E-H  Horizontal view of arbitrary points' pathways

2nd Overlay:
A-D  ACS in sagittal plane
E-H  ACS in horizontal plane

Total length of horizontal or vertical axis: 15 mm.
the ACS. Subject A/E in Figure 21 showed minimal Bennett movement of 0.5 mm. There appeared to be no relationship between the amount of Bennett movement and a subject's anterior dental relationship, except that only two subjects, all with Class II Division 2 anterior dental relationship, showed a lateral shift of the ACS which was greater than 2.5 mm (Figure 25 B). At the MIPT, during lateral excursion, the mandible moved antero-laterally in 35 subjects, postero-laterally in two subjects and laterally in seven subjects. No clear relationship was apparent between the direction of movement of the MIPT and the direction of movement of the ACS. For example, the smaller group of nine subjects whose MIPT moved posterolaterally or laterally, were part of the larger group of 31 subjects who showed upwards, backwards and laterally directed movement of the ACS.

All subjects displayed varying amounts of horizontal condylar rotation as determined from the horizontal ACS diagrams, and this rotation varied between 1.5-8° (mean±SD: 3.4±1.7) for the subject group (see Figure 24 A). There was poor correlation between horizontal rotation and maximum horizontal displacement of the ACS (r = 0.13), and between horizontal rotation and Bennett movement of the ACS (r = -0.11; Figure 26). For example, the subject with the largest horizontal rotation (8°), displayed only 1.25 mm horizontal displacement of the ACS and only 0.5 mm Bennett movement (Figure 26). In contrast the subject with the greatest horizontal displacement (4.0 mm) and Bennett movement (3.5 mm) only had moderate horizontal rotation (3°) during the lateral jaw movement (see Figure 26).

The two subjects with the anatomically derived sagittal plane condylar triangles and horizontal plane condylar quadrangles both showed variable displacement for the anatomical points. Although the direction of each anatomical point within a subject was generally similar the displacement was not, and Bennett movement was 1.5 mm for Subject 1
and 2.0 mm for Subject 2 (Figure 28). The Bennett movement calculated for these subjects from the ACS was 1.0 mm and 2.5 mm respectively. The condylar figures in Subject 1 moved posteriorly, superiorly and laterally which agreed with the movement of this subject’s ACS, and for Subject 2 the movement was inferior and lateral without appreciable posterior movement (Figure 28 D, H). (The antero-inferiorly directed movement of the ACS in Fig. 28 A, B occurred prior to and was not a component of the working-side condylar movement.) This did not agree with this subject’s ACS which moved posteriorly, inferiorly and laterally (overlay to Figure 28 C, G). These data indicate the variability that can be observed between the movement tracings of different arbitrary or anatomical condylar points on the working side during lateral excursive movements, and hence the caution that must be exercised in interpreting tracings of condylar points.

4.3.6.2 Lateral movement: Non-working side condyle

Although variation could be observed in the arbitrary condylar point pathways between different subjects during contralateral excursive movements, there was much less variation in the pathways of the different arbitrary and anatomical condylar points within a subject on the contralateral or non-working side. Figures 29, 30 and 31 show the sagittal and horizontal plane views of the movement of the primary condylar point and surrounding arbitrary points (1st overlay in each Figure) on the
Figure 24 Movement of ipsilateral ACS

A. Horizontal rotation of ipsilateral ACS for a lateral mandibular movement
B. Direction of ipsilateral ACS movement for a lateral mandibular movement

ubl: upwards, backwards and laterally directed
dfl: downwards, forwards and laterally directed
dbl: downwards, backwards and laterally directed
other: any other direction
Figure 25  Lateral shift of ACS

A. Lateral shift of ACS of 44 subjects for lateral mandibular movement
B. Bennett movement related to subjects' anterior dental classification
Figure 26 Rotation/displacement graphs for ipsilateral movement

A. Horizontal rotation vs horizontal displacement of ipsilateral ACS for a lateral mandibular movement of 44 subjects
B. Horizontal rotation vs Bennett movement of ipsilateral ACS for a lateral mandibular movement of 44 subjects
Figure 27 Displacement of ipsilateral ACS

A. Horizontal displacement of ipsilateral ACS for lateral mandibular movement
B. Sagittal displacement of ipsilateral ACS for lateral mandibular movement
Figure 28 Anatomic and arbitrary points' pathways for ipsilateral movement

A-D Sagittal view of anatomic and arbitrary condylar points pathways in correct spatial relationship to each other for ipsilateral mandibular movement
(to the right of page is anterior; to the bottom of page is inferior).
A, B Arbitrary and anatomical points of Subject 1
C, D Arbitrary and anatomical points of Subject 2

E-H Horizontal plane trajectories corresponding to sagittal plane trajectories above (to the right of page is subject's left side - the side the jaw moves away from; to the bottom of the page is anterior).

Overlay: Corresponding anatomical and arbitrary figures for the two subjects. A shape is plotted each 300 ms.

Pathway of terminal hinge axis point is located inferiorly to anatomical points’ pathways. The antero-inferiorly directed movement of the ACS occurred prior to and was not a component of the working-side condylar movement.

Total length of horizontal or vertical axis: 15 mm.
non-working side during lateral jaw movement with tooth contact for a representative sample of 12 subjects. In all subjects, all condylar points moved downwards, forwards and medially (i.e. to the side of jaw movement). Even though subjects were instructed to move laterally as far as comfortable, variation was noted however between subjects in both sagittal and horizontal planes in the length and direction of the paths of the condylar points. For example, subject C/G of Figure 29 exhibited a sagittal path that is relatively steep and short and shows only a small maximum lateral deviation (1.3 mm). In contrast, subject B/F of Figure 29 showed a longer and more curvilinear pathway in the sagittal plane, and lateral displacement of the condylar point was 4.5 mm.

The ACS (2nd overlay to Figures 29, 30 and 31) again provides a better illustration of the subject’s arbitrary condylar point movement, as it indicates rotation in the plane that is being viewed. For example, it can clearly be seen that the ACS in the horizontal plane not only followed the path of the primary condylar point, but also rotated to a variable extent. This rotation varied between 1.5-6.0° (mean±SD: 3.5±1.2°). Rotation in the sagittal plane was not as marked, and varied between 0.3-2.6° (1.2±0.6°). The anterior translation varied between 2.8-12.0 mm (7.2±2.5 mm), the inferior translation, 2.0-10.0 mm (5.9±1.8 mm), and the lateral translation 0.3-4.5 mm (2.3±1.0 mm).

When assessing the difference in maximum translations for the five arbitrary points in each subject, none of the subjects exhibited a range greater than 1 mm in either horizontal or vertical translation (Figure 32 B). The difference in maximal anterior translations of the 5 'condylar' points of each subject was between 0 and 1 mm for the total population (mean±SD: 0.4±0.2 mm). Similarly, the difference in maximal inferior translations was also between 0 and 1 mm for the same sample population (0.3±0.2 mm), and the difference in maximal lateral translations was between 0.3 and 1 mm.
with a slightly larger mean than the previous two translations (0.6±0.2 mm). These small differences in maximum translation contrast with the much larger differences observed during open-close movements (see above). The range in the lateral direction is relatively large when compared to the lateral displacement of the arbitrary points which ranged from 0.3-4.5 mm (2.3±1.0 mm). There was no apparent difference in the distribution of the range of horizontal and vertical translations with the four orthodontic categories of anterior dental relationships (Class I; II/1; II/2; III; see Figure 32A).

The radiographically derived condylar figures were dissimilar between the two subjects but were similar to their respective ACS (overlay to Figure 33). Slight differences in the average maximum translations were seen between the trajectories of the anatomical and arbitrary condylar points within a subject (Figure 33). Thus, in Subject 1, the average maximum translation for the arbitrary points in the anterior, inferior and lateral directions were 9.1 mm, 4.9 mm and 1.1 mm respectively, and for the anatomical points the average translations were 9.7 mm, 4.5 mm and 1.5 mm; and in Subject 2, the corresponding values for the arbitrary points were 7.8 mm, 9.7 mm and 2.1 mm, and for the anatomical points, 6.7 mm, 8.1 mm and 1.8 mm. The differences in maximum translations for the
Figure 29, Figure 30 and Figure 31  Arbitrary condylar points pathways for contralateral movement

A-D  Sagittal view of the pathways of the primary condylar points in 4 subjects for a right lateral mandibular movement, i.e. contralateral to the direction of mandibular movement (to the right of page is anterior; to the bottom of page is inferior).
E-H  Horizontal view of pathways. Each pathway corresponds to the sagittal pathway above it (to the right of page is subject's left side; to the bottom of the page is anterior).

1st Overlay:
A-D  Sagittal view of arbitrary points’ pathways
E-H  Horizontal view of arbitrary points’ pathways

2nd Overlay:
A-D  ACS in sagittal plane
E-H  ACS in horizontal plane

Total length of horizontal or vertical axis: 15 mm.
arbitrary points in the anterior, inferior and lateral directions were 0.5 mm, 0.3 mm and 0.8 mm respectively, and for the anatomical points, 1.0 mm, 0.8 mm and 1.0 mm respectively for Subject 1. In Subject 2, the corresponding values for the arbitrary points were 0.5 mm, 0 mm and 0.5 mm, respectively, and for the anatomical points, 1.0 mm, 1.8 mm and 0.8 mm respectively. Thus the difference in the maximum pathway displacements appeared to be slightly greater between the anatomical points than between the arbitrary points for both subjects.

4.3.6.3 Protrusive movement

The arbitrary condylar point pathways for a protrusive mandibular movement showed the least variability within a subject, but nonetheless a variety of protrusive paths were seen in the different subjects. Figures 34, 35 and 36 show the sagittal and horizontal plane views of the movement of the primary condylar point (1st overlay: surrounding arbitrary points) during protrusive jaw movement with tooth contact for a representative sample of 12 subjects. During protrusion in each subject, the primary condylar point moves inferiorly and anteriorly with little lateral deviation; and variation in both the length and angulation of the protrusive path is evident between subjects. For example subject A/E and B/F of Figure 34 show relatively short protrusive paths of the ACS, while subjects C/G and D/H of Figure 35 show flatter and steeper paths, respectively in relation to the reference plane (FHP).

For the subject group, the anterior translation varied between 3.0-25.0 mm (mean±SD: 14.3±5.3 mm), the inferior translation varied between 5.0-19.5 mm (10.2±3.1 mm), and the lateral translation varied between 0.0-2.0 mm (0.8±0.7 mm). Figure 38 A shows the lateral translation in all subjects, with 31 of the 44 subjects deviating 1 mm or less
during the protrusive jaw movement. Subjects with the larger lateral deviation (eg. subject G, Figure 34) demonstrated a similar lateral displacement of the mandible at the MIPT.

The first overlays to Figures 34, 35 and 36 show the surrounding arbitrary condylar points' paths in the sagittal and horizontal planes, and the second overlays show the movement of the subjects' sagittal ACS and horizontal ACS. An assessment was made, in all of the subjects, of the largest difference between all condylar points' maximum translations in each subject in the antero-posterior and supero-inferior directions during protrusion (Figure 37). As for the ACSs on the non-working side, none of the subjects exhibited a range greater than 1 mm in either antero-posterior or supero-inferior translations. The difference in maximal antero-posterior translations of the five arbitrary condylar points of each subject was between 0 and 1 mm for our population (0.4±0.3 mm). This means that for a single protrusive movement, the tracings of each subject's arbitrary condylar points showed, on average, only a 0.4 mm range in maximal antero-posterior displacement. Similarly, the difference in maximal supero-inferior translations was also between 0 and 1 mm for the same sample population (mean±SD: 0.4±0.3 mm). There was no apparent difference in the distribution of the range of antero-posterior and supero-inferior translations with the four orthodontic categories of anterior dental relationships (see Figure 38 B).

The pathways of the radiographically derived condylar points of the two subjects were similar in the horizontal plane, but in the sagittal plane the pathway of Subject 1 was flatter than the pathway of Subject 2. This trend was also exhibited in the pathways of the two subjects' arbitrary and anatomical figures (overlay to Figure 39). Only slight differences in the average maximum translations were seen between the anatomical and arbitrary condylar points trajectories within a subject. In Subject 1, the
average maximum translations for the arbitrary points in the anterior and inferior directions were 12.4 mm and 4.9 mm respectively, and for the anatomical points the average translations were 12.2 mm and 4.2 mm; and in Subject 2, the corresponding values for the arbitrary points were 10.9 mm and 9.6 mm and for the anatomical points, 10.6 mm and 9.0 mm (Figure 39). The difference in maximum translations for the arbitrary points in the anterior and inferior directions were 0.5 mm and 0.3 mm respectively, and for the anatomical points were 0.3 mm and 0.5 mm respectively for Subject 1. In subject 2, the corresponding values for the arbitrary points were 0.3 mm and 0.3 mm respectively, and for the anatomical points, 0.8 mm and 0.5 mm respectively. Thus the difference in the maximum pathway displacements was no greater than 0.8 mm, and was similar between the anatomical points and the arbitrary points for both subjects.
Figure 32 Arbitrary condylar point translation for a contralateral movement

A. Average anterior (x), inferior (z) and lateral (y) translation of arbitrary condylar point during contralateral mandibular movement (stdev: standard deviation)

B. Distribution of variation in maximum translation of arbitrary condylar points within each subject during contralateral mandibular movement
Figure 33 Anatomical and arbitrary points' pathways for a contralateral movement

A-D Sagittal views of anatomical and arbitrary condylar points' pathways in correct relationship to each other for contralateral mandibular movement (non-working ACS and condyle)
   A, B Arbitrary and anatomical points of Subject 1
   C, D Arbitrary and anatomical points of Subject 2.

NB. Pathway of terminal hinge axis point is located inferiorly to anatomical points' pathways (to the right of page is anterior; to the bottom of page is inferior).

E-H Horizontal plane trajectories corresponding to sagittal plane trajectories above (to the right of page is subject's left side - the side the jaw moves away from; to the bottom of the page is anterior).

Overlay: Corresponding anatomical and arbitrary figures for the two subjects. A shape is plotted each 300 ms

Total length of horizontal or vertical axis: 15 mm.
Figure 34, Figure 35, Figure 36  Arbitrary condylar point pathways for a protrusive movement

A-D  Sagittal views of the pathways of the primary condylar point in 12 subjects during a protrusive mandibular movement (to the right of page is anterior; to the bottom of page is inferior).
E-H  Horizontal views of pathways during same movements as in A-D (to the right of page is subject's left side; to the bottom of the page is anterior).

1st overlay:
A-D  Sagittal views of arbitrary points' pathways
E-H  Horizontal views of arbitrary points' pathways

2nd overlay:
A-D  ACS in sagittal plane
E-H  ACS in horizontal plane

Total length of horizontal or vertical axis: 15 mm.
Figure 37 Rotation and translation during protrusion

A. Distribution of variation in maximum translation of arbitrary condylar points within each subject for protrusive mandibular movement
B. Maximum condylar rotation for protrusive mandibular movement of 44 subjects
Figure 38 Condylar point displacement during protrusion

A. Lateral deviation of arbitrary condylar point during protrusive mandibular movement of 44 subjects
B. Average anterior (x) and inferior (z) translation of arbitrary condylar point during protrusive mandibular movement

(stddev: standard deviation)
Figure 39 Anatomic and arbitrary points' pathways during protrusion

A-D Sagittal views of anatomical and arbitrary condylar points' pathways in correct spatial relationship to each other for prosusive mandibular movement.

A, B Arbitrary and anatomical points of Subject 1
C, D Arbitrary and anatomical points of Subject 2

NB. Pathway of terminal hinge axis point is located inferioirly to anatomical points' pathways (to the right of page is anterior; to the bottom of page is inferior).

E-H Horizontal plane trajectories corresponding to sagittal plane trajectories above (to the right of page is subject's left side - the side the jaw moves away from; to the bottom of the page is anterior).

Overlay: Corresponding anatomical and arbitrary figures for the two subjects. A shape is plotted each 300 ms.

Total length of horizontal or vertical axis: 15 mm.
Although small, rotation in the sagittal plane did occur in all subjects and varied between 0.4-3.8° (mean±SD: 1.9±0.9°). Given the variation in steepness in overbites, one might expect some relation between rotation and orthodontic category, however there was no apparent difference in the sagittal plane condylar rotation with the four orthodontic categories of anterior dental relationships (Class I; II/1; II/2; III; see Figure 37 B). In 37 of the subjects the direction of rotation had the effect of closing the jaw. This means that as the mandible was protruded, the condyle (and mandible) rotated forwards and upwards for these subjects. In the remaining seven subjects, the direction of rotation had the effect of opening the jaw.

There was a variation between sagittal plane condylar point pathways within subjects for open, protrusive and contralateral mandibular movements, which supports the concept of a Fischer angle (Figure 40). Fischer angle was determined by superimposing sagittal plane pathways and measuring the angular separation between the pathways for the first 5 mm of the movement. Only five subjects demonstrated a lack of Fischer angle in all of their arbitrary condylar point pathways. When only the pathways for the protrusive and contralateral movements were analysed for sagittal plane coincidence, 39 subjects demonstrated superimposition for the first 5 mm of the pathway. This suggests that the main difference in the arbitrary point pathways is between the open movement and excursive movement.
Figure 40 Pathway coincidence for all movements

Sagittal plane pathway coincidence within each subject of arbitrary condylar points for open-close, contralateral & protrusive movements
5. DISCUSSION

Most investigations into human mandibular condylar movement have reported the variability of condylar path form and dimension between subjects, and suggest that these differences are attributed to natural human variation such as morphological and functional differences. The variety of recording instrumentation and methodologies however have also made comparisons of condylar movement studies difficult, and many recording systems show serious limitations including the recording of movement without six degrees of freedom, limitation of natural mandibular movement because of cumbersome design and the need for much technical expertise to operate. Furthermore, most condylar movement analysis has been derived from pathways of a single arbitrarily defined condylar point, which may not lie on or within the condyle.

As many studies have provided evidence that mandibular movement involves both rotation and translation, it would appear that the three-dimensional movement of the body of the condyle could not be described by the trajectory of a single point. Indeed the articulator-based experiment in the present study demonstrated under laboratory conditions the variability in the form of sagittal plane pathways of two different points on the condylar sphere. For the point selected on the anterior aspect of the condylar sphere, the open and close paths were not coincident, and description of the movement of the condylar sphere made solely on this trajectory would suggest distraction of the condylar sphere from the articulator's fossa box at the end of opening. This however was not what occurred as the condylar sphere was made to follow the same path along the fossa box during the opening and closing phases. The trajectory of the centre of the condylar
sphere alone however, does not illustrate the rotational component of the movement performed on the articulator.

In the simplified case of the articulator, the condylar sphere's movement could be described by the trajectory of the centre of the condylar sphere and the rotation that occurs along this pathway. This method of description however appears not to be the case for most descriptions of movement of the human condyle. In the first instance, the condyle is not spherical in the sagittal plane and thus cannot rotate smoothly about its centre; and secondly for most mandibular movements it appears that rotation occurs about a changing centre of rotation (Grant 1973; McMillan et al. 1989). Following an assessment of some of the features of the JAWS3D system's precision, and some of the features of the methodology, this study assessed whether or not the movement of a single condylar point could indeed describe the movement of the mandibular condyle. The movement patterns of arbitrary and anatomical condylar points during open-close and excursive mandibular movements were described and compared in a group of 44 healthy and asymptomatic adults.

**Variation in pathways of different condylar points within subjects**

An analysis of different arbitrary and anatomical points within a subject showed variability amongst all of the subjects for open-close and excursive movements which by inference, indicates that a single condylar point cannot describe the movement of the condyle. These differences were emphasised in the condylar paths for the open-close movements and were minimal for the protrusive mandibular movements. A comparison of the pathways from anatomically derived condylar points for the two subjects with their respective arbitrary condylar pathways showed general similarities in form between pathways from the two types of condylar point for open-close, contralateral and protrusive jaw movements. For these
mandibular movements, it appears the movement of an arbitrary condylar square (ACS), derived from the pathways of arbitrary condylar points, may provide a reasonable description of condylar movement. The movement of the anatomical condylar shapes was, however, different to the ACS for an ipsilateral mandibular movement in one of the subjects, and thus a description of condylar movement from the movement of the ACS may be misleading for at least some mandibular movements and further investigations into the validity with which an ACS describes condylar movement are needed.

The sagittal and horizontal plane anatomical figures were derived from CT-scan images of the mandibular condyle, and represent accurate line drawings of the two subjects’ condyles. For simplicity, to form the outline of the condyle, three anatomical points, associated with common condylar landmarks, were selected in the sagittal plane and four in the horizontal plane. Of course as more points are selected, the diagram of the condyle shall more accurately represent that of the subject’s condyle. It appears from the results of this study that, to accurately describe the movements of the condyle, especially those associated with ipsilateral lateral mandibular movement, anatomical condylar points should be selected, and the minimum necessary to describe motion of a body is three points. Any less and one or more of the three rotation components which partly describe motion may be missed and the importance of rotation in describing condylar movement will now be illustrated.

The representation of the condyle as an ACS, anatomical triangle and quadrangle help us to understand the variation in selected condylar point pathways. If the movement of these shapes is pure translation without rotation then the pathways of the vertices would be identical. This however, is not the case in the movements studied, especially the open-close mandibular movement. During an open-close mandibular movement,
although the general form of the selected condylar point (either primary condylar point or radiographically determined anatomical point) was a downward and forward pathway with little lateral deviation, there were clear differences in the degree of downward and forward movement depending on the point selected (see Figure 11 and 12). Differences in the dimensions of the condylar point pathways were noted and support the variability shown in the descriptive analysis of the subjects. The arbitrary condylar squares and the anatomical condylar triangles connecting the selected 'condylar' points move with varying amounts of horizontal and vertical translation, and each side of successive squares or triangles do not stay parallel during the open-close jaw movement which means that the condyle is rotating as well as translating downwards and forwards. Therefore the explanation for the variability between the tracings of different condylar points is the degree of rotation that occurs during mandibular movement. Points that are not on the axis of rotation will move in a different direction to each other and therefore different condylar points, whether they be anatomical or arbitrary, must undergo different trajectories in any jaw, and therefore condylar movement which involves appreciable rotation.

It must be emphasised that in the 2 subjects (Subject 1 and 2) in which the condylar points were radiographically determined, variability between the points' pathways within each subject was also a feature. In these two subjects, it was interesting to compare the anatomical condylar points' pathways with the pathways from the primary (lateral) condylar point (compare Figures 11 A, F and 16). The pathway of the primary condylar point in Subject 1 (Figure 11A) was similar to the pathway of that subject's posterior point pathway (Figure 16B), whereas in Subject 2 (Figure 11F) the primary point's pathway was more similar to that subject's anterior point pathway (Figure 16F). This implies variability in the anatomical location of the primary condylar poles and the inadequacy
of this point in accurately describing condylar movement. This may be due to a number of factors such as the variability in assessing the location of the lateral condylar pole by palpation (see below), and morphological differences between individuals (Oberg et al. 1971).

In Subject 1, the variation in maximum horizontal translations for the anatomical condylar points was greater than the variation in maximum horizontal translations for that subject's arbitrary points; for example, this Subject showed a variation of 6.8 mm between the anatomical pathways in the horizontal direction with only a variation of 5.3 mm between the arbitrary pathways. This was also the case for the maximum vertical translations for this Subject and Subject 2 displayed the same trend. This underscores the difficulties of quantitatively assessing condylar movement from the measurements of a single condylar point.

In a number of subjects, the variation in pathway form could be described as both cross-over differences and direction changes. In these cases, we then categorised the subject into the group that was more applicable. Differences in form were noted in every subject, with only 4 subjects fitting into the similar forms group, and although none of these subjects displayed sagittal pathways of identical form, their pathways showed the least variation. It must be noted that these subjects did not also show the least variation in dimension.

From the diagrams of condylar point movement, and anatomical shapes, the condyle does not necessarily follow the movement path of a single condylar point during an open-close movement, and therefore it is suggested that only reserved judgement of condylar motion anomalies, such as restricted motion or deviation in path form, should be made from a single point's trajectory.
Variation in pathways of different condylar points between subjects

Considerable variation has also been shown in the condylar point traces for open-close and excursive mandibular movements between the subjects studied. These differences existed in both the quantitative and descriptive analyses of the condylar points, and appeared more pronounced in the condylar point pathways for an open-close mandibular movement than for the excursive movements. Condylar point pathways for protrusive mandibular movements showed the least variation.

Most studies have reported variability in terms of displacement, and have not included a detailed descriptive analysis. The subjects in this study displayed sagittal plane pathways that ranged from almost completely inferiorly directed traces (e.g., Figure 10, Subject E) to traces which had a major anterior component (e.g., Figure 9, Subject B). For the majority of cases, open and close traces for a subject did not coincide. For the primary condylar points, the maximum anterior translation varied between 1.8-22.8 mm and maximum inferior translation varied 4.5-12.1 mm between the subjects. Similar dimensions have been reported in other studies (Hickey et al 1963; Smith 1985; Updegrave 1985; Obwegeser et al 1987; Merlini and Palla 1988; Zimmer et al 1991). As differences in translations between arbitrary condylar points within a subject has been found, the differences in displacement between subjects shall, in part, be determined by the condylar point that is selected.

Not only was variability apparent in maximal translation values but also the degree of rotation was variable between subjects. For example, sagittal plane rotation, which is a direct measure of sagittal plane condylar rotation, showed a range of 24.7° for the subject group; the smallest value for maximum opening was 19.3°. The amount of rotation in the sagittal plane was greater in the open-close movement than any of the excursive movements for every subject. This is to be expected as jaw opening
without rotation would produce an opening at the MIPT of approximately
similar dimensions to the condylar point's vertical displacement which
varied between 4.5-12.1 mm in this study. However the MIPT was found
to range 33-62 mm, which is similar to values found in other studies
(Agerberg 1974; Szentpetery 1993). The difference between the two ranges
reflects mandibular and therefore condylar rotation. Because subjects were
instructed to open as widely as possible without discomfort and were
allowed to practice the movement, any differences in the degree of rotation
appear to be a result of individual anatomical variation and not of the subject
opening sub-maximally. The excursive movements showed much less
sagittal plane rotation than seen in open-close movements although there
was still variability between subjects with rotation values ranging between
0.3-3.8° (see below).

The variability in path form between subjects was greater in the
open-close movement than in the contralateral side and protrusive excursive
movements, and this may be a reflection of the greater amount of rotation in
the open-close movement, and the possibility of closer proximity of the
condylar point to the rotational centre (see below).

In keeping with the variability observed between subjects, the rate of
translation to rotation usually varied throughout open-close movements with
37 subjects showing a variable relationship between the rotation and anterior
condylar translation. A linear relationship was apparent in only seven
subjects. This finding of variability in the relation between rotation and
translation is in agreement with the findings of Gallo et al (1993), but
contradicts Merlini and Palla (1988) who showed a linear relationship
between opening angle and anterior translation in the sagittal plane of a
palpated condylar point in all of their ten healthy subjects. Merlini and
Palla's subject group of ten individuals may not have been large enough to
display the variability found in the present study and that of Gallo et al.
In the group of subjects exhibiting a variable relationship between rotation and translation, a linear relationship could not be shown for any of the selected arbitrary condylar points for each of these subjects, and for each subject there was a similar variable relationship of that subject's primary lateral condylar point. This suggests that the common pattern of anterior rotation to translation displayed in a subject's condylar points also occurs for the entire arbitrarily determined mandibular condyle and since similar observations were made for CT-determined points, then also for the actual condyle. For 24 of the subjects, there was predominantly rotation and very little anterior translation at the beginning and end of opening and combined rotation and translation during the middle of the opening movement (S-shaped graph). These patterns of anterior condylar translation to sagittal plane rotation are also evident when the arbitrary condylar square in the sagittal plane is viewed. For example subject F of Figure 17 displays an S-shaped graph of anterior condylar translation to rotation, and the ACS of this subject (Figure 15E) during early opening shows predominantly rotation with minimal anterior translation, during mid-opening there is combined rotation and translation, and at final opening there is predominantly rotation in the sagittal plane. The remaining seven subjects exhibited a linear relationship between the rotation and anterior translation which indicates that rotation occurs with anterior translation. This is borne out in the sagittal views of the ACS in these subjects (e.g., Figure 15H). The graphs of rotation to translation only depict anterior condylar translation, whereas the sagittal plane views of motion of the ACS provide more information by showing anterior and vertical translation as well as sagittal plane rotation. The ACSs therefore show the variability, between subjects, of condylar motion by depicting both rotation and translation in the sagittal plane.

For the open-close mandibular movement, every subject's different arbitrary condylar points displayed variability in both form and dimension.
It has been shown that the pathway form and dimension depends on the arbitrary/anatomical condylar point selected. The qualitative descriptors, namely similar forms, cross-over differences, and direction changes, were used to classify the subjects into groups that indicate the variability in the condylar points' pathways in each subject. Since the trajectories of both arbitrarily and anatomically determined condylar points were not identical then by inference, the movement of any one of these points alone cannot accurately describe condylar movement.

Excursive jaw movements

The condylar point movement for excursive jaw movements showed more consistency between subjects than the open-close jaw movements, but nevertheless variability was still a common theme in both the form and dimension of the arbitrary condylar point pathways.

Working side condylar movement

The working-side condylar point during lateral jaw movements displayed the smallest amount of movement when compared with the other movements of this study. The horizontal displacement mean for the group was 2.0 mm, and the vertical displacement mean was 1.5 mm, and the Bennett movement was calculated to show a mean of 1.4 mm, which agrees with many previous investigations of lateral mandibular movement (e.g., Lundeen and Wirth 1973; Lundeen et al. 1978; Hobo 1986a and b; Curtise 1989; Theusner et al. 1993). The primary (lateral) condylar point moved in a variety of lateral directions which is also in agreement with previous investigators who reported the movement as laterally directed with varying amounts and direction of displacement in the sagittal plane (Frank 1948; Aull 1965; Guichet 1969; Kurth 1942; Lundeen et al 1978; Mongini 1980;
Hobo 1984; Colaizzi et al 1988). It was shown that the ACS moved in a similar direction to the primary condylar point.

During lateral mandibular movement, the working-side ACS was shown to shift laterally in all subjects, and this was clearly seen in the movement of the horizontal ACS. This lateral bodily shift cannot be deduced from the movement of a single arbitrary point, as the lateral displacement of a single condylar point does not indicate lateral displacement of the entire condylar body that it is representing. This is clearly seen in the horizontal ACS where each corner of the square does not move laterally to the same extent as the other corners. Rotation in the horizontal plane shall affect the size of displacement of different points depending on a point's location with respect to the centre of rotation. For the same amount of rotation, a point which is located at the centre of rotation shall show no displacement, and a point which is located distant to this rotational centre shall display displacement that increases as the distance of the point increases from the centre of rotation. This would appear to refute any possibility of a purely rotating working-side condyle during lateral mandibular movement, and thus support the existence of Bennett movement during lateral mandibular movement in every subject. However, as was seen in one of the subjects with radiographically determined condylar points, the movement of the ACS did not match the movement of the anatomical shape. This suggests that the ACS may not provide accurate movement information of the working-side condyle during a lateral mandibular movement. Thus, although the ACS may show a lateral shift, the actual condyle of that subject may not. It is conceivable that the actual working-side condyle of a subject may only rotate in the horizontal plane during a lateral movement. In the present study, the lateral shift of the ACS was as small as 0.5 mm. If the ACS does not accurately represent condylar movement in these subjects, then the actual condyle could translate more, or
less (i.e. no translation), than the ACS, depending on its position with respect to the centre of rotation in the horizontal plane of the mandible (and condyle). If the subject's working side condyle is located at the centre of rotation, then there would be condylar rotation and not translation occurring. For the subjects with minimal lateral shift, the horizontal centre of rotation is close to their ACS, and the situation outlined above of a rotating condyle may occur.

This lateral shift of the ACS did not appear to be related to the subjects' anterior dental relationship, although the three subjects displaying movement greater than 2.5 mm had deep and locked overbites, and consequently steep anterior and canine guidance. This does not seem to be in agreement with the increased Bennett movement found in subjects with severe attrition, and presumably reduced anterior and canine guidance (Lundeen and Gibbs 1982). As the subjects were from an asymptomatic population, and they did not exhibit any signs or symptoms of parafunctional activity including marked attrition, or joint hypo- or hypermobility, it was not possible to relate Bennett movement to variables such as attrition or joint laxity. The poor correlation observed between Bennett movement (and maximum horizontal displacement) and maximum horizontal rotation indicates that subjects do not necessarily compensate a reduced condylar rotation in the horizontal plane with increased lateral shift of the mandibular condyle to attain lateral movement of the mandible.

In this present study, almost three-quarters of the subjects displayed upwards, backwards and lateral movement of the primary (lateral) condylar point. The other movements of the arbitrary condylar point were downwards, forwards and laterally directed, or downwards, backwards and laterally directed. No points displayed only rotatory movement, or medially directed movement, or upwards, forwards and laterally directed movement, which contradicts reports by Aull (1965) and Guichet (1969). Aull (1965)
found subjects' condyles moved laterally and predominantly forward with an upward or downwards component, and Guichet (1969) described the movement as laterally directed along any path within a laterally directed cone-shaped area, which would include subjects with condyles that move upwards and forwards as well as laterally.

The variability these workers and indeed others have observed may in part be due to the location of the selected arbitrary point. In the present study, the point was located 15 mm medial to the skin surface, and in the studies by Aull and Guichet the arbitrary point lay lateral to the skin surface. These latter arbitrary points would presumably be located more distant from the mandibular condyle than in the present study and hence the pathways that such points would trace would be lateral projections of a point within or near the condyle. For movements involving pure translation, this lateral projection would be an accurate representation of the movement of any point medial to it; however when rotation in the horizontal plane occurs, which is the case in lateral mandibular movements, the projected point may exaggerate movement patterns of a point medial to it. For example, if the condyle rotated about its centre in the horizontal plane for a lateral mandibular movement, a point lateral to the condylar centre would not show a horizontal plane pathway of a point rotating on itself with no displacement, but would show a posteriorly and laterally directed pathway. This scenario is a simplified example as the present study shows that lateral mandibular movement is not a simple case of rotation about the working side condyle, but of combined rotation and translation of the mandible.

This neglect in considering the effects of horizontal rotation on laterally positioned arbitrary condylar points appears to have been a major fault by previous investigators who have equated the movement of a laterally positioned pantographic tracing with mandibular condylar movement. In the present study, although the direction in which the
horizontal ACS displaced was similar to that of the primary condylar point, in the majority of subjects different vertices moved in different directions and with different amounts of displacement. Hobo (1984a) also found appreciable variation in the movement patterns of selected points along an arbitrary terminal hinge axis in 50 subjects during lateral border movements. More recently, Lotzmann (1990a,b,c) showed that axiographic tracings of mandibular movements are distorted if the recordings start at an incorrectly located or arbitrary hinge axis when compared to tracings from the true hinge axis point. These data derived from working-side condylar movements support our contention that different points on and in the vicinity of the mandibular condyle describe different movement pathways during mandibular movements.

No relationship between the direction of movement of the MIPT and the ACS on the working side could be found, and subjects who moved their MIPT antero-laterally were found to move their ACS either superiorly, posteriorly and laterally, or inferiorly, anteriorly and laterally or inferiorly, posteriorly and laterally. This variation in ACS movement may be attributable to osseous and soft-tissue constraints of the TMJ and surrounding structures, while the MIPT movement is directed by tooth guidances which are usually in the anterior region. Interestingly, a change in lateral guidance has been demonstrated to be associated with a corresponding change in the direction of movement of an arbitrary condylar point (Coffey et al. 1989).

For lateral mandibular movement, horizontal rotation occurring when the jaw moved to the same side as the target frames of the JAWS3D system ranged between 1.5-8.0° and when the jaw moved to the side opposite to that which the target frames were positioned, the rotation ranged between 1.5-6.0°. It would be expected that this rotation would be similar for both lateral movements, and the mean (±SD) of the horizontal rotation
for the working side (3.4±1.7°) and non-working side (3.5±1.2°) reflected this similarity. It should be noted in relation to this, that working and non-working condylar movements were not recorded from a single lateral mandibular movement as the accuracy studies showed the error approximately doubled when an arbitrary condylar point was chosen on the side opposite to the target frames when compared to an arbitrary point on the same side as the target frames. Thus all condylar point analyses were performed on a point that was on the same side as the target frames. So, for measurement of working and non-working condylar movement, two mandibular movements were performed; in the first instance, the mandible was directed laterally towards the side of the target frames, and in the second instance, the mandible was directed away from the side of the target frames.

**Non-working side condylar movement**

Variation was noted between subjects in the form and dimension of the trajectories of the primary condylar point on the non-working side for a lateral mandibular movement. This arbitrary condylar point's anterior translation was on average 7.2 mm for the subject group, the inferior translation was on average 5.9 mm, and the lateral translation was on average 2.3 mm, which are similar to those reported by other investigators (e.g., Slavicek 1988a). The arbitrary condylar point did not describe as much variation in its path form for the lateral movement as it did for the open-close mandibular movement between subjects. The path for each subject was directed antero-inferiorly in the sagittal plane at varying relationships to the FHP and varying amounts of curvature (e.g., compare Figure 29, Subject C and D).

The path length was found to vary greatly between the subjects, however within a subject, the variation between arbitrary condylar point
pathways was no greater than 1 mm in the horizontal or vertical planes. This included the maximum lateral translation which varied within a subject on average by 0.6 mm. It must be noted however that the average lateral displacement for the subjects was 2.3 mm which was considerably smaller than the average displacement in the anterior or inferior direction, and so the variation between a subject's maximum lateral displacement, between the different arbitrary points, corresponded to almost 25% of the average lateral displacement of the subject group (see below). This, in effect means that, on average, a subject's different arbitrary pathways will vary in maximum lateral displacement about 25% of their average lateral length. The variation in the anterior direction was 0.4 mm, which corresponded to only 5.6% variation of the average anterior displacement, and in the inferior direction, the variation was 5.1% of the average displacement. Thus, in the sagittal plane, the pathways of the arbitrary condylar points within a subject were similar in dimension, and this was also borne out by the anatomically determined condylar point pathways. Thus for a non-working side condyle, a single point, whether arbitrary in the vicinity of the condyle or anatomical, does appear capable of providing a reasonably valid measure of condylar movement in the anterior and inferior direction, but not in the lateral direction.

When viewing the horizontal plane trajectories of a subject's arbitrary condylar points, the relatively more marked lateral variation was not readily apparent as the lateral movement is much smaller than the anterior movement. Therefore the overall anterolateral pathway, which represents relatively more anterior than lateral displacement does not appear to display very much variation. Horizontal plane rotation, averaging 3.5° for the subject group, is greater than the average sagittal plane rotation of 1.2°. This greater rotation in the horizontal plane, combined with a small displacement of the arbitrary point's pathways in the lateral direction as
compared to the anterior or inferior direction is the reason why lateral displacement variation is greater within a subject. Rotation has a more profound effect on a smaller displacement component and thus the amount of rotation does not have the same relative effect on the larger anterior displacement.

*Condylar movement during protrusion*

The pathways of the various arbitrary condylar points within a subject showed marked similarity in dimension and form because the protrusive movement consists predominantly of translation with very little rotation. As the mandible translates forward in protrusion, all points on the mandible move in a reasonably similar manner.

Much like the lateral movement on the non-working side, the protrusive path shows variability between subjects for the primary (lateral) condylar point. Interestingly, the mean anterior translation for the primary condylar point was 7.1 mm, which is very similar to the non-working condylar point displacement of 7.2 mm. Similarly, the average inferior displacement of the arbitrary condylar point for the protrusive movement was 5.1 mm, again similar to the non-working condylar point displacement of 5.9 mm. In the anterior direction, the arbitrary condylar point displacement was greater for the lateral movement than the protrusive movement in 23 subjects, and greater for the protrusive movement in 21 subjects. Inferiorly, 33 subjects displayed more displacement in the lateral mandibular movement when compared to the protrusive mandibular movement. Two subjects showed the same inferior displacement for the two jaw movements and only nine subjects showed greater inferior displacement for the protrusive movement.

If the condyle follows the articular eminence during these mandibular movements, as has been presumed or suggested by workers
(Mongini 1980), then the greater inferior displacement during a lateral movement suggests that the condyle moves along a steeper part of the articular eminence or further down the articular eminence than during a protrusive movement. These values are the maximum displacements, and not the actual path lengths for the various movements. However when the inferior and anterior displacement values are examined together it suggests that in this subject group, the primary condylar point pathway on the non-working side for a lateral mandibular movement would be longer than the corresponding pathway for a protrusive mandibular movement. This suggestion is in agreement with findings by Slavicek (1988a) who shows with axiography, that a point on the terminal hinge axis has a longer pathway for a lateral mandibular movement than the corresponding pathway for a protrusive movement. Slavicek (1988a) explains this phenomenon by stating that the protrusive movement is limited by the inextensibility of the stylomandibular ligament.

Sagittal-plane condylar rotation appears to close the mandible during the protrusive movement in 37 of the 44 subjects. This is in contradiction to Kohno and Nakono (1987), who found very few subjects with a closing rotation during protrusion. Rotation in the sagittal plane would be expected in subjects who show differences between the sagittal plane inclination of their anterior guidance and of their condylar guidance. If the anterior guidance is steeper than the condylar guidance, then as the mandible protrudes the condyle shall have to rotate open if it is to maintain contact with the articular eminence. Conversely, if the condylar guidance is steeper than the anterior guidance, then as the mandible protrudes the condyle shall rotate in a closing direction, otherwise anterior tooth contacts shall be lost during the protrusive movement. If the condylar guidance and anterior guidance inclination were the same then it is suggested that no rotation of the condyle would be seen in the sagittal plane. Although comparisons have
been made between condylar point tracings and radiographic images of the condyle (Mongini 1980), it is suggested that the condylar guidance is not directly related to the anterior wall inclination of the glenoid fossa as measured from the image as there is no assessment of soft tissue within the joint. Amongst other things this soft tissue includes the articular disc interposed between the condyle and fossa, which would presumably regulate the inclination of the condylar path to some extent.

Comparison of condylar point pathways for different jaw movements

A comparison of the sagittal-plane pathways of the five arbitrary condylar points for the protrusive, lateral (contra-lateral) and opening mandibular movements shows that the pathways do not coincide in each subject. When the five lateral, protrusive and opening arbitrary point pathways of a subject were superimposed in the sagittal plane, only five subjects showed pathway coincidence for all of their arbitrary points, and fourteen subjects showed no coincidence in the pathways in any of their arbitrary points for the three mandibular movements. This conflicts with the findings by Van Willigen (1979), Slavicek (1988b), Alswaf and Garlapo (1992) and Theusner et al. (1993) who report coincidence in the initial section of the pathways of a subject. However, their findings were based on the pathway of only one arbitrary condylar point. In the present study all arbitrary points of a subject were assessed for pathway coincidence. When only the lateral and protrusive arbitrary point pathways were compared within a subject, 39 of the 44 subjects showed coincidence for the initial 5 mm of the pathlength for all arbitrary point paths. This suggests that the arbitrary points follow a different path during mandibular opening as compared to the path followed during protrusive or lateral mandibular movements. This may be due to the greater sagittal plane rotation during the opening movement which could cause the arbitrary points' pathways to
diverge away from those pathways of the, essentially transitory, pathways that occur during protrusive and lateral mandibular movements.

**JAWS3D system accuracy**

In the present study, the relative error in measuring the displacement of an ipsilateral condylar point (on the same side as the target frames) was approximately twice that of measuring the displacement of the target frame LED. Similarly, the relative error for the contralateral condylar point was found to be approximately three times that of the LED, and so it was decided to perform all measurements on the same side as the target frames. For a static measurement of the LED of the target frame, the error has been reported as 0.1 mm (Mesquii and Palla 1985, Mesquii et al. 1985). Error of the system during kinematic studies has not been assessed, and when the system is used to record mandibular motion on a human subject, a number of factors which may affect the systems accuracy must be considered. These factors include the non-rigidity of the human mandible and dento-alveolar junction, and movement of target frames from lip impingement and from sudden tooth contact. Attempts were made to minimise these variables, however it is not possible to eliminate them, and thus the overall system’s error must include them. An estimate of the error of the JAWS3D system, in recording mandibular motion may be in the vicinity of 0.3-0.4 mm.

The system provides the co-ordinates of a selected point in integers only, so the precision of the arbitrary point selected can at best be ±0.5 mm. When comparing different condylar points, either arbitrarily or anatomically determined *within* a subject, the error is the same for the pathway of each point. In addition, this error is relatively small when compared to the pathway dimensions, and should not appreciably affect the comparison of different points within a subject. When comparing subjects, the error must be considered for small condylar movements such as working side lateral
movements. It appears that the displacement of a point can be determined to within 0.3-0.4 mm, and hence movements of 0.5 mm, which is the lateral shift of the ACS in some subjects, must be assessed with care.

Rationale for arbitrary condylar square

The ACS with internal diagonals of 10 mm (side length 7.1 mm) was selected for 2 reasons. First, upon repeated palpation of the lateral condylar pole and marking of the overlying skin surface by three clinicians, it was shown the selected co-ordinates for this single point varied considerably but the range of points corresponded to the size of the ACS. We felt our ACS, with its dimensions, would contain the co-ordinates of any primary lateral condylar pole identified by an operator. Second, our ACS dimensions were not dissimilar to the anatomical dimensions of the human condyle in the sagittal plane. Morphologic studies have found the mean anteroposterior dimension of the condyle to be 9.8 mm in autopsy specimens (Oberg et al. 1971), and 7.8 mm (right side) and 8.2 mm (left side) using computed tomography (Raustia 1990). Indeed, a comparison of the ACS dimensions with our anatomically derived figures of two subjects suggests that our ACS in the sagittal plane reasonably approximates the sagittal plane size of the condyle, but in the horizontal plane is smaller than the anatomical dimensions.

Computerised tomography and other radiographic imaging techniques are invasive and so it is suggested that condylar landmark localisation be obtained with magnetic resonance imaging (MRI). MRI is becoming a more feasible option, with its increasing availability, reduction in cost and no known invasivity. MRI, together with a three-dimensional motion recorder should provide accurate data in dynamic studies of the mandibular condyles that should be able to be compared both within and between subjects. We have performed some preliminary investigations with
MRI which have been promising, using a similar localisation technique as in the present study. For MRI, petroleum jelly markers of 1 mm diameter have been imaged successfully.

*Final Comments*

Much has been written on condylar movement utilising the trajectory of a single condylar point (e.g., Gibbs et al. 1971; Lundeen et al. 1973; Alsawaf et al. 1989; Coffey et al. 1989; Harper 1990; Rohrer et al. 1991). From this, purported relationships between condylar movement and masticatory disorders have been formed (Farrar 1978; Siganoudi and Knap 1983; Merlini 1988), however a review of the diagnostic value of condylar point tracings concludes that presently they cannot be considered diagnostically definitive and clinically useful (Mohl et al. 1990). Unfortunately the location of the condylar point selected in most of these various studies with respect to the actual position of the mandibular condyle is unknown, and our present findings indicate that caution must be taken when analysing the movement of any condylar point and then extrapolating the results to assess the kinematics of the mandibular condyle.

It is suggested that because of the appreciable variation in the pathways of arbitrarily located condylar points within a subject, it is necessary to track several accurately and *anatomically determined* condylar landmarks before conclusions about mandibular function and condylar movement may be made.
6. REFERENCES


Balkwill E. The best form and arrangement of artificial teeth for mastication. Trans Odontol Soc 1866;5:133-158.


Bell T. The anatomy and diseases of the teeth. 2nd ed, London S Highly 1833, 49.


Bennett NG. A contribution to the study of the movements of the mandible. J Prosthett Dent 1958; 8: 41-54. (Reprinted from 1908)


Burnett KR, Davis CL, Read J. Dynamic display of the temporomandibular joint meniscus by using fast scan MR imaging. AJR 1987;149:959-962


Campion CG. Some graphic records of movements of the mandible in the living subjects. Dental Cosmos 1905;47:39-42.


Farrar WB. Diagnosis and Treatment of Anterior Dislocation of the Articular Disc. NYJD 1971;41:348-351.

Farrar WB and McCarty WL. Inferior joint space arthography and characteristics of condylar paths in internal derangements of the TMJ. J Prosthet Dent 1979;41:548-554.


Hobo S. Formula for adjusting the horizontal condylar path of the semiadjustable articulator with interocclusal records. Part 1: Correlation between the immediate sideshift, the progressive sideshift and the Bennett angle. J Prostheth Dent 1986a;55:422-426.


Lotzmann U. Der einfluss der registrierplattenstellung auf die achsiographische erfasung der unterkieferbewegungen in der transversalsagittalbene. ZWR 1990b;99:538-543.


Stuart CE. Articulation of Human Teeth. D Items of interest 1940;8-17,106-112.


Walker WE. Prosthetic dentistry; the glenoid fossa; the movements of the mandible; the cusps of the teeth. Dent Cosmos 1896a;38:34-43.


Walker WE. The facial line and angles in prosthetic dentistry. Dent Cosmos 1897;39:789-800.


The Parramatta Hospitals  

Westmead Hospital  
Dental Clinical School

<table>
<thead>
<tr>
<th>Date</th>
<th>T.M. JOINTS</th>
<th>R</th>
<th>L</th>
<th>R</th>
<th>L</th>
<th>R</th>
<th>L</th>
<th>R</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pan — lateral</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pan — posterior</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clicking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crepitation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limited movement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Subluxation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inflammation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Score</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>JAW MUSCLE PALPATION</th>
<th>R</th>
<th>L</th>
<th>R</th>
<th>L</th>
<th>R</th>
<th>L</th>
<th>R</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temporal ant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temporal post</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temporal tendon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Masseter origin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Masseter body</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Masseter insertion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Masseter deep</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pterygoid med.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pterygoid lat.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Digastric ant.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Digastric post</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sternomastoid origin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sternomastoid body</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sternomastoid insertion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trapezius origin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trapezius insertion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tongue</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Submandibular sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Score</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total Score</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### ORO — FACIAL PAIN AND DYSFUNCTION

<table>
<thead>
<tr>
<th>Date</th>
<th>MANDIBULAR MOVEMENTS</th>
<th>mm</th>
<th>Pan</th>
<th>Click</th>
<th>mm</th>
<th>Pan</th>
<th>Click</th>
<th>mm</th>
<th>Pan</th>
<th>Click</th>
<th>mm</th>
<th>Pan</th>
<th>Click</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Opening</td>
<td>Max. incisor</td>
<td>2 1/2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical overbite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal overbite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max. intercuspation R</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max. intercuspation L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max. protrusion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Score pan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### DR-10
4. OCLUSAL ANALYSIS

<table>
<thead>
<tr>
<th>Type of jaw relationship</th>
<th>ant. post.</th>
<th>vertical</th>
<th>transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOP—</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Side**

<table>
<thead>
<tr>
<th>R/W-P distance ant.-post.:</th>
<th>mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>R/W-P distance lateral displacements</td>
<td>mm to R/L</td>
</tr>
</tbody>
</table>

**Laterotrusion**

<table>
<thead>
<tr>
<th>Laterotrusion R—</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>87654321</td>
<td>4</td>
</tr>
<tr>
<td>1 2 3 4 5 6 7 8</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Laterotrusion L—</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>87654321</td>
<td>4</td>
</tr>
<tr>
<td>1 2 3 4 5 6 7 8</td>
<td>2</td>
</tr>
</tbody>
</table>

**Partial denture**

<table>
<thead>
<tr>
<th>Complete denture</th>
<th>Initial lateral guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>satisfactory</td>
<td>Max. tooth</td>
</tr>
<tr>
<td>not satisfactory</td>
<td>mesial</td>
</tr>
<tr>
<td></td>
<td>incline</td>
</tr>
<tr>
<td></td>
<td>distal</td>
</tr>
</tbody>
</table>

**Protrusion**

<table>
<thead>
<tr>
<th>Protrusion—</th>
<th>Bruxism—</th>
</tr>
</thead>
<tbody>
<tr>
<td>87654321</td>
<td>4</td>
</tr>
<tr>
<td>1 2 3 4 5 6 7 8</td>
<td>2</td>
</tr>
</tbody>
</table>

**Soft tissue trauma**

<table>
<thead>
<tr>
<th>Tongue/cheek bite</th>
<th>Muscle ridging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Degree of attrition**

<table>
<thead>
<tr>
<th>Inc</th>
<th>Can</th>
<th>Prem</th>
<th>Molar</th>
<th>Can. Bites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Scoring:** MOP— RP— Lat. R— Lat. L— Pro— Brux— Attrition—

**DATA CODE**

T.M. Joint lateral palpation:
1 - mild discomfort; 2 - moderate discomfort/pain (palatal reflex); 3 - severe pain; 4 - very severe
Muscle palpation:
1 - mild discomfort; 2 - moderate discomfort/pain; 3 - severe pain; 4 - very severe
Muscular movement palpation:
1 - mild discomfort; 2 - moderate discomfort/pain; 3 - severe pain; 4 - very severe

Cure "IP", "RP" etc. Circle tooth with black for contact, red for interference.

**5. RADIOGRAPHIC SURVEY AND SPECIAL TESTS**

(Summary of radiographic analysis and other special tests)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
</table>

**6. ASSESSMENT**

**SUMMARY OF SUBJECTIVE AND OBJECTIVE FINDINGS**

1. Joints
2. Muscles
3. Jaw Movement
4. Occlusal Restorer
5. Parafunction
6. Psychological Profile

**DIAGNOSIS**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
</table>

**TREATMENT PLAN**

|                                |                |