The motion patterns of mandibular points were recorded in vivo in closed, free movements of the mandible parallel to the sagittal-vertical plane. The points ran along loops which were valued by their area and length. All points whose loops included the same area under regarding the sense of circulation formed a straight line. Lines belonging to different areas were parallel. When the absolute areas of the loops were plotted for particular points a hollow depression with two minima resulted. The point that showed the lowest minimum in the depression corresponded to the position of the neuromuscular mandibular axis of rotation. The points running along equal loop lengths formed elliptical lines with a minimum below the condyle. The lines of constant loop area and loop length were overlaid with lateral radiographs, to match the patterns of motion with anatomical structures. The mandibular axis of rotation lay mostly cranial anterior of the condyle whereas the point with the shortest path lay mainly below this axis point, inside the bony structures. The row of teeth in the maxilla was found to be located below the line of minimal loop lengths. The cervical spine was arranged along the depression of the minimal absolute areas.

Key words: human mandible, mandibular movements, neuromuscular system, dimeric link chain, cervical spine
INTRODUCTION

There have been a number of physiological studies in mammals and humans which have investigated how movements of the joints are controlled by muscles and nerves (1–3). We have previously shown that the human mandible is guided in space during plane sagittal movements by the principle of least action (4). Its movement can be described by a dimeric link chain under neuromuscular control (5): a maxillary and a mandibular axis of rotation which does not correspond to the centre of the temporomandibular joint (TMJ). During plane and closed mandibular motion cycles the mandibular axis of rotation which is adjusted under neuromuscular control moved back and forth on a circle-like path. The centre of this circular arc defines the maxillary axis. Simultaneously, each mandible point traversed a closed loop. The included area as well as the length of this loop could be measured (6, 7). The mandibular points whose curves included equal mathematical areas, taking into account the direction of circular movement, lay on straight lines. The absolute areas had a hollow depression with two minima. The relevant points $P_{\text{min}}$ and $P_{\text{sm}}$ lay near the line $s_{\text{l0}}$ whose points traversed curves with mathematical areas equal to zero (Fig. 1). The point $P_{\text{min}}$, which had the deepest depression, lay in the region of the condyle and defined the neuromuscular mandibular axis of rotation. On calculating the path lengths $L$, the points with path lengths of equal size lay on elliptical or even circular curves. The point with the minimal path length $L_{\text{min}}$ was found between the points $P_{\text{min}}$ and $P_{\text{sm}}$ and below the condyle.

Fig. 1. Overlay of contour lines of mathematical areas, absolute areas and path lengths, including the outline of the lower and upper jaw, the orbit and the sella turcica for patient TS. Cross: minimum of the absolute area $P_{\text{min}}$ defining the neuromuscular mandibular hinge axis, second minimum of the absolute area $P_{\text{sm}}$; triangle: minimum of path length $L_{\text{min}}$; square: minimal path length on line of constant mathematical area; dot: infra-orbital point OP, lower incisor edge IP.
We overlaid the motion patterns on lateral radiographs, to correlate movement patterns with the anatomical structures of the maxilla, mandible and cervical spine.

MATERIAL AND METHODS

Movement patterns of 41 juvenile class II patients (28 girls, 13 boys, aged from 9 to 16 years, 11.7y±1.5y) were collected several times during therapy. Altogether, 61 plots of contour lines of mathematical areas, absolute areas and path lengths, including the specific points Pmin, Psm and Lmin, were overlaid with 51 lateral x-ray radiographs of the patients, which were taken contemporary to the corresponding measurements. For the overlay, we took the two measured points, the infra-orbital point and the lower incisor point, into account (Fig. 2).

The Ethics Committee of Gottingen University approved this study and informed consent was obtained from each patient.
RESULTS

For the 41 patients we overlaid 51 lateral radiographs with the evaluated 61 measurements and plotted the three specific points, concerning the area and path length, together with the mean outlines of the posterior part of the mandible and the sella turcica, to provide better orientation (Fig. 3). We found that (a) 80% of the main minima of absolute areas, $P_{\text{min}}$ (dots), lay outside the bony structures of the condyle, mostly cranial anterior to it; (b) 69% of the second minima of absolute areas, $P_{\text{sm}}$ (crosses), lay outside the bony structures of the mandible, posterior to it; and (c) 77% of the minimal path lengths, $L_{\text{min}}$ (triangles), lay inside the bony structures of the mandible, mostly below the point $P_{\text{min}}$.

For the minimal path lengths on lines parallel to the straight line $s_{l0}$, where the mathematical areas were equal to zero (squares in Figs 1 and 2), for 93% of measurements taken, these points lay in the maxilla, in the upper row of the teeth. In addition, we found that, for 77% of the measurements, the straight line $s_{l0}$ lay parallel to the cervical spine and, for 60% of the measurements, $s_{l0}$ cut through the sella turcica, as can be seen for the case illustrated in Figs 1 and 2.

DISCUSSION

The results of the 3D-movement analysis of the mandible revealed the neuromuscular control of identified 2D-movements. By comparing the results of the evaluated areas and path lengths with lateral radiographs, it became clear that
we have to consider not only the mandible, but also the whole skull, together with the cervical spine.

It has often been postulated that there is a “movable hinge axis” which controls the movement of the human mandible and which might be located at the centre of the TMJ. But, we were able to show that persons with sound TMJs adjusted and used a mandibularly fixed hinge axis with a surprisingly high degree of precision (5). The distribution of the positions of point $P_{min}$ (Fig. 3) clearly shows that adjustment of the mandibularly fixed hinge axis is an individual process. There are some points around the area of the condyle, but most of the points are found anteriocranial the bony condyle in the region of the maxilla covering an area of about 3 cm$^2$.

In almost all evaluations of the area distribution, we found the second minimum $P_{sm}$. Up until now the physiological significance of this point and the double-minimum distribution of the area has remained unclear.

The third specific point, $L_{min}$, belongs to the shortest path length. During mouth opening, $L_{min}$ moved only around an area of about 1 mm$^2$, while the other parts of its movement had a similar length comparable to other mandibular points. Its position, mostly within the bony structures, may represent a kind of balance point of the rigid body “mandible”.

The line with the minimal path lengths on the straight lines with constant areas (squares in Figs 1 and 2) lay above the row of teeth in the upper jaw and had the same alignment as the teeth. This row of teeth is located on a line of the maximal possible increase in path lengths. This means that each tooth having a more anterior position increases with the maximal potential of area and path length compared to the preceding one having a more distal position (8, 9).

The orientation of the straight line $s_{10}$ parallel to the cervical spine was a truly remarkable finding. Since the patients sat upright while measurements were made, as well as while lateral radiographs were taken, these lines could be the balance lines for optimal mandibular movement, underlying the principle of least action.

Mandible movement is determined by the individual neuromuscular system, since the two hinge axes are adjusted by the neuromuscular system having no strong relationship to the bony structures of the TMJ. Therefore, the patterns of the movement of the mandibular points are also adjusted by the neuromuscular system.

Combining images of anatomical structures with the data for movement allows us to propose that mandible, maxilla and cervical spine can be regarded as a functional unit.

**Acknowledgements**: This work was supported by a grant from the Deutsche Forschungsgemeinschaft (SCHW 427/2-1, 2-2, and KU 535/6-3, respectively) and has been permitted by the ethics commission (8/10/02).

**Conflicts of interest statement**: None declared.
REFERENCES


Received: July 24, 2008
Accepted: September 15, 2008

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