The Reproducibility of Jaw Movement

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CONTENTS

FIGURES AND TABLES

ABSTRACT

This study was carried out to assess the reproducibility of jaw movement during chewing over a two week time period. Twenty asymptomatic adults, ten male and ten female, had their jaw movements studied. A Siemens Sirognathograph was used to track these actions during the eating of peanut and gum. This data was sampled by a computer which then indentified the individual chewing strokes. Ten parameters were selected to describe each envelope of movement. A data base of non-abherrent chewing strokes was created for each of the twenty-four chewing actions recorded for each subject.

Four thousand three hundred and thirty-seven chewing envelopes were identified and included in the data base. Statistical analyses were made to compare the inter and intra-sessional variations for each individual. Particular reference was made to the food that the subject was eating and manner in which the chewing movement was carried out.

The results indicate that the while all subjects show a considerable degree of variation in their chewing movements, fourteen out of the twenty subjects exhibited a greater degree of consistency than the remaining six. When gum was used as the test food it gave more reproducible results than peanut. If the subjects ate on their preferred side, without direction, once again more consistent results were obtained. Of the ten parameters describing the jaw movements, three (opening time, intercuspal pause and lateral range of movement) were found to show the greatest inter and intra-sessional reproducibility.

AUTHOR'S STATEMENT

This is to certify that the work presented was carried out by the candidate in the Department of Prosthetic Dentistry and has not been submitted for a higher degree at any other university or institution.

Sally D Ellis

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1. INTRODUCTION

1.1 THE STOMATOGNATHIC SYSTEM

Mammals have developed a highly sophisticated ability to capture prey and ingest food. Modern Man has a complex infrastucture of bones, joints, ligaments, tendons, nerves and muscles within the stomatognathic system for this purpose. The study of this highly specialised system has been the topic of scientific research for many years and a comprehensive understanding of the intricate anatomy and neurophysiology remains a challenge. It is of particular interest for those people involved in diagnosing and treating stomatognathic disorders in Man, such as temporomandibular joint dysfunction, muscle dysfunction, neurological disorders, dental malocclusions or dental pain. Many of these complaints are manifested as difficulties in the mastication of food and changes in the coordination of the stomatognathic system. Mandibular movement during the trituition of food is complex and unique to the individual. These factors complicate diagnosis and treatment of masticatory problems. The development of these skills result from learned processes and are influenced by diet, language, speech, social demands and jaw, muscle and joint development.

The analysis of jaw movement has been carried out for more than a century with many different types of equipment and different criteria for the experimental protocol. Previous studies have either recorded mandibular displacement during a single recording or have made comparative studies for groups of different subjects while carrying out a variety of tasks (Ahlgren, 1966, Jankelson, et al. 1975, Howell, 1987a, Proschel, 1987, Horio and Kawamura, 1989). It is universally accepted that individuals show large variations between each other and a wide range of recorded values can be obtained for similar tasks under similar experimental conditions. If such recordings are to be continued as an integral part of diagnosis and treatment planning of dental patients, some standardisation of the procedures must be established. No previous studies have carried out comparative recordings over a finite time scale for the same group of subjects. Neither has an assessment of jaw displacement reproducibility for a single person been thoroughly investigated.

1.2 THE AIMS OF THE STUDY

It is the aim of this study to test the reproducibility of jaw tracking recordings for a number of individuals in order to establish those factors which may influence jaw movement recordings over a period of time. The proposed project will be directed at a group of twenty asymptomatic subjects and the recordings will be completed during the mastication of peanut and chewing gum. These recordings will be repeated on two occasions separated by a two week interval. The results will be used as guidelines for future long term assessments of jaw movement for patients undergoing treatment in the Westmead Hospital Dental Clinical School.

A direct comparison of the results will be completed to test for the following hypotheses:-

1) Is there reproducibility of jaw movement recordings within a single session using standardised equipment?

2) Is there reproducibility of recordings between recording sessions?

Futher investigation of the results will clarify the following points in relation to the future use of recording techniques:-

1) Which variables in the recording procedure will contribute the most to a change in recording measurements?

2) Which parameters, or measurements, of jaw movement will give greater reproducibility?

2. REVIEW OF THE LITERATURE

The development of the masticatory system is a complicated and intricate process involving the integration of many different structures, including neurological, muscular, vascular, hard and soft tissue structures. The process commences in utero and there is evidence to show that finger or thumb sucking is carried out by the foetus (Kawamura, 1961). The development of the musculature, jaws and the dento-alveolar structures continues after birth. The developmental process is regulated by many different factors including social habits, diet, speech, dental occlusion and the individual response to these factors is widely variable.

2.1 THE DEVELOPMENT OF THE STOMATOGNATHIC STRUCTURES.

Few of the factors contributing to the development of the masticatory system will be influential at the same time or at the same rate. The new born child is able to carry-out suckling movements using the facial muscles and the tongue (controlled by the motor innervation of the facial and the hypoglossal nerves) but would not be able to perform chewing movements (regulated by the trigeminal nerve). The later development of mastication implies that the motor nucleus of the trigeminal nerve develops at a much slower rate than the motor nucleus of the facial nerve (Kawamura, 1964). The coordination and integrated action of the jaw muscles results in the required movement of the jaws and joints controlling masticatory activity.

2.2 PHYSIOLOGY OF THE STOMATOGNATHIC SYSTEM.

Man has developed a complex physiological system for the mastication and swallowing of food. The maintenance and function of this system is vital for the intake of food and personal survival.

2.2.1 Neuromuscular Control of Mastication.

The principle nerve supply to muscles of mastication originates from the trigeminal cranial nerve and contains motor and sensory fibres. The skeletal muscles supplied by the motor nerves are under possible voluntary control. The sympathetic and parasympathetic system, or autonomic supply, controls the smooth muscles of the body which are not under conscious control and show a different physiology. These variations enable a range of different muscle responses to be completed.

The neural control of mastication not only requires sequential opening and closing of the jaws but a variety of other movements involving the preparation of the food bolus. These include:-

- The maintenance of the food bolus over the tooth surfaces for crushing.
- Salivation to help in binding the food into a bolus.

- Coordination of the muscles of facial expression for maintaining and shaping the bolus.
- Reflex jaw movements to protect the jaw, cheek and tongue from damage by hard or unwanted materials.

The overall control of skeletal muscles is carried out by the sensori-motor cortex with separate areas coordinating specific muscle groups. The thalamus and cerebral peduncle are actively involved in the coordination of the tongue and jaw muscle movements via the facial, hypoglossal and glossopharyngeal cranial nerves. The muscles of mastication are innvervated by the trigeminal nerve, the nucleus of which is widely distributed throughout the pons, midbrain, bulb and rostral cord. Muscle spindle mechanoreceptors located within muscles provide information on changes in muscle length and thus in mandibular position via a complex feedback system.

However, masticatory movements are regulated at lower anatomical level by the pattern generator (Dellow and Lund, 1971). The pattern generator is programmed following reflex changes which occur as a result of growth and development. It controls the activation of muscles of mastication via alpha-motoneurones and this in turn, may be influenced by inputs from higher brain centres.

2.2.2 The Effect of Proprioception on Masticatory Movements.

A multiplicity of sensory nerve endings in the temporomandibular joint and oral cavity, contribute to the modification of masticatory movements via higher brain areas. Receptors in the lips and tongue are acutely sensitivity to taste and touch and help in the differentiation of different foods. The rich innervation of the posterior and postero-lateral areas of the temporomandibular joint capsule detect spatial changes in jaw position while muscle spindles will relay information regarding changes in length of the jaw muscles fibres. Numerous mechanoreceptors in the oral mucous membranes provide sensory input, via afferent nerve endings, to the sensory nucleus of the trigeminal nerve. Griffin and Munro (1969) and Matthews et al. (1969) believed that the mechanoreceptors of the periodontal ligament play an important role in the activation of the trigeminal motor nucleus in the control of jaw function. Different food textures or the presence of graded tooth contacts will stimulate mechanoreceptors and activate their afferent nerve. This afferent information is relayed via the mesencephalic nucleus in the brain stem to the trigeminal motor nucleus to modulate the pattern generator ouput in the regulation of masticatory movement.

Jerge (1964) proposed that stimulation of the periodontal receptors at the front of the mouth contributed to the regulation of the complex polysynaptic jaw opening reflex. The presence of mechanical stimulation of the teeth may initiate a protective reflex jaw opening. However, the jaw closing reflex was known to be a more simple monosynaptic pathway (Jerge, 1964 and Griffin and Munro, 1971).

Rioch (1934) and Dellow and Lund (1971) suggested that the envelope of jaw function was a learned reflex which was purely under the control of the central nervous system and not dependent on conscious regulation. The evidence in support of the conscious control of mastication system was illustrated by Stohler (1986) who showed that EMG recordings for habitual and deliberate chewing cycles were significantly different from one another. Matthews et al. (1969) and Hannam et al. (1970) found that with the application of local anesthesia to periodontal receptors, there was no loss in acuity of the jaw movement. These findings implied that the precision of mastication is not solely dependent upon peripheral feedback. This was contradicted by Bates et al. (1976), who suggested that jaw function was a reflection of individual neuromuscular systems and would be altered if part of the neural control was changed.

The swallowing movement, once triggered, is an all or nothing response which facilitates the removal of material from the oral cavity. This is usually a reflex action although it may be consciously controlled. Swallowing is limited by a variety of factors such as the consistency of the food, the size of the bolus, the psychic condition of the subject or the circumstances of the meal (Kawamura, 1964). All of these appear to be highly variable with no single factor playing a consistent role.

2.2.3 The Control of Jaw Movement.

The vertically orientated extrafusal fibres of the jaw elevator muscles are involved in the neuromuscular control of jaw position. Muscle spindle receptors associated with these muscle fibres, are sensitive to increases in muscle fibre length and will initiate a polysynaptic response for the reflex contraction of the muscle. This stretch response can be modified and regulated by stimulation of receptor endings in the antagonistic and synergistic muscle pairs. Summation of the stretch response is caused by the stimulation of nerve receptors in the synergistic muscles. Conversely, inhibition of the stretch response is brought about by stimulation of the antagonistic muscle groups. The reciprocal activity of the muscles of mastication allows the sychronisation of muscle contraction and relaxation, which is essential for fluent jaw movements.

The temporomandibular joint is richly innervated, primarily by fibres of the auriculo-temporal nerve to the posterior and postero-lateral parts of the joint capsule. Tension changes associated with joint or jaw movement, stimulate mechanoreceptors within the joint capsule. This activates afferent nerves which relay to the brain-stem and possibly the mesencephalic nucleus and may influence the output of the jaw muscles. Accessory innervation of the temporomandibular joint i.e from articular branches of nerves to jaw muscles, may also contribute motor control to the jaw muscles.

The stomatognathic system is a complex arrangement of many functional elements, each playing an important role in maintaining an efficient, coordinated and adaptable system. Jaw movement is determined not only by muscle function but by many other factors and neither one should be considered separately from the other.

2.3 JAW TRACKING TECHNIQUES.

As early as 1889, Luce used still photography to monitor the movement of the mandible and Bennett, (1908) documented jaw movement patterns which were taken from clinical observations. Hildebrand in 1931, gave a detailed account of jaw movement using simultaneous radiographs and photography. This cineradiography proved to a revolutionary step in mandibular movement assessment and was utilised by several other investigators (Schweitzer, 1961, Ahlgren, 1966, Watt et al. 1976, Thexton et al. 1980). This method was adapted by many other researchers and cineradiographic techniques were used in the description of various components of the stomatognathic system. For example, these included investigations into condylar movement (Saxby and Franks, 1976) Bennett movement (Landa, 1958), mandibular movement (Ahlgren, 1966) and the positioning of the tongue and soft palate (Jankelson et al. 1975). Radiographs were used by Benediktsson (1958) to monitor tongue and soft tissue movement during speech while Atkinson and Shepherd (1967) used cinephotography to analyse the envelope of jaw movement during function. Ardran and Kemp (1960) and Sheppard (1965), used radioactive tracers in oatmeal cakes to photograph jaw movement during chewing and swallowing. These techniques are unlikely to be accepted by the modern Ethical Review Committees now that an improved understanding of radiation hazards exists.

Different aspects of jaw movement have required the development of specialised techniques for successful analysis. Gillings et al.(1963), Graf and Zander (1963) and Schaerer et al. (1967) used radiotransmitters placed in partial dentures to analyse the number and frequency of tooth contacts during function. These miniature transmitters had the advantage of not interfering with natural tooth contacts and allowing freedom for "normal" movement. Joint sound analysis or "gnathosonics" (Watt 1976), was used to measure joint movement, while Waysenson and Salomon (1977), Jemt (1982), Faulkner and Atkinson (1983) and Faulkner (1989) used light emitting diodes attached to the teeth to trace mandibular movement.

The desire to follow more than two dimensions of jaw movement inspired Kurth (1942) to use still photography in three different planes to assess mandibular movement. The validity of these experiments was questioned by Chick (1953), who identified the problems of integrating a two dimensional image to represent a three dimensional movement. Further developments and improved technology lead to development of the "photoelectric mandibulograph" (Gillings, 1967) and the "Case Gnathic Replicator" (Messerman, 1967; Gibbs et al. 1971). The disadvantage of these methods was that they required bulky instrumentation to be placed around the head of the subject. This may have caused an alteration in proprioception resulting in a change away from a "normal" response. The Gnathic Replicator required the attachment of two clutches to the buccal surfaces of the upper and lower teeth, which was only a 60 g weight and should have minimised the variation in proprioceptive reflexes found in the habitual "intercuspal" relationship. This device recorded jaw movement in 6 degrees of freedom and was the first to use computer technology to analyse data and to replicate jaw movement. Hobo and Mochizuki (1983), also used clutches that were attached to the upper and lower teeth and claimed no interference with the occlusal table.

The use of the pantographs by van Rensburg et al. (1974) addressed the necessity to provide a recording apparatus with 6 degrees of freedom (3 rotational and 3 translational movements) of the mandible in function. This was supported by Hannam et al. (1980) who recommended that ideally 6 degrees of freedom must be recorded if a comprehensive analysis of jaw dynamics was to be undertaken.

2.3.1 The Modern Techniques of Jaw Tracking.

It is evident that after nearly a century of investigation, the previous recording systems still suffer from limitations. This has stimulated developments from several research groups into devices which would provide minimal occlusal interference, minimise the use of bulky equipment and be easy to use in routine clinical situations. It is generally accepted in dental research that there are wide variations in the recordings that are made from these recording systems. For this reason, the Neuroscience group of IADR recommended to the American Dental Association in September 1989, that jaw tracking devices should not be used by dentists in general clinical practice for the definitive diagnosis and treatment of temporomandibular joint disorders.

2.3.1.1 Gnathic Replicator. Messerman (1967) described an early system, later developed by Gibbs et al. (1971), which allowed completely free jaw movement and measured displacement in six degrees of freedom. Two clutches were attached to the labial surface of the upper and lower teeth, allowing lip competence and natural tooth contact. The fixed upper reference bow and the moving lower facebow member contained six transducers attached to them and the total weight of the equipment was 60grams. This was not thought to be sufficient to alter habitual jaw function. A computer system recorded the jaw movement information and sampled the data at a rate of 100 points per second. The ideal occlusal scheme illustrated reproducibility of movement within the 5%

significance level with an error of ± 0.13mm. This information was then used in a laboratory situation to recreate the mandibular movement. Facebows which supported study models of the patient simulated the envelope of jaw movement from the computer information. Movement tracings could thus be carefully analysed off-line and values were extrapolated for movements of the condylar head, mandibular midpoint on the central incisors in the vertical, horizontal and sagittal planes and mandibular first molar mesiobuccal cusp.

2.3.1.2 Light Emitting Diodes. The " Selspot" system was developed around a transducer mechanism which produced a pulse response to the movement of a light emitting diode (LED). The dental application was developed by Jemt (1979). The movement of a point on the mandible was traced by placing such a diode on the labial surface of the lower incisor teeth. The movement of the light emitting diode was detected by a camera and transformed into a signal which was used to record the diode position. A computer was then used to calculate a three dimensional representation of the diode location. The coordinates of the jaw position were stored on digital tape or paper. One camera was used to record the location of the diodes which contributed to the calculation of two dimensional jaw movement, in the frontal and vertical planes. Manual assessment of jaw movement tracings were used to calculate the functional jaw movement. Jemt et al. (1983) reported that there was reproducibility of intra-subject recordings on a sessional basis. A similar method was employed by Salomon et al. (1979a & b) for three dimensional jaw displacement recordings.

2.3.1.3 The Sirognathograph. Lewin et al. (1974) described the first recording device which enabled freedom of movement of the mandible without interference with the natural occlusal scheme or the use of bulky fixtures. The device involved the Hall effect which is an interaction between electrical and magnetic fields (Hall 1879). In this early description, it was pointed out that if a magnetic field was passed across a pure conductor then a potential could be measured. This principle was used and extended to develop two similar pieces of equipment for the measurement of mandibular movement: The Sirognathograph (Siemens AG, Bensheim, W Germany) and the Kinesiograph (Myotronics, Seattle 98101, USA). These devices have been widely used in the analysis of jaw movement with the various features of each apparatus allowing different criteria to be studied. Maruyama et al.(1984), Lewin (1985), Lucas et al. (1986b), Proschel and Hoffmann (1988), Mongini (1986) and Nishio et al. (1988) all described experiments using the Siemens Sirognathograph.

The Sirognathograph consists of a series of sensors which monitor the displacement of a magnet cemented to the labial surface of the lower anterior teeth. Maruyama et al. (1984) performed bench tests on the Sirognathograph to examine the reliability and reproducibility of the equipment. It was found that a movement of the magnet did not change the recording, although a 10^{o} rotation of the magnet did cause a 1mm deviation of the movement traces from the axis origin. The background noise of the recording was also reduced by ensuring that the subject maintained a fixed gaze on a point immediately ahead. Lewin (1985) stated that the Sirognathograph had superior linearity to the Kinesiograph and this was one of the most important features if comparative studies were to be made.

2.3.1.4 The Kinesiograph. Jankelson et al. (1975), Hannam et al. (1980), Klineberg (1980), Chew Choog Lin (1983), Stohler and Ash (1984), Neill and Howell (1986), and Howell (1987a), used the Kinesiograph. The Kinesiograph is based on the same Hall effect principles as the Sirognathograph and records the displacement of a magnet on the labial surface of the lower incisor teeth. The reliability and linearity of the apparatus has been stated to be ± 0.1mm within the vicinity of the intercuspal position (Jankelson et al. 1975). The linearity changes as the distance from the intercuspal position increases. Michler et al. (1987) illustrated an amplification and distortion of the recorded jaw movement at the limit of the movement by a factor of nearly 5%. However, Jankelson (1980) believed that within the normal range of mandibular movement during function, the non-linearity of the Kinesiograph was within 1.5% and this correction factor would compensate for any inaccuracies in the results. Mongini et al. (1984a) believed the Kinesiograph to be 1% accurate which was within the acceptable range of experimental error. However, he did restrict his measurements to the first 20mm of opening to minimise inaccuracies. Hannam et al. (1980) and Neill and Howell (1984), developed a means of linearising the Kinesiograph with a computer program, before the analysing the results. Hannam et al. (1980) identified several limitations of the Kinesiograph and suggested that the magnet should be placed 1 centimeter higher than the manufacturer recommended to improve the linearity of the equipment. The precise alignment of the sensor headframe and the orientation of the magnet are critical for the accuracy of the apparatus. A standardised method of orientating the headframe to various anatomical landmarks has been described using a facebow (Hannam et al. 1980). With these precautionary measures, the linearity of the Kinesiograph was found by Hannam et al. (1980) to be ± 0.14mm. The maintenance of a stable head position was not a requirement (Neill and Howell, 1986), although it is an important feature with the use of the Sirognathograph.

The Sirognathograph and Kinesiograph are similar with some minor differences in design and function. Both systems provide a standardised and comparable means of assessing jaw movement. The careful documentation of studies is imperative in the standardisation of techniques, enabling a comparison of results to be made between different centres.

2.4 THE APPLICATION OF COMPUTERS IN JAW TRACKING

The development of computers in recent years has become essential in handling the large volume of data for jaw movement recordings. In the last 20 years, computers have become readily available commercially and have been applied in medical research by cardiologists, speech therapists, chemistry laboratories, neurological units, paediatric units etc (Geister et al. 1975). The analysis of jaw muscle function as a component of jaw movement has provided the incentive for computer technology development in the field of dental research. The development of systems which record three dimensional jaw movement, has required computerisation of the data. Hannam et al. (1980) and Michler et al. (1987) promoted the use of computers for jaw movement analysis and identified the requirement for digitisation of the data for display and completion of analysis. This was endorsed by Geister et al. (1975), Neill and Howell (1984) and Mongini (1986). Hobo (1984a and b) developed a computer display of mandibular movement and Maruyama et al. (1984) used a system to display the continuous recording of 7 minutes of jaw tracking.

A major problem in the collection of data from jaw muscles and jaw movement is the accuracy and speed with which the signals can be collected without inaccuracies arising. Yuen (1989) developed a system which was capable of recording up to 2048 signals per second while Hannam et al. (1980), Belser and Hannam (1986) and Mongini (1986) used computer systems that sampled data at a rate between 1000Hz - 1600Hz. A sampling rate of 2000Hz was used by Barker et al. (1986). The personal computer system used has varied [eg. a Pet Commodore computer, (Neill and Howell 1984) to an Apple Mackintosh computer (Barker et al. 1986)] and the use of floppy disc drives for information back-up was described in studies by Barker et al. (1986) and Gervais et al. (1989). Lucas et al. (1986b) used the computer hard disc for data storage while Geister et al. (1975) utilised magnetic tape.

2.5 VARIABLES IN THE ANALYSIS OF JAW TRACKING DATA.

Studies of the recording of jaw movement have indicated the need to distinguish between factors which influence the variability and reproducibility of results. The precision of measurement of jaw position provided by the equipment was one of the more fundamental variables. Jankelson et al. (1975) and Hannam and Lund, (1981) reported that the resolution accuracy of mandibular displacement measured with the Kinesiograph was within 0.1mm and 0.2mm respectively. The reproducibility of light emitting diode techniques was well within acceptable limits of experimental error, (Karlsson 1977) and Hobo (1984a) claimed an accuracy of 0.06mm during the measurement of condylar movement. These results suggest that the resolution of the Kinesiograph and Sirognathograph provide satisfactory accuracy of recorded data.

2.5.1 Subject Numbers.

There has been a large variation in the number of subjects included in documented studies on jaw movement and this may influence the validity and interpretation of the results. Only three subjects were used in the early study of Atkinson and Shepherd (1955), Klineberg (1980) used five healthy adults and Mongini (1984a and b) used two groups of eight people. Stohler (1986) and Mongini (1986) used only twelve subjects while Howell (1987a and b) used a total of 97. Proschel (1987) conducted a large study using a total of 165 dysfunction and 185 "normal" subjects.

2.5.2 Sexual Differences.

Bates et al. (1975b) did not identify differences between male and female subjects. However, in some projects, the subjects were divided into male and female groups on the supposition that significant physiological differences might be observed during mandibular function. Lindqvist and Rindqvist (1973) found some differences between bruxing and non-bruxing boys and girls while Linderholm et al. (1971) observed no differences in "normal" boys and girls during the maximum clench. The changes in duration of the chewing cycle and the intercuspal pause was more marked for men than women (Munro and Griffin, 1970). Pullinger et al. (1987) related their observations of sexual differences during passive and active jaw opening to the size and form of the skeleton. Even with the compensation for differences in skeletal size it was seen that females had a larger mandibular opening than men during functional movement. This may indicate that women have a greater mobility of the temporomandibular joint. However, the findings of Agerberg and Carlsson (1972) suggested that women have decreased mandibular mobility in comparison to men. A detailed study into the differences between the chewing habits of males and females was carried out by Howell (1987b). He found that highly significant differences occur between men and women for the range of lateral movement, velocity of the movement and duration of the intercuspal pause. Studies by Greenfield and Wyke (1956) and Mongini (1986) and Horio and Kawamura (1989) made no allowances for possible differences between the sexes.

2.5.3 The Selection of Foods As Test Materials.

The literature shows that different foods or materials have been used as a means to examine jaw function. The most common foods were peanut (Blaton et al. 1970;

Garnick, 1975; Lucas, 1986b), chewing gum (Ahlgren, 1967; Hannam, Inster, De Cou and Scott 1977) and bread (Mongini et al. 1984b; Schaerer et al. 1967). Other foods included cheese (Gibbs et al. 1973), wine gums (Proschel, 1987), apple (Neill and Howell, 1984), banana (Sheppard and Markus, 1962), biscuit (Watt et al. 1976), celery (Jankelson et al. 1953), walnuts (Sheppard and Markus, 1962), gelatin (Gunne et al. 1982) and rubber (Hickey et al. 1963). There have been some more unusual foods used in the Japanese studies which included octopus, steamed fishpaste, radish, boiled fishpaste and beancurd (Horio and Kawamura, 1989).

A change in consistency and homogeneity of the food bolus will, of course, affect jaw tracking recordings. Gunne et al. (1982) suggested that a homogeneous bolus was important if consistent movements were to be recorded. This was contrary to a report from Jankelson et al. (1953) who claimed there was little variation in mandibular function when the bolus type changed. Proprioception of the bolus is important in controlling mandibular movement although Neill and Howell (1986) stated that shape or form of the envelope of function did not change with the type of food masticated. The hardness of the food resulted in a greater vertical displacement of the mandible during function (Lewin and Nickel, 1978; Horio and Kawamura, 1989) and lateral deflection of the mandible was reduced by using a softer food type (Gibbs, 1973; Lewin, 1986). Lucas et al. (1986b) noted a decrease in vertical jaw movement and duration of the chewing cycle as the number of chews increased and concluded that standardisation of the volume of the food bolus was an important consideration.

2.5.4 Individual Variation.

Jankelson et al. (1953) observed that individual variation of the chewing stroke action was an important variable, with unilateral chewing movements showing fewer inconsistencies than habitual chewing. In an attempt to standardise jaw movement, Howell, (1986) and George (1983) used a text of poetry for subjects to read while movement recordings were carried out. Jankelson et al. (1953), Kydd and Sandler (1961), Bates et al. (1975a) and Proschel (1987) all agreed that the type of food chewed or the differences in chewing action are less significant than variability between individual subjects. This was qualified by Gillings et al. (1973) who stated that for similar actions, the variation of individual jaw displacement and velocity deviated from population mean by at least 25%. In 1971, Gibbs et al. showed that variation of mandibular displacement according to a change in food bolus was greater than the variation between individuals. This was later contradicted by Gibbs et al. (1973) who suggested that individual differences within dysfunction groups, gave greater variation than 'normal' subject groups. This was supported by similar findings between dysfunction and non-dysfunction groups by Mongini et al.(1984b) who reported these differences in the velocity and displacement of the mandible during function.

2.5.5 The Sequence of The Recordings.

Few comparisons of jaw recordings have been made at different times of the day or on different days, although this has been done in EMG studies. Lippold (1952) claimed that EMG recordings were reproducible and this was confirmed by Frame et al. (1973), Gillings et al. (1973), Helkimo and Carlsson (1977) and Dahan and Boitte (1986). Mushimoto and Mutani (1986) stated that the similarity of results between EMG recordings were within acceptable experimental limits. The statements regarding jaw movement were disputed by Garrett et al. (1964) who believed that a comparison of results from one day to the next would show a 20% difference. Garrett and Kapur (1986) corrected this inconsistency to nearer 10% while Michler (1987) reported accurate reproduction of jaw movement recordings during swallowing, speech, chewing and maximum opening when studies were repeated over the period of one year! There is little documentary evidence to establish whether the consistency of jaw tracking would be similar to EMG values.

2.5.6 Influences of The Occlusal Scheme.

Changes to the occlusal scheme will cause a significant differences in sequential measurement of lower jaw movement (Michler et al. 1987). Gibbs et al. (1973) believed that an alteration to an individual's occlusal scheme had a greater influence on the consistency of the jaw tracking recordings than a change in the food bolus. Gillings et al. (1963) and Beyron (1964) concluded that an "optimal" occlusal scheme showed maximum uniformity in chewing pattern and George (1983) stipulated the importance of comparing subjects with a similar occlusal scheme to ensure consistency of the results. Deviations from classified tooth incisor and molar relationships caused a wider variation in the functional mandibular tracing (Gibbs et al. 1971). The general pattern of the jaw movement was said to change from a more lateral movement to a predominantly vertical movement with the removal of mediotrusive and laterotrusive interferences (Gordon, 1979). This may be explained by Bendiktsson (1958) who believed that jaw and tongue movements were determined by the occlusal relationship. Neill and Howell (1986) showed that a change in the incisor relationship altered the jaw movement tracing and Proschel (1987) supported this by showing significant differences in the jaw movement patterns for Class 1 and Class 3 occlusal schemes. Each displayed a predominance in a particular mandibular movement. The relationship of the jaw movement patterns did not precisely relate to occlusal schemes. This disagrees with the results of Ahlgren's study in 1967 which showed no correlation between the occlusal scheme and the envelope of jaw movement. Stafford et al. (1985) suggested that an edentulous subject will have a wide variation in the mandibular functional movement and Bates et al. (1975b) showed that the cusp angle on the artificial teeth is a determining factor in the envelope of jaw function. The theory of cusp angle being an important influence on mandibular movement was agreed with by Lewin (1985) who showed that wider sagittal jaw movements were generated by steeper tooth cusp inclines. Analysis of jaw movement in the frontal plane shows that attrition results in wider jaw movements at the level of the occlusal plane (Lewin 1985). The relationship between the EMG values and the alterations in the occlusal scheme have been reported by Klineberg, (1986) and Kahn, (1977) who agree that an increase in the presence of mediotrusive supracontacts caused an increase in the EMG value and the muscle activity. McCarroll, (1989) and Turker, (1988) illustrated that a slide or change from the centric jaw relation to the centric occlusal position caused a change in muscle activity. Modifications to the subject's occlusal scheme with occlusal splint therapy (Wood and Tobias, 1984; MacDonald and Hannam, 1984 and Miralles et al. 1988) illustrated that a change in the jaw relationship, to maximise the number of tooth contacts, changed the recorded EMG. It seems that discrepancies in occlusal patterns cannot be removed from influencing the envelope of jaw function as muscle activity is associated with the control of jaw movement.

2.6 PARAMETERS MEASURED FOR ANALYSIS OF JAW TRACKING.

2.6.1 The Shape of the Envelope of Jaw Movement.

The envelope of function of the mandible was divided into three distinct parts by Ahlgren and Owall (1970). These were: a) the opening phase with mandibular depression, b) the closing phase with mandibular elevation and c) the occlusal phase with the teeth in the intercuspal relationship. These contributed to the classic 'tear drop' shape of the functional envelope (Michler et al., 1987). Detailed studies have involved the analysis of individual chewing strokes during function with each categorised according to size and shape of the chewing envelope, (Ahlgren, 1967; Proschel, 1987). In this study, 73% of "normal" subjects maintained consistent chewing patterns with 80% of the closing phases occurring towards the chewing side. Neill and Howell (1986) found that the action of the mandible was habitually unilateral for the majority of the chewing cycles. This was not supported by Stohler (1986) who noted that although the chewing movement was predominantly on the right side, it was rarely unilateral and that there were differences in the analysis of habitual movement and unilateral chewing movement. The jaw movement for habitual and unilateral chewing actions showed marked differences. The food bolus will cause a significant alteration in the amplitude and duration of the opening phase, but not the closing phase, of the chewing cycle (Plesh et al. 1988).

2.6.2 The Duration of the Jaw Movement.

Although there maybe a variation in the duration of the opening and closing phases, the intercuspal pause will stay constant (Bates et al. 1975b). Sheppard and Markus (1962) stated that one fifth of the masticatory cycle was at the intercuspal position. In the analysis of the results, Gibbs et al. (1971) excluded the first and last chews of any chewing cycle to eliminate any incision or swallowing actions and restrict the analysis to chewing movements only.

2.6.3 The Velocity of Jaw Movement.

Bates et al. (1975 b) believed that there was an acceleration at the beginning of the opening and closing phases of the jaw movement with unilateral movement showing a reduced velocity compared to bilateral function. This is slightly different from the study completed by Mongini et al. (1984a) who maintained that the acceleration of the jaw movement was in the middle third of the opening stroke and the last third of the closing stroke. Woelfel et al. (1963) suggested that a homogeneous food bolus such as rubber, will give more regular values for velocity whereas an inconsistent food bolus, such as peanut, will show a wide range of velocity values during masticatory function. This was agreed by Jemt et al. (1979) who noted that the velocity of the chewing cycle increased with the increase in the number of chewing strokes and the mastication of the food bolus. The use of a homogeneous bolus such as rubber, caused slower chewing movements as did a smaller food volume (Lucas et al. 1983a). A smaller food bolus will increase the velocity of the chewing movement, suggesting that standardisation of the bolus volume is important in the reproducibility of the jaw recording (Lucas et al. 1986a).

2.6.4 The Range of Jaw Movement.

The range of the vertical and lateral movements of the mandible during function are larger for male subjects than female subjects (Neill and Howell 1986, Howell 1987b). The gliding or lateral component to the chewing stroke is increased with harder foods, although the occlusal scheme appeared to be more influential in controlling the limits of jaw movement (Proschel and Hoffmann 1988). Bates et al. (1976) suggested that the nature of the food bolus had an influence on the horizontal movement of the mandible with an increase in the hardness of the food causing an increase in the lateral component of the functional envelope. In increasing order of influence these foods were nut, meat and carrot.

2.7 SUMMARY.

The literature illustrates numerous accounts of jaw displacement analysis. The diversity of the recordings obtained between different centres changes according to the recording techniques used and the movements measured. The use of comparable equipment which is internationally available and has been used in a multiplicity of ways, will help to provide some uniformity of the recordings and allow comparisons of different results to be made.

3. MATERIALS AND METHODS

This study involved twenty subjects for whom jaw movement and electromyographic recordings were made on two separate occasions. The subjects were selected from the undergraduate clinics of the Westmead Dental Clinical School and equal numbers of males and females were chosen. Electromyographic recordings were taken using bipolar surface and hook electrodes. Jaw movement was recorded using a tracking system designed to monitor the movements of a magnet attached to the lower incisor teeth. The purpose of this project was to study jaw movement; a detailed investigation of the EMG material was not intended at this stage.

3.1 ETHICAL COMMITTEE APPROVAL.

Approval from the Cumberland Area Health Authority Human Ethical Review Committee was sought and authorised under the following conditions:

a) sterility to prevent infection and cross-infection;

b) subjects were able to refuse to join the study once the full procedure had been explained or discontinue once the study had begun.

No subjects refused to continue with the study after the recordings had commenced, although two people declined to take part after the procedure had been fully explained. All the subjects were required to read a consent form which explicitly described the experimental procedure (Appendix 1). This form was signed by each subject and countersigned by the dentist leading the investigation.

3.2 SUBJECTS.

The subjects who participated in this study were dental patients of undergraduate students of Westmead Hospital Dental Clinical School. A total of 28 people were asked to participate and 26 agreed to an initial clinical examination which followed a carefully prepared procedure. This maintained a uniform and consistent approach for all subjects. The dental history and examination forms from the Orofacial Pain and Dysfunction Clinic of Westmead Hospital Dental Clinical School, were used to provide the guidelines for this initial examination (Appendix 2). Following this, 20 subjects were selected to take part in the study (see section 3.7.1). Equal numbers of male and female subjects were selected. The male subjects had an age distribution of 19 years to 63 years with a mean of 35.2 years and the females showed an age range between 22 years and 53 years with a mean of 36.9 years.

3.3 JAW TRACKING EQUIPMENT.

Jaw tracking was carried out with a Sirognathograph (Siemens Atkiengesellschaft, Bensheim, W Germany). This apparatus is capable of monitoring jaw movement in three dimensions using a magnetic principle. The basic principles of this method were originally described by Hall in 1879, who showed that if a small current was passed along a pure conductor, the potential difference across it was zero. If a magnetic field was applied perpendicular to the electric current, then a potential was recorded. The magnitude and polarity of this potential was related to several factors:-

a) the direction of the magnetic field,
b) the intensity of the magnetic field,
c) the size of the conductive plate,
d) the thickness and nature of the conductive plate and
e) the applied voltage (Hall 1879).

3.3.1 The Magnet.

The equipment monitored the movement of a magnet, attached to the labial surface of the lower incisor teeth and this represented the displacement of the anterior mid-point of the mandible. The magnet is rectangular and of standard dimensions (5mm x 5mm x 10mm). It is covered by protective plastic which was colour coded red and blue to ensure its correct orientation.

3.3.2 The Sirognathograph.

The movement of the magnet was monitored by a series of eight sensors supported by a head frame. The sensitivity of the sensors was proportional to the current flow through each and this was enhanced by a short pulse of 800mA , 50 times per second. The 8 sensors were linearised and each was used to calculate and correlate the changes in the vertical, horizontal and sagittal planes making it possible to monitor the movement of the mandible three dimensionally.

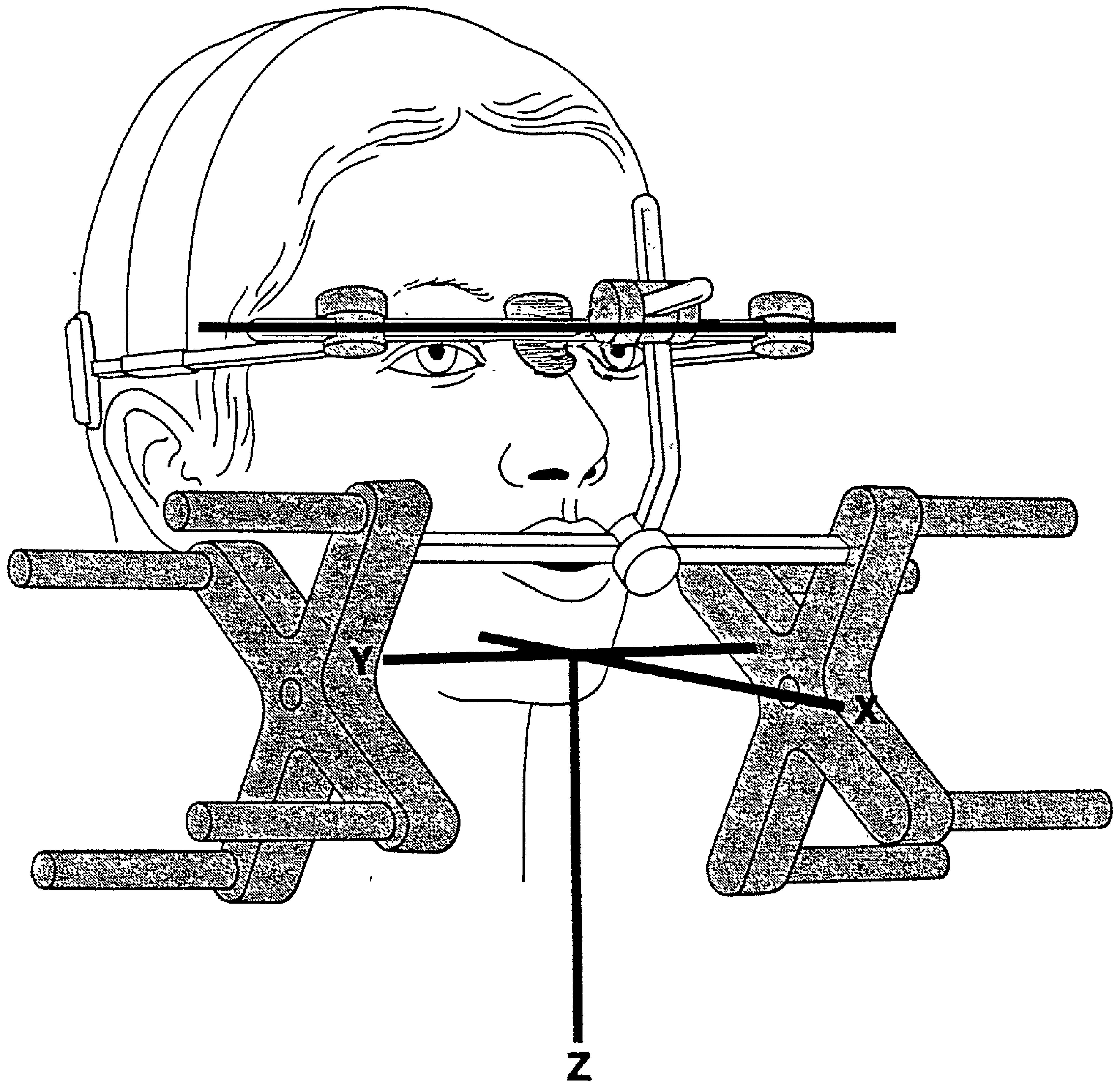

Figure 3.1 A Line Drawing to Show the Positioning of the Headframe for the Sirognathograph (after Lewin 1981).

The magnet of the Sirognathograph was cemented to the labial surface of the lower incisor teeth using zinc phosphate cement. The headframe contained sensors each of which contained a quantity of mu metal which was extremely sensitive to changes in magnetic field. The headframe was firmly placed over the subject's head using adjustable straps (Figure 3.1) and a small amount of polymerising silicone impression material was used to mould a nose piece that was attached to the headframe. This helped to provide stability as well as reducing pressure on the bridge of the nose. It was important that the frame was stable with no possibility of becoming dislodged during the experiment. In all cases the sensors on the headframe were very carefully positioned relative to several anatomical landmarks. This was accomplished with the aid of a plastic jig which had four holes which fitted exactly over the four sensors of the headframe (see fig 3.8). On the surface of the jig were a series of lines and these were orientated parallel to the Frankfort plane. This ensured the necessary standardisation for the headframe and sensor orientation. It was also important to ensure that the sensors were equidistant on either side of the subject's head and that the centre of the sensor arrangement was in the same horizontal plane as the magnet. This was mandatory if consistent jaw tracking records were to be made.

The system is based on the principle, that the movement of the magnet is detected by the sensors. The accuracy of this system was dependent on the stability of the headframe so that any recorded movements were only representative of the change in the position of the magnet and not to the movement in the headframe sensors.

3.4 EMG EQUIPMENT.

3.4.1 Electrodes.

Gold-plated silver-silver chloride surface electrodes and hook electrodes were used to record EMG signals from three pairs of jaw muscles. The muscles selected were the masseter, the anterior belly of digastric and the anterior temporal. Right and left muscles were recorded simultaneously. Bipolar surface electrodes were used for the masseter and anterior digastric muscles and hook electrodes were used for the anterior temporal muscle. In each case the interelectrode distance was 20mm.

3.4.2 Polygraph.

In nearly all cases the amplitude of the EMG signal did not exceed several hundred microvolts. In order to provide a recordable EMG signal each electrode output was amplified by means of a Polygraph (Grass Instruments, Mass, USA) which also provided a continuous tracing of chart paper for each channel. Monitoring the signal in this way enabled the operator to achieve and maintain a satisfactory recording level of the muscle activity. Optimal electrical signals were ensured by keeping the electrode leads as short as possible and providing an earth lead attached to the subject's arm. The vertical and horizontal jaw displacements were also traced by the Polygraph.

3.5 HARDWARE.

In this investigation a computer system was used for the recording and storage of data and its off-line analysis (Appendix 3).

a) The main computer - a PDP-11 with:-
  - visual display unit for clinical use;
  - visual display unit for daily use;
  - analogue to digital converter;

Mass storage units
  - internal hard disk;
  - external floppy disk;
  - streaming tape;

b) Graphical output devices - Hewlett Packard 7550A;
  - NEC APC IV

c) Printer - NEC Pinwriter P5300;

d) Personal computer - NEC APC IV.

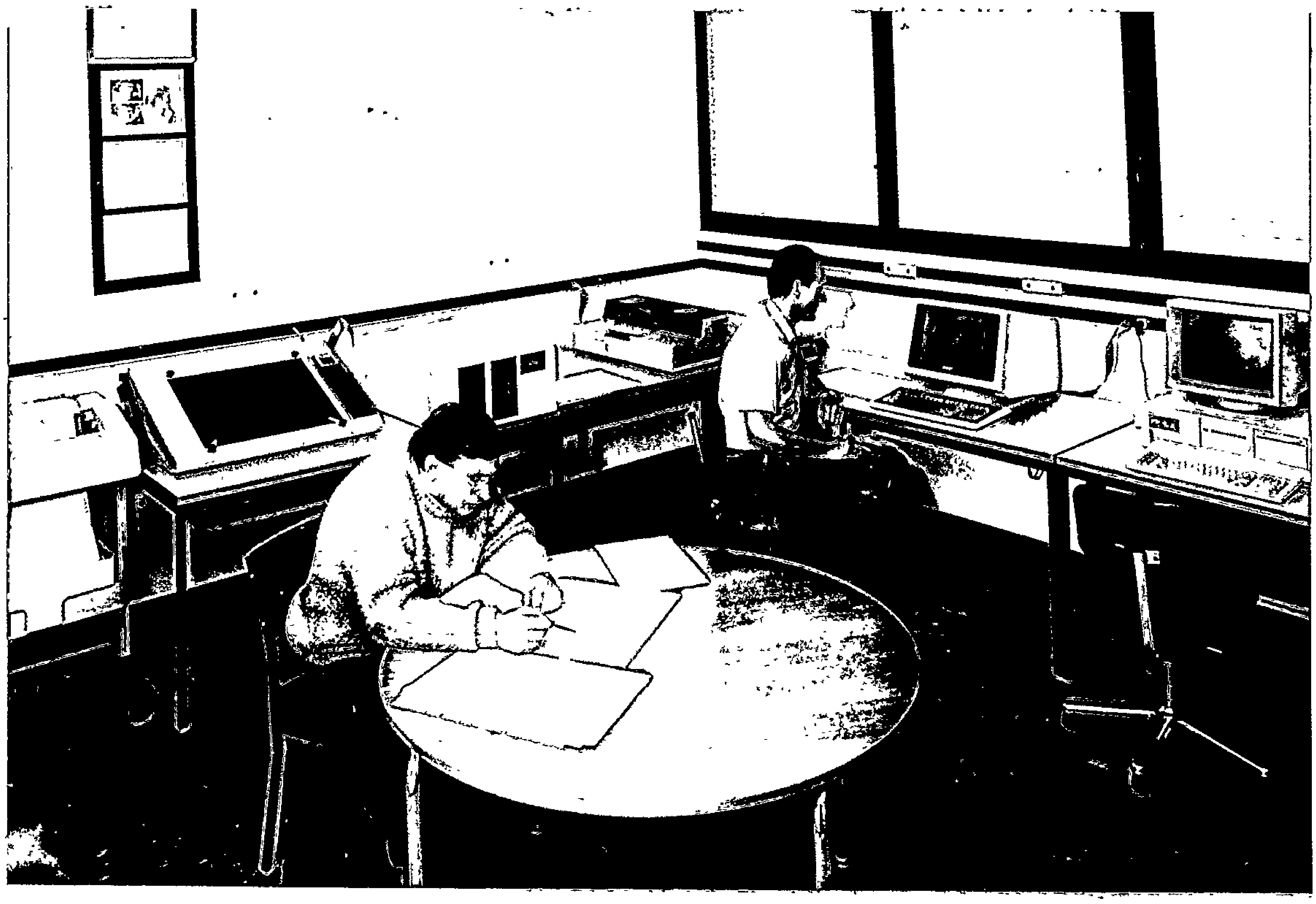

Figure 3.2 The computer hardware.

3.5.1 PDP-11 Computer.

The PDP-11 used in this study was built by General Robotics (Australia) Pty Ltd, to satisfy our requirements of data collection and storage. This computer was responsible for the on-line storage of EMG and jaw tracking information. The computer was based on an LSI 11/23 CPU and three storage media were available:-

i) Internal hard disk. This was a 128 megabyte hard disk with 512 kilobytes of RAM and a 16 channel analogue to digital converter.

ii) Floppy disk. Eight inch floppy disks were used to store the reduced data files.

iii) Streaming tape. This was used for storage of the raw data from the hard disk.

Under the control of specific software, the EMG and jaw tracking data raw signal was stored on the disk. The data was passed through a Butterworth filter to reduce background noise and to compensate for the asynchronous nature of the muscle depolarsation. The raw EMG data was always backed-up and stored onto streaming tape. The raw data was later rectified and integrated and this will be described in detail later (see section 3.6).

3.5.2 Clinical Visual Display Unit.

One display unit was situated in the clinical area and was directly linked to the PDP-11 in the computer room. It was located in the clinic to facilitate the input of the subject's details onto the main data files during each recording session. This information was stored on the main 'header' file for each subject session. An instant replay of the recorded EMG was also available on this visual display unit if required.

3.5.3 Analogue To Digital Converter.

An analogue to digital converter is essential for a digital computer to communicate with analogue or continuously variable signals found in the outside world. The system used was a 116 A/D converter, (Grant Technology Systems Co, 11 Summer St, Chelmsford, MA 01824 USA).

The A/D converter is responsible for 'changing' the analogue or electrical EMG or jaw tracking signal into a digital form. This was required to allow the computer to acess the information. The A/D converter used has an input voltage range between +5 volts and -5 volts and a possible maximum sampling rate of 35,000 conversions per second. There were 9 channels of data to be sampled and converted: 6 channels of EMG and 3 channels of jaw movement data. The computer required a sampling time of 600 microseconds to convert the data signal from all channels and a further 400 microseconds to transfer the digital data to the computer's hard disk. This resulted in a total sampling time of 1,000hz. In order to allow storage of the digital signal, without fear of loss of information, a double buffer system was utilised. This meant that the digital signal was stored directly into one buffer. When this buffer was full, the second buffer was used and the information from the first buffer was passed onto the computer hard disk. This enabled continuous storage of information for a maximum of nearly 90 minutes.

3.5.4 Visual Display Unit.

The visual analysis of the data was carried out on the console of the PDP-11 which controlled the computer to perform the analysis of the figures from the data base. Changes or additional information to the subject-related data, made at the start of each recording session, could be altered outside the clinic, using this terminal. The restoring of archived data was also made with this console. This was completed before the information was outputted and graphically displayed using a Hewlett-Plackard 7550A plotter.

The NEC APC IV personal computer (see 2.5.6) could also be used as a console for the PDP-11 if necessary.

3.5.5 Graphic Output Devices.

3.5.5.1. The main graphics device was a Hewlett Packard plotter 7550A. This had an automatic paper feed and the facility to use standard sheets of either A3 or A4 size paper. This unit was used to plot the "PLOT K", "OVERLAy" and "STROKE" graphics programs (see section 3, 4 and 6). These were controlled by the software packages of the PDP-11 computer. The Hewlett Packard plotter was also directly linked to the NEC APC IV to provide graphical output of the statistically analysed data.

3.5.5.2. The NEC APC IV microcomputer provided a means of instantly forming graphs, histograms and charts of the data formed as a result of the statistical analysis, using the software of the SAS program. This enabled the operator to have full control over the display of the graphs before the final output was made onto paper.

3.5.6 Personal Computer.

An NEC APC 1V personal computer was used to provide a means of statistically analysing all of the data using the "SAS" program (SAS Institute Inc, SAS Circle, Box 8000, Cary NC 27512-8000). Communication between the PDP-11 and the NEC APC IV was achieved using the public domain program KERMIT. This enabled the transfer of all of the reduced subject files to the hard disk of the personal computer. The flexibility of the NEC APC IV meant that the information could be handled and grouped in order that appropriate statistical analyses could be applied. All of the data output from the NEC APC IV was made either through the graphics devices or via a NEC Pinwriter P5300.

3.6 SOFTWARE.

A series of complex software programs were used to produce and analyse the large volume of data that was acquired as a result of clinical recordings. These programs were constantly tailored to meet the requirements of the current projects.

The computer package DAOS was used to control the A/D converter and enabled acquisition of the digitised data and facilitates the display on the visual display unit. The other computer programs were written in FORTRAN. All of the programs were controlled by simple command input via the console to the PDP-11 computer. The data recorded during a clinical session was handled by a specific sequence of programs at the instruction of the operator. The sequence was as follows:-

1) Data Acquisition
2) Data Reduction
3) Data Analysis
4) Data Processing

3.6.1 Data Acquisition.

Several different programs were used to gain access to the data for storage and later analysis.

3.6.1.1 HEAD. This program created a new file on the hard disk which stored information about the subject and the recording session. This file was appended to each individual recording during a particular session. The intention was to enable the content of the file to be easily identified. The file included details of the subject's name, their address, the date of the recording session, the reason for the recording session and details of the people present and supervising the recording. The initials of the subject were used to identify the file which recorded the sequence of the jaw movements and the type of food that was used.

3.6.1.2 CHANGE. It is inevitable that mistakes may occur in the filing of information during a recording. This program was developed to allow the operator to modify or change the header file where necessary at a later time or date. This was usually completed before the data was analysed.

3.6.1.3 ENTGNS. At the end of each recording session, the gains on the amplifier of the Polygraph were carefully recorded for the EMG of each channel and stored in all file headers. This allowed the correction of the EMG data base to ensure that the amplification and rectification of each signal was proportional and accurate. This meant that analysis and display of the EMG data could be made in absolute as well as relative terms.

3.6.1.4 GET. This short program in DAOS allowed the acquisition of the data during each recording session. It also enabled the operator to modify the header file and correctly record the order in which the jaw movements were carried out. The Polygraph enabled the amplification of the data before it was written to the hard disk to form the raw data file.

3.6.1.5 SEE. After recording the data this program enabled the operator to display immediately up to 2 seconds of data from any 2 channels on the screen. In this way problems in the collection of the data could be identified at the completion of each recording sequence and allow it to be repeated. It also helped ensure that the recording levels of data were not compromised due to operator error or poor electrical contact.

3.6.2 Data Reduction.

3.6.2.1 REDUCE. The program REDUCE was necessary to condense the data into a more manageable size for analysis. It was carried out for all data files recorded for both EMG and jaw tracking data.

EMG data was first rectified to its absolute value. A running average was made by finding the mean value of five consecutive EMG values. This created a file which was reduced by a fifth of its original size. The data was then filtered using a Butterworth filter which smoothed the data and created a form of integrated signal with a cutoff frequency. In this study a cut off frequency of 20Hz was selected after extensive comparison with raw EMG and equivalent electronic (rather than digital) integration.

For the movement data a five point median filter was passed through the data. The data was sorted in ascending order of magnitude and the median value taken to be representative of the whole. This was used in preference to the mean value as it maintains the sharp edges of the data values and it was these which were found as a consequence of rapid jaw opening and closing movements during chewing. This whole process meant that the initial recorded data was reduced in size by a factor of five. The data was then labelled by the suffix .RED and filed. It was this that was used for all subsequent data analyses.

3.6.2.2 ZEROAD. This program was developed to ensure that the data was adjusted to an appropriate baseline. At the beginning of all jaw movement recordings, the Sirognathograph was adjusted to 'zero' with the subject's teeth in the 'start' position or centric occlusion. If for some reason complete tooth contact was not achieved, the end point of the jaw tracking information would not be the same baseline value as the minimum closure found during chewing and there would be inaccuracies in the data processing. The ZEROAD program corrected for any small changes in this zero position. The program did this by searching through the vertical jaw movement data to find its minimum value. All jaw movement data was then related to this value which was taken to be the 'zero' and data could be continued.

3.6.3 Data Analysis.

3.6.3.1 SPLIT. This program searched the jaw movement data in the reduced file and identified the boundaries of each chewing stroke. The program initially identified each point of intercuspal position. This was taken to be the reference point from which all jaw measurements were made. The beginning of the stroke was taken to be the point where the vertical jaw movement started to take place. The boundary of each stroke was defined as the boundary between one stroke and the next. The program also assessed each chewing stroke and evaluated up to 19 different measurements for later examination. These parameters included:-

a) maximum vertical, lateral and horizontal displacement,
b) maximum velocities during opening and closing movements,
c) time from the start of movement to maximum opening and closing to occur,
d) total stroke time and dwell time between strokes,
e) time to achieve maximum open and close.

These numerical values were added to the header of each data file so that they could later be analysed.

3.6.3.2 EXAMINe. Each of the numerical parameters that were originally identified by SPLIT could be visually displayed using EXAMINe. This program allowed the operator to identify the strokes that were to be rejected from later statistical analysis. Some were rejected for the following reasons:-

a) Stroke closure that did not occur on the requested side during unilateral chewing.

b) Irregular closure pathway.

c) Unusually long or zero dwell time that was uncharacteristic for that subject.

d) Strokes that showed an unusually small minimum opening.

For the majority of the files, it was hoped that there would be a minimum of 10 strokes available for statistical analysis. This was true in most cases. Using the numerical data from EXAMINe to accept or reject strokes, the selection was completed with the aid of the displays from STROKE, OVERLAy and PLOT. The individual strokes and the statistical data were then printed in a table (see Appendix 5).

3.6.4 Data Processing.

3.6.4.1 PLOTK. This program displayed all of the jaw movement and the EMG data for each chewing stroke, identified by the SPLIT program. It facilitated the analysis of the data and provided a visual means of relating the different channels of data to one another. The data were displayed as a continuous trace for the duration of the recording and the display was arranged so that the jaw displacement traces were placed at the top of the page with the muscle EMG values below (see Appendix 6). The scale along the bottom of each page indicates the time of the movement in seconds from the start. Three dimensions of jaw displacement data were represented: the X, Y and Z channels. These displacement traces were superimposed along a single axis to facilitate assessment of the sequential timing of each movement. The paired EMG muscle traces were also superimposed on one another according to the muscle from which the recording was taken. The temporal muscle recordings were grouped together for both the right and left sides. The digastric and masseter muscles were represented in a similar way. The plots from this program, when combined with the selected strokes from EXAMINe, formed the basis for which all of the data were analysed and used for the program STROKE.

3.6.4.2 STROKE. This program displayed the individual chewing strokes in sequence, for each of the chewing cycles recorded. Plots in frontal, horizontal and sagittal planes were represented separately so that it was possible to analyse the direction of the individual strokes and the integrity of each chewing cycle (see Appendix 7). This program aided the implementation of the EXAMINe program.

3.6.4.3 OVERLAy. OVERLAy was a program that plotted jaw movement traces in the frontal, horizontal and sagittal planes. It differs from PLOTK in that it does not include any EMG traces. OVERLAy plots the individual strokes over one another on a true scale. The representation is of all accepted strokes resulting from the implementation of the EXAMINe program (Appendix 8a-8b).

3.6.4.4 MOVGRP. The MOVGRP program displayed the jaw displacement data for those strokes accepted under the EXAMINe program. Means and standard deviations for all parameters were also available. These parameters included such values as:-

a) maximum displacement in the vertical, horizontal and sagittal planes,

b) time of maximum displacement with respect to the beginning of the stroke,

c) time of the 50% displacement with respect to the beginning of the stroke.

3.6.4.5 EMGTAB. The EMGTAB program was used to tabulate the EMG data from those strokes accepted under the EXAMINe program. Numerical values for each muscle were available for the following parameters:-

a) maximum amplitude,
b) 50% of maximum amplitude,
c) 50% of maximum growth and 50% of maximum decline.

Means and standard deviations for each parameter were also printed to give access to the EMG data.

3.6.4.6 Other programs used. Commercially available programs which were utilised for the transmission of data from one computer to another or to facilitate further analysis of the data - KERMIT and SAS.

i) KERMIT. This is a public domain program which permits the transfer of data or files from one computer to another using a serial interface for this transfer to take place. In this study, it was used to transfer files from the PDP-11 to the NEC APC IV. The header files from EXAMINe were transferred to the NEC APC IV where the powerful SAS statistics program could be used to help the analysis of the data. This program was an important communication interface between the different types of hardware.

ii) SAS. The Statistics Analysis System or SAS (SAS Institute Inc, SAS Circle Box 8000 Cary NC 27512) is a suite of computer programs which were run on the NEC APC IV personal computer. It is a complex and comprehensive statistics package which has the facility to allow the examination of data and to perform on these selected statistical analyses. Within the package, ANOVA tests, Student 't'-tests, Mann-Whitney U tests and many other statistical tests are available. For the purposes of this study particular use of the student test and the ANOVA were made. The graphical output from

SAS was also available through:-

a) Screen display in colour of the graphs, charts or histograms.

b) Printed numerical data via the NEC 7550a printer.

c) Screen 'dump' to the Tectronics plotter 4696.

d) Screen 'dump' to the Hewlett Packard 7550a colour pen plotter for high quality output.

3.7 EXPERIMENTAL PROCEDURES.

3.7.1 Subject Examination.

Twenty-eight subjects were asked to participate in this study. Twenty-six subjects volunteered to take part in the initial clinical examination which formed the basis of the selection procedure. A thorough dental clinical examination following the standardised procedure of the Orofacial Pain and Dysfunction Clinic (Appendix 2) was carried out. The results of this examination were used as the basis for the subject selection or rejection. The criteria for selection were:-

a) unrestricted and fluent jaw movements,

b) no myofascial pain or temporomandibular joint dysfunction,

c) Angle's Class 1 incisor relationship,

d) a minimum of 26 natural teeth,

e) no dental extraction within the last 12 months,

f) no restorative procedures to be carried out during the recording period,

g) no relevant medical history.

The criteria for exclusion of subjects were:-

a) history of trauma to the temporomandibular joint or the facial skeleton,

b) medical history which may include conditions that are normally felt to compromise regular dental treatment eg hypertension, diabetes, steroid therapy,

c) subjects who appeared to be apprehensive or anxious about any of the described procedures.

If the subject satisfied the above selection criteria, they were invited to take part in the study and to complete the consent form. Twenty subjects, 10 male and female, participated. The age range of the males was 19 to 63 years (mean age = 35.2 years) and the age range for the females was 22 to 56 years (mean age = 36.9). The initial examination of each of subject ensured that each person satisfied the above criteria and that they were familiar with the equipment that would be used during the recording. This would try to minimise the possibility of apprehension during the recording session.

3.7.2 Assembly of EMG Recording Equipment.

The recording equipment was assembled while the subject was comfortably seated in the dental chair. However, all recordings were carried out while the subject was seated in a custom-made wooden chair with a head support.

3.7.2.1 Skin preparation. Before the electrodes were placed, the surface of the skin was abraded with waterproof silicone carbide paper and wiped with 70% alcohol. This was carried out to remove all dead skin cells and surface oils from the skin to ensure an optimal skin contact with the electrodes.

3.7.2.2 Positioning of the electrodes. Bipolar surface electrodes were used to record EMG signals from masseter and anterior digastric muscles and hook electrodes were used for the anterior temporal muscle. In all cases bilateral muscle recordings were made from each muscle pair. The electrode position was determined by direct muscle palpation and they were located over an area of optimal muscle bulk.

Figure 3.3 A subject with surface electrodes positioned over the right masseter and anterior digastric muscles and hook electrodes positioned within anterior temporalis muscle.

i) Two surface disc electrodes, with an interelectrode distance of 20mm, were placed over the masseter and anterior digastric muscles bilaterally (Figure 3.3) Each electrode was secured into position using colloidin adhesive gel (Medical Applications Buffalo Road, Gladesville). As the colloidin dries, it contracts to provide an intimate contact with the skin surface (Lippold 1967). Conductive gel (Smith & Nephew Pharmaceuticals Ltd, Welwyn Garden City, Herts, England) was injected between the elevated part of the disc and the underlying skin.

ii) Intradermal hook electrodes were used in all instances within the hairline to ensure the electrodes were secure and thereby minimise the possibility of background noise (Figure 3.3). A plastic block, 20mm in width, was used to maintain a precise inter-electrode distance. This block was held over the midpoint of the first electrode and used to locate the midpoint of the second electrode. This method was felt to be more accurate than using a calibrated measure.

All electrode leads were secured with adhesive tape close to the subject's head and neck. This prevented movement of electrode wires and reduced the possibility of the electrodes being displaced, which may have occurred if the subject inadvertently moved the head between or during a recording procedure.

3.7.2.3 Connection to the Polygraph. The "plug-in" board, located behind the head rest of the wooden chair provided the connection of the electrodes to the Polygraph. When the subject was comfortably seated in the chair, the electrodes were carefully placed in order into the board (Figure 3.4). To prevent earth loops, the subject was earthed using a large copper mesh electrode contacting the subject through a gauze dressing soaked in saline. This was firmly attached to the subject's forearm with straps. The copper mesh was also connected to the "plug-in" board.

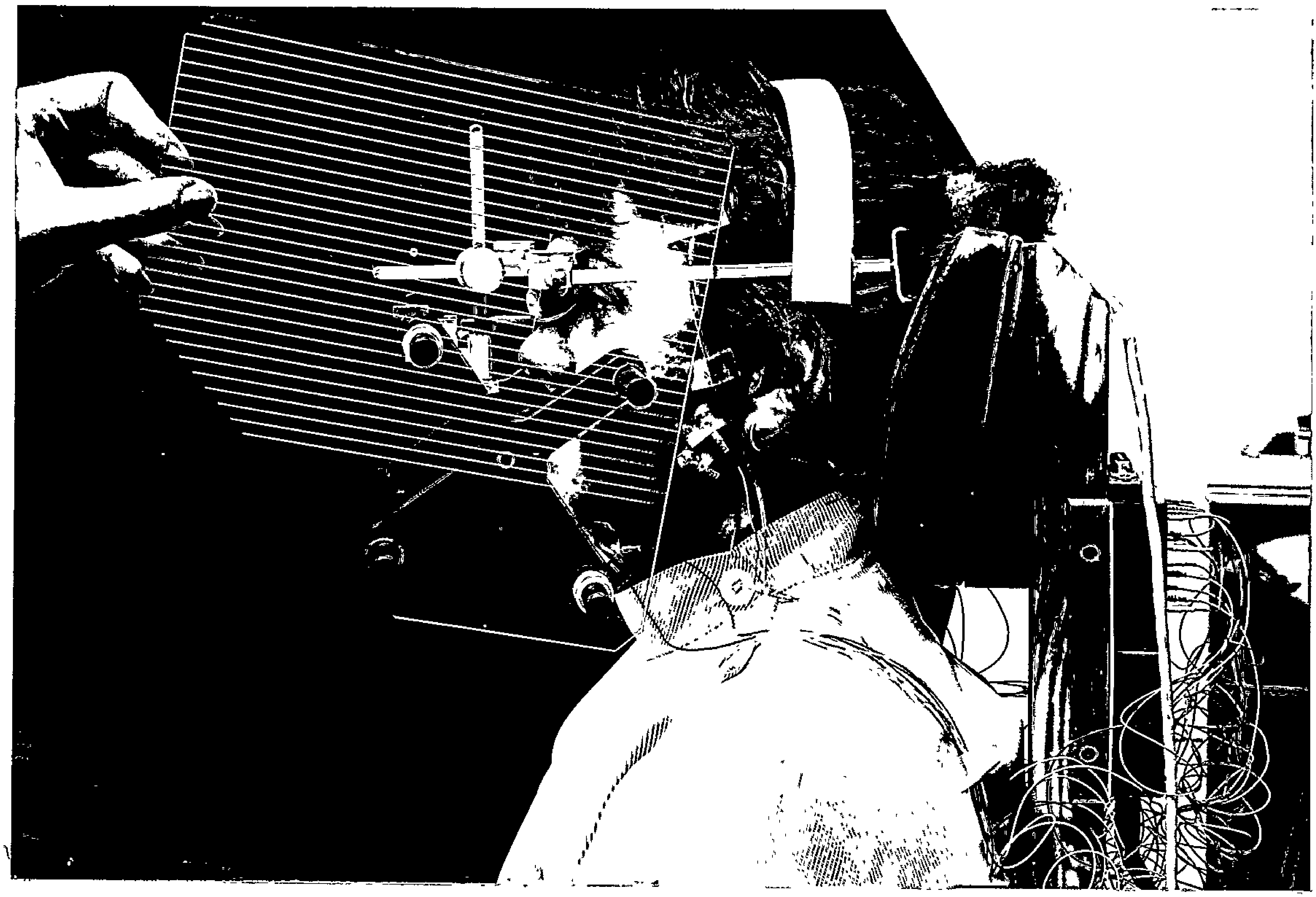

Figure 3.4 Connection of the electrode wires into "plug-in" board at the back of the wooden recording chair.

All connections to the Polygraph were visually tested by asking the subject to carry out simple jaw movements and to clench their teeth while the amplified signals were displayed on the Polygraph. This provided an indication of the amplitude of the individual EMG signals to be assessed so that the amplification could be modified if necessary. Where excessive background noise or an inadequate recording level was observed the electrode conductivity was checked. In some cases it was necessary to inject more conductive gel beneath the electrode or to improve the electrode connection to the skin or reposition the electrode. When a satisfactory electrical signal was achieved the recording session was commenced.

3.7.2.4 Recording of the electrode coordinates. The precise location of each electrode was noted (Figure 3.5) in order that its position could be re-established for the second recording session. This was carried out with the help of a plastic grid developed especially for this task (Murray & Klineberg, 1981). It was constructed from two sheets of Perspex hinged in the middle and orientated to two main reference points. A teflon ear-piece was located in the external auditory meatus and the upper line of the grid was orientated along the tragus - outer canthus line. The surface of the grid was marked with a series of parallel lines which were aligned with the centre of each of the electrodes. Each line was labelled with numbers which facilitated the recording of exact coordinates for each electrode, which were used as future reference points. The coordinates for each electrode were noted and retained in the subject's file for the next recording session. This method was, unfortunately, only suitable for the masseter and anterior temporal muscles. The relocation of the surface electrodes for the digastric muscle was performed by muscle palpation.

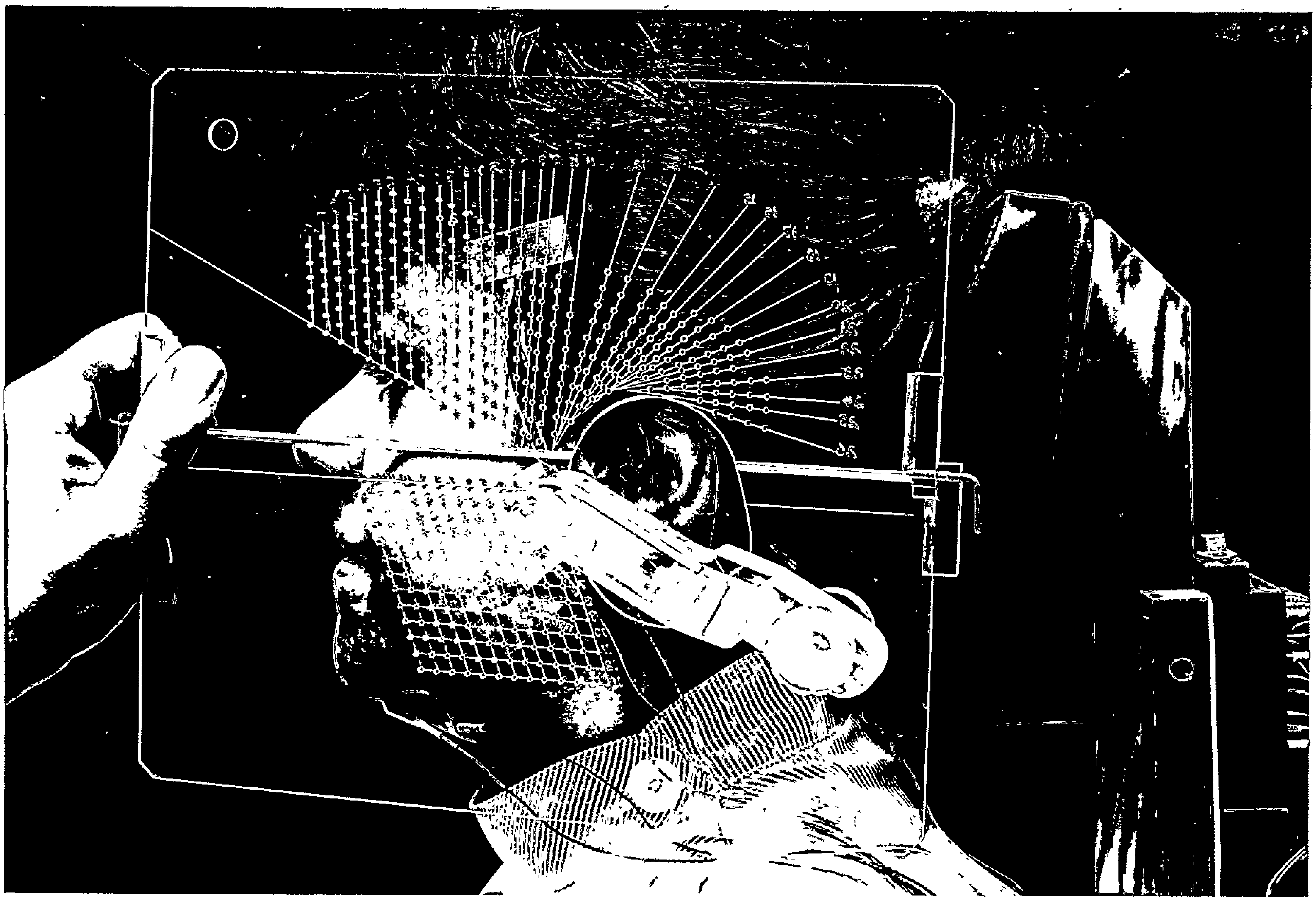

Figure 3.5 Recording the coordinates of the EMG electrodes using a purpose built Perspex grid.

3.7.2.5 Positioning of Sirognathograph Magnet. The magnet of the Sirognathograph was carefully cemented onto the labial surface of the lower incisor teeth (Figure 3.6). The area was isolated with cotton wool rolls and dried. The midline of the magnet was aligned with midline between the two lower central incisors. This point was selected regardless of whether the upper and lower midlines corresponded exactly. The protective cover of the magnet was divided into red and blue halves and the red half was orientated to the subjects right hand side. The orientation of the magnet was an essential part of the experimental technique. The magnet was placed parallel to the Frankfort plane in the horizontal plane and rotation of the magnet in the sagittal plane was avoided. The magnet was cemented with zinc phosphate cement. If it became dislodged during the procedure, the magnet was recemented using a thin lute of cyanoacrylate between the zinc phosphate layer and the teeth, thus ensuring precise relocation.

Figure 3.6 An intraoral view of the magnet of the Sirognathograph luted to the lower incisor teeth with zinc phosphate cement.

3.7.2.6 Positioning of the Sirognathograph headframe. The headframe of the Sirognathograph was carefully positioned over the subject's head and supported with adjustable straps (Figure 3.7). Care was taken to ensure that the headframe did not interfer with the wires of the electrodes. It was supported on the subject's nose with a customised nose support made from silicone putty material (Optosil, Bayer Dental Laboratories). This ensured that the headframe was stable. The nose-piece was labelled and retained for the subsequent recording to assist the accurate relocation of the headframe.

3.7.2.7 Orientation of the Sirognathograph sensor array. The sensor array of the Sirognathograph, which monitored the movement of the magnet on the teeth, was attached to the main headframe. It was precisely aligned so that the sensors were placed equidistant from the magnet and parallel to the Frankfort plane. The orientation of the sensors was aided by the use of an orientation jig containing four holes which allowed it to be placed over the four sensors (Figure 3.8). A series of horizontal lines across the jig were orientated to the Frankfort plane. Finally, the sensors were aligned by viewing from above to ensure that the sensors were in line with the magnet in the coronal plane. The sensor array was located in this standardised way.

3.7.2.8 Positioning of the subject. Once the magnet, headframe and electrodes had been correctly positioned, the subject was seated in a custom-built wooden recording chair. The chair was designed to provide the subject with good head support and to help maintain an upright posture. Its construction minimised electrical interference which was expected from a conventional dental chair. It was recommended that all electrical appliances and metal objects be kept at a distance of at least 1 metre away from the recording equipment (Siemens instruction manual for the Sirognathograph).

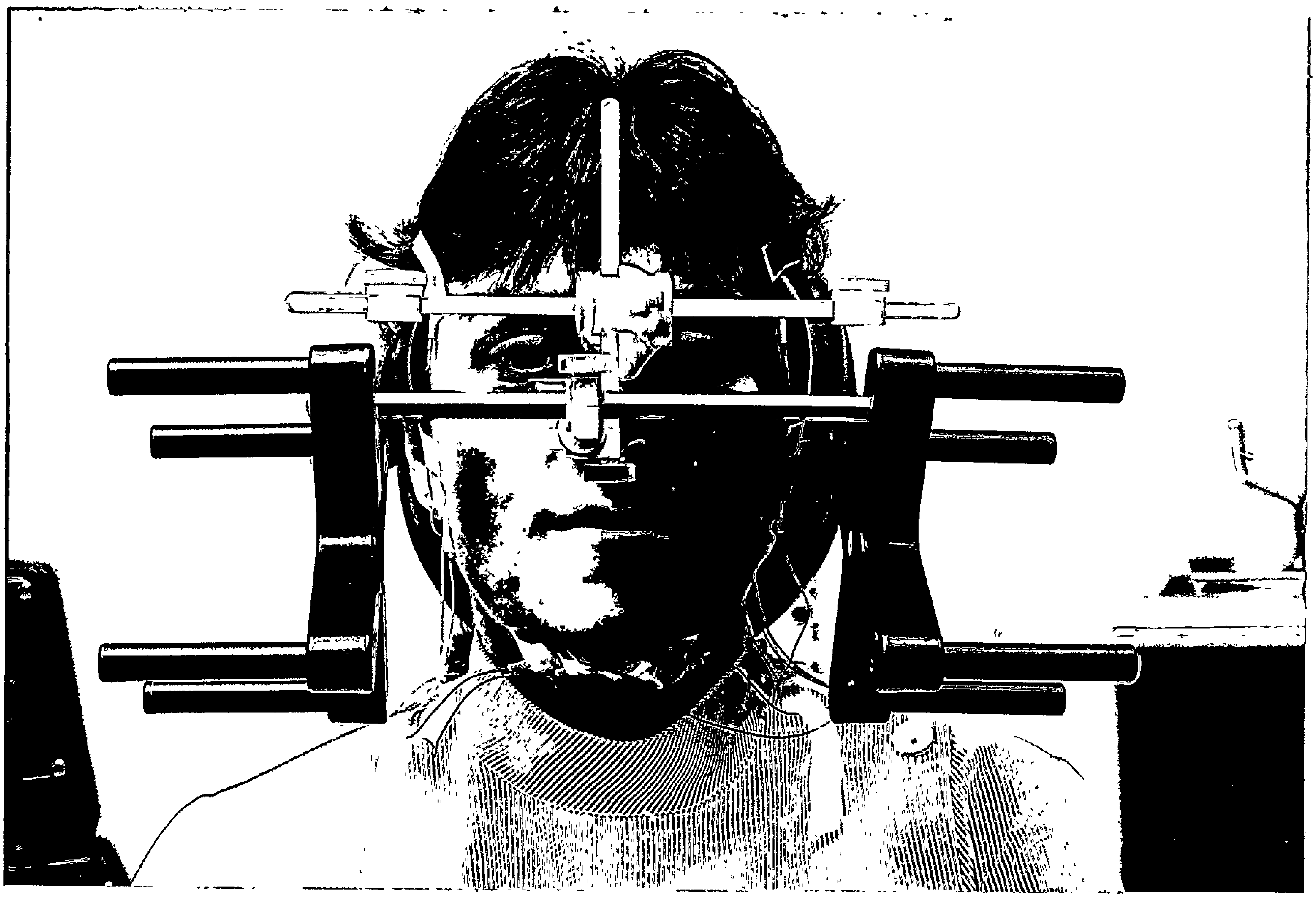

Figure 3.7 Subject with the Sirognathograph positioned.

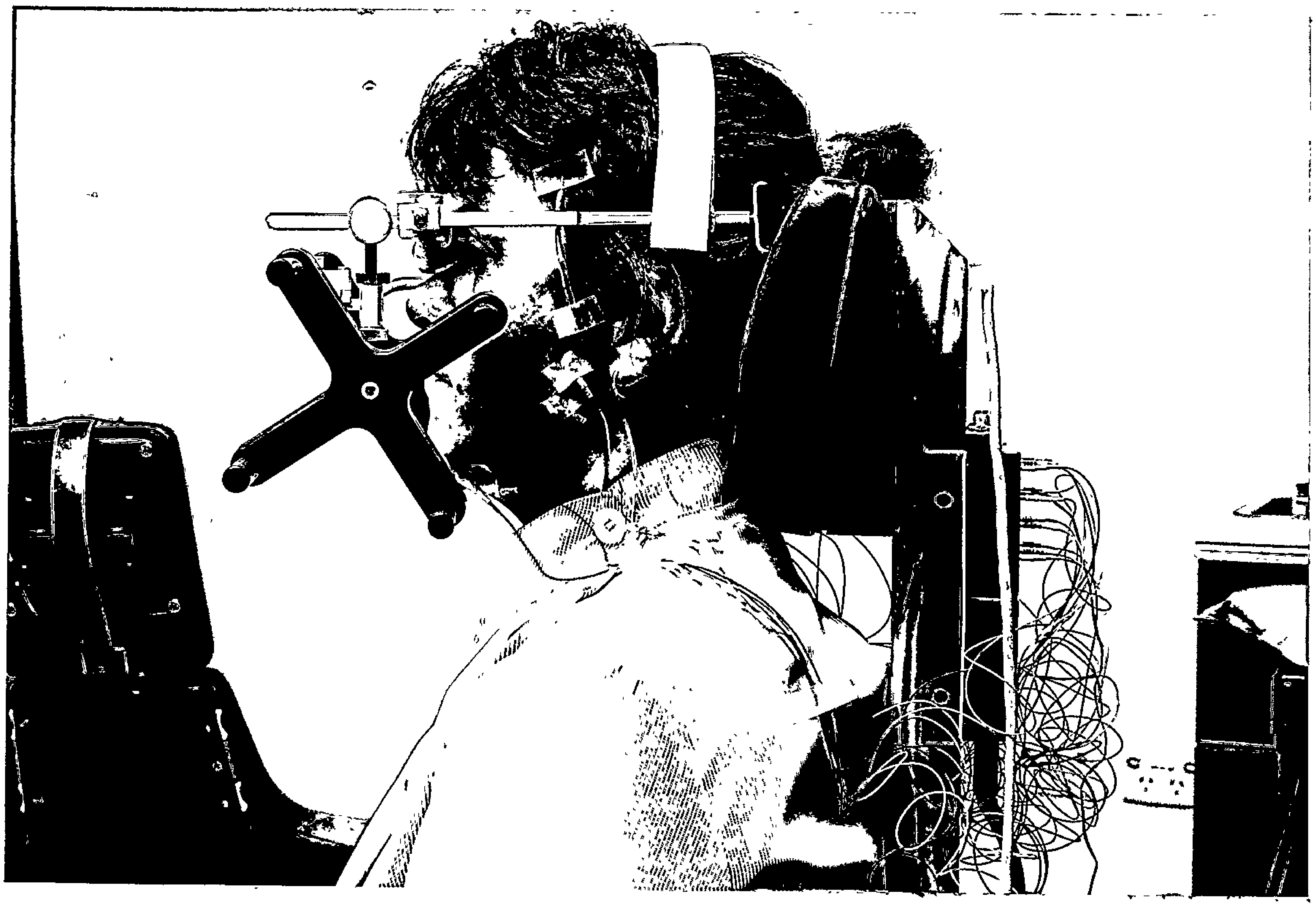

Figure 3.8 Alignment of sensor array; grid lines will lie parallel to the Frankfort plane.

3.7.3 Recording Protocol

After seating the subject in the wooden chair the recording procedure could begin. In every case the following procedures were ensured:-

i) The subject was made ready and asked to place the teeth in light contact in the intercuspal position. This was referred to as the subject's "start" position.

ii) The amplitude of the EMG channels was checked on the Polygraph.

iii) The computer was made ready and the personal header file for the subject was completed.

iv) It was emphasised to the subject that a constant head position should be maintained. A specific point in front of the person was identified to help them focus their eyes and avoid head movement.

v) The recordings were completed using the 'Get' command on the clinical console.

vi) A sample of the EMG output was checked via the 'See' command. This facilitated the viewing of 2 seconds of EMG data to ensure that an adequate signal was obtained.

Prior to an individual recording, a note of the task was recorded and saved as part of the computer file. Each subject was asked to perform a sequence of movements and chewing tasks with gum and nut, which were standardised for every subject. These included a range of jaw movements as well as maximal muscle activities. The standard recording procedure was followed for all subjects on each of the recording sessions. Each jaw movement was carefully explained and practised to ensure that the subject was confident and capable of carrying out the requirements. The jaw movements carried out were designed to provide a comprehensive range of jaw displacement and muscle activity to allow a complete analysis.

When chewing movements were recorded, the chewing gum and peanut were placed in the centre of the dorsum of the tongue with the aid of plastic tweezers. First a standard half stick of gum was used for each chewing action and was restricted by the operator to approximately 15 chewing strokes. This was felt to be an adequate number to provide a representative selection of chewing strokes. Next, one half of an unsalted peanut was chewed until the subject swallowed. A minimum of 12 chews were desirable. All chewing movements were recorded twice within the same recording session and a resting period of 30 seconds was allowed between each chewing cycle, to reduce the possibility of muscle fatigue. After each of the chewing actions with the peanut, the subject was offered a drink of water to clear any fragments of nut that remained in the mouth. Each recording session was limited to a maximum of 90 minutes.

In summary, the sequence of performed tasks was:-

Maximum intercuspal clench.

Maximum incisal contact clench.

Opening against resistance.

Posselt's envelope of movement in the frontal plane.

Posselt's envelope of movement in the sagittal plane.

Sliding tooth contact during protrusive and lateral movements.

Chewing gum on the subject's preferred side and on the right and left sides (repeated).

Chewing nut on the subject's preferred side and on the right and left sides (repeated).

A total of 20 separate chewing movements were recorded for each subject.

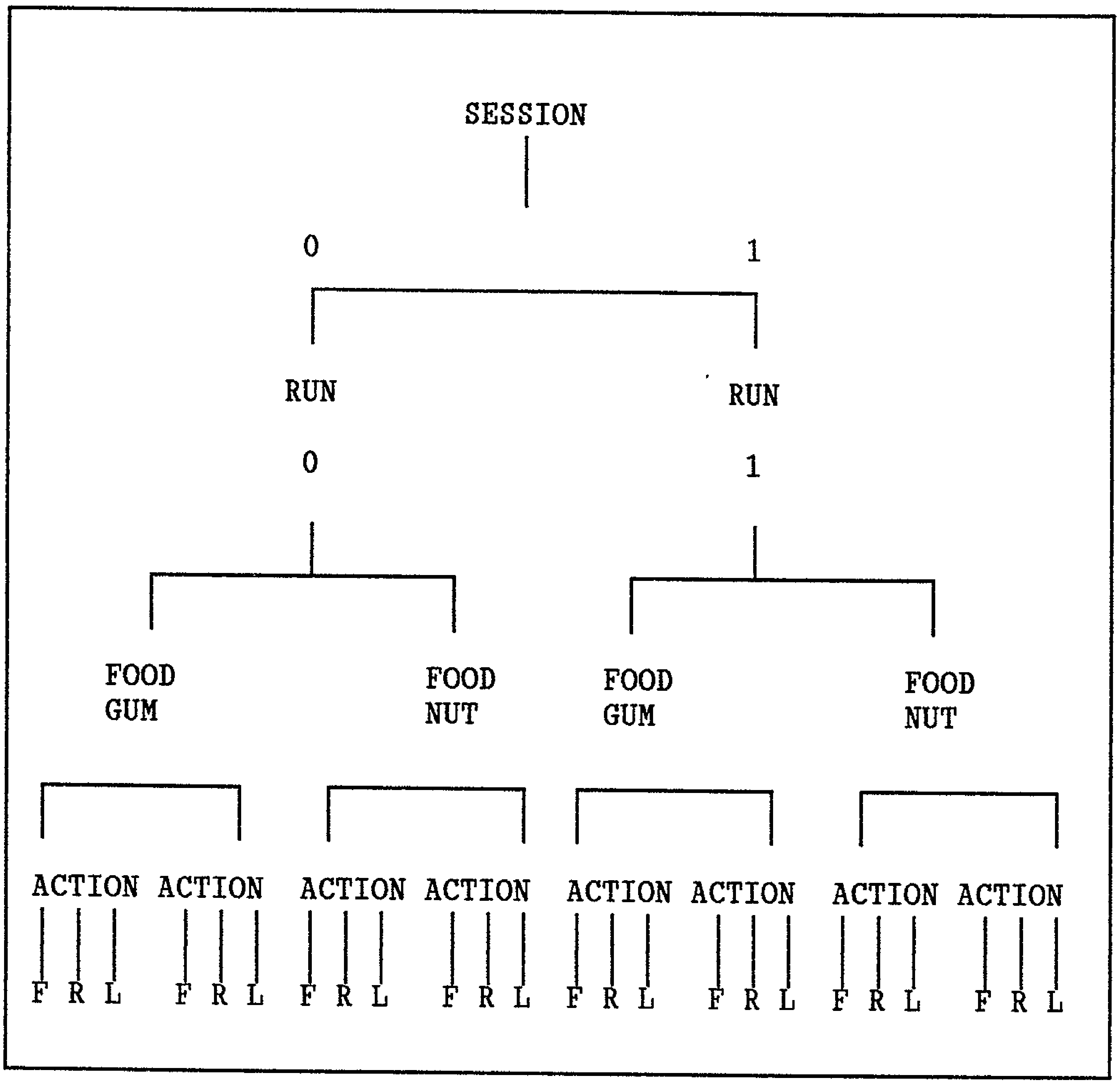

Figure 3.9 A chart to show the full sequence of chewing recordings made for each subject. Actions include free choice chewing (F), right chewing (R) and left chewing (L).

At the conclusion of each recording session the muscle activity was recorded at maximum clench to ensure that the electrode contact with the skin had been maintained. The coordinates of the masseter and anterior temporal muscle electrodes were noted and recorded in the subject's file.

3.7.4 Data Analysis

At the conclusion of the recording procedure, a detailed analysis of the data began. The whole process required more than 15 hours of computer processing for each recording session. The sequence of events for each was as follows.

3.7.4.1 Data Storage. All the raw data files were backed-up onto streaming tape. This meant that all the files could be restored if they were unintentionally lost from the computer's hard disk.

3.7.4.2 Data Reduction. The raw data files were reduced to one fifth of their original size using the REDUCE program (see section 3.6.2). This facilitated further data analysis and enabled easy storage of a number of files on the computer hard disk. The reduced files were all archived onto eight inch floppy disks.

3.7.4.3 Data Display. There were two main graphics programs which were used visually to represent the data: PLOTK and OVERLAy (see section 3.6.4).

3.7.4.4 Data Analysis. The numerical values for the reduced data files from the EXAMINe program were used in conjunction with the graphical display of the data from PLOTK and OVERLAy programs to enable the rejection of unwanted strokes from the data base according to the criteria previously described (see section 3.6.2).

The program EXTRAC collated the data into male and female files. These data files were transferred from the hard disk of the PDP-11 to the NEC APC IV using KERMIT (see 3.6.4). Thus two data files, FEMALE.EXT and MALE. EXT were created on the NEC APC IV computer. The files were transferred to the APC IV in such a way so that they could be analysed by SAS. After the files had been successfully transferred, they were concatenated (or combined) to form one file. PEOPLE.EXT using the MSDOS COPY command.

In order that the SAS program could be applied to the data, the PEOPLE.EXT file was converted from an ASCII-type data file into a SAS data set called POPULUS.SSD. The full facility of the SAS program could then be utilised to examine the data and give graphical representation of the analyses. Plots of the data could be made of one parameter against the other using the visual display unit of the NEC APC IV. This enabled quick visual correlations to be made in addition to the available statistical comparisons.

The data was analysed to test the reproducibility of the recording procedure and four main variables were selected to help identify this; RUN, SESSION, FOOD and ACTION. The differences within a single recording (RUN) and the between recordings (SESSION) were assessed. These two measurements would give some indication on the reproducibility of the chewing action according to a change in time. These were referred to as the intra and inter-sessional differences respectively. It was expected that differences in the recordings would occur as a result of the type food chewed and way in which it was chewed. This required the further analysis of the results on the basis of FOOD and ACTION to assess the relative importance of these two parameters on the results. For a more detailed analysis, the chewing movements were examined in detail and measurements made for each of the chewing strokes. There were ten separate measurements made for each subject as identified by the EXAMIN program. These included 5 different timing movements, 2 velocity measurements and 3 displacement measurements:-

a) total time of chewing movement (timetotl),

b) time for opening movement (timeopen),

c) time for closing movement (timeclos),

d) time for intercuspal pause (timedwel),

e) time for complete chewing stroke (timemove),

f) maximum velocity for opening stroke (maxopvel),

g) maximum velocity for closing stroke (maxclvel),

h) anteroposterior displacement range (aprange),

i) horizontal displacement range (latrange),

j) vertical displacement range (verrange).

Using the SAS statistical procedure, PROC MEANS gave mean values, standard deviations for each parameter and PROC GLM (General Linear Model) carried out an Analysis of Variance (ANOVA) on the POPULUS.SSD data file (Figure 3.10). A comparison of the means was made using the SAS student t-test and a confidence limit of 95% or 0.01 was taken as the significance level. Variance tests were carried out to ascertain the level of importance for the RUN, SESSION, FOOD or ACTION on the reproducibility of the results.

Finally, the use of PROC GCHART and PROC ANNOTATE, enabled high quality graphs to be produced of the analysed data. These graphs could either be produced on the screen of the personal computer or as a hard copy via the Hewlett Packard 7550A plotter.

A simple BASIC language program was written to display the individual variation in the mean values for each person when calculated on the basis of RUN, SESSION, FOOD and ACTION. The twenty-four possible variations in sequences of recordings were plotted side by side to give a scatter-plot for the twenty individuals. The plots show not only mean values but relationships of the individual's data in relation to the mean and plus or minus one standard deviation or plus or minus two standard deviations of that mean (Figures 4.1-4.10).

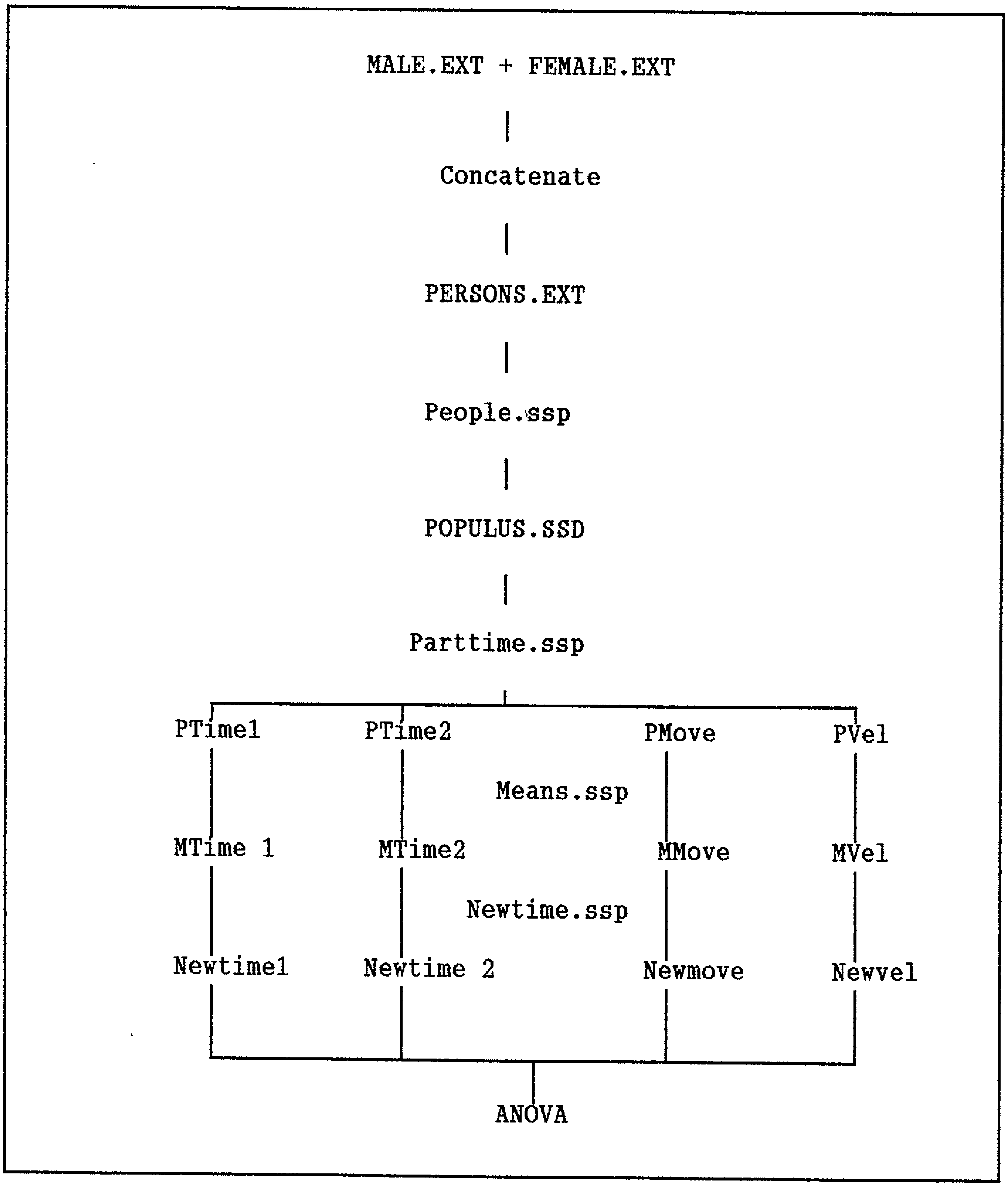

Figure 3.10 A chart to show the sequence followed in the calculation of results from the data files.

4. RESULTS

The jaw tracking movement recordings of 20 individual subjects were analysed on the NEC APC IV personal computer using the SAS statistics program (section 3.7.4.4). For each subject, data were analysed for two recording sessions and within each recording session the movement tracings were repeated to give a total of twenty-four chewing movements to be analysed. Four important variables were considered in the analysis of the results for each chewing stroke: the SESSION, the RUN, the ACTION of the chewing movement and the FOOD that was masticated. The SESSION related to the day on which the recordings were made and the RUN referred to the number of times a movement was repeated within a particular session. The chewing movements included chewing of nut and gum on the right and left sides and during free choice chewing movements. A comprehensive range of values could be analysed with the computer system available. For the purposes of this study, ten parameters were selected for analysis of each chewing movement. This provided a detailed examination of the results for the jaw movement tracings recorded.

T-tests were carried out for individual subjects to observe the level at which significant differences occurred between paired means. The GLM (General Linear Methods) procedure of the SAS statistics package performed an analysis of variance, ANOVA, to identify the level of significance for individual values. This level of significance was taken to be 0.001. A graded score was calculated for the variables SESSION, RUN, ACTION of chewing movement and the FOOD that was selected. This was carried out to find which factor influenced the variability of the recordings the most.

The results were extended to provide information on the whole subject group, the PEOPLE population (see section 3.7.4.4). The values for the PEOPLE group were calculated from the means of each chewing ACTION for each subject in order to provide an overall mean. All chewing strokes were repeated within a single recording SESSION. For the PEOPLE data set, a mean value for individual chewing strokes was used to evaluate the mean value for the population.

4.1 THE SUBJECTS.

Twenty subjects were chosen for the study with equal numbers of men and women. The details of the occlusal scheme for each person were recorded on the subject's file following the analysis of the examination sheet used in the Oro-Facial Pain Clinic of the Westmead Hospital Dental Clinical School (see section 3.7.1). The initials of the subject's name were used to identify the recorded files on the computer 'header' and also on the subsequent analyses programs that were carried out. Several criteria were used to select the subjects (section 3.7.1). A summary of the subject details are given in Appendix 4. The subjects recorded showed the following characteristics:-

SAB was 45 years old and had a total of 27 natural teeth with a canine guided occlusion and a chewing preference to the left side. There was an Angle's Class 1 incisor relationship.

SA had a Class 1 incisor relationship with group function and 25 teeth present. He was 35 years old and showed a preference to chew on the left side.

TC had 28 teeth with an overbite of 3mm and an overjet of 2mm. There was a preference to chew on the right side and there was canine guidance in lateral movements. He was 22 years old.

GC was a 50 year old lady who had a total of 28 natural teeth present with an overbite and overjet of 3mm and 2mm respectively. There was anterior guidance in lateral movements with favour to the right side during function.

CE demonstrated canine guidance in lateral excursions with a complement of 28 teeth. He preferred to chew on the left side. The overbite and overjet both measured 3mm and the subject was 23 years old.

SE was a 28 year old lady and showed canine guidance with 28 teeth. The preferred chewing side was to the right and the overbite and overjet measured 3mm and 2mm respectively.

RH had 28 teeth present and preferred to chew on the left side. There was an overbite and overjet of 3mm with canine guidance in lateral excursions. He was 35 years old.

AH was a 53 year old lady with a total of 25 natural teeth. There was anterior guidance in lateral movements and a preference to chew on the right side. An equal measurement of 3mm was taken for the overbite and overjet.

JH had anterior guidance on the right side and canine guidance to the left with a total of 24 teeth. The overbite and overjet were both measured at 3mm. He was 62 years old and habitually chewed on the right side.

SH was 35 years old and a had complement of 30 teeth. There was an equal overbite and overjet of 2mm and canine guidance on the right and left sides on lateral movement. She preferred to chew on the right side.

IG had 28 teeth with canine guidance. The habitual chewing movements were to the left. He was 32 years old and had an overbite of 3mm and an overjet of 2mm.

MJ was a 56 year old male who had 24 natural teeth with canine disclusion in lateral movements. The preferred chewing side was on the right. The overbite and overjet were both 2mm.

HK displayed a minimal overbite and overjet with group function in lateral movements. There were a total of 25 natural teeth with a preference to chew on the right side. She was 32 years of age.

DL was a 31 year old lady with a complement of 28 teeth. The overbite was 4mm and the overjet was 3mm with canine disclusion on lateral movements. DL preferred to chew on the right side.

AM had a total of 31 teeth and chewed habitually on the left. The subject was a 20 year old male and showed canine guidance in lateral movements with both an overbite and overjet of 1mm.

SM had an equal overbite and overjet of 2mm with a total of 32 teeth. She was 22 years old and had anterior guidance in lateral movements with a preference to the right side.

SMU was 26 years old with 26 teeth. There was canine guidance during lateral excursions and she had a preference to chew on the right side.

RS had a full complement of 32 teeth with an overbite and overjet measurement of 1mm. Canine guided disclusion was present and the subject preferred to chew on the right. He was 18 years old.

MS was a 44 year old lady with a preference to eat on the right. There was a total of 22 teeth with a minimal overbite and an overjet measurement of 1mm. Anterior guidance in lateral movements was evident.

GZ had an equal overbite and overjet of 2mm and a complement of 28 natural teeth. The lateral movements showed group function with a preferred chewing side to the right. The subject was 46 years of age.

4.2 THE ANALYSIS OF THE RESULTS.

The results for each subject were examined individually and ten different parameters were studied in detail. These parameters were selected to represent different aspects of the jaw movement. Four different parameters related to time during the jaw movement cycle were measured, including opening (timeopen) and closing (timeclos) phases of the movement as well as the intercuspal pause between chewing movements (timedwel). The timemove parameter was the sum of the opening and closing phases and the total time (timetotl) was the time for the whole chewing movement to be completed from one stroke to the next. All of these movements were measured in milliseconds (msec). The maximum velocity of the chewing movement was measured at two places; the opening and closing components (maxopvel and maxclvel respectively). These were measured in millimeters per second (mm/sec). The maximum displacement of the mandible during the chewing cycle was measured in the vertical, lateral and horizontal planes, in millimeters (mm). All of these values were calculated and printed by the EXAMIN program (Appendix 5).

The mean values, minimum and maximum ranges and standard deviations for each parameter were calculated for the subject group using SAS (Appendix 9). Separate mean values, minimum and maximum ranges and standard deviations were also calculated on the basis of FOOD for the same population (Appendix 10a and 10b). The overall mean values for PEOPLE were calculated on the basis of FOOD, ACTION , RUN and SESSION for each recorded chewing stroke (Appendix 11). The individual mean values for the 20 subjects were plotted against the mean and standard deviations for the PEOPLE (Figures 4.1-4.10). The individual plots give the mean for each FOOD and chewing ACTION for the ten measured parameters. This illustrates the range of mean values for each individual when compared with the group. It also shows the necessity to analyse values for each person separately.

Paired T-tests were carried out on the results from one person to assess significant differences between values obtained on the basis of SESSION, RUN, FOOD or ACTION (Appendices 12a & b, 13a & b). The level of significance was set at the 0.01 level or a one in one hundred chance of significant differences occurring.

An analysis of variance, ANOVA, was also carried out to complement the large number of t-test comparisons which were made and eliminate the chance of any false positive results occurring. The level of significance for the ANOVA was again taken at the 0.01 level and the incidence of significant differences occurring was tabulated as shown in Appendices 14-17. These tables show that 14 of 20 chosen subjects show good reproducibility of results for all measured parameters with few significant differences on the basis of RUN or SESSION. It was accepted within the group that certain people give a greater reproducibility of results than others. The ANOVA was used to assess the general trends for the reproducibility of results for individuals and the group.

4.2.1 Total Time of Chewing Stroke (Timetotl).

A complete chewing stroke is defined as the start of mandibular movement through the opening and closing actions and back to rest in the intercuspal position. The time for this whole cycle to be completed was defined as the total time of the chewing cycle (timetotl) and was measured in milliseconds.

For the 20 individuals that took part in this study, the average chewing stroke had a duration of 920 msec (sd = 200 msec) with an overall range of 568 msec to 1641 msec (Appendix 9).

The total time for the chewing movement for nut was significantly less than the value for gum. The mean values for the total chewing time for gum and nut were 983 msec and 567 msec respectively (Appendix 10a and 10b). There were also some differences noted according to the day on which the recording was made (Appendix 11).

The wide variation shown was dependent on the subjects themselves, the food that was eaten and the way in which it was chewed. The mean values for the 24 separate chewing strokes for each of the 20 subjects, were tabulated (Appendix 11) and shown as a scatter-plot (Figures 4.1-4.10). The scatter-plots show the variation according to the RUN, SESSION, FOOD and ACTION for each recorded movement and illustrates the distribution of the individual means against the population mean and standard deviation. The differences between recording sessions was not marked, although there was a marked difference in the values when comparing foods. There appeared to be some consistency of results according to a single chewing action, with fewer similarities shown between different chewing actions.

The reproducibility of the results was assessed using t-tests. This evaluation showed significant differences between mean values for the time total parameter on the basis of inter- and intra sessional comparisons. A total of 12 out of 80 measurements were significantly different on the basis of RUN (Table 4.1a) and 15 out of 80 significantly different on the basis of SESSION (Table 4.1b). These apply to the free selection chewing action for both foods. The number of significant differences between the different FOODS was equal on a sessional basis although a total of 36 out of 120 differences were noted for gum compared to 18 out of 120 for nut on the basis of RUN. More than twice number of significant differences were shown for right and left chewing of gum than for free choice chewing of the same food. These figures were 17 and 13 out of a possible 40 values respectively.

FOOD	ACTION			
	FCC	RTC	LTC	TOTAL
GUM (n=40)	6	17	13	36
NUT (n=40)	6	8	4	18
TOTAL (n=80)	12	25	17	

Table 4.1a. The number of times there was a significant difference in the total time value between the means calculated on the basis of the RUN for nut and gum according to the side upon which the food was chewed.

FOOD	ACTION FCC	 RTC	 LTC	 TOTAL
GUM (n=40)	8	8	11	27
NUT (n=40)	7	10	10	27
TOTAL (n=80)	15	28	21	

Table 4.1b. The number of times there was a significant difference in the total time value between the means calculated on the basis of the SESSION for nut and gum according to the side upon which the food was chewed.

An ANOVA was employed to assess the incidence of significant differences occurring on the basis of inter and intra-sessional differences, FOOD and ACTION (Appendices 14-17). For RUN, SESSION, FOOD and ACTION , most of the subjects showed significant differences for the total time measurement. On the basis of RUN (Appendix 14) 10 out of the 20 subjects showed significant differences, with 14 subjects showing significant differences on the basis of SESSION (Appendix 15). The reproducibility of results on the inter and intra-sessional differences was greater than for FOOD or ACTION.

The scatter-plot (Figure 4.1) illustrates the variation of each mean value for 24 different chewing strokes for each subject. The plots which are highlighted in red represent the mean values for a single person and show a trend in values for each of the different chewing actions. This confirms the consistency of a single person despite the wide range of values for the subject group.

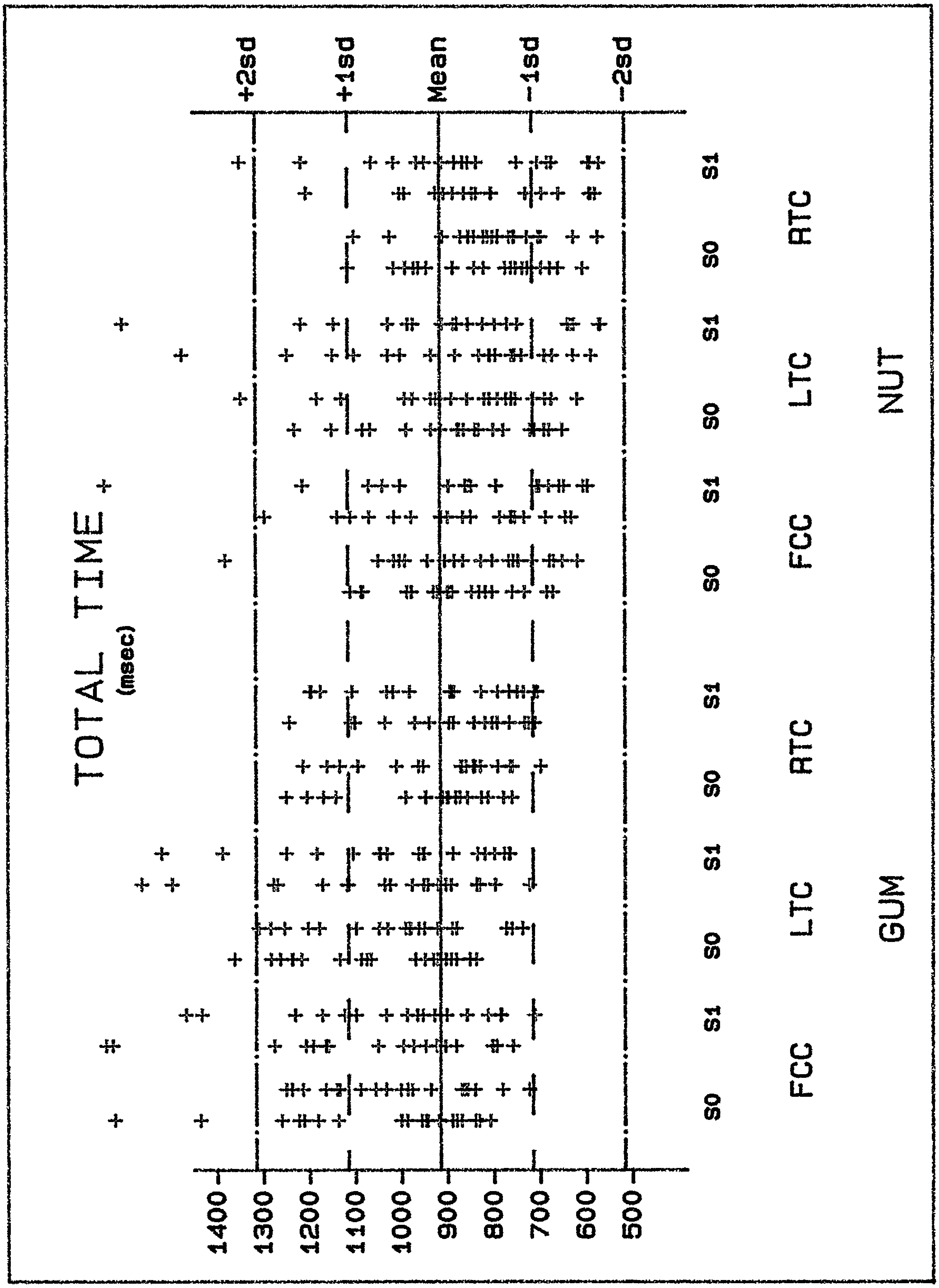

Figure 4.1 Scatter-plot to show individual mean values for time total for 20 subjects for the nut and gum. Values are given for free choice chewing (FCC), right-sided chewing (RTC) and left-sided chewing (LTC) for each food on session 0 (S0) and session 1 (S1).

4.2.2 The Time For Maximum Opening (Timeopen).

This parameter measured the time taken from the start of the movement of the mandible to the point of its maximum opening.

The average figure for the subjects in the study was 340 msec (sd = 89 msec) with a range of 141 msec to 613 msec (Appendix 9). The mean for timeopen for gum and nut were 384 msec and 296 msec respectively (Appendix 10a and 10b). Nut gave a significantly lower mean than gum. The individual means for each chewing stroke for all 20 subjects are illustrated in Appendix 11.

The number of significant differences illustrated by the t-tests indicated that the free choice of chewing gave the most reproducible results, on a basis of SESSION and RUN (Tables 4.2a and 4.2b). These differences were 4 out of 40 values and 2 out of 40 respectively. On the basis of FOOD, the chewing of nut gave a total of 15 out of 120 possible results showing significant results on a sessional basis and 6 out of the 120 results showing significant differences according to RUN. Similar results for chewing gum on an intra and inter sessional basis were 12 and 13 out of 120 respectively or about 10% incidence. On the sessional comparisons the free choice movement gave the smallest number of significant differences at the 0.01 level for both FOODS.

FOOD	ACTION			
	FCC	RTC	LTC	TOTAL
GUM (n=40)	2	6	5	13
NUT (n=40)	4	2	0	6
TOTAL (n=80)	6	8	5	

Table 4.2a. The number of times there was a significant difference in the time for maximum opening value between the means calculated on the basis of the RUN for nut and gum according to the side upon which the food was chewed.

FOOD	ACTION			
	FCC	RTC	LTC	TOTAL
GUM (n=40)	4	4	4	12
NUT (n=40)	4	6	5	15
TOTAL (n=80)	8	10	9	

Table 4.2b. The number of times there was a significant difference in the time for maximum opening value between the means calculated on the basis of the SESSION for nut and gum according to the side upon which the food was chewed.

An analysis of variance (ANOVA) indicated that the major cause of the variation for the total opening time was the variation in the food bolus (Appendix 16) with 19 of 20 subjects showing significant differences. The ACTION of the chewing movement was the second most influential variable (Appendix 17). On the basis of RUN and SESSION (Appendices 14 & 17), less than half of the total number of subjects showed any significant differences.

The scatter-plot (Figure 4.2) shows the wide individual range of means with a difference in range of values on the basis of FOOD and ACTION rather than SESSION or RUN. There was a marked difference observed in the distribution of means for gum and nut with all plots for gum falling between minus one standard deviation and plus three standard deviations. All the means for nut fell within plus or minus two standard deviations. A comparison between similar chewing actions and different foods illustrated that there was a marked difference in the range of means.

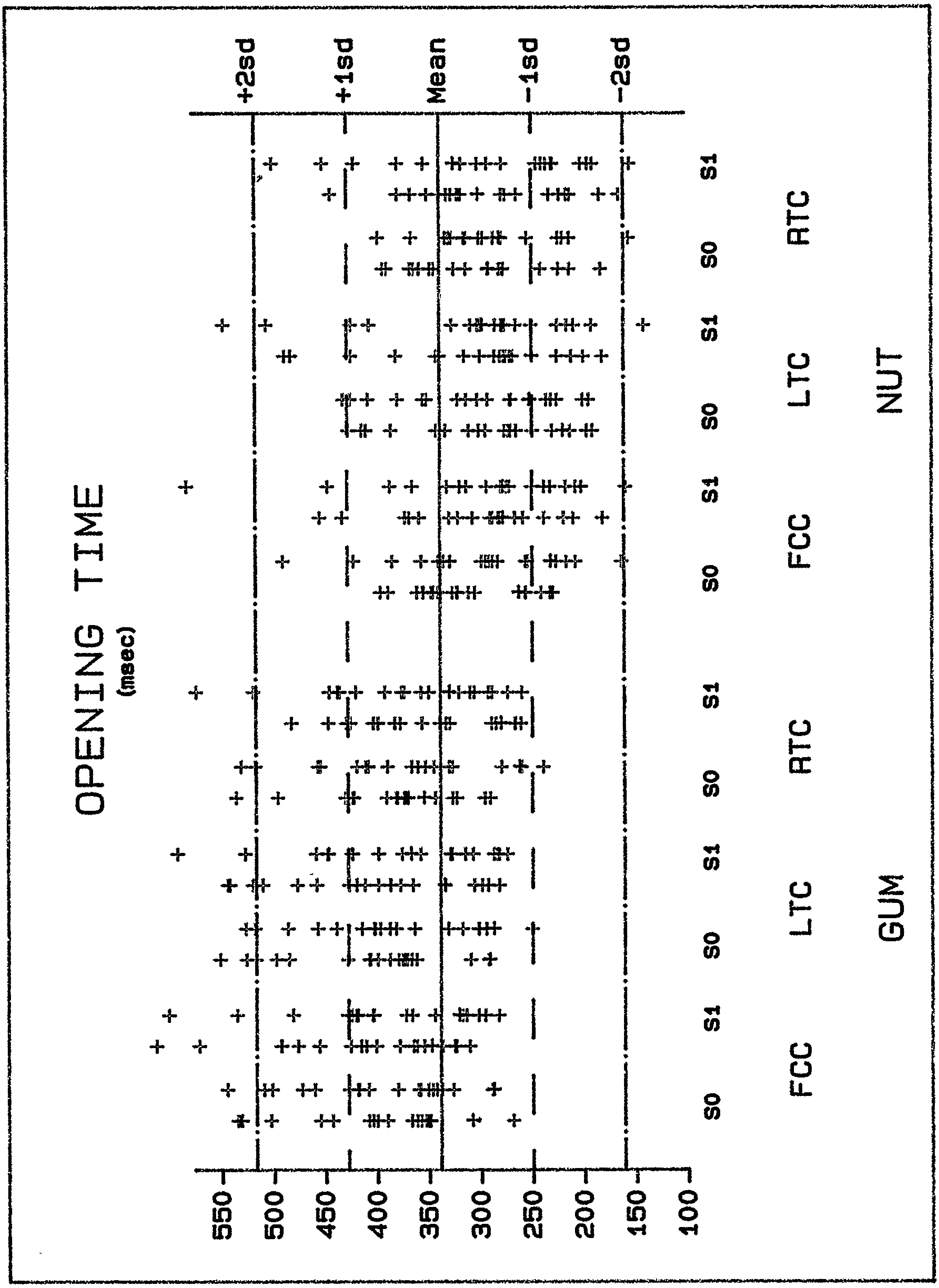

Figure 4.2 Scatter-plot to show individual mean values for time open for the 20 subjects for nut and gum. Values are given for free choice chewing (FCC), right-sided chewing (RTC) and left-sided chewing (LTC) for each food on session 0 (S0) and session 1 (S1).