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A METHOD FOR RECORDING AND ANALYZING
LABIAL AND GNATHIC MOTION IN
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A METHOD FOR RECORDING AND ANALYZING
LABIAL AND GNATHIC MOTION IN THREE DIMENSIONS

By

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ABSTRACT

A METHOD FOR RECORDING AND ANALYZING
LABIAL AND GNATHIC MOTION IN THREE DIMENSIONS

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The objective of this investigation was to use stereo photogrammetric techniques to record the motion of the lips and jaw. For this purpose, targets were affixed to the subject's face and the subject was filmed during movement. Three-dimensional coordinates of each target were determined throughout the motion and were used to analyze the soft tissue motion of the lips and the rigid body motion of the jaw.

Twenty-nine parameters characterizing the shape of the lips were examined. It was hoped that a single subset of the parameters could be chosen to completely characterize and study the mouth during speech. No such subset was found, rather the subset chosen depends upon the application.

Joint translation and rotation were also examined. It is not known whether soft tissue motion significantly corrupted these results. Further research and refinement of the system is necessary in order to be certain.

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I. INTRODUCTION

The objective of the following work was to use high speed stereo cinematography to record and analyze the motion of the lips and jaw during speech and function. Passive rather than active targets were used in order to provide a non-invasive data collection system. This non-invasive technique for recording the motion yielded three-dimensional position data of the targets. Much of the knowledge of the motion of the lips and jaw had previously been gained through two-dimensional analysis. Thus, this technique for capturing the motion yielded a more complete spatial description and added to current understanding of the kinematics of the lips and jaw.

The information provided as a result of this research could prove to be valuable to investigators in such fields as dentistry, orthodontics, oral surgery, speech pathology, otorhinolaryngology, physical therapy, and neurology, as well as biomechanics. Specifically, this quantitative description of the motion of the lips and jaw may aid in the study of temporomandibular joint dysfunction, occlusal dysfunction, speech motor planning, the dynamics of speech, and in prosthodontic reconstruction, to name a few applications.

II. SURVEY OF LITERATURE

Quantitatively examining the movement of the mandible and related structures of the mouth has been a concern of researchers in the fields of speech and dentistry since the 1800's. One of the earliest attempts to capture motion of the jaw during function was by C.E. Luce in 1889 (53). In order to record the motion of the mandible in the sagittal plane, he placed bright beads opposite the condyle, angle, and symphysis and anchored them to the lower incisor teeth. He then took a profile photograph, exposing the photographic plate during the motion of the jaw - thus obtaining a record of the motion of each bead (see Figure 1). He also obtained recordings of movement in the frontal plane in an analogous manner.

Similar techniques were commonly used by other researchers into the 1960's (8,25,51,54). The devices used for tracing the motion varied, but the idea was essentially the same. For example, Bennet used small lights placed next to the condyle and the lower lip (8). The lights were mounted on wires which were extended through the lips and banded to the teeth. He then darkened the room and placed a biconvex lens between the subject and the wall to obtain a projection on the wall that could be traced. Posselt discussed the use of pins anchored by orthodontic splints to the maxilla and mandible (51). The maxillary pin extended out of the mouth and was connected to a brass frame that held the tracing table -- a glass slide. The mandibular pin extended out of the mouth and traced the motion of the mandible on the slide (see Figure 2).

FIGURE 1. An Opening Movement Redrawn After Luce.

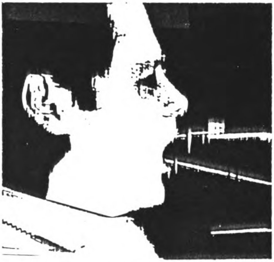


FIGURE 2. Graphical Tracing Device.

Radiography became a popular technique around the 1930's and many improvements and variations have been developed over the years. The earlier x-ray methods were static (47). An x-ray was taken with the jaw in one position. The jaw was moved and either another x-ray was taken or a double exposure was made. Lead pellets and/or anatomical landmarks were used to track the motion.

Later, dynamic radiographic techniques were developed (2,3,6,9,15,30,41,47,49). Direct techniques were initially used, i.e. the x-ray images were photographed directly from a fluorescent screen. These techniques were very limited due to the high levels of radiation necessary for even one complete movement to be captured at intervals as low as 16 frames per second. This concern for radiation exposure gave rise to indirect approaches. These methods used lower levels of radiation than the direct techniques. Electronic means were then used to intensify the low-level x-ray images before photographing them. The hazard of radiation was greatly reduced and sampling rates on the order of 64 frames per second were possible.

The most recently developed radiographic technique was the x-ray microbeam method of the 1970's and 1980's (2,3,30). With this system, the x-ray beam used was so small that the typical x-ray exposure to a subject during 15 minutes of actual x-ray time was less than one third that of a single dental x-ray. With this system, the data was automatically digitized and sampling rates on the order of 200 images per second were possible. All of these radiographic techniques are used to some extent today. It is important to note that they all record a planar projection of three-dimensional movement.

In the 1960's, application of various electronic transducer systems to the study of lip and jaw movement began. Strain gage transducers and linear variable displacement transducers were first used to determine one-dimensional components of movement - typically, to measure the vertical separation of the lips and/or jaw during speech (5,13,26,27,48). Later, the strain gages were used in pairs and oriented such that two-dimensional recordings of the motion of various points could be obtained (1,38). (See Figure 3.) Many other types of transducer systems were also developed to register two-dimensional movement, e.g. electromagnetic techniques (38), and synchro-transmitters (16).

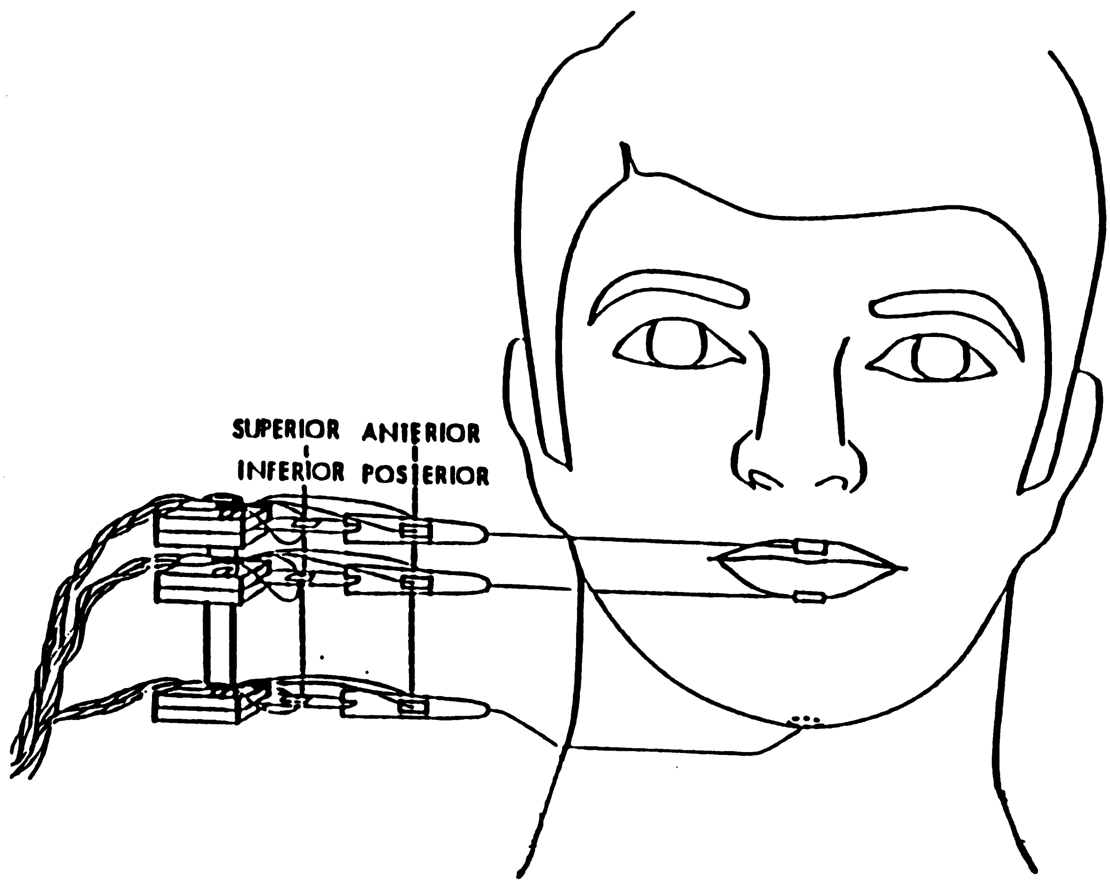


FIGURE 3. A Two-Dimensional Transducer System.

Transducer systems capable of detecting three-dimensional movement emerged in the late 1960's and early 1970's. The mandibular kinesiograph was one such system (17,18,40,46). It required a bar magnet to be attached to the point of interest, e.g. the lower incisor teeth. Three magnetometers were oriented on a framework attached to the subject's head. The magnetometers were able to monitor the position of the bar magnet in three dimensions (see Figures 4a and 4b). There was also a photoelectric mandibulograph which operated on the same basic principle. The three-dimensional description of the motion of a point was obtained in an analogous manner; however, a small light and photocells were used rather than a magnet and magnetometers (21).

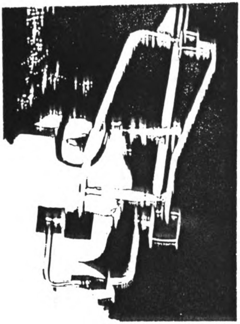


FIGURE 4a. Framework Supporting Magnetometers. (Attached to Spectacles.)

FIGURE 4b. Bar Magnet Attached to Lower Incisor Teeth.

A transducer system capable of measuring three-dimensional movement of the entire mandible with respect to the maxilla was developed at Case Western Reserve University (19,20,45). (See Figure 5.) This instrument was coupled with the Case Gnathic Replicator which duplicated the jaw motions using casts of the subject's teeth properly mounted in the replicator. The mandibulograph was a similar device designed by Araiche, et al. (25).

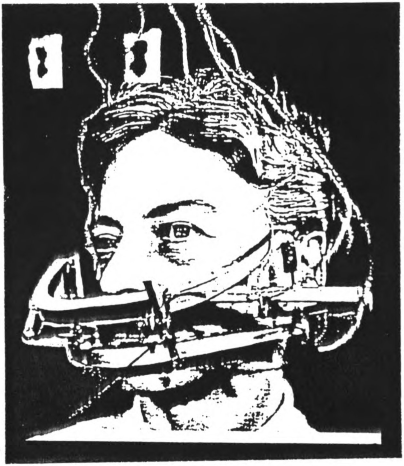


FIGURE 5. A Transducer System Capable of Measuring the Motion of the Mandible in Three Dimensions.

Photographic means have also been used to enable researchers to understand the motion of the lips and jaw. These also began with one and two-dimensional methods, some being variations of still photography (12,53), others being cine photographic techniques (4,14), and still others being video methods (60).

Three-dimensional cine photographic analysis of motion has recently become routine for applications such as gait and sports, however, remains rare for studying the motion of the lips and jaw. This is probably due to the necessarily small size of targets to be tracked, the relatively large amount of soft tissue motion of the face, and the fact that the use of these methods is still relatively new. One researcher avoided the problem of soft tissue motion by drilling metal pins into the subject's jaw, and tracking the motion of these pins (33). However, this has not become routine practice.

Another researcher used miniature Leds (dia = 1mm) as well as cameras to track motion in three dimensions (35). The LEDs emit infrared light which is able to penetrate soft tissue. In this pilot study, the researcher tracked the motion of one point on the mandible and one reference point on the forehead. It is conceivable that modification of this study to include more LEDs may be possible. Thus, the three-dimensional description of the motion of the entire mandible would be possible without soft tissue interference.

There are advantages and disadvantages to all of the methods presented. An obvious drawback to many of the methods is that one or two-dimensional recordings of three dimensional movements are being obtained. With other methods, three-dimensional recordings are obtained but only of a particular point. With the transducer methods, a three-dimensional description of motion of the mandible is possible but it involves anchoring devices on the teeth and then passing part of the device through the lips, which in turn may affect the motion of the lips. In addition, many methods require that apparatus be mounted to the head which may affect the muscles controlling the movement. The photographic techniques do not interfere with the motions to be captured but they have the problem of targets anchored to soft tissue rather than rigid bodies.

In light of all of the advantages and disadvantages, the possibility simultaneously studying the motion of the lips and jaw using three-dimensional cine photographic analysis will be explored. This approach lends itself well to many settings, does not require any recording instrumentation to be mounted on the head, and carries no risk of radiation; however, the precision lost due to soft tissue when examining jaw motion will have to be considered.

III. EXPERIMENTAL METHODS

A. The Subject

The subject participating in this study was a 22 year old female. She had no previous injury to the face, jaw or neck and no history of pathological temporomandibular joint symptoms. She had the full complement of teeth, except for extracted third molars. She had no history of neurological, muscular, hearing or speech problems.

B. The Targets

Targets were made out of small styrofoam half-spheres, three to four millimeters in diameter, and weighing an average of 0.025 grams each. The curved surfaces were covered with 3M Scotchlite Brand High Gain 7610 Sheeting -- a retroreflective tape. The flat surfaces were then affixed to circles of vinyl material of the same diameter. The vinyl enabled similar circles of double-sided non-allergenic tape to be pressed into place to secure the targets to the skin, and to be easily removed for reuse of targets at a later date (see Figure 6).

Under ambient lighting conditions, the retroreflective tape is neutral gray in color, however, it "illuminates" in the presence of an incident light ray as can be provided by a flood light. The intensity of this reflected light is very sensitive to observation angle -- i.e., the angle between the incident light ray, the tape, and the eye or camera lens. For maximum intensity, the observation angle must be as small as possible. The ideal situation of a zero degree observation angle yields retroreflected light 1600 times brighter than a perfectly diffusing white surface. An observation angle of one degree reduces the intensity by a factor of sixteen. Thus, the smaller the observation angle, the better the visibility and ease of location of the targets once they are filmed (42).

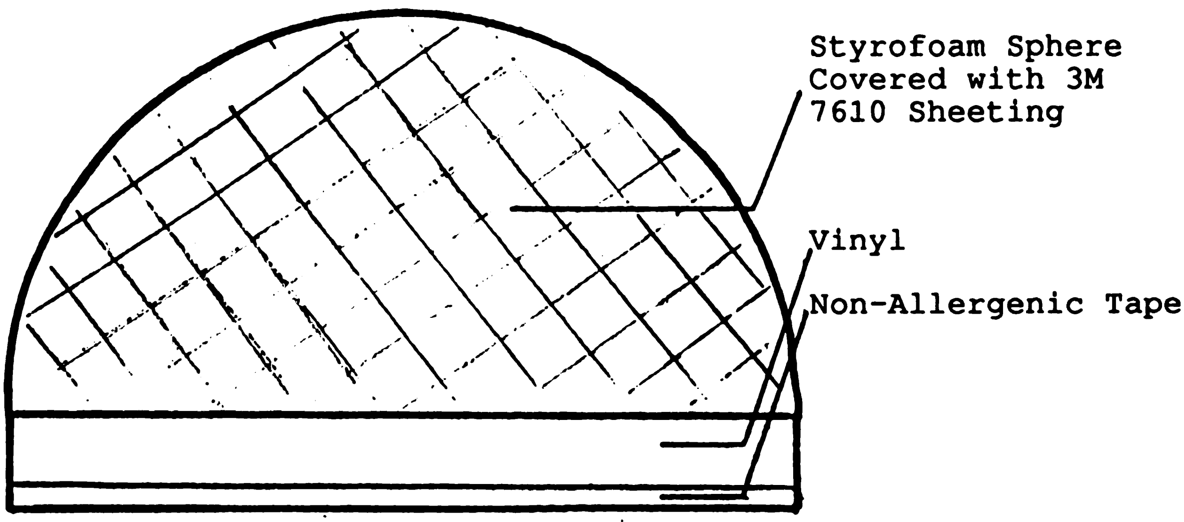


FIGURE 6. A Target.

C. Experimental Protocol

Filming of the motion of the lips and jaw during function was carried out at the Michigan State University Center for the Study of Human Performance. The activity was set up in accordance with the cine-photogrammetric techniques of Walton (7), Soutas-Little (55), and Beavis

(59). Two LOCAM motor driven 16 mm cine-cameras were used. The cameras were placed approximately four feet high, oriented with an included angle of approximately 45 degrees, and a distance of approximately 12 feet from where the subject was seated. Such a positioning of the cameras was relatively arbitrary, however, care was taken so that all targets would be within the field of view of both cameras while trying to achieve the maximum included angle between the cameras and the subject.

Prior to any filming, the subject was targeted with the retroreflective markers. Three targets were affixed to the subject's forehead to later be used as reference points for the head. Four targets were affixed to the subject's mandible so that three of the four points could be chosen later as reference for the jaw. Eight targets were placed along the lip line and at the base of the nose to later "map" the motion of the lips (see Figure 7).

The filming sequence began by placing a calibration structure in the field of view where the subject would be filmed (7). The calibration structure was then filmed in order to calibrate the object space. Such a calibration technique provides the necessary transformation coefficients for a direct linear transformation, enabling the three-dimensional position of the subject targets to be determined throughout the subsequent motion (7,59).

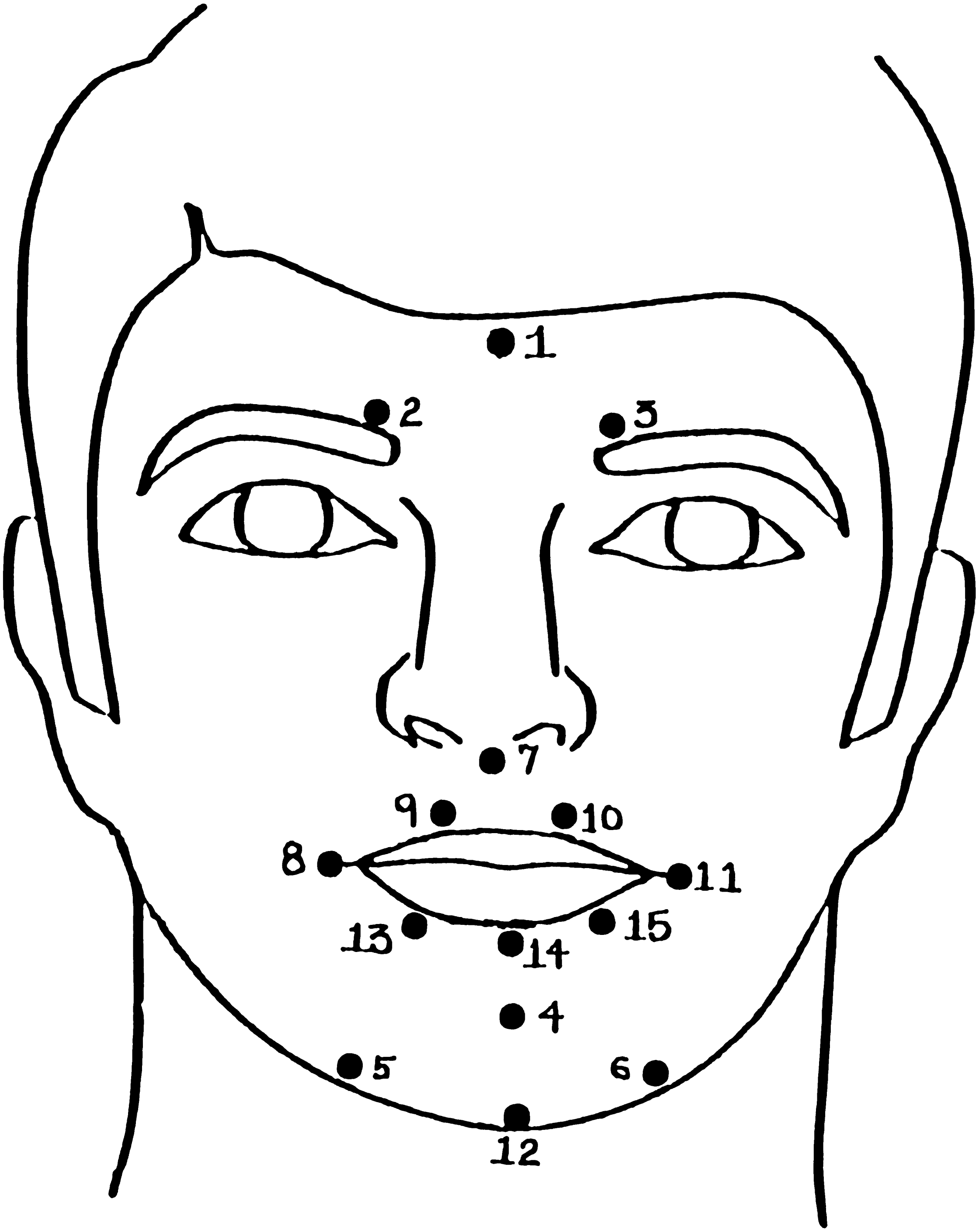


FIGURE 7. The Targeting Configuration.

The calibration structure was removed and small floodlights were mounted on the cameras as close to the lenses as possible (approximately two inches) to provide a small observation angle for the retroreflective targets. The subject was then seated with her head positioned within the previously calibrated space. The subject was instructed to maintain good posture during the following filming sequence and this was facilitated by a physical therapist observing the subject throughout the test. The subject was instructed to perform the following motions: open the mouth as far as possible and then return to a comfortable position, extend the mandible forward and then retract back to the original position, extend the jaw to the right and back, then to the left and back. She was then cued to enunciate the following words and phrases: "apple, banana, pear, tomato, star, forever, read my lips, no more taxes, o.k., and biomechanics".

The sequence of motions and words was repeated under various film speeds and ambient lighting conditions. Film speeds of 75, 100, and 64 frames per second were used coupled with differing amounts of background lighting provided by overhead spotlights. Such a variety of situations was necessary to insure proper conditions for the retroreflective tape. After processing the film and reviewing it, the film speed of 75 frames per second together with ceiling lights located behind the subject were chosen for analysis because they yielded the most intense and well-defined targets. This attention to target visibility and definition is beneficial for the digitizing process. It is assumed that the better the quality of the imaged targets, the less the occurrence of human error in digitizing.

Every other frame of the film from each view of the selected sequence of motions and words was digitized using an ALTEK rear projection digitizer. The calibration structure was digitized first, followed by several frames of the subject in a neutral position, followed by the subject's sequence of jaw motions and speech patterns. For each motion or speech pattern, five frames prior to the event and five frames after the event were digitized due to the fact that during data filtering and differentiation, these frames will be lost.

The timing device available in the Department of Biomechanics at Michigan State University consists of a large set of timing lights to be filmed in the view of the motion to be recorded. Due to the close focus necessary in this study, these particular timing lights could not be seen and therefore were not used. Because a timing device was not used, special care had to be taken during digitizing. The onset of each motion or word had to be visually located for both camera views and each event later synched in time using the film speed. This produces data that is synched in time artificially rather than in strict actual time. As long as there is no discrepancy between the two camera views in what is determined to be the first frame of a particular motion or word, the error in using the film speed to calculate time is minimal (43).

The digitizing process along with associated software produces two-dimensional positions of each target for each frame that was digitized. Three-dimensional target coordinates are produced via a direct linear transformation developed by Walton (59). His computer programs time-match the two-dimensional coordinates of each target and perform the necessary direct linear transformation using coefficients determined from calibration. The result is three-dimensional position data referenced in calibration space for each target throughout each event. These data are in discrete form and each instance that the target positions are calculated is termed an "observation" (see Table 1).

TABLE 1. Three-Dimensional Target Coordinates. (Sample Data.)

```
SKILL 1:
FOR WHICH THERE IS(ARE)  1 TRIAL(S).
TRIAL  1:
INITIAL TIME   =      0.020000 SECS.
TIME INCREMENT =    26599*10-6 SECS.
CUTOFF FREQ'S:
OBSERVATION     1 FOR WHICH T =  0.020000
                      IS AT X =     19.4195 Y =      7.3935 Z =     13.4220
                      IS AT X =     17.6692 Y =      7.1768 Z =     11.9500
                      IS AT X =     21.2586 Y =      7.3608 Z =     11.8207
                      IS AT X =     20.1614 Y =      6.0567 Z =      0.6601
                      IS AT X =     17.5255 Y =      7.2024 Z =     -1.2439
                      IS AT X =     21.9119 Y =      7.0033 Z =     -1.1921
                      IS AT X =     20.0105 Y =      5.7610 Z =      4.7743
                      IS AT X =     17.3098 Y =      7.0427 Z =      2.3640
                      IS AT X =     19.4663 Y =      5.4984 Z =      3.6091
                      IS AT X =     20.6588 Y =      5.5643 Z =      3.6239
                      IS AT X =     22.5138 Y =      7.3896 Z =      2.3192
                      IS AT X =     19.8569 Y =      6.2144 Z =     -1.6726
                      IS AT X =     18.7334 Y =      5.7314 Z =      1.6457
                      IS AT X =     20.1330 Y =      5.6864 Z =      1.5221
                      IS AT X =     21.5638 Y =      6.2566 Z =      1.6126
OBSERVATION     2 FOR WHICH T =  0.046600
                      IS AT X =     19.6029 Y =      7.4226 Z =     13.5799
                      IS AT X =     17.9142 Y =      7.2405 Z =     12.1441
                      IS AT X =     21.5073 Y =      7.5529 Z =     11.9957
                      IS AT X =     20.3671 Y =      6.1630 Z =      0.8534
                      IS AT X =     17.7296 Y =      7.2703 Z =     -1.1025
                      IS AT X =     22.0797 Y =      7.0529 Z =     -0.9940
                      IS AT X =     20.1796 Y =      5.7938 Z =      4.9444
                      IS AT X =     17.4594 Y =      7.0614 Z =      2.5071
                      IS AT X =     19.7113 Y =      5.5244 Z =      3.8423
                      IS AT X =     20.7592 Y =      5.7942 Z =      3.8746
                      IS AT X =     22.6614 Y =      7.3564 Z =      2.5029
                      IS AT X =     19.9365 Y =      6.2209 Z =     -1.5250
                      IS AT X =     18.8974 Y =      5.7248 Z =      1.7705
                      IS AT X =     20.3014 Y =      5.5346 Z =      1.6575
                      IS AT X =     21.6621 Y =      6.1580 Z =      1.7952
OBSERVATION     3 FOR WHICH T =  0.073200
                      IS AT X =     19.5948 Y =      7.4971 Z =     13.6208
                      IS AT X =     17.9095 Y =      7.4455 Z =     12.1282
                      IS AT X =     21.4878 Y =      7.6606 Z =     12.0219
                      IS AT X =     20.3241 Y =      6.3239 Z =      0.8092
                      IS AT X =     17.7097 Y =      7.4326 Z =     -1.0143
                      IS AT X =     22.0604 Y =      7.1863 Z =     -1.0240
                      IS AT X =     20.1798 Y =      5.8287 Z =      4.9840
                      IS AT X =     17.5200 Y =      7.1205 Z =      2.5094
                      IS AT X =     19.6681 Y =      5.7842 Z =      3.8610
                      IS AT X =     20.7460 Y =      5.7493 Z =      3.8831
                      IS AT X =     22.7424 Y =      7.3805 Z =      2.4579
                      IS AT X =     19.9740 Y =      6.2585 Z =     -1.5492
                      IS AT X =     18.8633 Y =      5.9450 Z =      1.7556
                      IS AT X =     20.3649 Y =      5.6494 Z =      1.7087
                      IS AT X =     21.6882 Y =      6.1746 Z =      1.7974
OBSERVATION     4 FOR WHICH T =  0.099800
                      IS AT X =     19.6201 Y =      7.7110 Z =     13.6161
                      IS AT X =     17.9388 Y =      7.6146 Z =     12.1398
                      IS AT X =     21.4855 Y =      7.9353 Z =     12.0262
                      IS AT X =     20.3495 Y =      6.4625 Z =      0.7980
                      IS AT X =     17.7233 Y =      7.5639 Z =     -1.0616
                      IS AT X =     22.0932 Y =      7.3451 Z =     -1.0247
                      IS AT X =     20.1980 Y =      5.9539 Z =      4.9789
                      IS AT X =     17.5471 Y =      7.3936 Z =      2.4763
                      IS AT X =     19.7413 Y =      5.8509 Z =      3.8179
                      IS AT X =     20.7317 Y =      5.9901 Z =      3.8280
                      IS AT X =     22.7241 Y =      7.6020 Z =      2.4968
                      IS AT X =     20.0191 Y =      6.4983 Z =     -1.5446
                      IS AT X =     18.8856 Y =      5.9960 Z =      1.7788
                      IS AT X =     20.3166 Y =      5.9016 Z =      1.6440
                      IS AT X =     21.7381 Y =      6.4124 Z =      1.8303
```

IV. ANALYTICAL METHODS

The three-dimensional position data resulting from digitizing and related post-processing were analyzed with two separate goals in mind. The first was to gain insight into the motion of the lips during function, i.e. soft tissue motion. The second was to gain insight into the motion of the mandible relative to the head, i.e. rigid body motion. These two problems were treated separately, so will be discussed separately.

A. Soft Tissue Motion

The targets located along the lip line, as well as the target at the base of the nose and the target in the center of the chin (i.e. along the symphysis menti) were used to track the motion of the lips. (These are targets 4, 7, 8-11, and 13-15 of Figure 7.) The position of each target was plotted in the xz plane for one observation of the neutral position and then lines were drawn joining the points (see Figure 8). This same schematic was drawn for every observation of one of the words to determine whether it was a suitable tool for gaining knowledge of the motion of the lips.

The schematic proved to be a useful visual aid for the examination of lip motion. However, it utilized only two coordinates of each target. Therefore, the idea was extended in order to make use of the three-dimensional information now available.

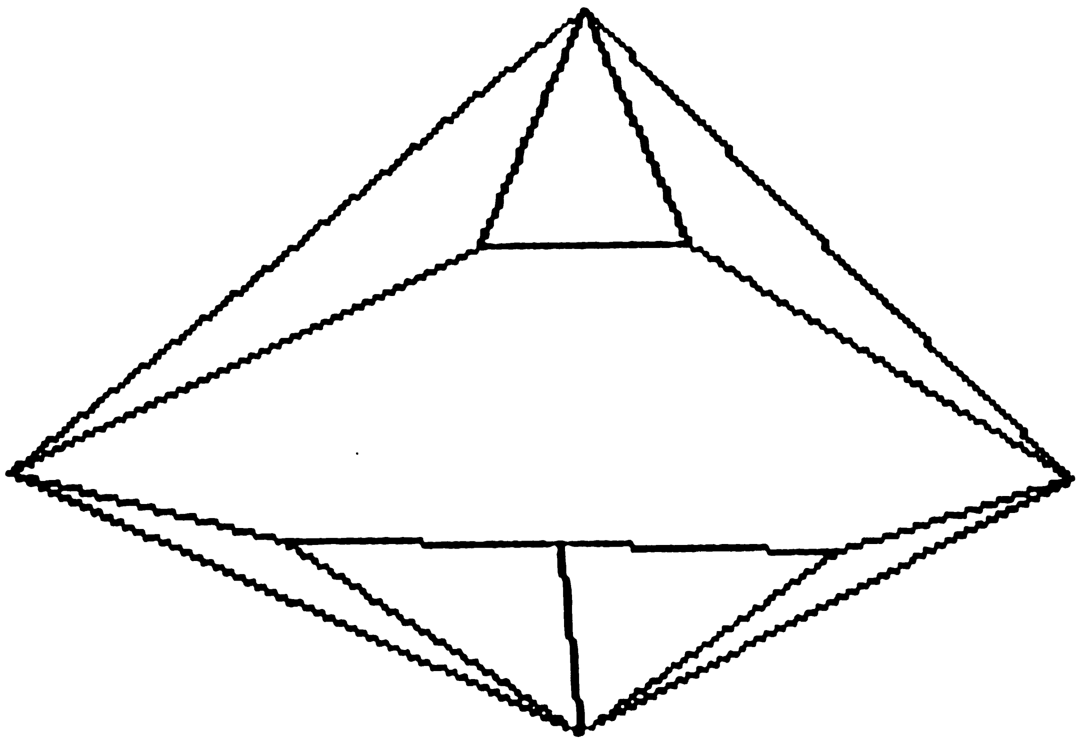


FIGURE 8. The Schematic of the Mouth.

Two computer programs were written and used in conjunction with an existing graphics program written by Southward, a Ph.D. candidate in Mechanical Engineering at Michigan State University. These programs allowed the same schematic to be drawn on the computer screen, using all three coordinates of each target rather than only the x and z coordinates. Interactive programming enables the user to display a particular motion or speech pattern from any viewpoint. Only one planar view is visible at a time but any view is possible. The image may be viewed in "animated" form, or with each observation superimposed over the previous observation to show a complete record of the motion. For obtaining clarity in printouts of the graphics, it is possible to display every fifth observation rather than every observation, if desired. It is also possible to magnify the image (see Figures 9 and 10).

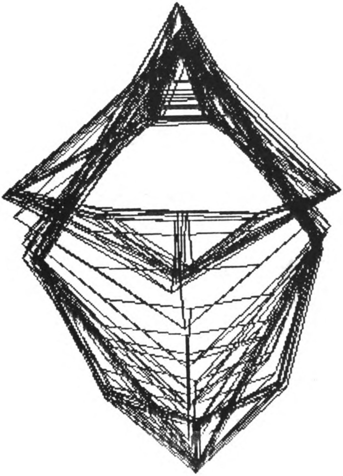


FIGURE 9. The Superimposed Form of the Image of the Mouth Opening--Every Observation (Front View)

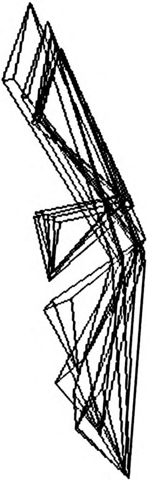


FIGURE 10. The Superimposed Form of the Image of the Mouth Opening--Every Fifth Observation (Side View)

Because the three-dimensional coordinates of each target are known throughout any particular event, many parameters may be measured. For example, the distance between any two targets or the included angle between any three targets can be calculated at each observation as a measure of how the shape of the lips changes throughout the event. Software was written to calculate 29 such measurements (see Figures 11 and 12).

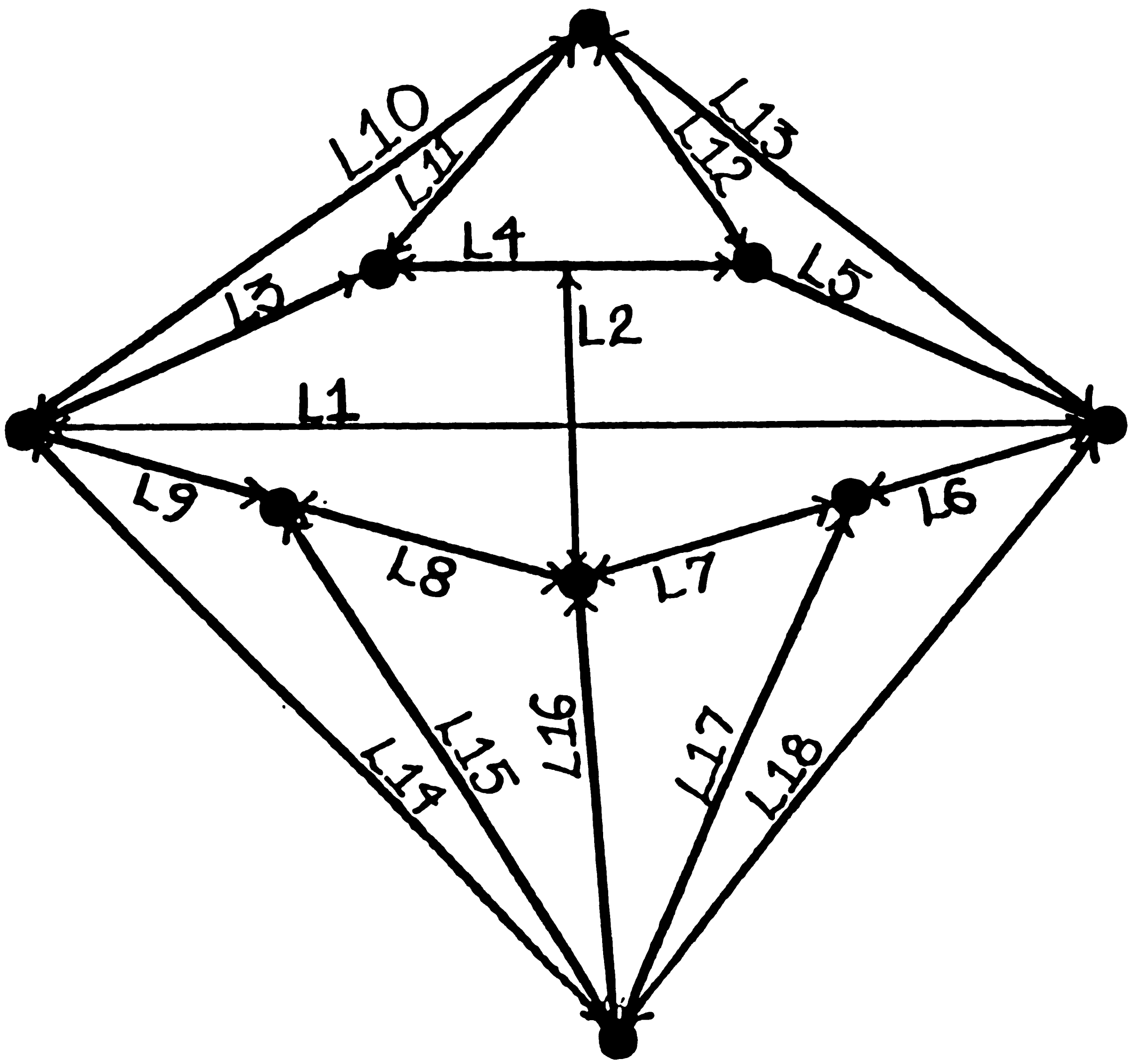


FIGURE 11. Length Parameters.

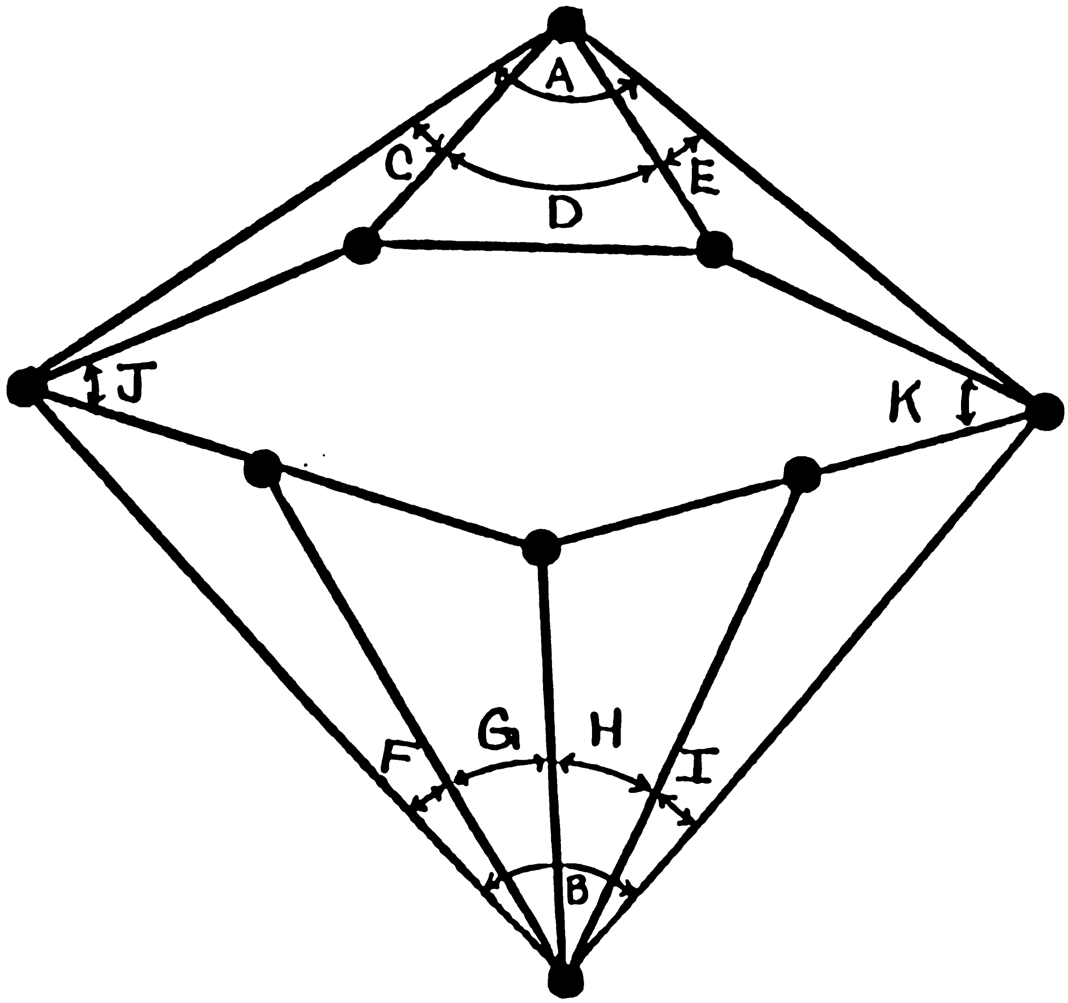


FIGURE 12. Angle Parameters

The following simple formulas of vector mathematics were used in the calculations:

(1) $|\vec{AB}| = \sqrt{(BX - AX)^2 + (BY - AY)^2 + (BZ - AZ)^2}$

Where $|\vec{AB}|$ is the magnitude of the vector between Targets A and B.

AX is the X coordinate of Target A.

AY is the Y coordinate of Target A.

AZ is the Z coordinate of Target A.

BX is the X coordinate of Target B.

BY is the Y coordinate of Target B.

BZ is the Z coordinate of Target B.

(2) $Q = \cos^{-1} (\vec{V1} \cdot \vec{V2} / (|\vec{V1}| |\vec{V2}|))$

Where Q is the angle between vectors $\vec{V1}$ and $\vec{V2}$.

The lengths and angles may then be plotted for examination. Trajectories of individual targets and individual distances traveled may also be sorted out of the position data and plotted for analysis. The subset of the possible parameters chosen depends upon the goal of a particular study (see Section V for details).

Thusfar, all calculations (i.e. lengths, angles, schematics, etc.) have been carried out in the calibration reference system. Calibration space is adequate when considering measurements such as the length between two points or the included angle between three points which are measures of distortion or change in size and shape. However, when considering the actual motion of the lips, this approach may yield appreciable error. Any rigid body motion of the head will be included in the calculated motion of the lips.

For the subject in this particular study, head motion was negligible. So, although it was not utilized in this investigation of soft tissue motion, a computer program was written to convert all position data in calibration space to position data referenced in a coordinate system fixed to the forehead. To establish the "head coordinate system," Targets 1, 2, and 3 of Figure 7 were assumed to form a rigid triad and were used in the following manner:

For each observation, a right-handed coordinate system was established with origin at Target 3, x in the direction from Target 3 to Target 2, y perpendicular to the plane formed by Targets 1, 2, and 3, and z perpendicular to the xy plane. For ease of vector description, Target 1 will now be referred to as Target A; Target 2 as Target B and Target 3 as Target C. The head coordinate system axes will be x, y, and z; and the calibration coordinate axes will be X, Y, and Z (see Figure 13).

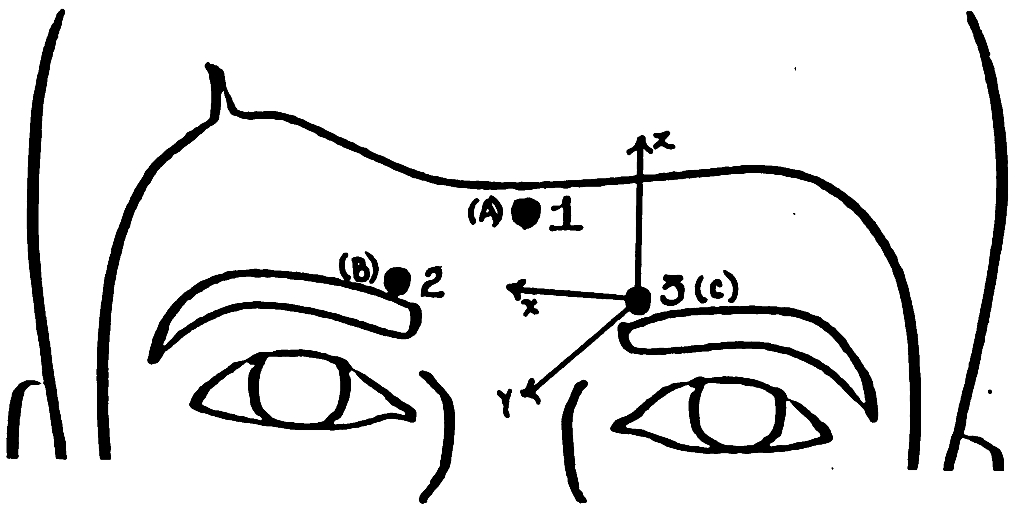


FIGURE 13. The Head Coordinate Axes.

The details are as follows:

(3) $\hat{i} = \vec{CB}/|\vec{CB}|$

(4) $\hat{j} = (\vec{CA} \times \vec{CB})/|\vec{CA} \times \vec{CB}|$

(5) $\hat{k} = \hat{i} \times \hat{j}$

(6) $$[A] = \begin{bmatrix} \cos(\hat{i},\hat{I}) & \cos(\hat{i},\hat{J}) & \cos(\hat{i},\hat{K}) \\ \cos(\hat{j},\hat{I}) & \cos(\hat{j},\hat{J}) & \cos(\hat{j},\hat{K}) \\ \cos(\hat{k},\hat{I}) & \cos(\hat{k},\hat{J}) & \cos(\hat{k},\hat{K}) \end{bmatrix}$$

$$= \begin{bmatrix} iX & iY & iZ \\ jX & jY & jZ \\ kX & kY & kZ \end{bmatrix}$$

Where: $\hat{i}$ is a unit vector in the x direction.
$\hat{j}$ is a unit vector in the y direction.
$\hat{k}$ is a unit vector in the z direction.
$\hat{I}$ is a unit vector in the X direction.
$\hat{J}$ is a unit vector in the Y direction.
$\hat{K}$ is a unit vector in the Z direction.

cos(U,V) is the cosine of the angle between any vectors U and V.

iX is the component of i in the X direction.
iY is the component of i in the Y direction.
iZ is the component of i in the Z direction.
(Similar for jX, jY, jZ, kX, kY, kZ.)

[A] is the transformation matrix from the calibration coordinate system to the head coordinate system.

The transformation is as follows: For any target, P, the vector $\vec{p}(X,Y,Z)$ is a vector expressed in the calibration system from the origin of the head coordinate system to that target, P. The vector $\vec{p}$ is then transformed into the head reference system giving the coordinates of P in "head space," P(x,y,z). Thus:

(7) $\vec{p}(X,Y,Z) = P(X,Y,Z) - C(X,Y,Z)$

(8) $\vec{p}'(x,y,z) = [A]\ [\vec{p}(X,Y,Z)] = P(x,y,z)$

Every target, P, is now expressed in the head coordinate system. When this is done for every observation, the head system becomes a coordinate system that travels with the head as it moves. Therefore, head motion is effectively "subtracted out," thus mathematically avoiding the necessity of many researchers in the past to fix the head when studying the motion of the lips.

Although for this study there was no need to convert the coordinates from calibration space to head space in order to examine the soft tissue motion of the mouth, in future studies this may not be the case. Many people with nervous disorders as well as many "average" people without any pathology whatsoever exhibit movement of the head when speaking.

B. Rigid Body Motion

The mandible will be treated as a rigid body moving relative to the head. In order to completely describe this motion, it was necessary to know the location of three non-colinear points on the head and three non-colinear points on the mandible. The positions of the 15 targets were known and therefore were candidates for this purpose. However, because both the head and the mandible are considered as rigid bodies, it is of great concern that targets are chosen that do not track soft tissue motion.

The placement of Targets 1-6 and 12 had been chosen prior to filming with attention given to place them at locations of minimal soft tissue motion (see Figure 7). Based only on gross observation of the subject, soft tissue motion did not appear to be a problem with Targets 1, 2, and 3 located on the forehead. The locations of Targets 4, 5, 6, and 12 exhibited the least amount of visible soft tissue motion for the mandible, although a certain amount was unavoidable.

As an aid in determining which three out of the four targets of the mandible should be used to represent a rigid triad, a program which calculates the distances and angles between three points of interest as well as how these quantities change throughout a particular motion or speech pattern was written. These calculations served as a measure of distortion of the triangle which, for this application, was a measure of soft tissue motion. This program was also used to verify the assumption that Targets 1, 2, and 3 were appropriately located. Based on the output from this program, Targets 4, 5, and 6 were chosen to represent the triad rigidly attached to the mandible.

Once the targets were selected that would be included in the rigid body motion analysis, a non-orthogonal joint coordinate system was constructed. Such a system has been used by Grood and Suntay to give a clinical description of the translation and rotation which occurs at the human knee joint (31). This system has also been used by Soutas-Little et al. to describe rotation at the ankle joint during gait (56); and is routinely used in gait analysis at Michigan State University in the Department of Biomechanics.

The joint coordinate system was constructed as follows: A local coordinate system was set up for the head and for the mandible in a manner similar to that previously described by equations (3), (4), and (5) of Section A. X, Y, Z denoted the calibration system, x, y, z denoted the head coordinate system and x′, y′, z′ denoted the mandible coordinate system (see Figures 14a and 14b). The unit base vectors for the non-orthogonal joint coordinate system are

are denoted $\hat{e}_1$, $\hat{e}_2$, and $\hat{e}_3$. The $\hat{e}_3$ axis was chosen from the head coordinate axes and is in the direction of z. The $\hat{e}_2$ axis was chosen from the mandible coordinate axes and was in the direction of y′. $\hat{e}_1$ is the "floating" axis perpendicular to both $\hat{e}_2$ and $\hat{e}_3$ (see Figure 14c). That is:

(9) $\hat{e}_3 = \hat{k}$

(10) $\hat{e}_2 = \hat{j}'$

(11) $\hat{e}_1 = \hat{e}_2 \times \hat{e}_3 / |\hat{e}_2 \times \hat{e}_3|$

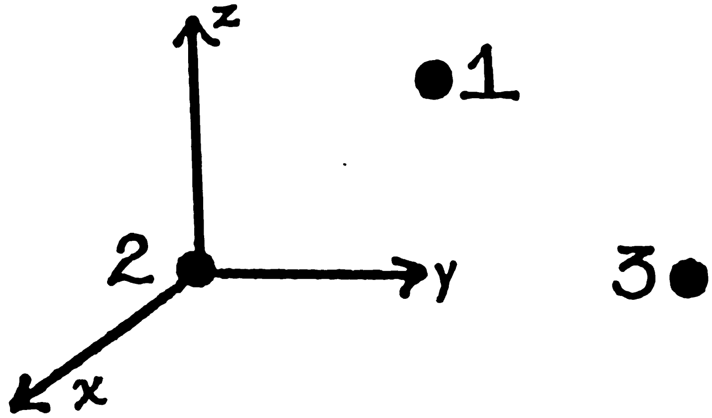


FIGURE 14a. The Head Coordinate System.

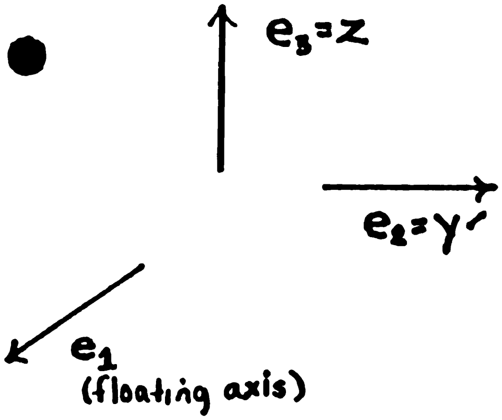


FIGURE 14c. The Joint Coordinate System.

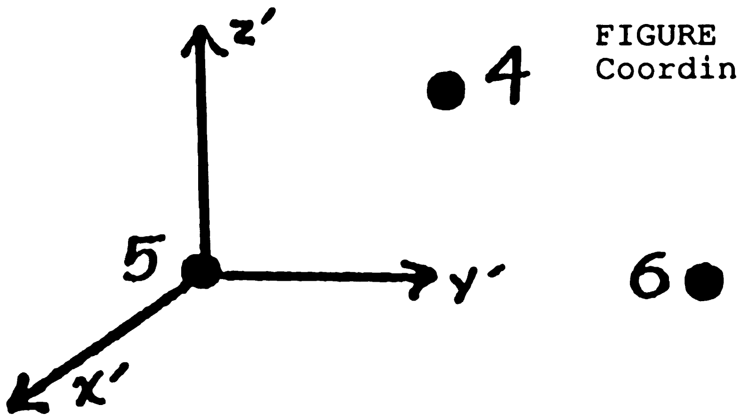


FIGURE 14b. The Mandible Coordinate System.

Constructing such a coordinate system allowed three independent angles (Euler Angles) to be calculated (24). Therefore, the joint motion calculated using this system was not dependent on the order in which the component translations and rotations occurred.

The Euler angles were calculated and physical descriptors were associated with each. A rotation about the $\hat{e}_2$ axis was the primary rotation exhibited when a person yawns and was termed the "pitch" angle. A rotation about the $\hat{e}_1$ axis was the primary rotation exhibited when the right or left side of the jaw "elevates" relative to the opposite side. ("Elevates" is in quotes because this is only a strict vertical elevation when the mandible is in a horizontal position.) Regardless of mandible orientation, rotation about the $\hat{e}_1$ axis was termed the "roll" angle. A rotation about the $\hat{e}_3$ axis may be visualized as the rotation produced if one styloid process was to move in an anterior or posterior direction relative to the other. This type of rotation was termed the "yaw" angle (see Figure 15.)

The following equations were used to calculate these angles:

(12) $\text{Pitch} = \sin^{-1} (\hat{e}_1 \cdot \hat{k}')$

(13) $\text{Roll} = \sin^{-1} (\hat{e}_2 \cdot \hat{e}_3)$

(14) $\text{Yaw} = \sin^{-1} (\hat{e1} \cdot \hat{j})$

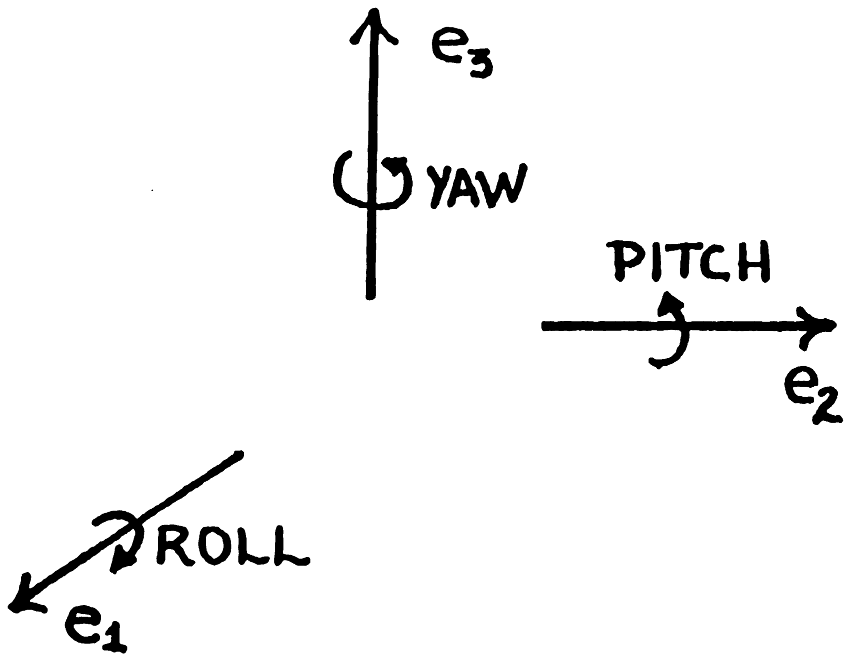


FIGURE 15. The Joint Angles.

A measure of the translation that occurred at the temporomandibular joint was also calculated. The method used was that of Grood and Suntay (31). A vector was constructed between a point on the head and a point on the mandible in order to simulate the temporomandibular joint. This vector was called $\vec{H}$. $\vec{H}$ was expressed in the joint coordinate system, such that:

(15) $\vec{H} = S_1\hat{e}_1 + S_2\hat{e}_2 + S_3\hat{e}_3$

The clinical descriptors associated with the three components of the joint translation were: q_1 = protrusion-retraction along the $\hat{e}_1$ axis; q_2 = horizontal glide along the $\hat{e}_2$ axis; and q_3 = joint distraction-compression along the $\hat{e}_3$ axis. These were the projections of $\vec{H}$ along each of the joint axes:

(16) $q_1 = \vec{H}\cdot\hat{e}_1$

(17) $q_2 = \vec{H} \cdot \hat{e}_2$

(18) $q_3 = \vec{H} \cdot \hat{e}_3$

(Note that q_1, q_2 and q_3 are not necessarily equal to S_1, S_2 and S_3 because the joint coordinate system is non-orthogonal.)

Because there were no targets placed in the joint area and no radiographs taken, the location of the two points used to construct the vector $\vec{H}$ had to be arbitrarily chosen. Because the amount of translation for any one individual depends in part on the location of these two points; the absolute magnitude of translation was not considered. The goal was only to get a general understanding of the translation. Clinicians have stated that the motion in the sagittal plane when opening the mouth consists of pure rotation followed by translation followed by more rotation (29,32,36). It was hoped that examination of the vector $\vec{H}$ would reveal such a movement order.

The joint coordinate system for each observation was established via software. The three joint angles and three joint translations were then calculated for each observation. The angles obtained when the jaw was in a neutral position were subtracted from the values obtained for each observation so that a measure of deviation from neutral was calculated. This subtraction was not done for translations because the actual magnitudes were not of interest.

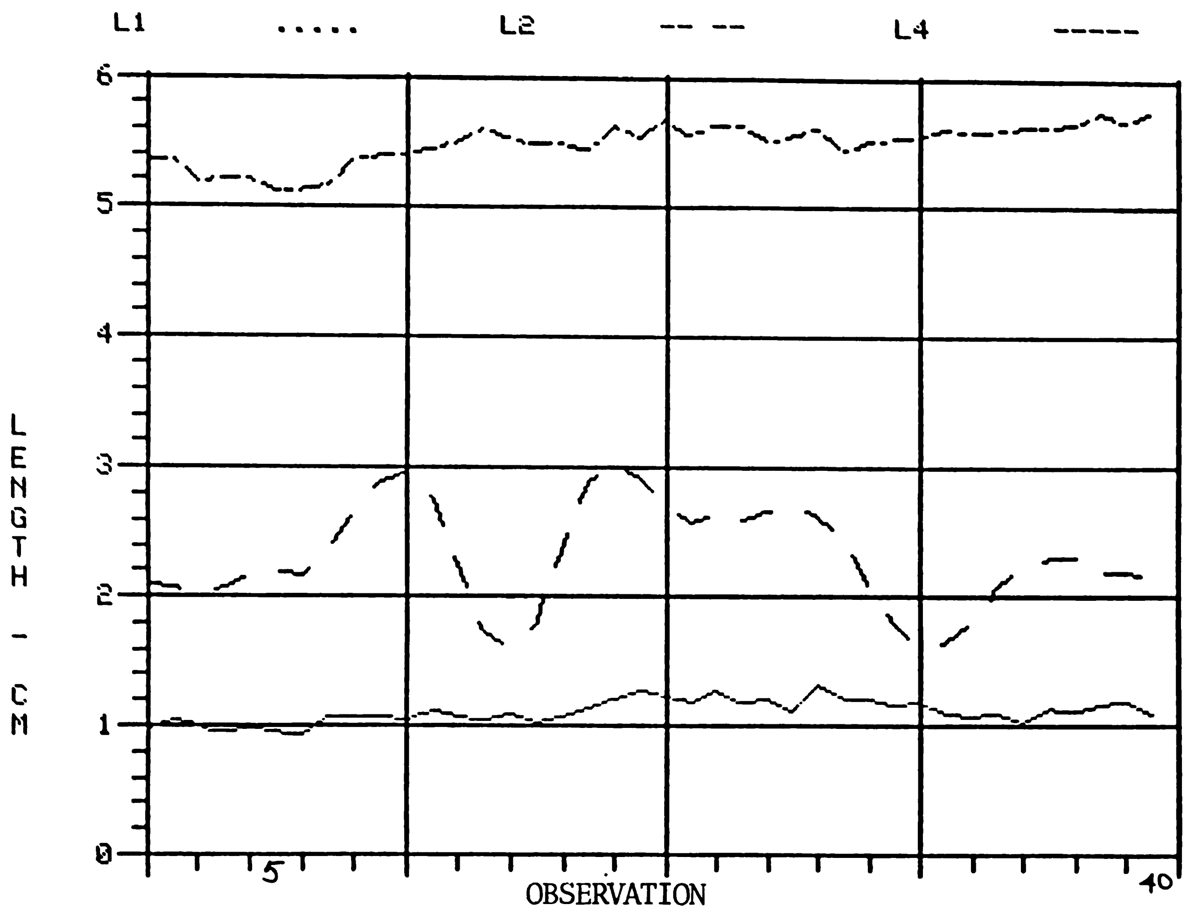
Once the angular displacements were obtained, it was possible to proceed with the analysis using the software routinely employed for gait analysis in the Department of Biomechanics at Michigan State University: The angular data may be filtered using the existing two-pass Butterworth filtering routine. Once filtered, it may then be numerically differentiated, via the use of another existing program, to yield angular velocity and angular acceleration information, if desired. This researcher was concerned only with angular displacement information, therefore, the analysis of this data stopped after filtering the angular position data using a cut-off frequency of 3 Hz. Velocity and acceleration information was not investigated.

V. RESULTS AND DISCUSSION

A. Soft Tissue Motion

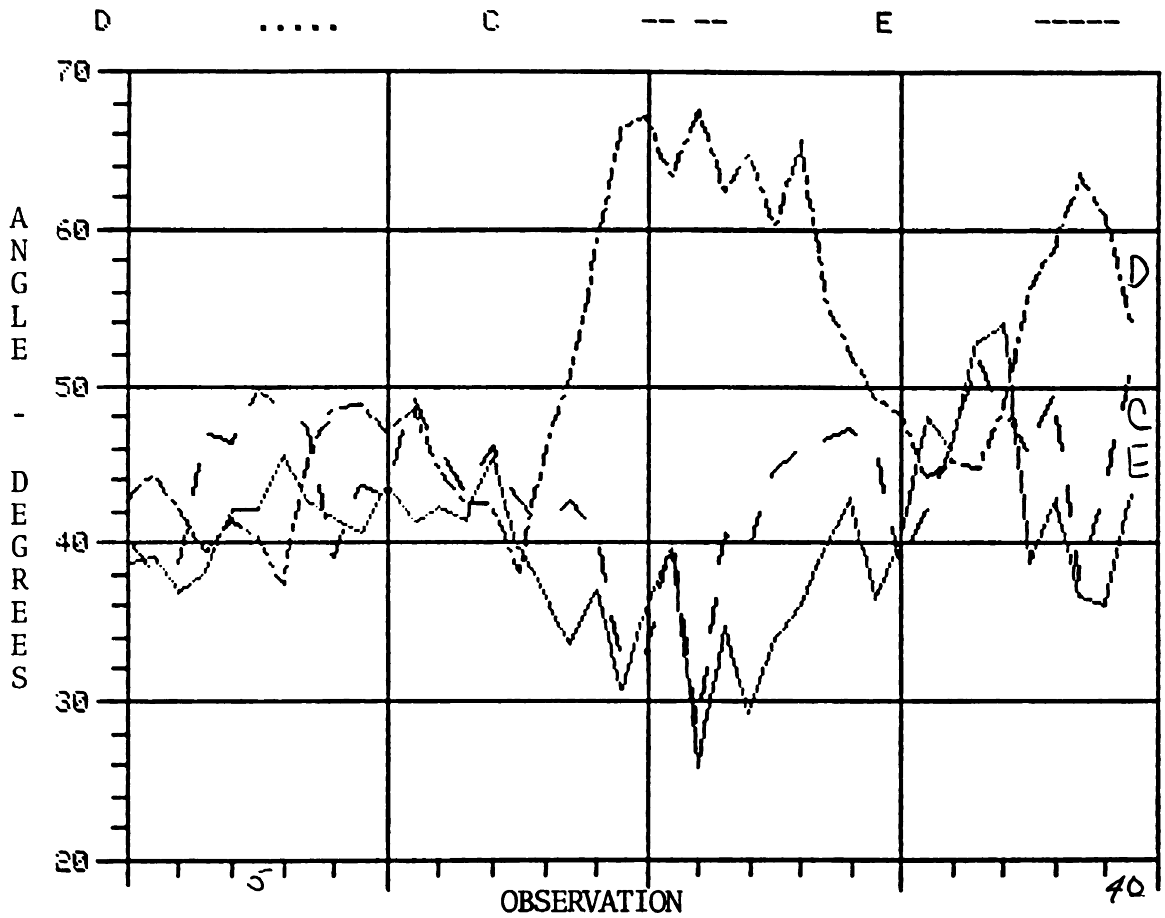
The computer graphics of the schematic of the mouth was used as a tool to aid in understanding and visualizing the movement. Although this tool was used in a qualitative manner to aid in visualizing a particular movement, it may also prove useful in comparative studies. It may be beneficial to record the final superimposed tracings of a particular movement so that the final shape may be compared in a fashion analogous to the many different parameters traced and compared by other researchers (17,20,34,39,46). For example, a tracing such as that of Figure 9 could be made of several subjects to study the opening movement of the mouth. Because scaling and correction for head motion are possible, a uniform comparison may be made and magnitudes could be considered separately.

The 29 parameters that were measured at each observation for each event were shown on Pages 21 and 22. These lengths and angles were plotted versus observation and several parameters are shown in Figures 16 and 17. It was hoped that the 29 parameters could be reduced to a few parameters that would completely characterize the movements of speech. The 29 parameters were compared with this goal in mind. For example, the plot of Angle A was compared to



"READ MY LIPS" L1, L2, L4
L1 = Length Between the Corners of the Mouth (see Page 21)
L2 = Vertical Separation of the Lips (see Page 21)
L4 = A Segment Along the Upper Lip (see Page 21)

FIGURE 16. Three Lengths are Plotted for a Particular Speech Pattern



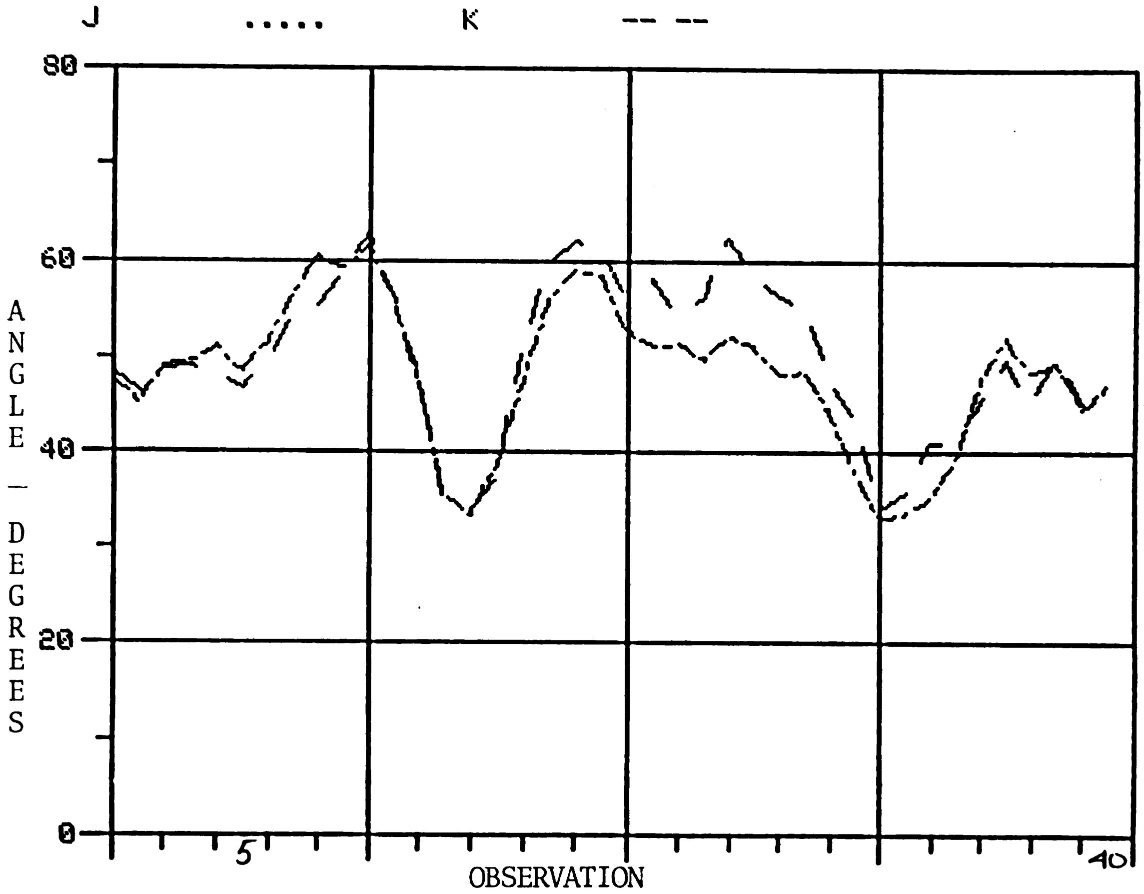
"READ MY LIPS" C, D, E
(See Page 22 for an Illustration of the Angle Parameters)

FIGURE 17. Three Angles are Plotted for a Particular Speech Pattern

the plot of Length 1 to see if a similar pattern was exhibited. This would indicate that the parameters were related and so only one of the two need be considered in the future as an independent parameter.

Very few parameters were found to be redundant. Those that were found to be related, (e.g. Angles J and K, and Angles C and E), were usually related by symmetry (see Figure 18). Thus, for some applications, no information would be lost by considering either the parameter on the left side of the mouth or the parameter on the right side of the mouth. However, for other studies this may not be appropriate. For example, studies specifically concerned with oral asymmetries, or studies concerned with the function of the mouth of a subject who has lost control of one side of the mouth, would have to consider the parameters on both sides.

Although no one subset of parameters emerged as the obvious choice to fully characterize and study the motion of the mouth, a certain subset may be chosen based upon the goals of a particular study. For example, in order to repeat many previous studies using this cine-photogrammetric technique, only the vertical separation of the lips need be considered. That is, as defined in this study, only Length 2 must be considered. In order to study asymmetries of the mouth during speech, a larger subset of parameters consisting of lengths and/or angles on one side of the mouth and their counterparts on the other side would be of interest. In order to quantify the functional labial



"READ MY LIPS" J and K
J = The Angle at the Right Corner of the Mouth (see Page 22)
K = The Angle at the Left Corner of the Mouth (see Page 22)

FIGURE 18. The Relationship Between Angles J and K

evaluation given to TMJ patients at hospitals, yet another subset should be selected (32).

B. Rigid Body Motion

The joint angle calculations appeared to be reasonable, although further refinements of the system are necessary in order to be certain of reliable measures. For example, the maximum pitch angle calculated for the open-close movement was 29 degrees when using Targets 4, 5, and 6 as references for the mandible. For this particular motion, Targets 5, 6, and 12 were also used in order to compare results. When these targets were used, this angle was found to be 37 degrees (see Figures 19 and 20). After examination of the film and the output of the program that tested for soft tissue motion, this researcher determined that for this particular movement Targets 5, 6, and 12 were the better choice. That is, film showed less soft tissue motion at Targets 5, 6 and 12 than at Targets 4, 5 and 6 for this movement and the output from the program showed less distortion of the triangle described on Page 27. Therefore, Points 5, 6 and 12 were chosen to define the rigid body because they minimized these two measures of soft tissue motion. So the maximum angle is probably closer to 37 degrees than to 29 degrees.

The discrepancy illustrated above is due in part to inherent error of the system and in part to soft tissue motion and experimental protocol. For all motions, with the exception of the open-close movement, Targets 4, 5 and 6

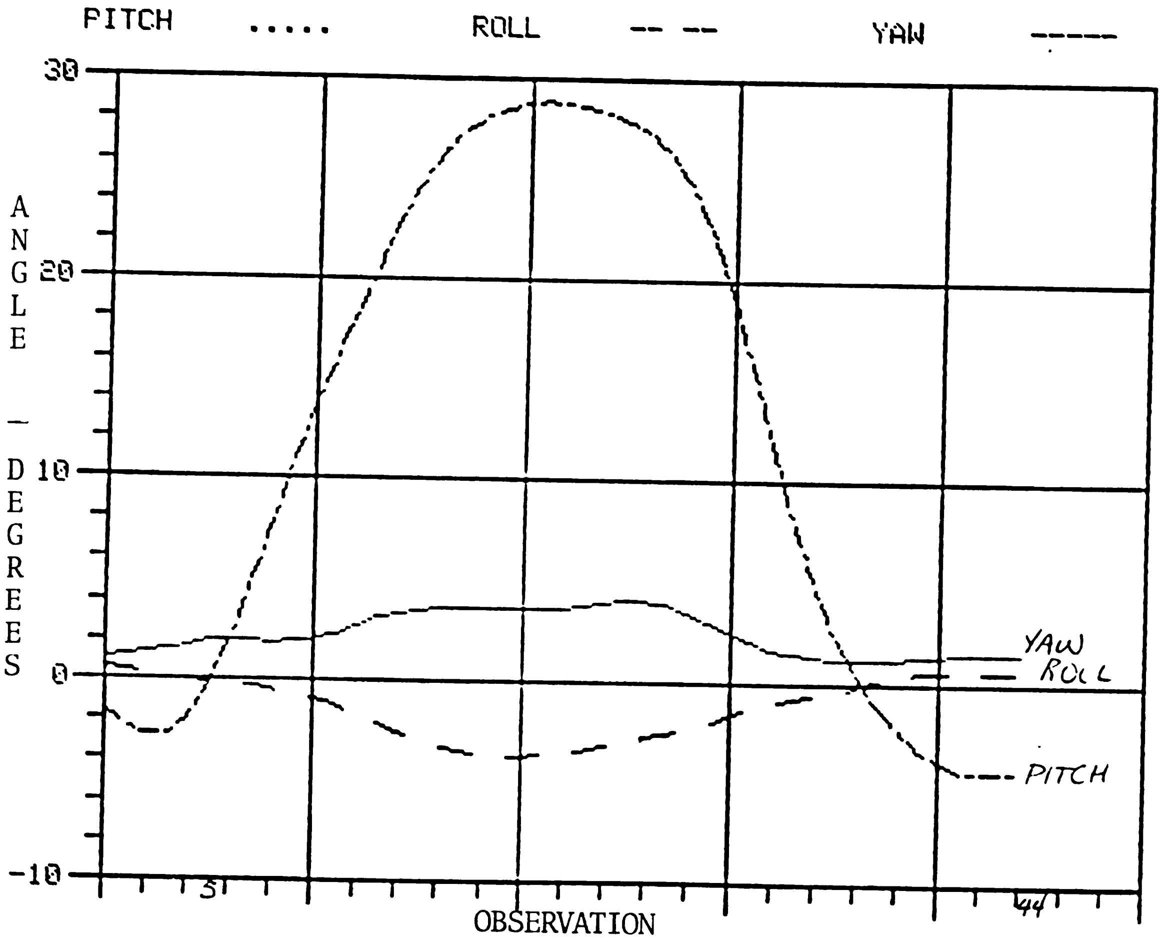


FIGURE 19. Joint Angles of Open/Close Movement
Using Targets 4, 5, 6

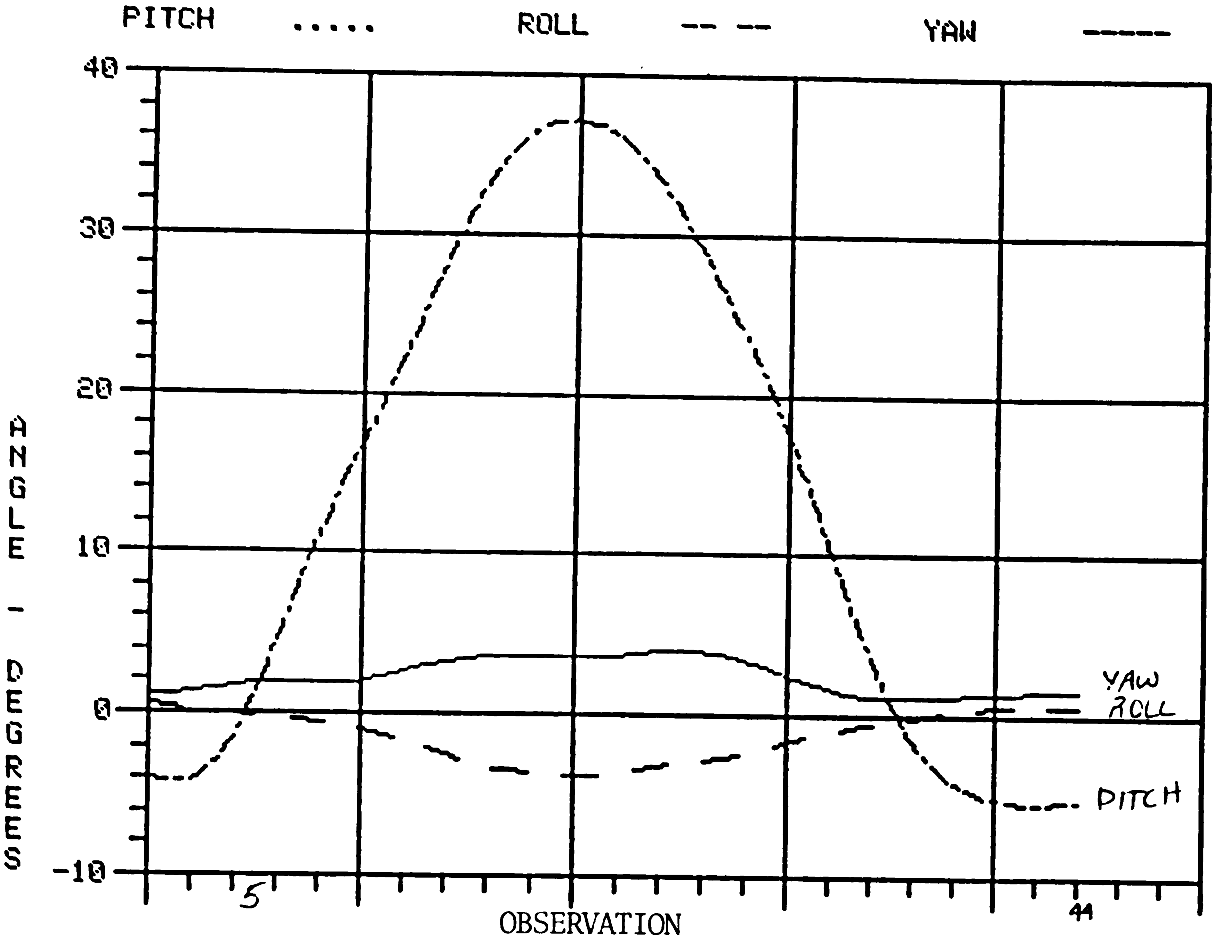
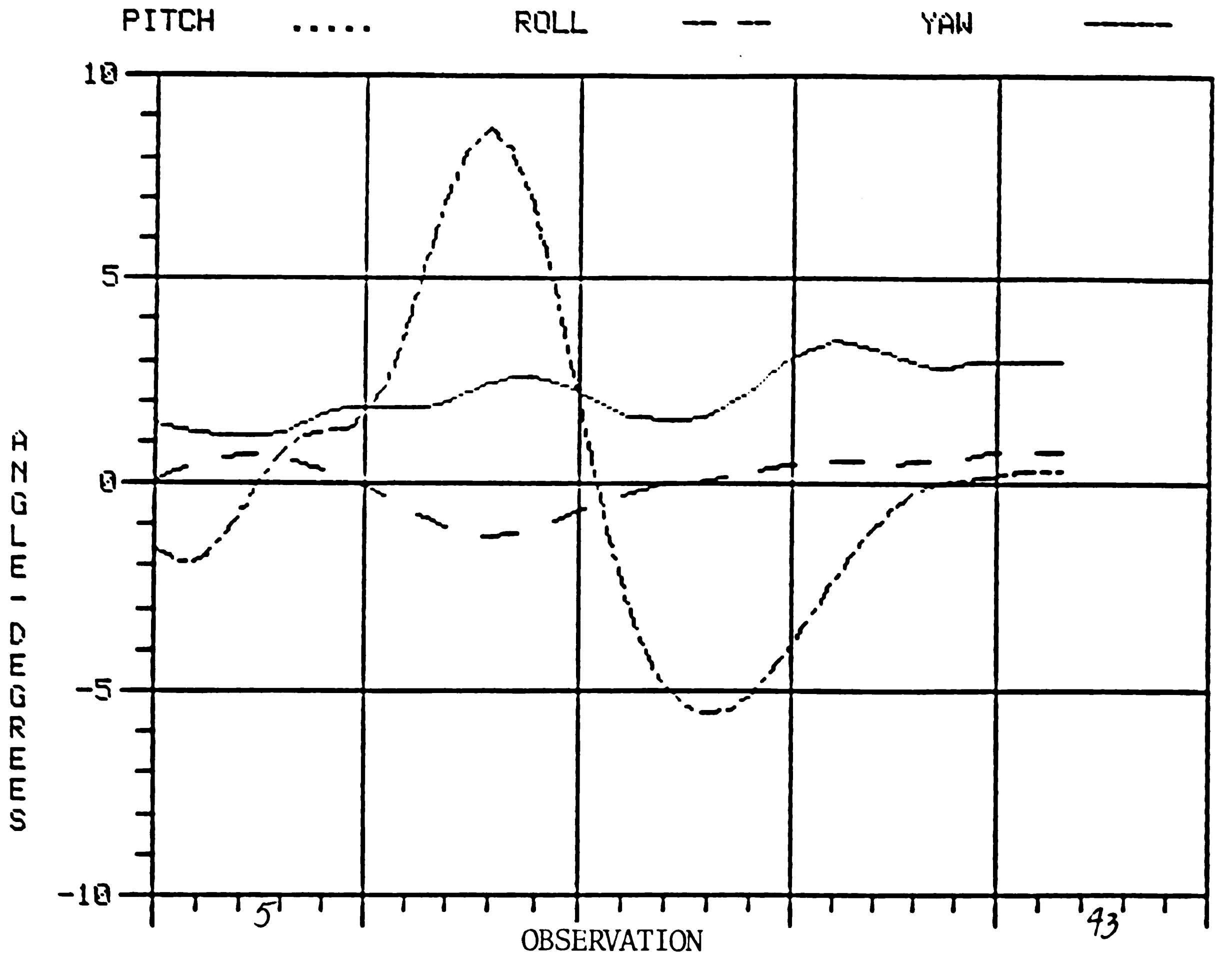


FIGURE 20. Joint Angles of Open/Close Movement Using Targets 5, 6, 12

were used as reference for the mandible. Targets 4, 5 and 6 were chosen because, in general, they formed a triad exhibiting less distortion throughout each movement than Targets 5, 6 and 12 and so were used for tracking rigid body motion. Such a blanket choice is acceptable for this initial study; however, in the future the choice should be made on an individual movement-by-movement basis in order to minimize distortion for each movement rather than for a set of movements. An additional suggestion for attending to the problem of soft tissue motion is made in Section VI.

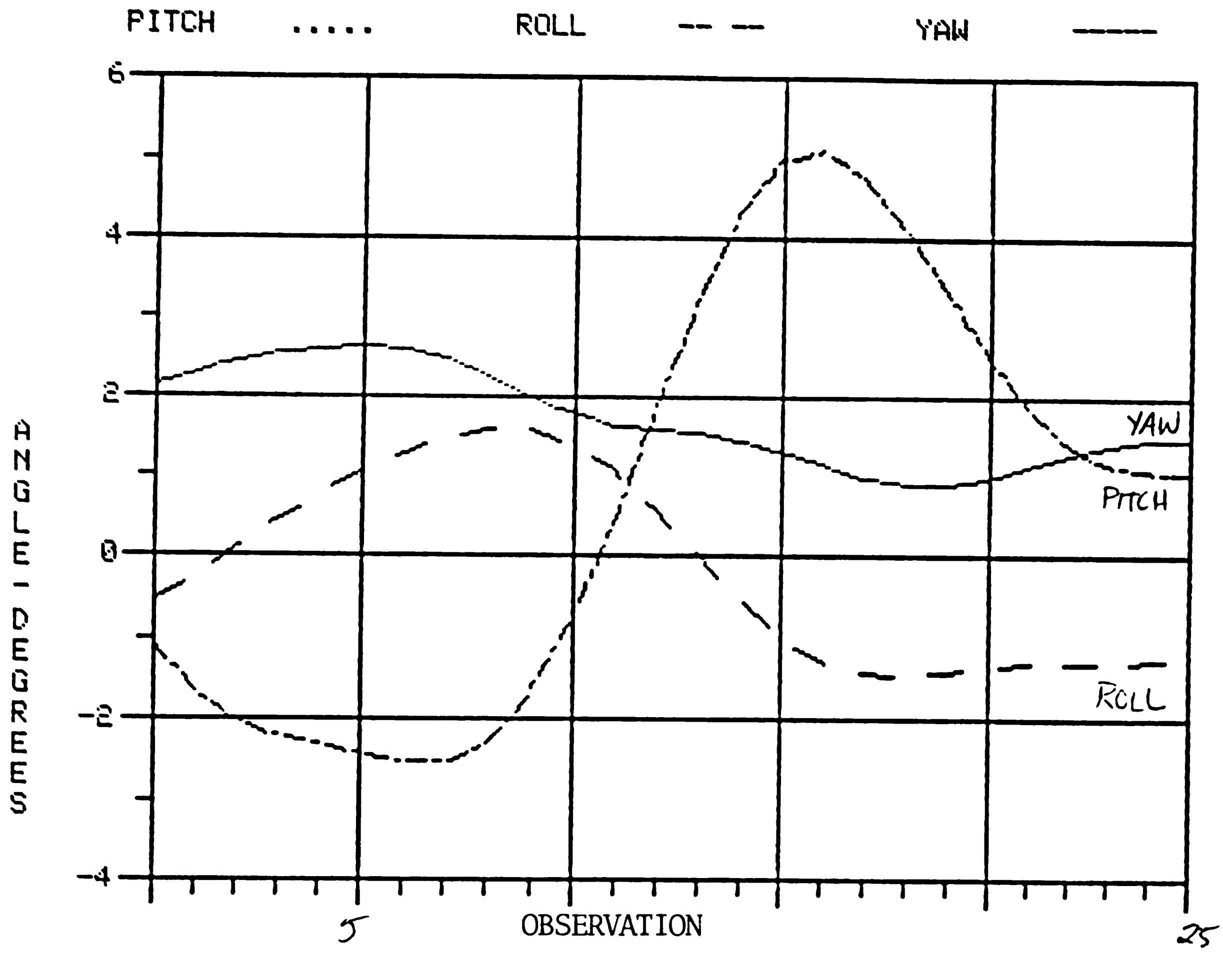
The angular information obtained during speech also appeared reasonable. The pitch angle varied the most throughout a particular speech pattern, changing as little as four degrees to as much as fifteen degrees from the first observation to the last. As would be expected, the roll and yaw angles did not vary as much as the pitch angle within a word (or phrase). Angles of roll and yaw changed as little as one degree and only as much as four and a half degrees for any particular event. The magnitudes of all three angles were below ten degrees, with all but the word "apple" being below 6 degrees (see Figures 21-23).

Although much of the inherent error of the system is corrected through filtering the data, and although the angular results appear reasonable, improving the precision of the system is advisable before the joint angles are scrutinized in greater detail. The system is calibrated to detect target coordinate changes within a radius of error of approximately 3.5 mm when targets of 1/4" (about 0.6 cm)



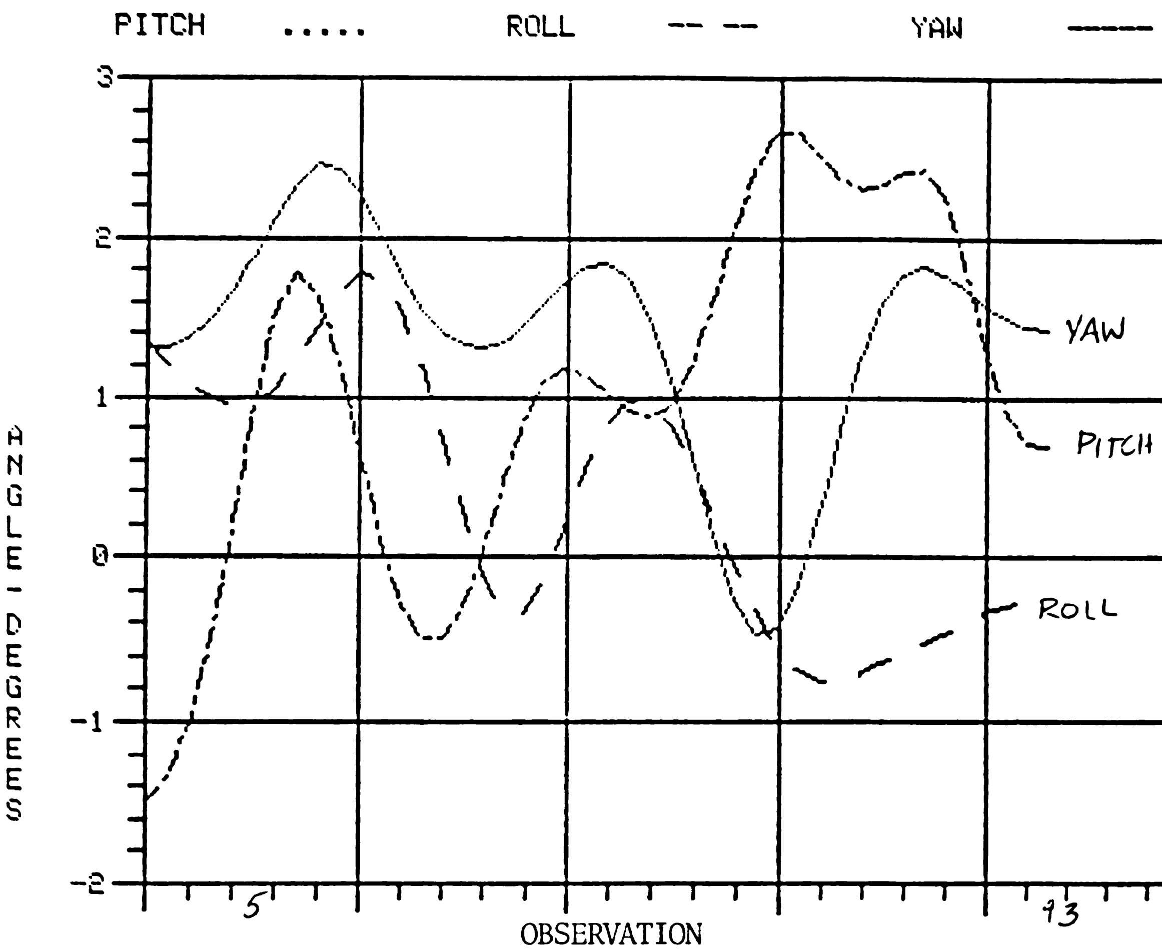
"APPLE" (Filtered)

FIGURE 21. Joint Angles for the Word "Apple"



"PEAR" (Filtered)

FIGURE 22. Joint Angles for the Word "Pear"



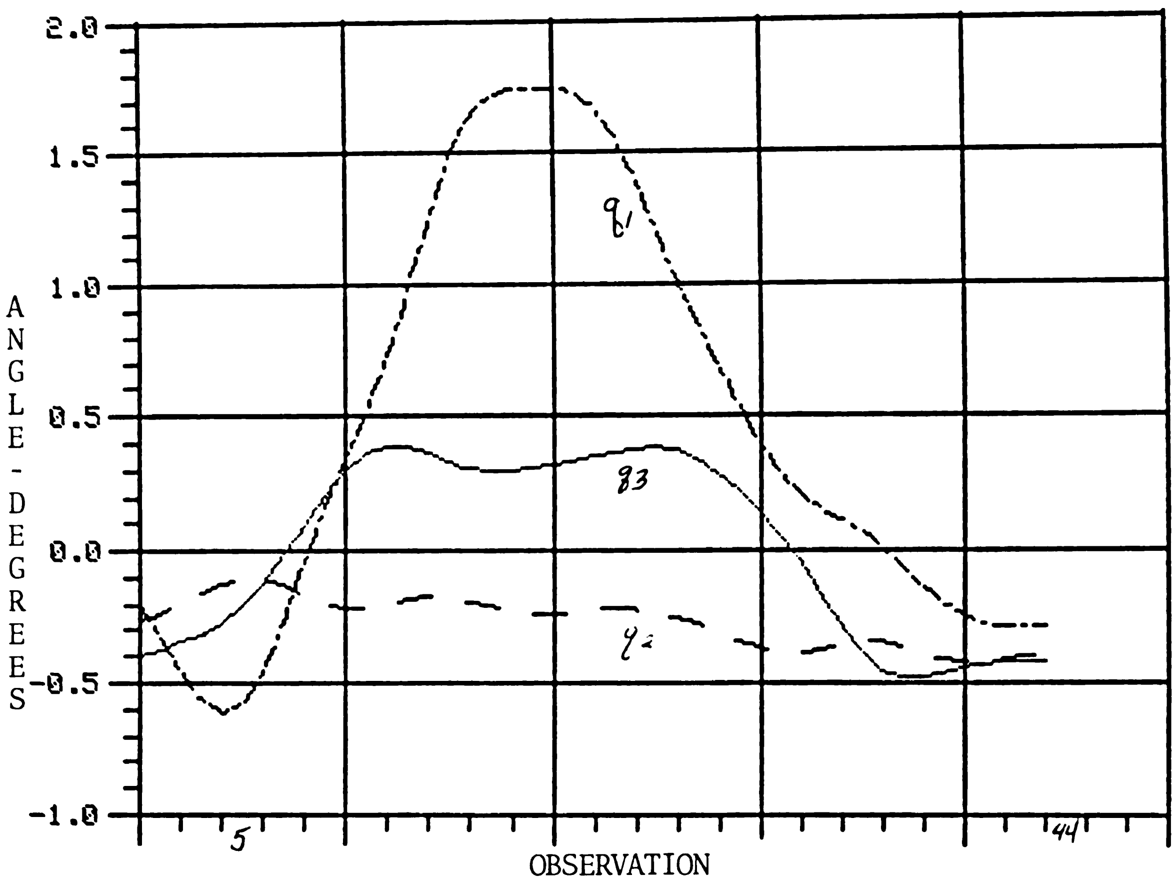
"BIOMECHANICS (Filtered)

FIGURE 23. Joint Angles for the Word "Biomechanics"

diameter and calibration targets of 3/8" (almost 1 cm) are used (7). Based on this information, and because the targets chosen to make up the triads were relatively close together, an error of three millimeters in locating a target could easily produce an error of five degrees for a particular joint angle. Although the error is reduced because smaller targets were used, several improvements are advised before analyzing angular changes of this order of magnitude in greater detail (see Section VI).

Calculation of the joint coordinate components of the translation Vector $\vec{H}$ did not support the "rotation-translation-rotation" description of motion given by many clinicians. The three translation values for the open-close movement are shown in Figure 24. Although magnitudes are meaningless, as stated previously, the general trends exhibited show greater values for protrusion-retraction and joint distraction-compression than horizontal glide, as would be expected.

An increasing slope in q_3 between Observation 5, where the motion begins, and Observation 11 is illustrated in Figure 4. q_3 levels off at approximately Observation 11 and then a decreasing slope is seen at Observation 27 until the end of the motion. (The mouth is completely open at approximately Observation 20.) q_1 shows an increasing slope when the mouth is opening and a decreasing slope when the mouth is closing. q_2 does not significantly contribute to the total translation. Examination of these three components of translation suggested that translation begins



"OPEN/CLOSE" (Filtered)

FIGURE 24. Joint Translations for the Open/Close Movement

with the onset of motion and then levels off when the mouth is about half open. As one would expect, the findings indicated that the process was reversed during the closing of the mouth. This does not agree with the "rotation - translation - rotation" description which suggests that translation does not initially occur at the joint.

Because the experimental results did not agree with the clinical description, and also because of the arbitrary construction of the Vector $\vec{H}$, the "rotation-translation-rotation" description can neither be supported nor refuted at this time. However, these preliminary results and the clinical description both suggest that the translation at the joint does not occur gradually, rather that translation occurs during only a portion of the motion. Further examination using a Vector $\vec{H}$ constructed based on radiograph measurements or at least based on targeting at the joint is necessary to be certain of the nature of translation at the temporomandibular joint.

VI. CONCLUSIONS

The use of cine stereo-photogrammetric techniques to quantitatively record and analyze the motion of the lips and jaw has yielded satisfactory preliminary results. That is, clinically reasonable and possible results were obtained, although overall precision of the system must be increased in order to adequately describe small movements. The basic methodology fits this application, however, several modifications are suggested.

Improvements can be made to reduce the radius of error in locating the targets in three-dimensional space. A smaller calibration structure with smaller calibration targets should be used. The current structure calibrates a larger than necessary control volume with suitable precision for larger movements, such as the movement of the legs during gait. The calibration targets are 3/8" and are not retroreflective. For studies involving smaller motions, such as the motion of the lips and jaw, a scaled-down version of the existing calibration structure would be more appropriate. A smaller calibration structure with smaller retroreflective calibration targets would yield greater resolution and therefore greater precision.

It is extremely important to reduce the radius of error in locating the targets when considering propagation of error. An increase in resolution would result in a smaller radius of error in locating the targets. Therefore, less error would be propagated during calculations of the joint and soft-tissue angles. If it were possible to place the targets used in angular calculations farther apart, the error in angular calculations would also be reduced. However, because this option is limited by the size of the face, it is important to reduce the error as much as possible by other means. Hence the importance of increased resolution.

Additional reduction of error in locating targets can be accomplished by using non-subjective means to synchronize the two camera views. Because the two views were artificially synched as described in Section III, there is a possibility of human error in locating the first frame of motion in both views. This source of error is reduced greatly by filming a timing device along with the subject; and is eliminated completely by using cameras with synchronized shutters.

Human factors are also a source of error in the digitizing process. Although care is taken, errors are a possibility. Manual digitization also contributes to the problem of exactly locating the targets in space. This source of error can be kept minimal by exercising great care when digitizing but can only be eliminated by an automatic digitizing system.

One goal of the experimental and analytical procedures used in this research was to minimize the effects of soft tissue when examining the rigid body motion of the jaw. Minimizing the effects of soft tissue was accomplished by the careful choice of targets used to track the rigid body motion. Some of the soft-tissue motion was probably also corrected for during filtering. In this manner, the error due to soft tissue was minimized. It may indeed be negligible, however it is not known to be so at this time.

It may prove to be beneficial to anchor a wire to the teeth, pass it between the lips, and mount a large triad of small targets on it. If the structure is kept very lightweight and only the rigid body motions are studied, the physical interference should be minimal. The results could then be compared to those obtained by the general methods of this study. If the results are very close, it is probably valid to assume that when care is taken to minimize the effects of soft tissue, the soft-tissue effects are indeed negligible. Both the motion of the jaw and lips could then be studied simultaneously as outlined in this work.

The preliminary results obtained by the methods outlined in this work are encouraging. The number of parameters that are possible to analyze when considering the motion of the lips is limited only by the interest of the researcher. In the past, many researchers have analyzed some measure of the vertical separation of the lips during function. This information is readily available in three dimensions through the use of cine-photogrammetric means, as is any other desired parameter characterizing the shape or movement of the lips. To illustrate this fact, 29 such parameters were calculated. The methods outlined to study this soft tissue motion of the lips are the theoretical foundation that can be modified in the future to yield an increase in accuracy and precision.

The rigid body rotations and translations at the temporomandibular joint were also calculated. It is not known at this time whether true values were obtained or whether soft tissue motion significantly corrupted the results. Further research is necessary in order to be certain. In any event, progress has been made in the study of labial and mandibular function.

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