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A THREE DIMENSIONAL TECHNIQUE FOR ANALYZING
FUNCTIONAL HAND STRENGTH AND INDIVIDUAL
PHALANGEAL JOINT LOADING USING A "PILL
BOTTLE DYNAMOMETER"

presented by

Brock Wells Horsley

has been accepted towards fulfillment
of the requirements for

M.S. degree in Biomechanics

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Major professor

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**A THREE DIMENSIONAL TECHNIQUE FOR ANALYZING FUNCTIONAL
HAND STRENGTH AND INDIVIDUAL PHALANGEAL JOINT
LOADING USING A "PILL BOTTLE DYNAMOMETER"**

By

Brock Wells Horsley

A THESIS

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in partial fulfillment of the requirements
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1992

ABSTRACT**A THREE DIMENSIONAL TECHNIQUE FOR ANALYZING
FUNCTIONAL HAND STRENGTH AND INDIVIDUAL PHALANGEAL
JOINT LOADING USING A "PILL BOTTLE DYNAMOMETER"**

By

Brock Wells Horsley

A six load component "pill bottle" dynamometer was developed by A.M.T.I. to detect the forces and torques applied to open various types of caps. Adapters were designed to allow clinical hand strength testing. A data analysis program was created to calculate the resultant force administered onto the dynamometer, the point of contact between the digit and the dynamometer and the forces and torques at this point of application. For comprehensible reasons, an imaging program was developed that creates a computer generated three dimensional replica of the pill bottle, then images the position of the center of pressure and the magnitude and orientation of the reaction forces and torques at that point of application.

A method for calculating individual phalangeal joint loads about an approximate joint center and flexion/extension axis was also developed.

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To my wife Donna, thank you for understanding when I couldn't come home until my computer program worked and thank you for understanding and sharing in my enthusiasm. Now that I'm done maybe you can start loving me "for richer" instead of "for poorer".

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I. HISTORICAL PERSPECTIVE OF HAND HELD DYNAMOMETRY METHODS:

The first reported test of hand strength using a hand held dynamometer was performed by Regnier nearly 180 years ago⁸. Since then, several hand held dynamometer designs have been created and used.

The Sklar and Geckler, and Collins dynamometers have been used in an attempt to measure grip strength in the past but these devices have been proved unsatisfactory for reasons not given²⁹.

In 1954, Bechtol⁵ introduced the Jaymar dynamometer as a device to measure hand strength among male and female subjects of various ages using various grip sizes for the dominant and nondominant hand. This hydraulic system has remained as the standard instrument for hand strength testing among clinicians to the present day. The Jaymar dynamometer entails two handles, a dial gage and a hydraulic system. Both handles are designed to be large and smooth to prevent pain from accompanying forceful grips. One of the handles can also be adjusted closer to or farther from the opposite handle to create various grip sizes (Figure 1). Larger handle spacings were used for testing grasp strength. Smaller handle spacings were used for testing finger tip pinch and lateral pinch strength.

In 1956, the Subcommittee for the Study of Grasping Power of the Committee on Industrial

Health and Rehabilitation of the California Medical Association recommended the Jamar dynamometer as the most acceptable instrument manufactured at the time for the quantitative measurement of grasping power²⁹.

The Jaymar dynamomter was considered reliable, easy to use, accurate, produced reproducible results and could be a standard test device to simplify comparisons between studies.

In 1958, Clarke et al.⁹ used a unique type of hand held dynamometer to test the influence of external temperature on the functional strength of the hand. Grip tests were performed on a "hand grip strain gage dynamometer". Grip strength was produced by the hand while it was submerged in a heated water bath. Loads produced by the hand were sensed by strain gages cemented to a steel bar 1.5 centimeters thick located above the water surface (Figure 2). Loads were read on a galvanometer.

In 1970, Schmidt et al.²⁹ created the largest grip strength data base at that time by testing 1,128 male and 80 female subjects using the standard Jaymar dynamometer. "The handles of the dynamometer were coated with a sand paint mixture to aid in obtaining a secure grip." All of the grip tests were performed at a 1.5 inch spacing and the subjects were instructed on the proper hand positioning and proper method of applying pressure to the dynamometer. The subjects were also asked to exert a maximum effort.

Also in 1970, Long et al.¹⁹ created some unique devices for examining extrinsic and intrinsic muscle patterns while



Figure 1: Jaymar Dynamometer

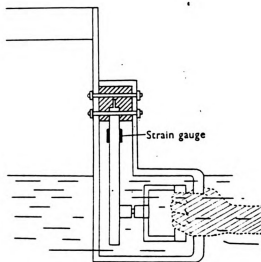


Figure 2: Hand Grip Strain Gage Dynamometer

performing numerous precision and power grip tests. The tests included squeeze tests, hammer grip tests, hook grip tests, ball grasp tests, screw driver squeeze tests and disc grip tests. The simple squeeze testing device consisted of split metal cylinders with diameters of 1.3, 2.5 and 5.0 centimeters. Strain gages were attached to the cylinders to measure these loads while electrodes simultaneously recorded EMG activity. The rest of the tests entailed weighting numerous objects using various combinations of external weights, cords and pulleys. In the hammer grip test, weights were connected to a hammer handle with a cord and pulley. The subject was then asked to move the handle against the resistance of the weights. The hook grip test was performed by weighting a simulated suitcase handle with weights and then asking the subjects to hold the handle at their side. The ball grasp test was performed by weighting a 7.6 centimeter wooden ball with weights and asking the subject to hold the ball at their side. The screwdriver squeeze test was performed using a simulated screwdriver handle connected to a weighted cord and pulley system. Subjects were asked to remain isometric while resisting the torques produced by the weights and pulley system. Disc grip tests were performed by attaching a weighted disc to the same pulley mechanism. Again, subjects were asked to remain isometric while resisting these torques.

In 1974, Keller et al.¹⁶ used the standard Jamar dynamometer and an Osco pinch meter to measure hand strength

among males and females of various ages. Grip, 3-point pinch, lateral pinch and palmar pinch strength tests were performed on 274 patients ranging in age from 18 to 60 years old.

In 1975, Hazelton et al.¹³ were interested in detecting phalangeal forces in different wrist positions. Their study was based on the idea that "one determinant for the capacity of a musculotendinous unit to generate force is the effective functional length". As wrist position changes, the effective functional length of the hand's extrinsic musculature will also change. The magnitude of force generated by the hand in various wrist positions should then change. Loads produced by the finger flexors were measured in five different wrist positions using a "Digital Dynamometer" developed through a joint effort between the University of Iowa Division of Hand Surgery, the Department of Orthopedics, the Department of Physical Therapy and the Departments of Mechanical Engineering.

The dynamometer consisted of three components:

- (1) The base assembly with arm and forearm restraints.
- (2) The cage assembly which rotated around a horizontal axis for setting radial/ulnar deviation angles.
- (3) The transducer assemblies attached to a support bar that rotated around a vertical axis to fix the hand in set dorsi/volar flexion orientations.

Wrist orientations encompassed a range from 45 degrees volar flexion, 60 degrees dorsi flexion, 21 degrees ulnar deviation and 14 degrees radial deviation. "The transducer assembly consisted of:

- (1) A flexible woven wire mesh strap for attachment to a finger.
- (2) A ring with four strain gages.
- (3) A universal joint attached to a support bar (Figure 3).

In 1977, Berme et al.⁶ developed a unique type of six load component strain gaged transducer in the form of a water tap handle (Figure 4). This dynamometer was designed to measure the isometric torques generated by the hand when attempting to turn a tap as well as the component forces and torques developed by pinching the 45 millimeter cylinder with opposing sides of the hand. Targets were also attached to various anatomical landmarks on the index finger and hand using adhesive. These targets were then filmed from two orthogonal directions while subjects performed the isometric tests to obtain spatial information. A coordinate system was created at the center of the second metacarpal head with an origin corresponding to the approximate joint center. The component force and torque information was then combined with position data to determine the forces and torques acting about this approximate joint center. No specific descriptions for the method of determining the origin of the external loadings were given. However, joint forces, flexor forces, extensor forces, radial ligament forces, ulnar ligament forces, radial abduction/adduction forces, ulnar abduction/adduction forces and flexion angles of the index finger were given.

Armstrong et al.³ (1979) evaluated the adequacy of estimating hand forces from surface EMG on the medial side

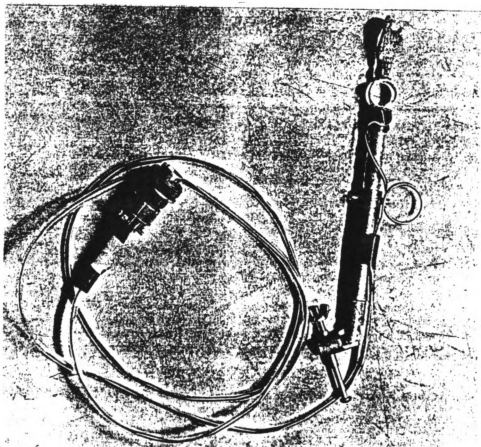


Figure 3: Digital Dynamometer

of the forearm. A fixture was devised to determine the relationship between hand force and surface EMG in various hand positions. The device consisted of two bars held apart by springs which could be stretched to produce desired force levels (Figure 5). Electrodes were placed near the medial epicondyle. The subjects were asked to pinch the handles together in various hand positions until they nearly touched while EMG activities were recorded. A meter displaying the EMG signals was placed into the cameras field of view so that both the activity and the EMG signal outputs could be viewed simultaneously. This test was performed so that work related tasks could be performed using only EMG electrodes and the forces corresponding to the muscular activity levels could be determined indirectly.

The purpose of Petrofsky et al.²³ (1980) study was to measure the maximum voluntary contraction (MVC) of subjects when gripping objects of various sizes and to also measure the endurance of a contraction at 25%, 40%, 55% and 70% MVC. Physiologically, optimal grip size relates to the optimal degree of crossover of the functional unit of muscle fibers; the sarcomere. "At the optimal handspan, the sarcomeres are stretched to that length at which the greatest number of actomyosin cross bridges can form". Loads exerted by the hand were measured using a "portable strain gage hand grip dynamometer". The handles could be preset to any of the six grip sizes ranging from 3.2 to 8 centimeters.

Studies, prior to Pryce's work, concluded that wrist

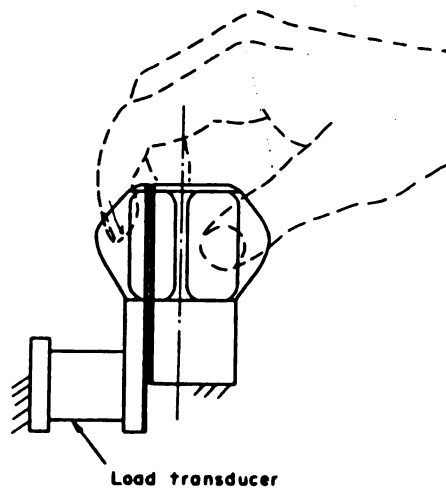


Figure 4: Instrumented Tap

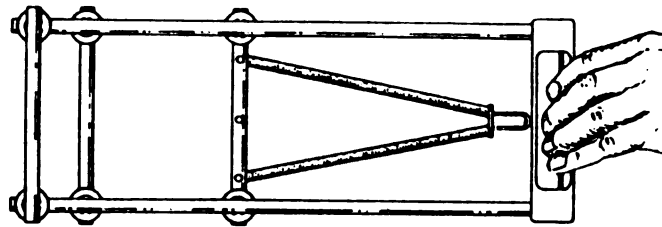


Figure 5: Method Deviced By Armstrong et al.

dorsiflexion and ulnar deviation positions of the wrist orient the extrinsic muscles of the hand to produce maximum grip strength. Pryce et al.²⁶ (1980) intended to define a more specific optimal position of the wrist. Materials included a forearm positioning table, a Pacific Scientific T-5166 grip device connected to a load cell adapter, bridge amplifier and digital multimeter. The grip device was calibrated by equilibrating voltage readings with known weights. A calibration chart was then formulated to convert the voltage readings to pounds of force. The subject's forearm could be positioned in any combination between zero and thirty degrees ulnar deviation and between fifteen degrees volar flexion and fifteen degrees dorsiflexion. This was done using a splint stabilized with Velcro fasteners, (Figure 6).

The most detailed work on the biomechanics of the hand has been performed by Chao, Cooney, An and Linscheid⁸ at the Mayo Clinic over a span of approximately 15 years. Complete analyses of hand function have included strength evaluations, manipulative ability tests, range of motion tests and observations of joint deformity. Functional tests include pinch, grasp and lateral deviation tests. The first device described by Chao et al. was the "pinch meter". It was comprised of two steel beams separated and fastened to a base to form a tuning fork structure. Strain gages attached to the beams measured the strains caused by the loads produced by the fingers (Figure 7). Two different devices



Figure 6: Pacific Scientific T-5166 Grip Device

were used to detect the functional strength of grasp. The first device was used to measure the overall hand strength whereas the second one was used to measure the loads produced by individual phalanges of a finger or thumb. The first device consisted of "various sized plexiglass cylindrical covers with a gap in between two halves " (Figure 8). The second device consisted of;

three steel beams instrumented with strain gages at their base and fastened inside of an aluminum cylinder for contact with the volar surface of the three phalanges of a finger engaged in grasp. Each beam can be adjusted independently to provide accurate placement of the contact surface to the phalanx. Simultaneous recording of each beam is performed. Shifting the hand longitudinally along the cylinder allows a particular finger to be placed over the measuring slot (Figure 9).

A "universal gage" has recently been designed to measure uniaxial loads for various hand and finger functions. An adjustable spacing capability between the beams of the gage allow it to test grasp strength, adduction/abduction strength, tapping strength, opposition strength, etc (Figure 10). Loads are read with a digital readout meter.

Functional strength tests have also been combined with biplanar X-ray techniques to simultaneously measure finger joint angles, joint centers, anatomical landmarks and loads. This information was then incorporated into a mathematical model of various joints including the ligamentous and tendinous structures surrounding them in order to determine tendon and joint forces that exist when performing various functional tests. According to Chao et al.⁸,

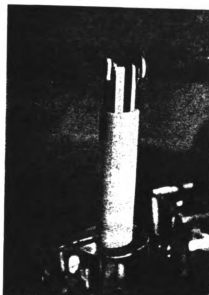


Figure 7: Pinch Meter

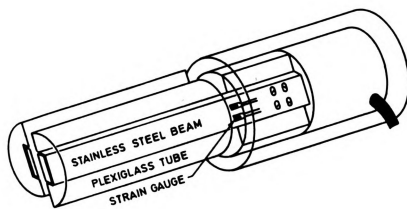


Figure 8: Grasp Meter

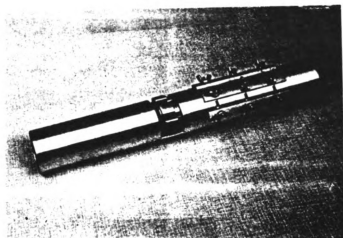


Figure 9: Individual Phalanx Grasp Meter

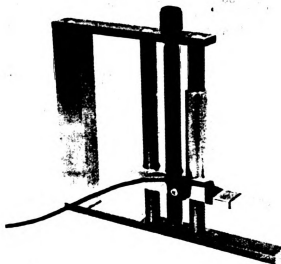


Figure 10: Universal Gage

these results will be used to quantitate the pattern and magnitude of functional impairment in diseased and disabled hands as well as assess the functional improvement after surgical reconstructive procedures.

Toft et al.³³ (1980) combined position data with force and moment data to measure loadings of the muscle, ligament and joint forces of the thumb.

Hands were dissected to establish relationships between load bearing structures and externally palpable landmarks. Load bearing structures were identified with colored pins. A scale was put into view and specimens were photographed from two orthogonal angles. Spatial descriptions of the structures were established.

A dynamometer in the form of a screw top jar was used to measure individual digit grip strength and isometric turning torques. A six load component transducer was attached between a reference frame and the part of the two piece tube which came in contact with the thumb. The other half of the tube was fixed to the reference frame (Figure 11). Subjects were asked to squeeze the tube and attempt to unscrew the jar with maximum loads. Position data of the hand was acquired using film from two orthogonally placed cameras. Landmarks of interest on the thumb were marked with targets adhered to the skin. Coordinate systems were created at each joint to define the orientation of the hand and the thumb. Force and moment components transmitted to each joint were determined from the external loads and position data. Equilibrium equations were then created to determine loads on the muscles, ligaments and joint components.

Initially the dynamometer was not designed to monitor

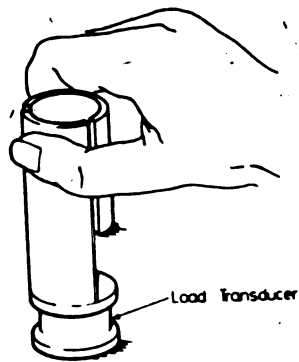


Figure 11: Instrumented Screw Top Jar

the overall torque applied by the hand. However, they found based on the initial design that half the subjects "used their thumbs in a way to contribute to the twisting moment. The other two subjects in fact opposed the overall torque with their thumbs". The dynamometer was subsequently modified to allow detection of overall torques applied by the hand when unscrewing a lid. However, a description of this alteration was not given.

Swanson et al.³² (1987) recommended an alternative grip strength device for detecting lesser grip strengths; the sphygmomanometer cuff or bag. "A blood pressure cuff is rolled to a 5 cm. diameter and inflated to 5 mmHg. The cuff is then squeezed and the change in mmHg. from 50 mm. is recorded as the power grip". However, this technique was considered unacceptable to the California Industrial Accident Commission²⁹.

Swanson et al.³² also performed strength tests on 100 healthy subjects to create a normative database on grasp, chuck, 3-point pinch, pulp pinch and lateral pinch strengths. Grasping forces were measured with a Jamar dynamometer and pinching forces were measured with an electronic pinch meter.

Exos Incorporated²⁰ (1990) developed a device capable of measuring grip force and wrist orientation simultaneously. To measure wrist orientation, the "Grip Master" uses three Hall effect sensors; two for flexion/extension and one for radial/ulnar deviation of the wrist. Resistive ink force

sensors can be attached to the hand using an adhesive. Force sensors are "thin and flexible" so they don't interfere with normal work performance and are "inexpensive and disposable". The Grip Master is able to measure the interactions between workers and their environments to attempt to determine the "causes of stress-related injuries in the workplace".

In an abstract form, Moore²¹ (1990) announced that a system has been developed that can incorporate wrist and hand position data, grip force data and forearm EMG to calculate soft tissue loadings of the structures in the carpal tunnel based on the parameters of a model of these structures.

II. RESEARCH CONCLUSIONS:

Hand held dynamometry tests alone and in combination with electromyography and various position acquisition techniques have yielded results in the categories of grip strength and gender, grip strength with increasing age, the effect of wrist position on functional strength, the effect of grip size on functional strength, hand dominance, force contributions from individual digits and individual phalanges, tendon loads, test results from arthritic patients and peripheral neuropathy patients.

A. NORMATIVE GRIP STRENGTH:

Norm values of functional grip strength are clinically useful in determining how a patient's grip compares to the general population. Bechtol⁵ (1954) was the first to measure grip strength among males and females using the standard Jaymar dynamometer. Most subsequent Jaymar strength tests seem to agree with Bechtol's results. Male grip strength ranged between 60 and 130 pounds with a median value of approximately 105 pounds. Female grip strength ranged between 30 and 70 pounds with a median value of approximately 45 pounds^{5,32}.

In comparison to the results from Swanson et al. (1970), Chao et al.⁸ (1989) stated that their average grasp values were slightly lower. Chao et al. believe that the

difference in the structure of the grasping device and, likewise, the patient's grasping techniques may account for this difference. Swanson et al. used a Jaymar dynamometer whereas Chao et al. used a 1.25 inch diameter cylinder. Chao concluded that the results from Jaymar dynamometry tests should not be compared with the results from a cylindrical grasp device.

In 1980, Toft³³ stated that "the average torque applied by the overall hand approximated 1.92 Nm".

B: DOMINANT VS. NONDOMINANT GRIP STRENGTH CONTROVERSY:

Although most researchers agree that, in general, the dominant hand tends to be stronger than the nondominant hand, there seems to be a controversy as to the percentage difference. A standard difference is important for clinicians so as to determine approximate values of grip strength loss in a unilaterally affected hand based on the strength of the opposite, unaffected hand. Schmidt²⁹ (1970) stated that the initial test of strength versus hand dominance was "derived from a survey of the Canadian Army in World War I". This study observed a ten percent weakness in the nondominant hand compared to the dominant hand. Bechtol⁵ stated that "although the major hand may be as much as 30% stronger than the minor hand... most subjects presented a difference of 5-10%". Schmidt et al.²⁹ found the average difference between the major and minor hand to equal 3.5 pounds among males and 5.9 pounds among females.

This constituted a 3.2% difference. Schmidt added to the inconsistency of the dominance/nondominance relationship by stating that 28% of his test population had stronger nondominant hands. Chao et al.⁸ (1989), Swanson et al. (1970) and Dickson et al. (1972) found no significant differences between grip strengths of the dominant and nondominant hands.

C: AGE AND GRIP STRENGTH:

Controversy also exists in the relationship between functional hand strength and age. A general agreement among researchers would be beneficial for clinicians in both predicting the degree of loss with a patients increasing age and comparing hand strength of older patients to norm values. In 1954, Bechtol⁵ found the strongest grips among subjects aged 25 to 40. He also noted a small variation in grip strength between the ages of 18 and 65. Schmidt et al.²⁹ found grip strength to increase between the ages of 18 and 32 and then gradually decrease to the age of 62. Keller¹⁶ found that strength linearly decreased with age throughout adulthood.

D: WRIST POSITION AND GRIP STRENGTH:

Wrist position affects functional grip strength due to the origin/insertion points and the orientation of the finger flexors (flexor digitorum superficialis, flexor digitorum profundus) and the concept of optimal functional

length of muscle. Both finger flexors have a common origin point at the medial epicondyle of the humerus. Their tendons pass over the carpal bones and insert either medially and laterally on the middle phalanges (superficialis) or on the anterior surface of the distal phalange (profundus). The finger flexors are therefore oriented medially to laterally. Angulations of the wrist tend to increase or decrease the length of these muscles either above or below their functional length. Hazelton¹³ measured the force generated in a grip test while stabilizing the wrist in various positions. He found that, in general, the greatest forces were produced in ulnar deviation followed in a decreasing order by neutral, radial deviation, dorsi flexion and volar flexion. Pryce²⁶ (1980) wanted to complement Hazelton's work by testing functional grip strength in more specific wrist positions. He found maximum grip strength to coincide with coupled wrist orientations within the ranges of zero to fifteen degrees dorsi flexion and zero to fifteen degrees ulnar deviation. Hazelton et al.¹³ contributed knowledge to both wrist position studies and individual finger force contribution studies by comparing relative finger forces to wrist position. He found that, regardless of wrist position, the long finger produced 33.5% of the total grip force, the index and ring fingers produced 25% of the total force and the little finger produced 16.5% of the total force. The percent contribution of the thumb was not given. Hazelton

et al.¹³ thus concluded; "the fact that the percentage of total force that is exhibited on each finger bears a constant relationship to each other in any wrist position makes it possible to determine the amounts of functional loss on an objective basis". Therefore, wrist position is not important in determining relative strength among fingers of the same hand to determine functional loss of individual fingers. In addition, right and left hands are comparable as percentage differences between corresponding fingers if a deformity or dysfunction is believed to affect the whole hand. Chao et al.⁸ (1989) were able to measure normal forces of each phalange in an individual finger during grasp. They found an inconsistent distribution of force among the phalanges although forces tended to decrease proximal to distal.

E: MODELING OF THE HAND:

Some studies combined force data with position data and used mathematical models to determine the loads exerted on various internal structures of the hand. Chao and Cooney published articles in 1976 and 1977 using similar data acquisition and modelling techniques. They concluded that the intrinsic muscles produced greater loads than the flexor tendons in grasp tests. In the pinch tests the intrinsic muscles performed in the following descending order; Flexor Profundus, Flexor Sublimis, Radial Interosseous, Ulnar Interosseous and Lumbrical⁸. Berme⁶ (1977) did not leave

many internal structures out when he concluded that the "principle load bearing elements of the metacarpo-phalangeal joint of the index finger are the flexor and extensor tendons, collateral ligaments on the radial and ulnar sides, ulnar interosseus muscle, radial interosseus muscle, lumbrical muscles and the joint surfaces".

F: GRIP SIZE AND HAND STRENGTH:

Relations have also been made between grip size and hand strength. Petrofsky et al.²³ found that the greatest strength for the male and female subjects occurred within the range of 5-6 centimeters. Although those subjects with larger hands exerted greater loads in a wider grip span than those with smaller hands, the difference between each groups optimal grip size was within one centimeter. An increase or decrease of grip span by only 0.6 centimeters resulted in a loss of grip strength. They concluded that this could be due to a "stretching of the intrinsic and extrinsic forearm muscles below or above their optimal contractile length or due to a mechanical disadvantage of the wrist or finger orientation".

G: PATIENT POPULATION STUDIES:

Hand functional strength tests, manipulative ability tests and range of motion tests have been performed on various diseased populations by Chao et al.⁸. One specific category of patients includes preoperative arthritic

patients. "In general, the advanced arthritis patients had hand strengths only 30% of normal with rheumatoid arthritis patients weaker than osteoarthritis patients." Another category of patients included pre and postoperative carpo-metacarpal joint and metacarpo-phalangeal joint replacement patients. In general, presurgery CMC patients could only produce grips 30-35% of normal. Patients tested two years after this surgery increased their strength, dexterity and range of motion to 60% of normal. MP joint replacement surgery does not seem as productive. Rheumatoids before and after MP joint replacement showed that at a one year follow-up, finger joint,

deformities were corrected but the range of motion did not improve. Functional strength was only 25% of the normal range but the joint deformity correction was significant in improving patients' daily activities.⁸

Functional hand strength tests have also been performed on various types of peripheral neuropathy patients in order to determine the degree of functional strength loss and areas of strength loss both as a means of verifying a particular type of neuropathy (radial, median, or ulnar nerve lesion) and the severity of the disease. Doctors Chao, An, Cooney and Linscheid⁸ hoped these tests would prove equal to or better than EMG tests currently used. The strength of grasp, pinch, abduction/adduction between fingers was measured using pinch and grasp meters. Isolated strength of the thumb and fingers were also measured. They then developed a normalization procedure to allow

comparisons between populations.

III. INTRODUCTION: DISEASES AND DEFICIENCIES OF THE HAND

A. CARPAL TUNNEL SYNDROME:

Cumulative trauma disorders are injuries that result from performing repetitive tasks. "...Anyone whose job involves the constant repetition of awkward hand and arm motions in a forceful manner that leaves insufficient time to rest or recover" is at risk of developing a cumulative trauma disorder²⁰.

CTDs were the fastest growing occupational injury of the 1980's. According to a survey by the Bureau of Labor Statistics, the number of cases increased from 26,700 in 1983 to 72,940 in 1987. This increase is mainly due to a transition of work style from labors requiring larger muscle groups to more repetitive smaller muscle activities. Compression neuropathies are commonly called "tunnel syndromes" because they frequently occur where a nerve passes through a fibrous or fibro-osseous tunnel²⁵. One of the most cited compression neuropathies is "Carpal Tunnel Syndrome"²⁰.

Carpal Tunnel Syndrome was first described by Sir James Paget in 1854 as a "complication of trauma" but no one knew what was causing the syndrome. Investigators suggested many different possibilities including thenar motor branch injury, digital nerve ischemia and brachial plexus compression²⁴.

In 1913, a French neurologist named Pierre Marie believed that the lesion was located on the median nerve where it passed beneath the transverse carpal ligament; the carpal tunnel. This observation was overlooked however, resulting in approximately thirty years of misdiagnoses and incorrect surgical and nonsurgical treatments²⁴. Nonsurgical treatments included galvanism, electric current, strychnine and cannabis, shoulder girdle physiotherapy, heat application and vitamin B1 ingestion. The most accepted surgical treatment was cervical rib excision²⁴.

In the 1940's, Pierre Marie's observations were proven to be accurate and the causes of carpal tunnel syndrome were accurately defined. In 1941, Learmouth performed the first carpal tunnel release at the Mayo Clinic. "...In 1947, Lord Brain published the first report on the diagnosis, pathophysiology and surgical treatment of spontaneous CTS"²⁴.

Carpal tunnel syndrome is caused by an entrapment or compression of the median nerve within the carpal tunnel. The median nerve passes medially and anteriorly at the elbow, continues down the anterior aspect of the forearm and through the carpal tunnel (Figure 12). The motor and sensory portion of the nerve split distal to the tunnel. The motor portion innervates the intrinsic thenar muscles of the thumb; the abductor pollicis brevis, the opponens pollicis, the superficial head of the flexor pollicis brevis and the radial lumbricals (Figure 13). The sensory portion

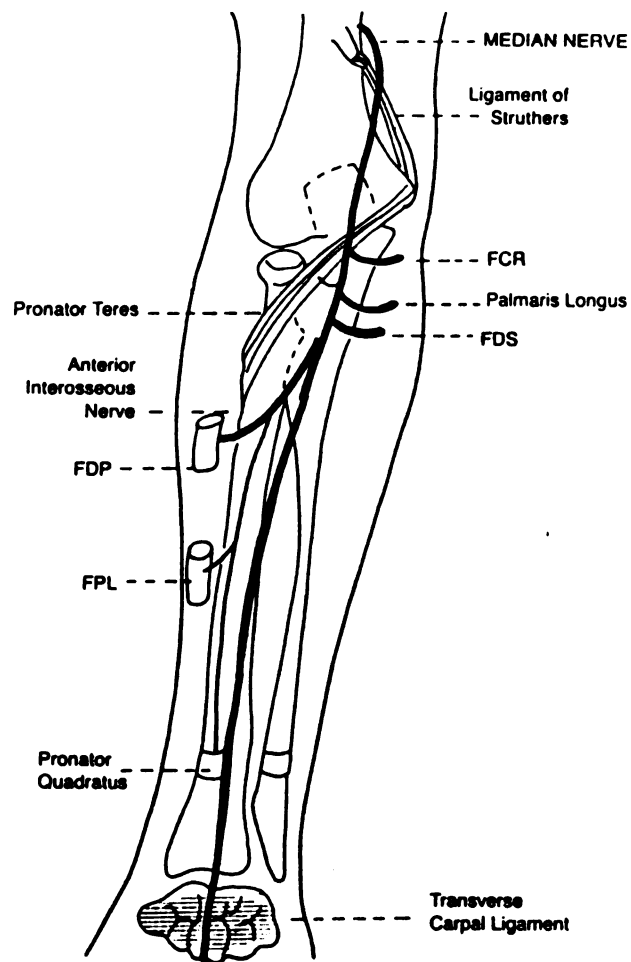


Figure 12: Pathway Of The Median Nerve

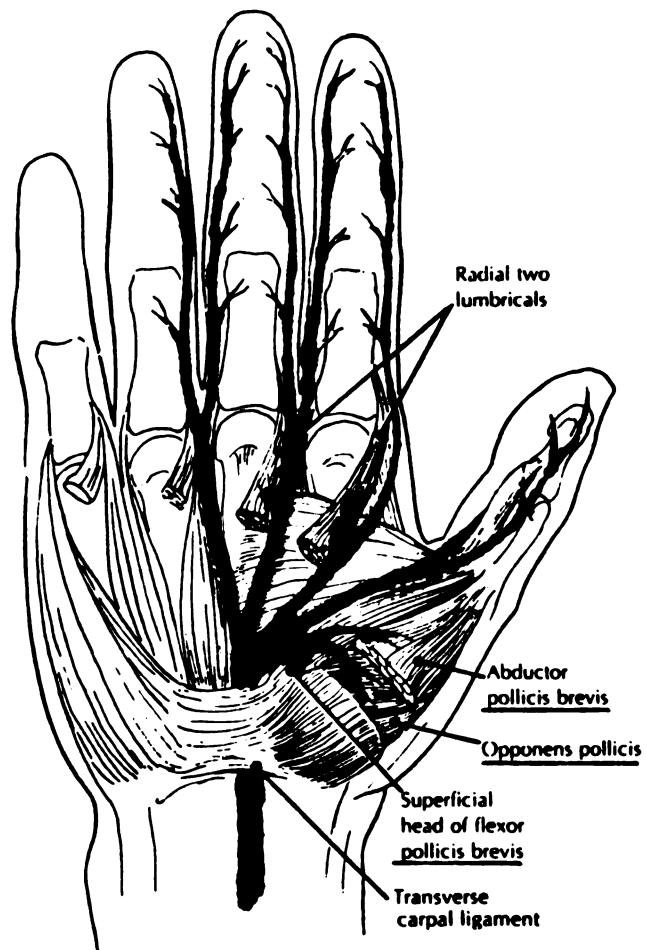


Figure 13: Median Innervated Muscles

innervates the radial half of the hand (Figure 14). The carpal tunnel is a four centimeter long tunnel whose floor is formed by the concave arch of the carpal bones covered by the radiocarpal, intercarpal and carpometacarpal ligaments²⁸. The tunnel is roofed by the transverse carpal ligament^{10,28}. The median nerve is accompanied in the tunnel by the flexor digitorum sublimis tendons, the flexor digitorum profundus the flexor pollicis longus and the arteria mediana. The cross section of the carpal tunnel is smallest 2-2.5 centimeters distal to its origin. This is due to a thickening of the transverse carpal ligament and protrusions of the carpal bones into the carpal tunnel. Any decrease in volume of the canal due to a protrusion of the osseous trough, thickening of the transverse carpal ligament, or tendon inflammation can cause compression of the tunnels contents. Since nerves are more compliant than tendons, they will tend to compress more easily. Nerve compression tends to obstruct signal transmission of both the sensory and motor components and causes characteristic compression neuropathy symptoms to develop.

Some of the contributing factors of carpal tunnel syndrome include extreme wrist positioning^{2,4,10,30,28,25}, synovial membrane inflammation^{24,6,28}, rheumatoid arthritis of the hand or wrist^{31,25}, diabetes mellitus^{31,25}, increased age^{31,14}, trauma to the wrist³¹, pregnancy³¹, use of the birth control pill³¹, small wrist size or abnormal wrist shape³¹, forceful and repetitive hand motions^{26,10}, calcium deposits

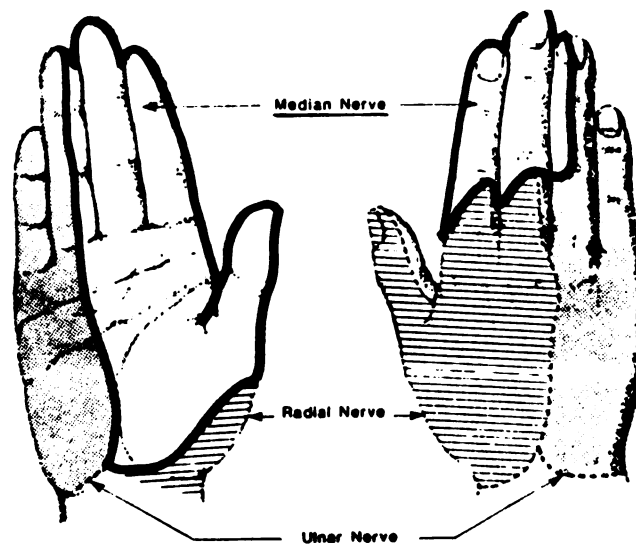


Figure 14: Sensory Distribution Of The Median Nerve

near the carpal tunnel³⁰, abnormally low muscle bellies^{28,25}, hematomas in the wrist area²⁸ and fracture or dislocations of the lunate bone^{28,25}.

CTS symptoms stemming from compression of the sensory portion of the median nerve may include pain, numbness and tingling in the median nerve distribution of the hand^{31,24,25}, discomfort along the anterior aspects of the forearm and upper arm^{33,24} and increased pain in these regions at night^{25,24}. Motor involvement usually occurs later in the course of carpal tunnel syndrome and can include stiffness and clumsiness of the hand²⁴, weakened pinch and grasp^{4,17,14}, and atrophy of the thenar muscles^{24,17}. Weakness of the median innervated thenar muscles generally precedes atrophy and is a sign of severe CTS²⁴. Although complete paralysis of the thenar muscles is rare, permanent nerve damage can lead to permanent muscle weakness in some patients^{24,17,14}.

Myelinated nerves are less resistant to the effects of pressure than are unmyelinated nerves. Since there is a predominance of myelinated fibers in motor nerves, which supply muscles, they are more susceptible to the effects of compression than are the thinner sensory nerves with less myelin. Compression of nerve fibers results in distortion of the myelin and eventually interferes with the ability of the nerve fiber to conduct a normal impulse. First, there is a segmental block of nerve impulse conduction. As paranodal swelling occurs, internodal myelin becomes thin and segmental demyelination occurs, resulting in a more pronounced decrease in conduction velocity. Various degrees of remyelination may occur when the compression is released. Regeneration of a nerve is possible if the axon remains intact. Damage to the myelin sheath in the presence of an intact axon can be repaired in the peripheral nervous system. However, irreversible change in

the axon results in secondary loss of myelin function in the involved fibers. Prolonged and repeated damage of myelin affects the axon distal to the site of injury resulting in so-called Wallerian degeneration¹¹.

If a diagnosis of CTS is made too late, after the nerve has been irreparably damaged, little or no improvement in thenar muscle strength may occur. Those who had weakness and atrophy for periods longer than one year usually had permanent thenar atrophy, significant muscle weakness and EMG evidence of denervation^{24,14}. Tests are performed in an attempt to determine both sensory and motor dysfunctions of carpal tunnel syndrome. However, since the purpose of this thesis is to develop methods of measuring functional strength, this report will concentrate more on motor dysfunction of the median nerve and its effects on functional strength of the thenar muscles.

Normal contractions of the median innervated thenar muscles produce a motion called "thumb opposition". Thumb opposition is the essential movement of bringing the pulp of the thumb into contact with any other finger to form a pollicidigital pincer¹⁵. For the thumb to be in true opposition, it must not only be forward and opposite to the fingers but also rotated so that the pads of the thumb directly face the pads of the fingers⁷. "Thumb opposition is a complex movement variably made up of three components: (1) anteposition, (2) flexion and (3) pronation"¹⁵.

Anteposition is the process of moving the thumb

anteriorly and laterally to the plane of the palm. This is performed by the abductor pollicis longus; not innervated by the median nerve. The median innervated thenar muscles (flexor pollicis brevis, abductor pollicis brevis and opponens) contract to produce the final stages of thumb opposition by "tilting the first metacarpal anteriorly and medially while also producing a slight degree of axial rotation". Pronation is due in part to the curved saddle joint structure between the trapezium and the first metacarpal. An additional thirty degrees of pronation occurs at the distal joints when the thumb is maximally opposed. "At the MP joint, pronation of 24 degrees is produced by the abductor pollicis brevis and the flexor pollicis brevis¹⁵.

A form of opposition called "minimal opposition" is often observed in patients with median nerve damage. "The movements of minimal opposition are associated with almost linear displacement of the first metacarpal so that its head comes progressively to lie anterior to the second metacarpal. This movement is produced mainly by ulnar nerve innervated muscles, occurs in the plane of the palm and is of little functional value for manipulations of the hand¹⁵.

Merely placing the thumb into a position that is in contact with the fingers or drawing it into the palm is not opposition, nor is it when the thumb fails to rotate and its nail is still at a right angle to the palm⁷.

Accurate functional strength tests of the thenar muscles in carpal tunnel syndrome patients are a valuable

tool in assessing the severity of muscle strength loss due to a compression of the median nerves motor component. Examples of valuable strength tests to determine the maximum force capabilities of the thumbs thenar muscles include thumb opposition and slight deviations of thumb opposition; grasp, and pinch.

B: OTHER COMPRESSION NEUROPATHIES:

Other types of compression neuropathy affecting hand strength include cubital tunnel syndrome (tardy ulnar palsy) and ulnar tunnel syndrome (ulnar nerve compression in Guyon's tunnel)²⁵.

C: RHEUMATOID ARTHRITIS:

Rheumatoid arthritis is another common disease that affects the functional strength of the hand. Rheumatoid arthritis is a joint inflammatory disease affecting one to three percent of the U.S population. Fifty percent of rheumatoid diseases occur in the hands¹².

The first general description of arthritis was given in 1800 by Landre-Beauvais. He used the terms "arthritis deformans" and "chronic rheumatism" to describe arthritis in general. In 1876, the more specific term "rheumatoid arthritis" was first used. In 1957, rheumatoid arthritis was first defined as a "chronic systemic inflammatory disorder of unknown etiology characterized by the manner in which it involves the joint"¹². In 1958, the American

Rheumatism Association developed standardized criteria for the diagnosis of rheumatoid arthritis. However, this disease is difficult to describe and differentiate from other forms of arthritis so new criteria are being developed¹².

Inflammation of rheumatic arthritic joints is characterized by redness, swelling, pain, tenderness and effusion. Tendon sheaths can also become affected by this disease. A swelling of the sheaths, called tenosynovitis, can cause loosening or rupturing of the tendons that they encompass^{30,12}. Approximately 55% of patients with rheumatoid arthritis also exhibit signs of tenosynovitis. Inflammation of tendons that lie in close proximity to nerves can lead to compression neuropathies. For example, tendon sheath swelling within the carpal tunnel can cause median nerve compression producing carpal tunnel syndrome. Synovitis occurs most frequently at the metacarpo-phalangeal joints of the thumb, index and middle fingers.

Although symptoms of pain and stiffness within a joint tend to precede the major characteristics of the disease, few significant precipitating factors related to habits or lifestyle have been found. Tissue typing tests seem to be the best early detection test of rheumatoid arthritis. A correlation has been found between the presence of the cell surface antigens HLA-Dw4 and HLA-DR4 to the incidence of the disease¹².

"Although hand function deterioration can be shown to

correlate with the extent of deformity in advanced cases, there is also detectable loss of function before deformity is apparent." In advanced cases of rheumatoid arthritis, signs of muscle atrophy exist. This is due to decreased manipulative abilities of the deformed hand and factors resulting from tenosynovitis; compression neuropathy and tendon weakness or rupture. Tendon weakness or rupture is best exemplified in the abductor tendons of the thumb and the extensor carpi ulnaris of the fourth and fifth fingers³⁰. Since carpal tunnel syndrome can be related to rheumatoid arthritis of the hand, those functional strength tests described for CTS patients would also apply for rheumatoid patients. However, an additional consideration exists when testing rheumatoids; joint deformity, joint laxity or subluxation and tendon weakness or rupture. These symptoms introduce additional factors related to functional loss. Functional strength tests may produce pain¹⁸. In these cases, pain may become the limiting factor in the magnitude of force generated by the phalanges, not muscle weakness. The primary purpose of the functional strength tests may be to determine the maximum strength at the threshold of pain and the joint loads that exist to produce this pain.

D: OTHER DISEASES PRODUCING HAND DEFORMITY AND WEAKNESS:

Other diseases that produce joint swelling include Psoriatic arthritis, r's syndrome, Osteoarthritis,

Hemochromatosis, Gout, Calcium pyrophosphate deposition disease and Thiemann's disease.

Other diseases that produce finger or thumb deformities include Parkinson's disease, Ehlers-Danlos syndrome, Systemic lupus erythematosus, Jaccoud's postrheumatic fever arthropathy, Wilson's disease, Dupuytren's contracture, Camptodactyly and Mucopolysaccharidoses. .

Other diseases that produce tendinitis and fasciitis include Malignancies, Diabetes, Amyloidosis and Hypothyroidism¹².

IV. EXPERIMENTAL MATERIALS:

A. PILL BOTTLE DYNAMOMETER:

This thesis research focuses on the applications of a unique type of hand held six load component transducer. This transducer detects forces and torques in three orthogonal directions; X, Y and Z (Figure 15). The uniqueness of this transducer is that it is housed within a standard plastic pill bottle (Figure 16).

This "Pill Bottle Dynamometer" is a modified SRMC3A series six load component transducer built by Advanced Mechanical Technology Incorporated (A.M.T.I.). A.M.T.I. describes its structure in their instruction manual.

The single allen head screw visible from the top with the cap off holds the male threaded bottle top onto the dyno. Loosening the screw relieves compression on two O rings and allows the threaded stem to be slipped off. Four 6-32 thread holes are visible after removing the screw and countersunk washer. They can be used for clamping and bolting other tops to the dyno... The bottom of the dyno has the lower portion of a pill bottle held on by four screws which compress O rings..."¹

The sensing elements of this SRMC3A-6-250 AMTI transducer are bonded strain gages potted into a high strength aluminum alloy (7075-T6) specimen¹. Strain gages are comprised of an etched foil section placed on a carrier substrate and cemented to the surface of a specimen. The specimen will deform in response to the loads administered onto it. The strain gages will deform comparably to the surface they are attached to. Its deformation or strain produces a proportional change in

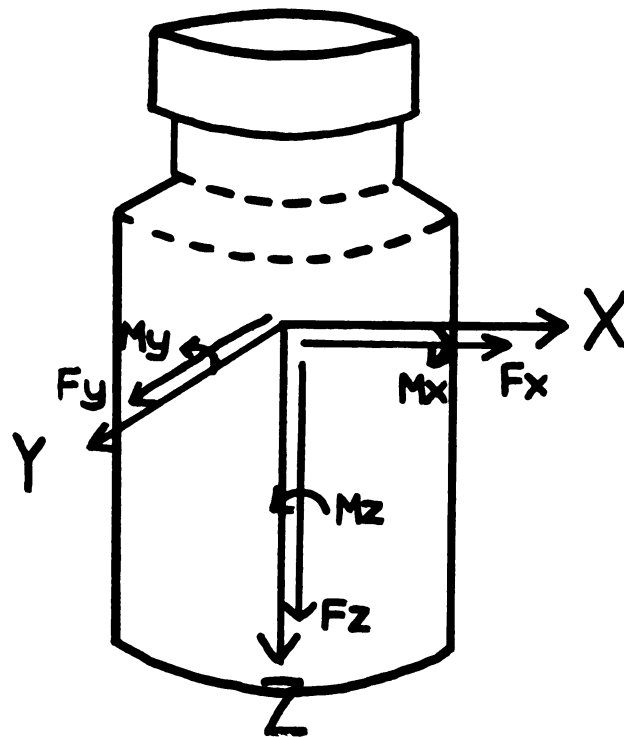


Figure 15: Six Load Component Dynamometer



Figure 16: Pill Bottle Dynamometer

resistance of the etched wires according to the equation below.

$$\frac{\Delta \text{length}}{\text{length}} = \frac{\Delta \text{resistance}}{\text{resistance}}$$

Strain gauges within the pill bottle sense slight deformations in the aluminum alloy when loads are applied to the cap or neck of the bottle. By strategically orienting and positioning strain gages onto the specimen, unique combinations of resistive changes can be combined into Wheatstone bridges to produce voltage signal changes according to Ohm's Law. Voltage readings from each bridge characterize the loads in each component direction. Computer controlled calibrations were performed by A.M.T.I. to relate the electrical signals to the loads producing them.

The dynamometer is bolted to a precise calibration stand and loads are then applied at various points in the three coordinate directions while the output from all six channels is monitored by the computer. The location of the X,Y,Z origin is computed from the data and given relative to the geometrical center of the plate¹.

The transducer center is located 2.3 inches below the surface of the cap. Calibration coefficients are then incorporated to convert the output voltages to the applied component loads relative to the transducer center. Six channels of output are read from the dynamometer in hexadecimal form; three orthogonal force components and three orthogonal moment components, i.e. Fx, Fy, Fz, Mx, My, Mz.

The vertical load capacity of the dynamometer is 250 pounds. The horizontal load capacities are half of the vertical rating (125 pounds). Other characteristics of the transducer are "high stiffness, high sensitivity, low crosstalk, excellent repeatability and long-term stability"¹. For more specifics on the pill bottle refer to the AMTI dynamometer instruction manual located in the Appendix.

One of the more obvious applications of the pill bottle dynamometer is that it can detect the forces and torques required to open or close a standard twist off cap, a child-proof cap, or a pop-off cap. A few of the less obvious applications are observed when closely analyzing the functional positions of the hand when opening or closing a bottle cap. For example, two common methods of opening a bottle are to laterally pinch the cap between the thumb and the side of the index finger or to form various point pinches between the pads of the fingers and the thumb. The opposite hand grasps the cylindrical base of the bottle to stabilize the bottle's position. Forces and torques are then generated by both hands to perform the task.

The purpose of this research project is to develop methods for performing basic functional strength tests both for clinical applications and packaging applications. Clinically these tests could be used to measure hand strength and phalangeal joint loads in various functional positions among patients afflicted with hand deformities or

dysfunction; i.e. Carpal-Tunnel Syndrome, Rheumatoid Arthritis, etc... In terms of packaging applications, the process of opening and closing a bottle cap or manipulating any other type of package could be broken down into its component parts and analyzed. This can be accomplished using various adapters for the pill bottle dynamometer.

B: MODIFICATIONS OF THE PILL BOTTLE DYNAMOMETER:

In common hand functions, the forces generated by the thumb against the fingers and the forces generated by the fingers against the thumb allow us to manipulate objects using various pinch, grasp and opposition positions of the hand. During an isometric gripping exercise the fingers and thumb produce forces equal and opposite to each other resulting in an approximate net zero force. Without a net force, the strain gages housed within the dynamometer will not sense a deformation of the specimen. The resultant reading is then zero. Therefore it was mandatory that opposing sides of the hand exert against objects external to one another; one of those objects being the transducer. The strain gages are located just beneath the neck of the pill bottle and only sense deformations in its neck or cap. Since the neck and cap of the bottle are smaller in circumference than its body, it was possible to confine the pill bottle securely within a cylinder of PVC whose inner circumference is equal to the outer circumference of the bottle's body. Using this design, the deformation sensitive

areas are allowed to suspend or deform freely within the PVC. By placing one opposing side of the hand against the PVC shell and the other against the cap, each side administers its load against objects external to one another. A net force and moment about the center of the transducer is detected from the side of the hand exerting its load on the transducer. These PVC components are called the "Pill Bottle Adapters" (Figure 17).

1: THE BASE ADAPTER:

The function of the base adapter is to provide a secure bottom for the pill bottle to rest on while allowing the hardware beneath it to suspend freely. A cable connection from the bottom of the pill bottle to the AMTI amplifier is bent slightly and exited through a small window in the side of the base adapter. The base allows the dynamometer to sit flat on the surface of a table and prevents the cabling from becoming damaged (Figure 18). Four set screws were placed against the sides of the hexagonal nut suspended beneath the pill bottle to prevent any movement of the dynamometer within the adapters.

2: THE THUMB OPPOSITION ADAPTER:

The thumb opposition adapter can be secured into the base adapter to confine the body of the pill bottle. The cap and a portion of the neck are exposed (Figure 19). Thumb opposition tests are performed by straddling the



Figure 17: Pill Bottle Adapters

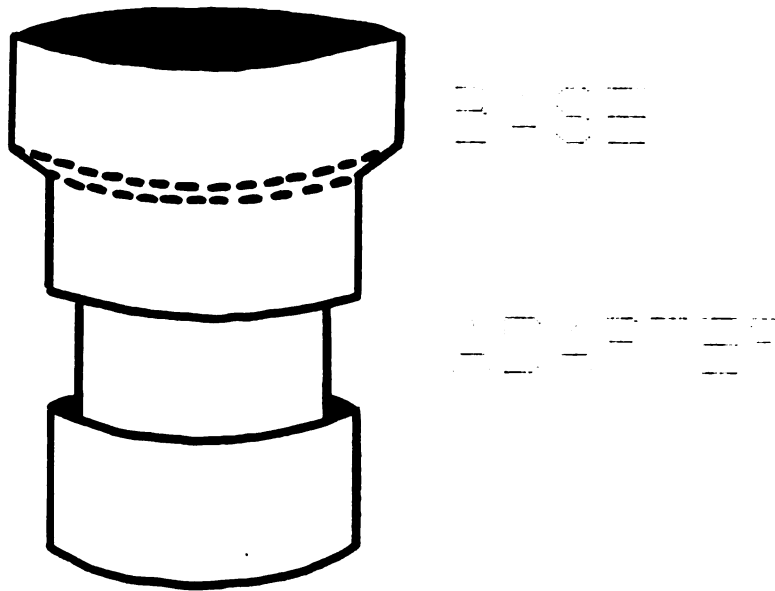


Figure 18: Base Adapter



Figure 19: Thumb Opposition Adapter

dynamometer between two adjacent phalanges and pushing down on the top of the cap with the thumb. Positions of thumb opposition are defined by the position of the thumb relative to the phalanges. The thumb can be oriented to oppose between the index and middle finger (position 3), the index and ring finger (position 5) and the ring and little finger (position 7).

3: THE PINCH ADAPTER:

The pinch adapter can be secured into the base adapter to confine the body of the pill bottle also. Only a small portion of the cap is exposed (Figure 20). This adapter is used for two-point, three-point, four-point, five-point and lateral pinch tests. In each condition the thumb opposes the fingers in a pinching position. The opposing side of the hand exerts its load against the PVC shell while the side being tested loads the side of the dynamometer cap.

4: THE GRASP ADAPTER:

The grasp adapter can be secured into the base adapter to confine the body of the pill bottle also. In order to expose the deformation sensitive area of the dynamometer a window in the PVC shell exists over the cap's location. In order to confine the dynamometer securely within the PVC shell, the cylinder was cut a few centimeters superior to the cap and a layer of plexiglass was cut and glued across its top. A cylindrical section of foam was then laid



Figure 20: Pinch Adapter

inside. This constrains the dynamometer with a cushion to prevent the bottle from sliding within the PVC cylinder and misaligning itself with the window. An additional 7 1/8" of PVC is attached superiorly to counterbalance the weight of the dynamometer and to provide more area to place the hand. Two cross-sections of PVC were attached to the side of the cap. Then, when the dynamometer is placed within the PVC shell and the cap is screwed into the neck of the bottle, the glued cross sections jut through the window and lie flush with the outer surface of the PVC shell without touching the sides of the window (Figure 21). This adapter was designed so that the dynamometer can detect individual finger forces or thumb forces in a grasping position. To perform this type of test, the individual finger or thumb to be tested is positioned over the window and the patient is asked to grasp the cylinder as tightly as possible. Although the whole hand participates in grasping the cylinder, only the forces generated by the individual digit positioned over the window are detected by the dynamometer. The pill bottle dynamometer and the adapters are unique to any designs found in the literature.

C: TARGETS:

Spherical objects were covered with 3M Scotchlite Brand High Grain 7610 Sheeting commonly called "retro-reflective tape". This tape has a reflectivity of light that is 1600 times greater than the reflectivity of a white surface. The



Figure 21: Grasp Adapter

"retro-reflective" constituents are small prisms or spheres that reflect light rays directly back to their source. This is an example of a passive target. Unlike active targets, they contain no energy source but work with an active external source instead. The retro-reflective targets are illuminated by four 100 watt indoor floodlights mounted approximately two inches from the center of the camera lens. Since the retroreflective prisms reflect light rays back to the light source, each increase of one degree between the light source and the camera lens reduces the intensity of light entering the lens by a factor of sixteen. This angle between the incidence light ray, the reflective target and the reflective light ray is called the observation angle. A distance of two inches between the camera lens and the light source allows maximum reflectivity of light without causing heat damage or thermal distortion to the camera components. This setup produces a high contrast image between the targets and the rest of the area. "When the subject is illuminated correctly, only the small markers are imaged with the subject outline and background disappearing." (22)

Twelve targets were positioned at known three dimensional positions to create a calibrated space. Additional targets were glued to a backing material and attached to predetermined landmarks on the hand and pill bottle for data acquisition.

V. METHODS OF DATA ACQUISITION:

A: CALIBRATION OF KINEMATIC SPACE:

A calibrated volume with a minimum of six control points is required prior to motion and position data acquisition (22). The first step of the calibration process is to create an accurate X,Y space on the floor of the lab.

Four calibration stands were used to vertically suspend targets on a plumb line. Plumb bobs located at the ends of each line were used to accurately position the targets over the four corners of the horizontal calibration area.

Vertical measurements of each target were also made. Each control point then represented a measured three dimensional location in space.

Twelve control points comprised the calibration volume. Vertically adjacent targets were spaced twelve centimeters apart (Figure 22). "The use of redundant targets is advised to minimize the impact of improperly located control points. In general, 8-16 control points will produce a good calibration." (22) Using twice the number of required control points contributed to the accuracy of the kinematic data while still allowing adequate separation of the targets in each camera view. The dimensions of this calibrated volume (30 inches X 30 inches X 24 inches) seemed optimal in that all of the predetermined hand strength tests could be performed entirely within the calibrated space but tight



Figure 22: Calibration Space

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enough around the activity that the cameras could be positioned closely. The space was also designed so that its lower perimeter was positioned below the table surface on which the tests were to be performed. This ensured that the targets would remain within the calibrated space.

Four NEC high speed solid state video cameras with a shutter speed of 60 Hertz were connected to an advanced VP320 model dynamic image processor. The video processor sends synchronized signals to each camera so that each frame of video data from all four cameras are synchronous in time. The visual images from the lens are focused on a light sensitive surface within each camera producing electrical outputs back to the VP320. A threshold setting on the video processor sets a voltage threshold line of demarcation between images that will appear white and those that will appear black on the binary display screen. An ExpertVision software digitizing program sweeps across a grid of pixels 240 high and 256 wide for each camera image. Voltage differences between adjacent pixels that cross this preselected threshold value are marked on the video screen. Targets then appear hollow. The program computes the centroids of each hollow image using an automated centroid calculation and determines its two dimensional coordinates. Each camera views the targets in a two dimensional plane perpendicular to the camera position. Through a rotation, translation and scaling of each camera image a calibration matrix is obtained equilibrating the measured target

location to the perceived target location in each camera view (22).

B: ENVIRONMENTAL OPERATOR:

At this point, the system has defined two dimensional positions for each target in each camera image. The next two steps were to assign target numbers to each image in each camera and then prompt the software to determine the three dimensional position of each target. The initial step requires the user to manually identify each target with a number for each camera view. This process is called "initializing". This two dimensional information is then combined from each camera via "direct linear transformation" to determine the perceived position of each target in three dimensional space. These perceived coordinate locations of each target are then compared with the measured coordinate locations. The degree of error between these values are determined by a least-squared-means process by the system (22). In this research test, the perceived coordinate locations versus the measured coordinate locations varied by no more than 0.5 millimeters. This produced a maximum norm of residuals of 0.30. Once the space had been calibrated, the targets were lowered to the bottom of the string, the strings were raised, a table was positioned inside the calibrated space and the plumb bobs were lowered to the surface of the table in order to approximate the outer parameters of the X,Y space on the tabletop (Figure 23).



Figure 23: Location Of Calibration Over The Table Top

This ensured that the functional tests were performed within the calibrated space.

C: TEST PREPARATION:

Five targets were used in the test. Two targets were placed on the joint to be examined and three targets were placed on the base adapter of the pill bottle. The joint targets were positioned on the medial and lateral sides of the first interphalangeal joint using two sided hypo-allergenic tape (Figure 24). The midpoint between these two target positions approximated the coordinates of the joint center of rotation and the position vector between them approximated the axis of joint flexion/extension.

Two targets on the base adapter were aligned with the X-axis of the transducer coordinate system. The third target was positioned between the other two at an equivalent height. These targets represented the coordinate positions of three non-collinear points that were used to define a coordinate system aligned with the coordinate system of the transducer with its origin at target A (Figure 25).

D: DATA ACQUISITION:

Position and force data were collected simultaneously by a data acquisition software called "PILL". While the patient performed each of the functional strength tests, the force data was sampled every ten milliseconds (100 Hz) and the motion data was sampled every 16.67 milliseconds (60Hz).

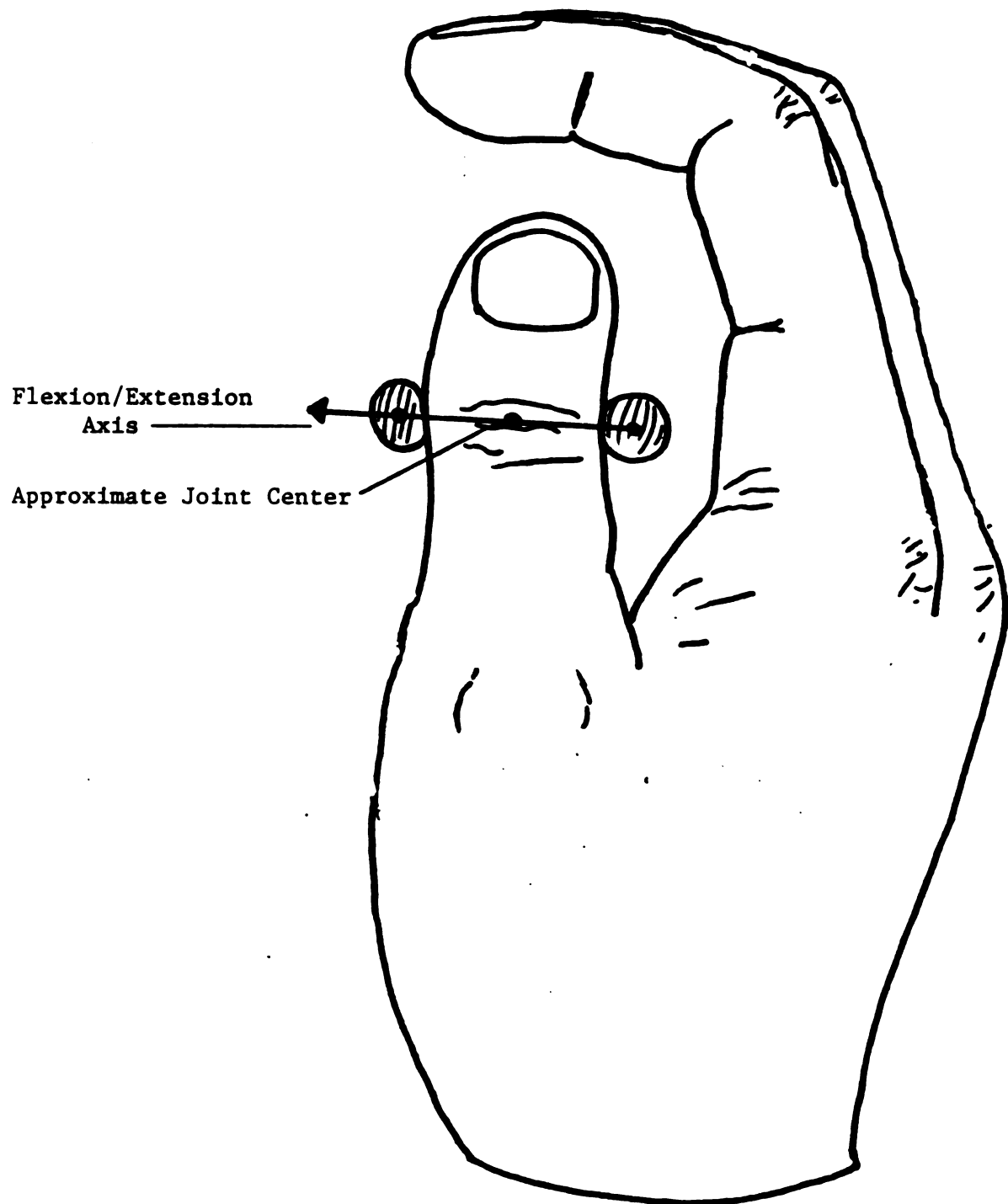


Figure 24: Target Placement On Phalangeal Joint

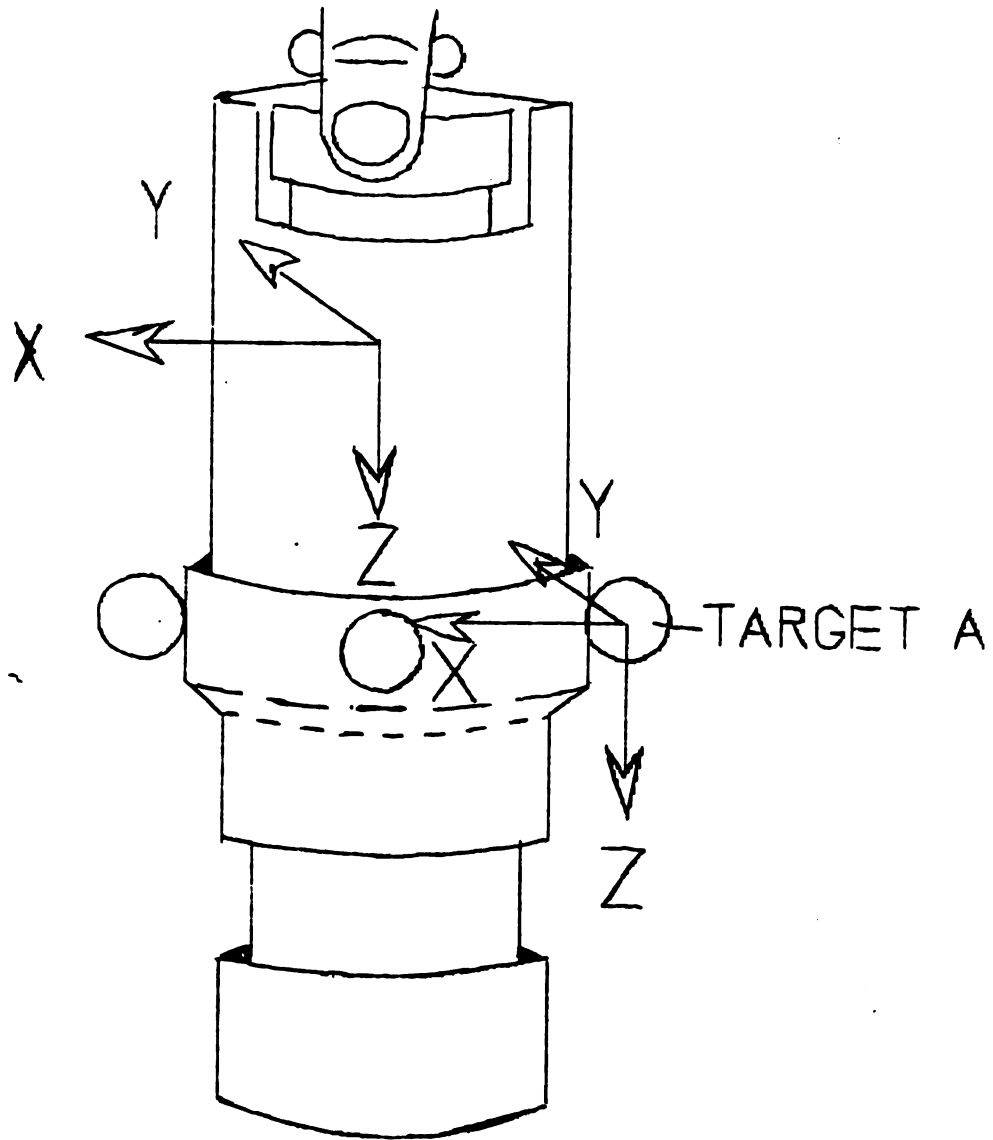


Figure 25: Target Placement On Base Adapter

VI: METHODS OF DATA ANALYSIS:

A: FORCE DATA ANALYSIS:

The force data was decoded from its hexadecimal form using the program "SPDCD" abbreviated for "special decoding program".

1: CENTER OF PRESSURE AND WRENCH AXIS CALCULATIONS:

The force and moment data were stored in a file in component form; F_z , F_x , F_y , M_z , M_x , M_y (Table 1). These values were sensed relative to the transducer center. It is possible to mathematically determine the magnitude and direction of the component forces and moments occurring at the point of contact between the finger or thumb and the bottle cap. This point of application is called the "Center of Pressure". It is defined as a point along the wrench axis where it penetrates the surface of the dynamometer; in this case the cap.

The data collected from the pill bottle dynamometer is defined as a "General Force System". This describes a condition where the resultant force and resultant moment are not perpendicular to one another. Only a "Coplanar" or "Parallel Force System" can be resolved into a single force or moment. In a coplanar system, all of the force vectors lie in the same plane. Therefore the resultant moment about any point would be perpendicular to that plane and likewise

Table 1: Output Form Of Decoded Force File

TIME	FZ	FX	FY	MZ	MX	MY
0	12.600	-33.382	-79.645	-0.008	-3.749	1.528
1	12.600	-32.999	-79.645	-0.019	-3.749	1.538
2	12.600	-33.382	-80.030	-0.008	-3.749	1.538
3	12.600	-33.382	-79.645	-0.019	-3.749	1.538
4	12.600	-32.999	-80.030	-0.008	-3.749	1.538
5	12.600	-32.999	-80.030	-0.008	-3.749	1.538
6	14.175	-32.999	-80.030	-0.019	-3.759	1.528
7	12.600	-32.999	-80.030	-0.019	-3.759	1.528
8	12.600	-33.382	-80.030	-0.019	-3.759	1.538
9	11.025	-33.765	-80.415	-0.008	-3.759	1.528
10	12.600	-33.382	-80.030	-0.019	-3.759	1.548
11	12.600	-33.382	-80.415	-0.008	-3.759	1.548
12	12.600	-33.382	-80.030	-0.019	-3.759	1.548
13	12.600	-33.382	-80.030	-0.008	-3.759	1.538
14	12.600	-33.382	-80.030	-0.008	-3.759	1.548
15	12.600	-33.765	-80.030	-0.019	-3.759	1.548
16	12.600	-33.765	-80.415	-0.008	-3.759	1.548
17	12.600	-33.382	-80.030	-0.008	-3.759	1.548
18	12.600	-33.382	-80.030	-0.008	-3.749	1.548
19	11.025	-33.382	-80.030	-0.008	-3.759	1.558
20	14.175	-33.765	-80.030	-0.008	-3.749	1.558
21	12.600	-33.382	-80.030	-0.008	-3.749	1.558

perpendicular to every force vector. In a parallel force system all of the force vectors lie parallel to each other. Therefore the resultant moment about any point would be perpendicular to that parallel direction and likewise perpendicular to each force vector. Using the concept of couples it is possible to calculate a point in space where the moment equals zero or only a pure moment exists.

General force systems can be expressed as a wrench by describing the resultant moment as a component parallel to the resultant force vector and a component perpendicular to it. By using the concept of couples the components of the perpendicular moment can be used to define a unique line of action relative to a point where the perpendicular moment equals zero. The resultant system is comprised of a force with a specific line of action and a parallel moment. This is the description of a wrench axis. The common point that exists both on the wrench axis and the cap surface or cap extended is defined as the point of application or the center of pressure. This mathematical application is limited to six load component dynamometers. Therefore, many hand held dynamometer designs are incapable of determining the point of contact between the digit and the dynamometer. No prior hand dynamometry studies describe calculations of the wrench axis although it is a necessary step in calculating internal loads at a joint. Therefore it is assumed that this mathematical process is unique to this thesis.

In the thumb opposition tests, the wrench axis penetrates the top surface of the cap or cap extended (Figure 26). Therefore the Z coordinate (vertical axis) of the COP is described as the distance from the origin of the transducer to the top surface of the cap. AMTI notes this distance to be 2.3 inches above the origin (1). Since the Z axis is directed downward the Z coordinate of the COP equals -2.3". The X and Y coordinates of the center of pressure point are determined mathematically by solving for "px" and "py".

The specific equations used to define the coordinates of the center of pressure, the direction and magnitude of the resultant force and the direction and magnitude of the parallel moment component for the thumb opposition test are described as:

Components of the force:

$$F_r = F_x i_x + F_y i_y + F_z i_z$$

Magnitude of the force:

$$|F_r| = (F_x^2 + F_y^2 + F_z^2)^{1/2}$$

Unit directions of the force:

$$i_r = \frac{F_x i_x + F_y i_y + F_z i_z}{|F_r|}$$

Components of the moment:

$$M_{ir} = M_x i_x + M_y i_y + M_z i_z$$

Moment component parallel to the force:

$$M_{||} = (M_o \cdot i_r) i_r$$

Moment component perpendicular to the force:

$$M_{\perp} = M_{ir} - M_{||}$$

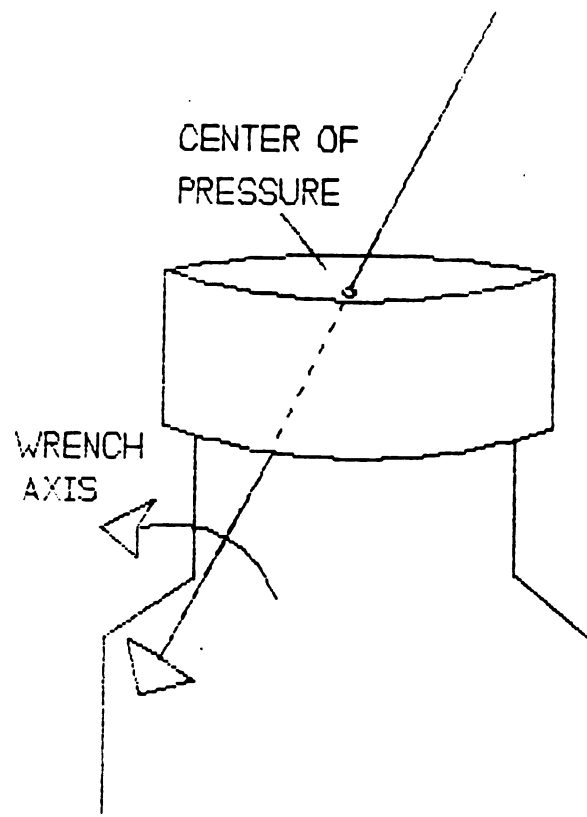


Figure 26: A Wrench Axis In Thumb Opposition

Calculating the coordinates of the COP relative to the transducer center

$$M = p \times F$$

$$M_x = p_y F_z - p_z F_y$$

$$M_y = p_z F_x - p_x F_z$$

$$M_z = p_x F_y - p_y F_x$$

The specific equations used to define the coordinates of the center of pressure, the direction and magnitude of the resultant force and the direction and magnitude of the parallel moment component for the pinch and grasp tests are more difficult to determine. In these types of tests, the thumb or fingers exert loads against the side of the cap instead of the top surface. Therefore the height or Z coordinate of the COP is not a constant. The only constant value is the radius of the cap. For the pinch tests, the radius of the cap is two centimeters. For the grasp test two cross sections of PVC have been added to the cap increasing its radius to three centimeters. Instead of describing the system in Cartesian coordinates (X,Y and Z) it is easier to describe using cylindrical coordinates. Cylindrical coordinates describe this system in terms of the radius of the cap, the angle between the X axis and the COP in the XY plane and the vertical distance of the COP from the origin of the transducer (Figure 27). These values are abbreviated as R, theta and Z.

The specific calculations are listed below.

The polar cylindrical coordinate system:

$$\hat{e}_r \times \hat{e}_\theta = \hat{e}_z$$

$$\hat{e}_\theta \times \hat{e}_z = \hat{e}_r$$

$$\hat{e}_z \times \hat{e}_r = \hat{e}_\theta$$

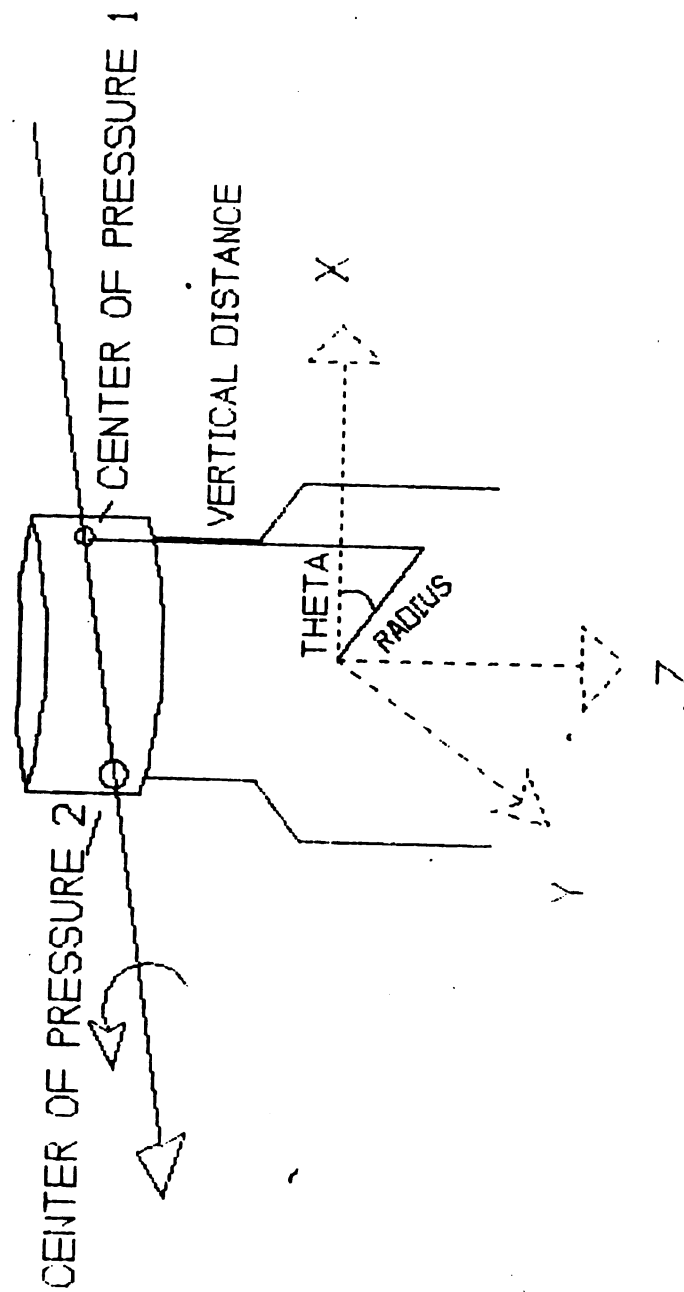


Figure 27: A Wrench Axis In Pinch And Grasp

The components to calculate the perpendicular moment:

$$p = R \cdot \hat{e}_r + Z \cdot \hat{e}_z$$

$$F = F_r \cdot \hat{e}_r + F_\theta \cdot \hat{e}_\theta + F_z \cdot \hat{e}_z$$

$$M_\perp = M_r \cdot \hat{e}_r + M_\theta \cdot \hat{e}_\theta + M_z \cdot \hat{e}_z$$

The relationship between Cartesian and cylindrical coordinate systems:

$$F_r = F_x \cos\theta + F_y \sin\theta$$

$$F_\theta = -F_x \sin\theta + F_y \cos\theta$$

$$F_z = F_z$$

$$M_r = M_x \cos\theta + M_y \sin\theta$$

$$M_\theta = -M_x \sin\theta + M_y \cos\theta$$

$$M_z = M_z$$

Calculating the perpendicular moment vector using cylindrical coordinates:

$$M_\perp = p \times F$$

$$M_{r\perp} = -Z \cdot F_\theta$$

$$M_{\theta\perp} = -R \cdot F_z + Z \cdot F_r$$

$$M_{z\perp} = R \cdot F_\theta$$

$$M_{z\perp} = R \cdot (-F_x \sin\theta + F_y \cos\theta)$$

$$M_{z\perp} = -F_x R \sin\theta + F_y R (1 - \sin^2\theta)^{1/2}$$

$$F_y R (1 - \sin^2\theta)^{1/2} = M_{z\perp} + F_x R \sin\theta$$

$$F_y^2 R^2 (1 - \sin^2\theta) = M_{z\perp}^2 + 2M_{z\perp} F_x R \sin\theta + F_x^2 R^2 \sin^2\theta$$

$$\sin^2\theta R^2 (F_x^2 + F_y^2) + \sin\theta (2M_{z\perp} F_x R) + (M_{z\perp}^2 - F_y^2 R^2) = 0$$

Quadratic equation equals two solutions (two COP's):

$$ax^2 + bx + c = 0, \quad x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \sin\theta$$

$$a = R^2 (F_x^2 + F_y^2)$$

$$b = 2M_z \perp F_x R$$

$$c = M_z \perp^2 - F_y^2 R^2$$

$$\sin\theta = \frac{-2M_z \perp F_x R \pm \sqrt{4M_z \perp^2 F_x^2 R^2 - 4[R^2 (F_x^2 + F_y^2)] * [M_z \perp^2 - F_y^2 R^2]}}{2[R^2 (F_x^2 + F_y^2)]}$$

$$\sin\theta = \frac{-2M_z \perp F_x R \pm 2R F_y \sqrt{F_x^2 R^2 - M_z \perp^2 + R^2 F_y^2}}{2[R^2 (F_x^2 + F_y^2)]}$$

Solve two equations for $\sin\theta_1$ and $\sin\theta_2$:

$$CPY1 = R * \sin\theta_1$$

$$CPY2 = R * \sin\theta_2$$

Solving for the cosine of the angle:

$$\sin\theta = \sqrt{1 - \cos^2\theta}$$

$$M_z \perp = R * F\theta$$

$$M_z \perp = R * (-F_x \sin\theta + F_y \cos\theta)$$

$$M_z \perp = -F_x R (\sqrt{1 - \cos^2\theta}) + F_y R \cos\theta$$

$$F_x^2 R^2 (1 - \cos^2\theta) = M_z \perp^2 - 2M_z \perp F_y R \cos\theta + F_y^2 R^2 \cos^2\theta$$

$$M_z \perp^2 - 2M_z \perp F_y R \cos\theta + F_y^2 R^2 \cos^2\theta - F_x^2 R^2 + F_x^2 R^2 \cos^2\theta = 0$$

$$\cos^2\theta R^2 (F_y^2 + F_x^2) + \cos\theta (-2M_z \perp F_y R) + (M_z \perp^2 - F_x^2 R^2) = 0$$

Quadratic equation equals two solutions for the cosine of the angle:

$$ax^2 + bx + c = 0$$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$x = \cos\theta$$

$$a = R^2 (F_y^2 + F_x^2)$$

$$b = -2M_z \perp F_y R$$

$$C = M_z l^2 - F_x^2 R^2$$

$$\cos\theta = \frac{2M_z l F_y R \pm \sqrt{4M_z l^2 F_y^2 R^2 - 4[R^2(F_y^2 + F_x^2) * (M_z l^2 - F_x^2 R^2)]}}{2(R^2(F_x^2 + F_y^2))}$$

$$\cos\theta = \frac{2M_z l F_y R \pm 2R F_x \sqrt{R^2 F_y^2 - M_z l^2 + R^2 F_x^2}}{2(R^2(F_x^2 + F_y^2))}$$

Solve for $\cos\theta_1$ and $\cos\theta_2$ to calculate the X coordinates of the COP's:

$$CPX_1 = R * \cos\theta_1$$

$$CPX_2 = R * \cos\theta_2$$

Solve for the Z coordinates of the COP's:

$$M_r = -Z * F_\theta$$

$$Z = -M_r / F_\theta$$

$$M_r = M_x \cos\theta + M_y \sin\theta$$

$$F_\theta = -F_x \sin\theta + F_y \cos\theta$$

$$Z = \frac{-(M_x l \cos\theta + M_y l \sin\theta)}{-F_x \sin\theta + F_y \cos\theta}$$

The force and parallel moment components of the wrench axis describe the load and torque that the fingers or thumb administer onto the pill bottle dynamometer at the center of pressure point. According to Newton's third law, the pill bottle also administers an equal and opposite load and torque onto the fingers or thumb tested. These equal and opposite loads are called the "Reaction Force" and "Reaction Torque" (Figure 28). They will be used to describe the loading that occurs on the finger or thumb at the point of contact with the dynamometer for thumb opposition tests, pinch tests and grasp tests.

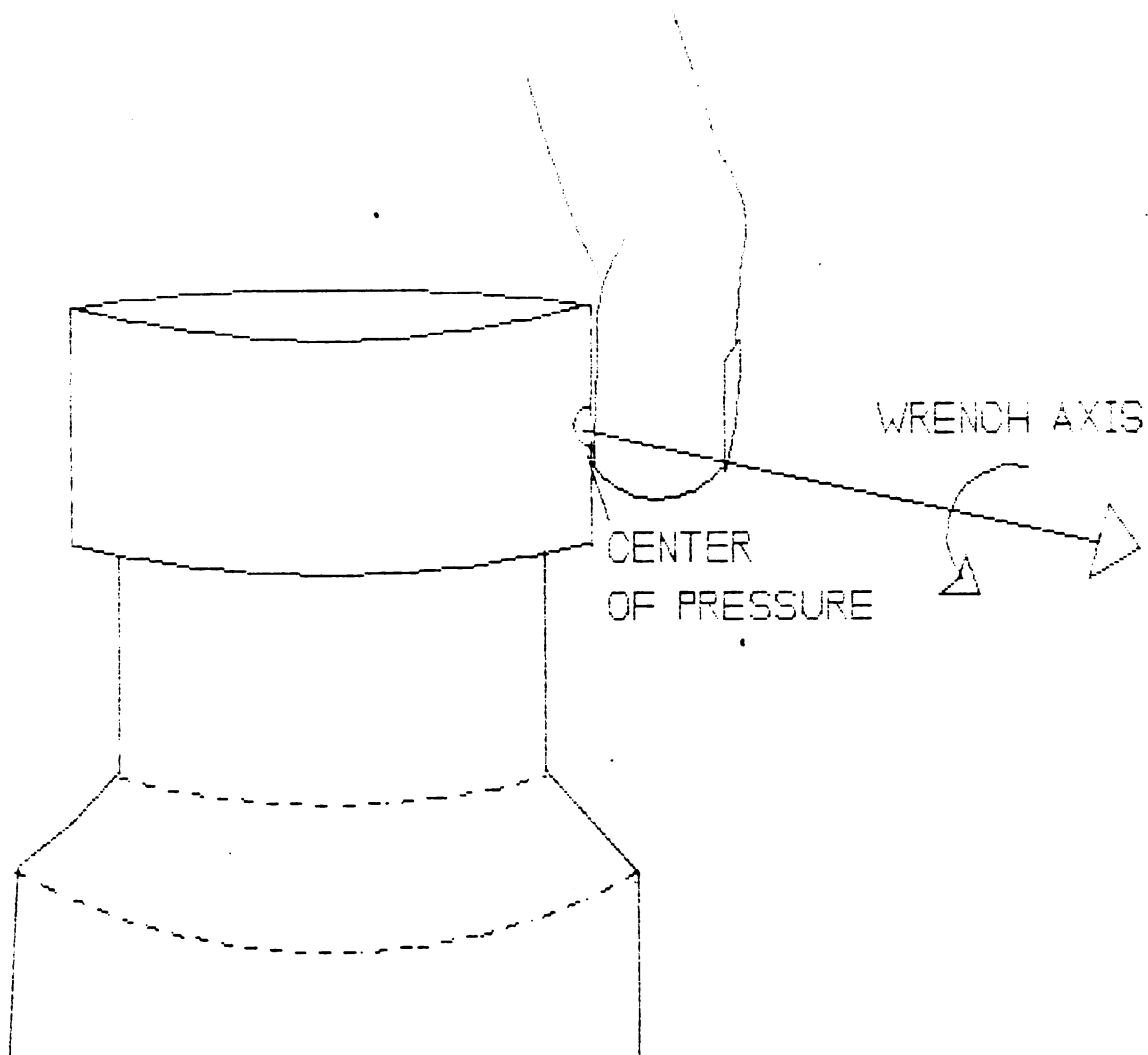


Figure 28: Pill Bottle Reaction Force And Torque

2: BOTTLE OPENING AND CLOSING:

The last type of functional hand test requires minimal mathematical analysis; opening and closing a bottle cap. In this type of test both opposing sides of the hand contact the cap and turn it either counterclockwise (to loosen the cap) or clockwise (to tighten the cap). Since both sides of the hand come in contact with the cap and oppose one another, it is not possible to determine the center of pressure and characteristics of the screw axis beneath each opposing side. Instead, raw torque and force values about the origin of the transducer are analyzed to determine the magnitudes of the loads created by the hand in opening and closing standard bottle caps or "child-proof" caps.

Equations for bottle opening and closing.

$$R = Xix + Yiy + Ziz$$

$$Fr = Fxix + Fyiy + Fziz$$

$$Mo = Mxix + Myiy + Mziz$$

$$Mo' = Mo + (R \times Fr)$$

$$Mo' = (Mx - ZFy)ix + (My + ZFx)iy + (Mz)iz$$

$$Mx' = Mx - ZFy$$

$$My' = My + ZFx$$

$$Mz' = Mz$$

3: THE PILL BOTTLE IMAGING PROGRAM:

The program, "PBIMAGE" (Pill bottle image), was written in Fortran77 and utilizes a three dimensional commercial graphics package called IGL (Interactive Graphics Library).

IGL subroutines were used to help create a three dimensional image of a pill bottle with its axes aligned with those on the dynamometer. The program then calculates the COP, the reaction force and the reaction torque and images this information on the pill bottle. The purpose of this program is to give the user a conceptual understanding of the loading position, direction and magnitudes of the forces and torques acting on the finger performing the functional strength tests. PBIMAGE begins by prompting the user for all required input. Brief descriptions of each prompt have been added below.

ENTER THE FORCE FILE (EX: FILENAME.DEC2)

Enter the name of a file containing decoded force plate data. The file must be decoded; must have a .dec2 extension)

ENTER THE BEGINNING TIME IN MILLISECONDS

Enter the first millisecond that the calculations and imaging will begin on.

ENTER THE END TIME IN MILLISECONDS

Enter the last millisecond that the calculations and imaging will end on.

ENTER THE TYPE OF TEST PERFORMED.

0= THUMB OPPOSITION TEST

1= PINCH TEST (LATERAL, 2-POINT, 3-POINT)

2= GRASP TEST

3= BOTTLE OPENING OR CLOSING TEST

Enter the integer that corresponds with the type of standardized test performed.

ENTER THE TYPE OF IMAGE PERFORMED

0= REACTION FORCE

1= REACTION TORQUE

Enter the integer that corresponds with the type of vectors that will be imaged from the center of pressure points.

ENTER THE VECTOR SCALE FACTOR

Enter a multiplicative factor that will be combined with the magnitude of the actual reaction force or torque vectors in order to increase or decrease their imaged magnitudes.

ENTER THE X COORDINATE VIEWPOINT

ENTER THE Y COORDINATE VIEWPOINT

ENTER THE Z COORDINATE VIEWPOINT

The X,Y, and Z coordinates of this point define the displacement of the viewer eye position from the origin of the pill bottle image according to the screen axis system.

Figure 29 gives an example of the input portion of this program.

After all of the input data has been given, the IGL subroutines are accessed to set up the graphic environment parameters. The graphics environment is a three dimensional space within which the images are drawn. This space is called a three dimensional graphics window. Lines, arrowheads and text are imaged using specific subroutines within the graphics package. The dimensions of the pill bottle are imaged based on the bottle's actual dimensions (Figure 30). The components of the pill bottle are imaged by drawing successive circles in three dimensional space. The program initially positions the cursor a predetermined vertical distance (Z) from the origin of the bottle and a distance equivalent to the radius of the circle in the X,Y plane for every 16 degrees of rotation within that plane. It then draws a line from the old cursor position to the new cursor position. The program performs this function 24 times to image one complete circle made up of 24 points with defined three dimensional coordinates. The program then

```
ENTER THE FORCE FILE (EX:FILENAME.DEC2)
dhp2.dec2
ENTER THE BEGINNING TIME IN MILLISECONDS
1
ENTER THE END TIME IN MILLISECONDS
380
ENTER THE TYPE OF TEST PERFORMED.
0 =THUMB OPPOSITION TEST
1 =PINCH TEST (LATERAL,2-POINT,3-POINT)
2 =GRASP TEST
3 =BOTTLE OPENING OR CLOSING TEST
1
ENTER THE TYPE OF IMAGE PERFORMED.
0= REACTION FORCE
1= REACTION TORQUE
0
ENTER THE VECTOR SCALE FACTOR
2.5
ENTER THE X COORDINATE VIEWPOINT
5
ENTER THE Y COORDINATE VIEWPOINT
2
ENTER THE Z COORDINATE VIEWPOINT
-0.3
```

Figure 29: Input Portion Of PBIMAGE Program

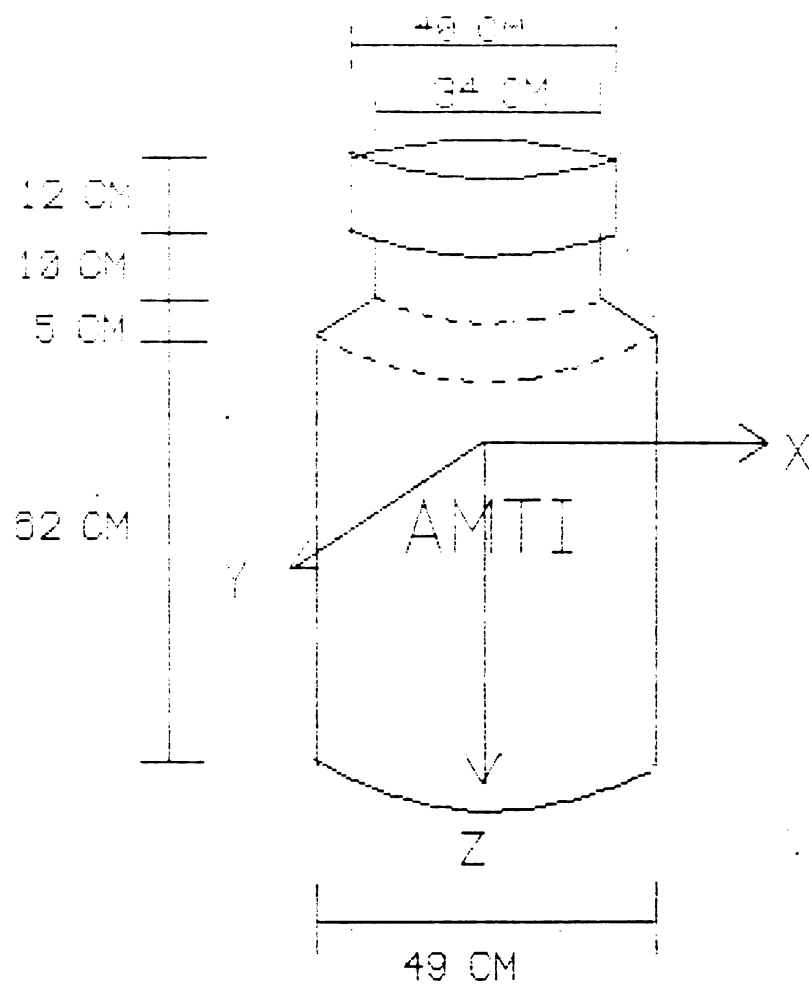


Figure 30: Dimensions Of The Pill Bottle Dynamometer

moves the cursor to a new predetermined distance in the Z direction and repeats the process again.

The base of the bottle consists of 48 circles with a radius of 25 mm. A distance of 1.3 mm between each circle creates an image of the bottle's base 65 mm in height. The neck of the bottle consists of 10 circles with a 17 mm radius. A distance of one millimeter between each circle creates an image of the bottle's neck 10 mm in height. The funnel of the pill bottle is a transition area connecting the smaller radius of the neck to the larger radius of the base. Five circles are drawn with each successive circle decreasing in radius by one millimeter. The cap of the bottle is drawn with a 20 mm radius for the thumb opposition, pinch and bottle opening and closing tests. It is imaged with an increased radius of 30 mm for grasp tests. Two circles comprise the cap with a distance of 12 mm in between. Vertical lines are drawn from each calculated point of the upper circle to corresponding positions on the lower circle of the cap. Dashed lines are then drawn across the top surface of the cap in alignment with the X and Y axes. More vertical lines are drawn from the outer edges of the dashed lines on the top of the cap to the bottom of the cap (Figure 31).

The pill bottle is initially oriented with its axes and the screen axes aligned. The image is then rotated 90 degrees about its X axis, scaled by a factor of three in the X,Y and Z directions and translated fifty millimeters in the

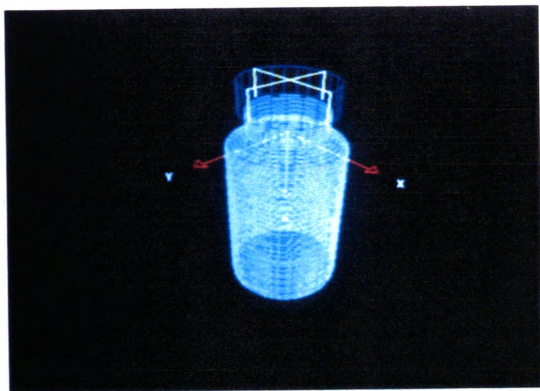


Figure 31: 3-D Image Of The Pill Bottle Dynamometer

positive Z direction of the pill bottle's coordinate system.

Once the dynamometer has been imaged, the program then calculates the center of pressure point, reaction force and reaction torque for each millisecond of the test performed. The center of pressure is drawn and the reaction vectors are then scaled proportionally and imaged. The program can also image raw moment and force data for cap opening and closing tests by translating the force and moment components from the origin of the dynamometer to the center of the cap's top surface. Figures 32, 33 ,34 and 35 give an example of the images created for each type of functional hand strength test. Figure 36 represents a schematic outline of the PBIMAGE program.

4: THE PBCOP PROGRAM:

The "PBCOP" program performs the same calculations as the PBIMAGE program (center of pressure, reaction force and reaction torque) for each type of functional strength test. In addition, it calculates the resultant magnitude of force exerted against the cap. However, it does not image the pill bottle or any of the calculated data. Instead, it creates an output file that either lists the coordinates of the COP, and the components of the reaction force and the reaction torque or lists the resultant magnitude of the force for each millisecond sampled. The output files for both conditions are listed in table form. An example of the input portion of PBCOP is shown in Figure 37. A schematic

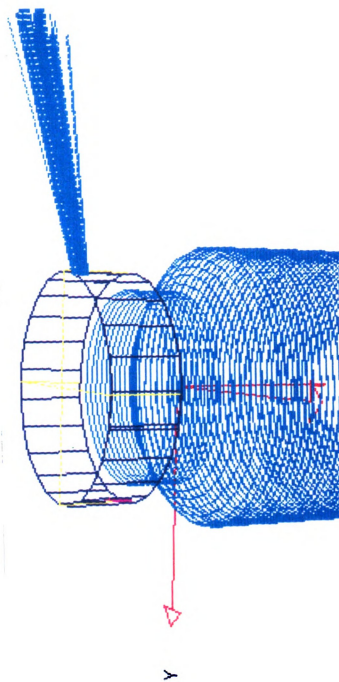


Figure 32: Example Of Imaging A Pinch Test

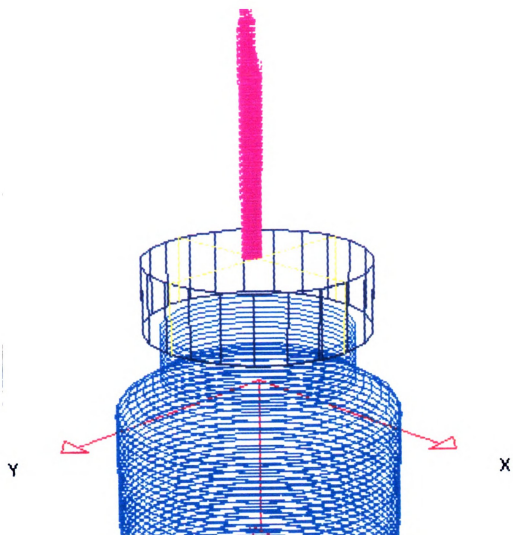


Figure 33: Example Of Imaging A Thumb Opposition Test

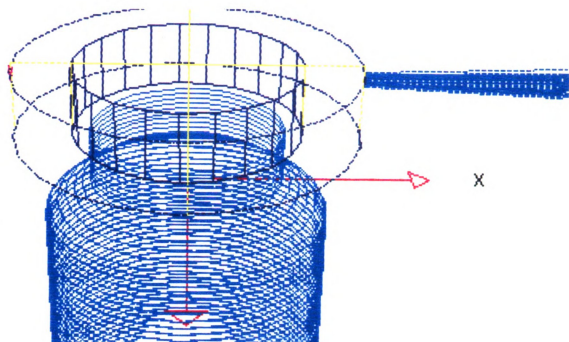


Figure 34: Example Of Imaging A Grasp Test

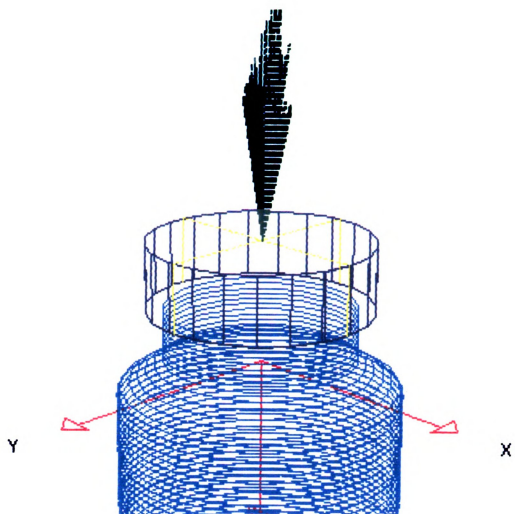


Figure 35: Example Of Imaging A Cap Opening/Closing Test

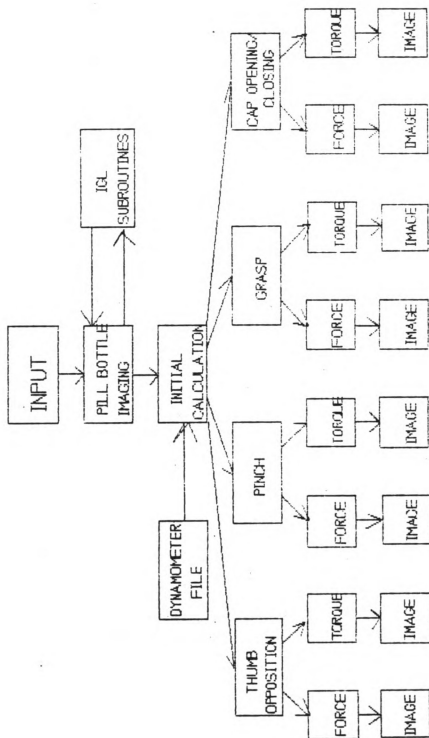


Figure 36: Schematic Outline Of PRIMAGE Program

```
SunOS/frith 39% pbcop
ENTER THE FORCE FILE (EX:FILENAME.DEC2)
dhp2.dec2
ENTER THE BEGINNING TIME IN MILLISECONDS
1
ENTER THE END TIME IN MILLISECONDS
380
WOULD YOU LIKE AN OUTPUT FILE CONTAINING COP,
PBRF AND PBRT DATA OR RESULTANT FORCE DATA?
TYPE "COP" OR "RES".
COP
ENTER THE TYPE OF TEST PERFORMED.
0= THUMB OPPOSITION TEST
1= PINCH TEST (LATERAL, 2-POINT, 5-POINT)
2= GRASP TEST
3= BOTTLE OPENING OR CLOSING TEST
1
THE PINCH TEST OUTPUT FILE WILL CONTAIN COORDINATES
OF THE COP, REACTION FORCE AND REACTION TORQUE.
ENTER THE NAME OF THIS OUTPUT FILE (EX:FILENAME.P2)
dhp2.fce
```

Figure 37: Input Portion Of PBCOP Program

outline is shown in Figure 38. Figure 39 exemplifies the graphs of resultant force over time for each type of functional strength test. The test subject was a 25 year old female with no apparent hand problems. Figures 40, 41 and 42 exemplify the graphic outputs of C.O.P. coordinates, reaction force components and reaction torque components over time for each type of functional strength test performed by the same subject.

B: POSITION DATA ANALYSIS:

After the targets have been initially identified by the user, the Motion Analysis Corp. software assigns target names to target images for subsequent frames of data. This process is called "tracking". The system accomplishes this by keeping track of each target's trajectory in order to approximate where it will appear in the following frames. It does this by creating a window around an area it expects the image to appear in the next frame. If an image lies within this window the system continues to assign the same target name to it. Sometimes, however, the system can get confused and user intervention is required.

The targets were tracked from a point prior to the dynamometer triggering frame to the end of the test. The file was then reformatted into a form that lists the coordinates of all the targets for each frame collected. This data format lists the relative positions of each target at each instant in time so that angle calculations, midpoint

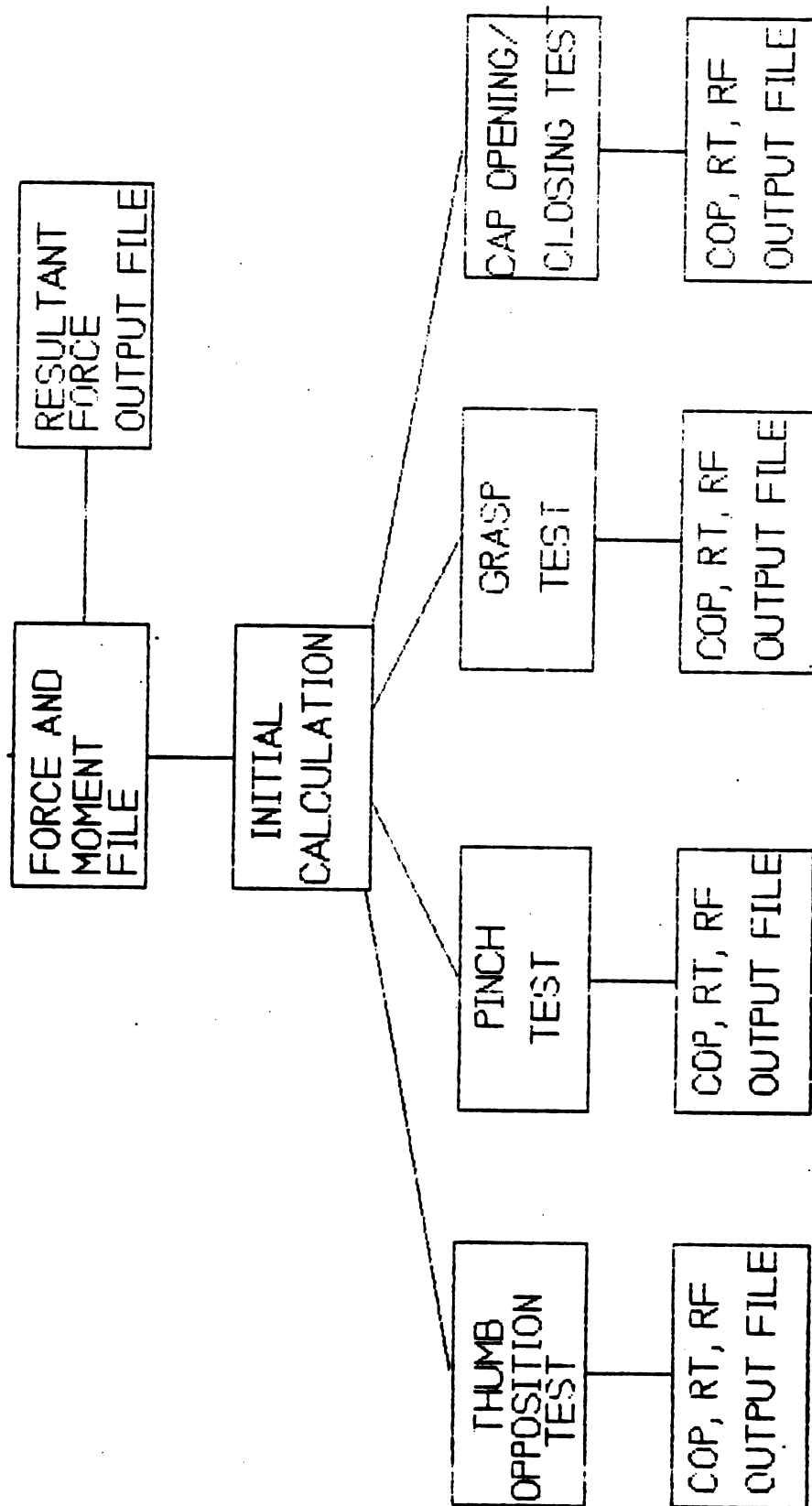


Figure 38: Schematic Outline of PBCOP Program

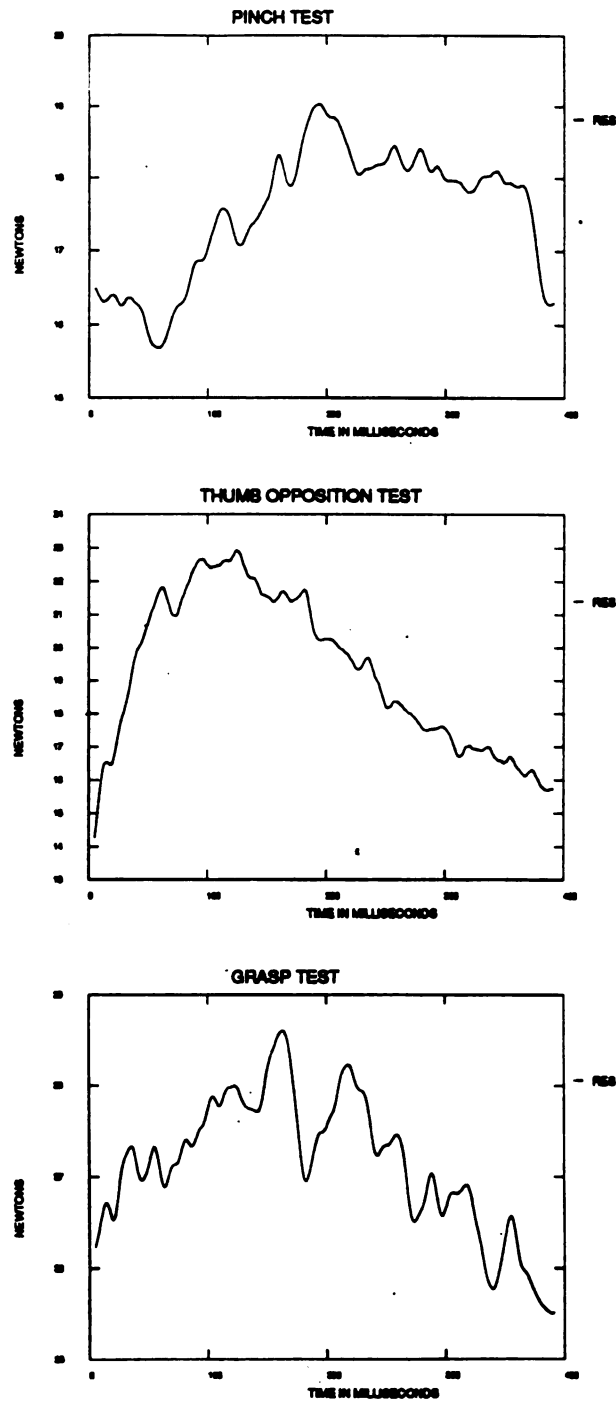


Figure 39: Resultant Force Output Graphs

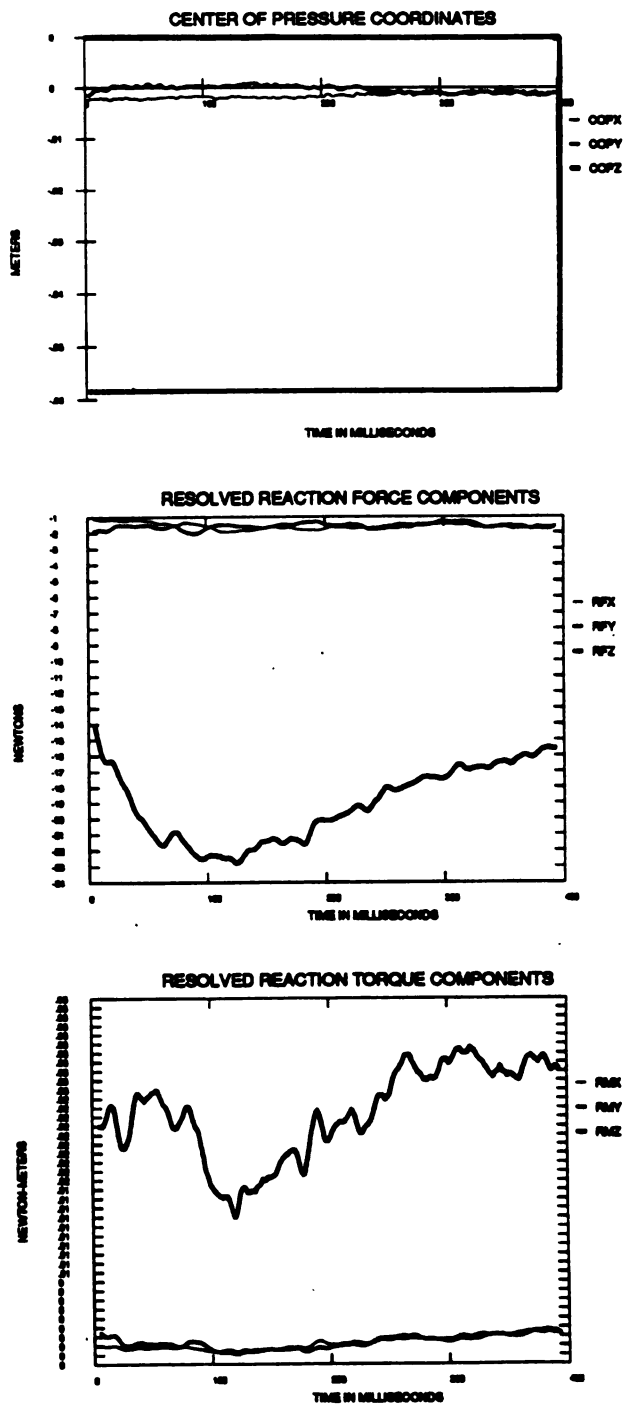


Figure 40: Thumb Opposition Test: Reaction Wrench Comp.

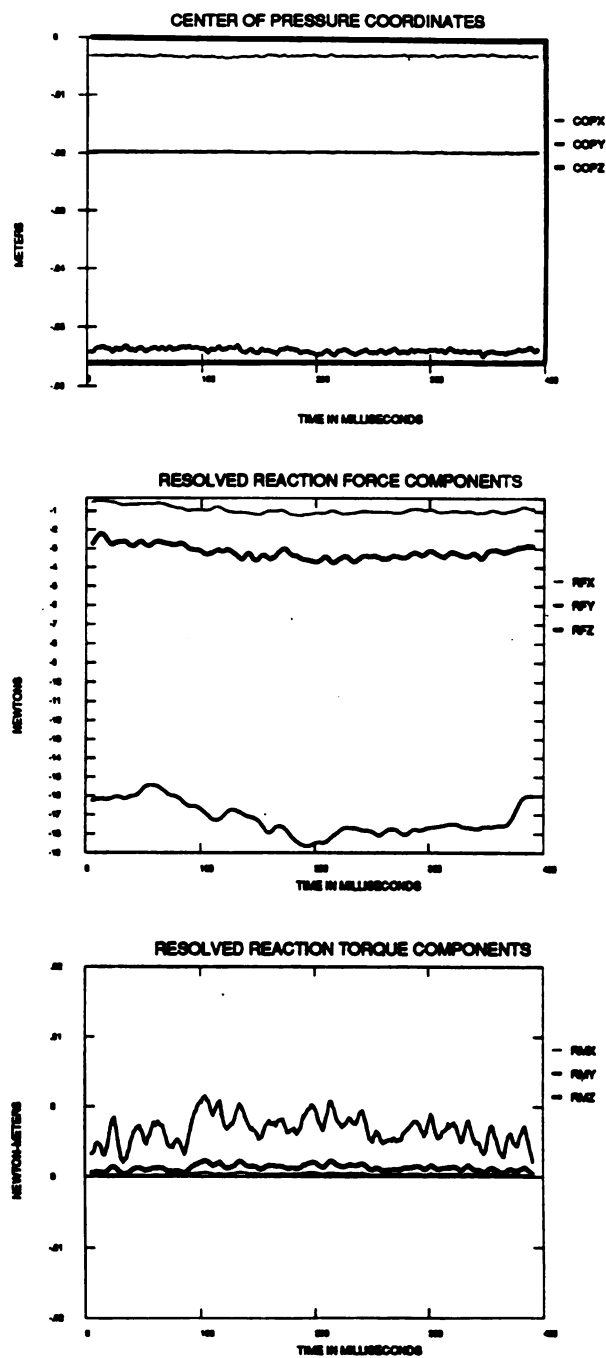


Figure 41: Pinch Test: Reaction Wrench Components

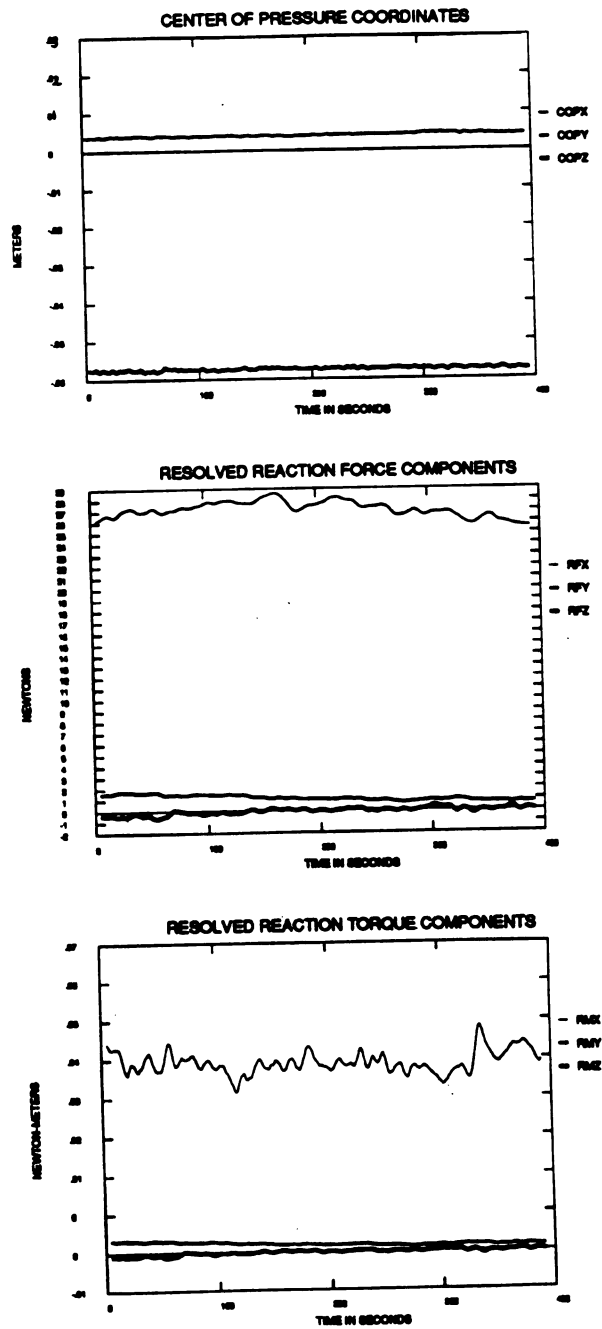


Figure 42: Grasp Test: Reaction Wrench Components

calculations or local coordinate system calculations can be performed.

The two phalangeal target locations were extracted from the reformatted file and stored in an external file using a program called "TARGSEL2". TARGSEL2 is an abbreviation for "select two targets". It allows the user to extract numerical data of two targets from the main motion file. Another program called "TARGSEL3" allows the user to extract numerical data of three targets from the main motion file. TARGSEL3 was used to extract the coordinate positions of the three pill bottle targets.

C: SYNCHRONIZATION OF FORCE AND MOTION DATA:

By examining the changes in the acquired data (exam/ch) the frame of motion data that the force plate was triggered on can be assessed. This frame is the initial synchronization point of the force and motion data.

1: THE PBMOM PROGRAM:

PBMOM is abbreviated for the "pill bottle phalangeal moment program". PBMOM synchronizes force and motion data with time, calculates the approximate center of the phalangeal joint, calculates the flexion/extension axis of the phalangeal joint, creates a coordinate system aligned with the transducer's coordinate system, determines the coordinates of all points in this new coordinate system and calculates the loads about the phalangeal joint center and

flexion/extension axis. It performs these functions every 50 milliseconds or at a frequency of 20 Hz.

This program recognizes the frame corresponding with force plate triggering to be the initial synchronization point between the force and motion files. Due to the sampling frequencies of these files the data become synchronized every 50 milliseconds after this point (20 Hertz). This corresponds to every third frame of motion data and every fifth frame of force data.

In a more detailed form, the program reads the entire motion and force files. It recognizes synchronous motion and force data and stores this information separately in temporary files. The program then reads these temporary motion and force files and repeatedly performs all of the calculations to define phalangeal joint loading at each synchronous moment in time (Figure 43). In order to utilize both the force and the motion data to calculate the loads at the approximate joint center, both types of data have to be described in the same system.

Initially, the force data is read relative to the origin of the coordinate system located at the center of the transducer. The position data is read relative to the origin of the calibration space. The first series of calculations creates a coordinate system on the pill bottle using the three non-colinear points attached to it. This coordinate system is aligned with the coordinate system within the transducer but its origin is located at target A.

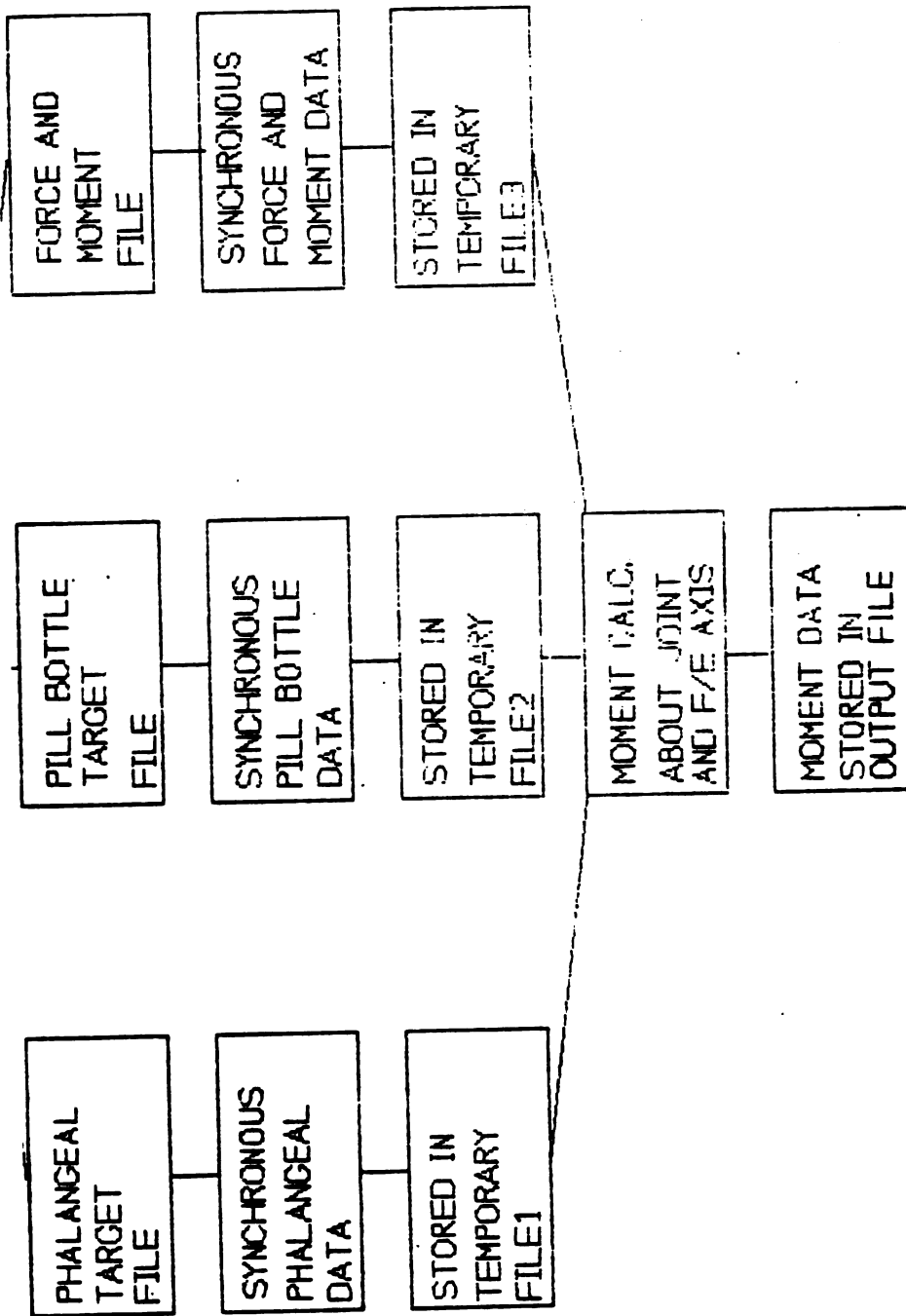


Figure 43: Schematic Outline of PPMOM Program

The directional cosines used to describe the orientation of the coordinate system located on the pill bottle provide the transformation matrix needed to describe the force data and position data in the same coordinate system. The coordinates of the phalangeal targets, the approximate phalangeal joint center, the transducer center, the center of pressure, the position vector between the COP and the phalangeal joint center and the position vector describing the flexion/extension axis are described in this new coordinate system via transformation equations. Joint loading about the approximate joint center of the phalangeal joint is calculated using a cross product between the position vector of the COP and the joint center and the reaction force component program. The reaction torque is then added to this value to determine total component moments about the joint center. Moments about the flexion/extension axis of the phalangeal joint are calculated by computing the dot product between the previously calculated moment and the unit vector describing the direction of the flexion/extension axis. Figure 44 conceptually describes this process. The calculations used to perform this operation are given below.

Creating a coordinate system on the pill bottle:

$$AB = X = B - A$$

$$ix = AB / |AB|$$

$$AC \times AB = Z$$

$$iz = AC \times AB$$

$$\text{-----}$$

$$|AC \times AB|$$

$$iy = iz \times ix$$

$$\begin{array}{lcl} \text{transformation} & & \begin{matrix} ix & iy & iz \\ iy & iz & ix \\ iz & ix & iy \end{matrix} \\ \text{matrix} & = & \end{array}$$

Describing coordinates of target A in pill bottle coordinate system.

$$\begin{array}{lcl} \text{targetA } x' & & ix \quad iy \quad iz \\ \text{targetA } y' & = & iy \quad iz \quad ix \\ \text{targetA } z' & & iz \quad ix \quad iy \end{array} \quad * \quad \begin{array}{l} x \\ y \\ z \end{array}$$

Describing coordinates of target B in pill bottle coordinate system.

$$\begin{array}{lcl} \text{targetB } x' & & ix \quad iy \quad iz \\ \text{targetB } y' & = & iy \quad iz \quad ix \\ \text{targetB } z' & & iz \quad ix \quad iy \end{array} \quad * \quad \begin{array}{l} x \\ y \\ z \end{array}$$

Describing coordinates of medial phalangeal target in pill bottle coordinate system.

$$\begin{array}{lcl} \text{medphal targ } x' & & ix \quad iy \quad iz \\ \text{medphal targ } y' & = & iy \quad iz \quad ix \\ \text{medphal targ } z' & & iz \quad ix \quad iy \end{array} \quad * \quad \begin{array}{l} x \\ y \\ z \end{array}$$

Describing coordinates of lateral phalangeal target in pill bottle coordinate system.

$$\begin{array}{lcl} \text{latphal targ } x' & & ix \quad iy \quad iz \\ \text{latphal targ } y' & = & iy \quad iz \quad ix \\ \text{latphal targ } z' & & iz \quad ix \quad iy \end{array} \quad * \quad \begin{array}{l} x \\ y \\ z \end{array}$$

Calculating the coordinates of the approximate phalangeal joint center in the pill bottle coordinate system.

$$\begin{aligned} \text{joint center } x' &= (\text{medphal } x' + \text{latphal } x')/2 \\ \text{joint center } y' &= (\text{medphal } y' + \text{latphal } y')/2 \\ \text{joint center } z' &= (\text{medphal } z' + \text{latphal } z')/2 \end{aligned}$$

Calculating the coordinates of the transducer in the pill bottle coordinate system.

$$\begin{aligned} \text{center } x' &= (\text{targetA } x' + \text{targetB } x')/2 \\ \text{center } y' &= (\text{targetA } y' + \text{targetB } y')/2 \\ \text{center } z' &= \text{targetA } z' - (\text{height} - 0.0584) \\ & \quad ** \text{ height} = \text{height from target A to cap top.} \end{aligned}$$

Calculating the coordinates of the COP in the pill bottle coordinate system

$$\begin{array}{lcl} \text{cop } x' & = & \text{cop } x + \text{center } x' \\ \text{cop } y' & = & \text{cop } y + \text{center } y' \\ \text{cop } z' & = & \text{cop } z + \text{center } z' \end{array}$$

Calculating the distance between the COP and the approximate joint center in the pill bottle coordinate system.

$$\text{distance} \begin{matrix} x' \\ y' \\ z' \end{matrix} = \text{cop} \begin{matrix} x' \\ y' \\ z' \end{matrix} - \text{joint center} \begin{matrix} x' \\ y' \\ z' \end{matrix}$$

Calculating the moment about the phalangeal joint center in the pill bottle coordinate system.

$$\text{moment} \begin{matrix} x' \\ y' \\ z' \end{matrix} = s \begin{matrix} x' \\ y' \\ z' \end{matrix} \times \text{reactionf} \begin{matrix} x \\ y \\ z \end{matrix} + \text{reactiont} \begin{matrix} x \\ y \\ z \end{matrix}$$

Calculating the resultant moment about the phalangeal joint center in the pill bottle coordinate system.

$$\text{resmoment} = (\text{momentx}'^2 + \text{momenty}'^2 + \text{momentz}'^2)^{1/2}$$

Calculating the direction of the flexion/extension axis of the phalangeal joint in the pill bottle coordinate system.

$$f/e \begin{matrix} x' \\ y' \\ z' \end{matrix} = \text{medphal} \begin{matrix} x' \\ y' \\ z' \end{matrix} - \text{latphal} \begin{matrix} x' \\ y' \\ z' \end{matrix}$$

$$\text{magnitude } f/e = (f/ex'^2 + f/ey'^2 + f/ez'^2)^{1/2}$$

$$\begin{aligned} f/ex' &= f/ex' / |f/e| \\ f/ey' &= f/ey' / |f/e| \\ f/ez' &= f/ez' / |f/e| \end{aligned}$$

Calculating the moments about the flexion/extension axis of the phalangeal joint in the pill bottle coordinate system.

$$f/e \text{ moment} = (f/ex' \times \text{momentx}') + (f/ey' \times \text{momenty}') + (f/ez' \times \text{momentz}')$$

PBMOM begins by prompting the user for input.

ENTER THE FORCE FILE CONTAINING COP, REACTION
FORCE AND REACTION TORQUE INFORMATION:
This is the output filename from the pbcop
program.

ENTER THE MOTION FILE CONTAINING THE PHALANGEAL
TARGET LOCATIONS:
This is the output filename from the targsel2
program.

ENTER THE MOTION FILE CONTAINING THE PILL BOTTLE
TARGET LOCATIONS:
This is the output filename from the targsel3
program.

ENTER THE NAME OF THE OUTPUT MOMENT FILE:

This is the output filename for this program that will contain the force and moment components about the approximate phalangeal joint center.

ENTER THE FRAME NUMBER THE DYNAMOMETER WAS TRIGGERED ON:

This is the initial synchronization point of the force and motion data observed from the examine changes program (exam/ch).

ENTER THE FIRST FRAME NUMBER OF THE _____.TED FILE:

This is the initial frame of the track edited file.

ENTER THE FRAME NUMBER TO BEGIN MOMENT CALCULATIONS:

This is asking the user to input the frame to start calculating joint loads.

ENTER THE LAST FRAME NUMBER OF MOMENT CALCULATIONS:

This is asking the user to input the frame to stop calculating joint loads.

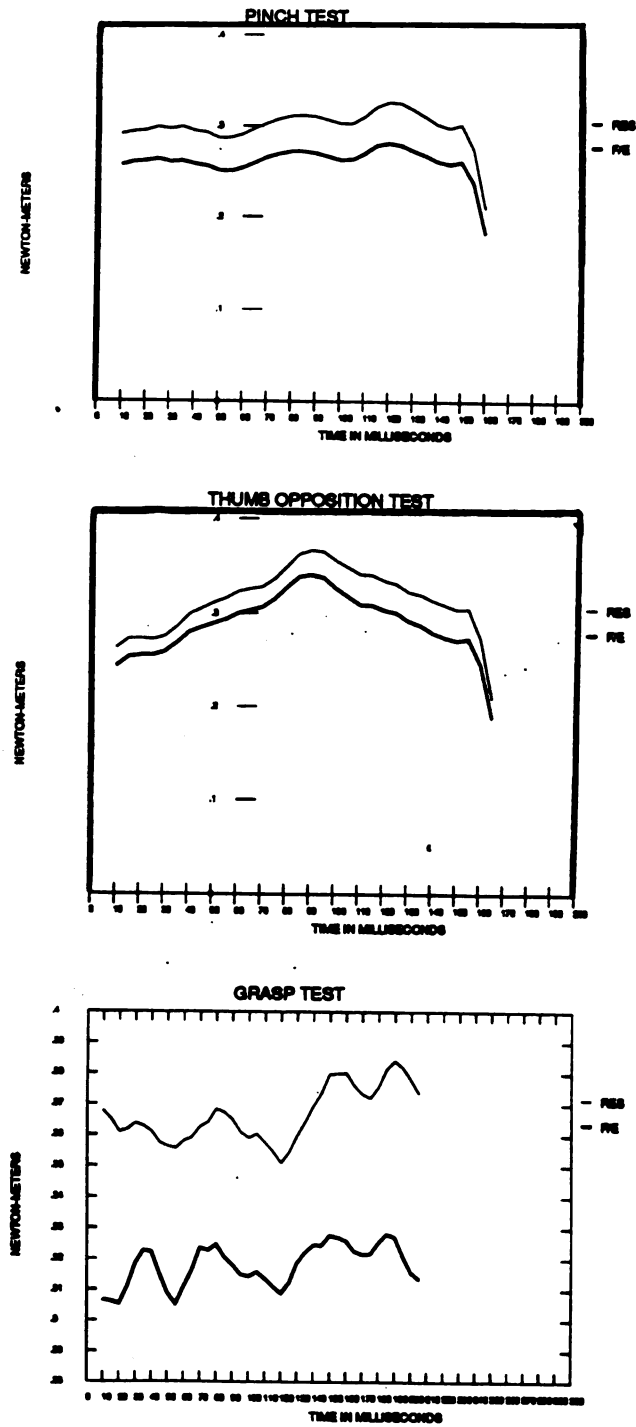
Figure 45 gives an example of the input for Pbmom.

PBMOM allows the user to input the block of time in which to perform the moment calculations about the phalangeal joint center or flexion/extension axis. However, the frame number inputted to begin moment calculations may not be one of the frames synchronous with force data. Therefore, the program actually begins calculations on the first synchronous frame number after the one inputted. Likewise, the last frame number inputted to perform moment calculations may not be a frame that is synchronous with force data. PBMOM stops the calculations on the last synchronous frame number prior to the one inputted.

Figure 46 is a graphical example of phalangeal joint loads from a 25 year old female norm. The output is comprised of phalangeal joint moments about the approximate joint center

SunOS/frith 40% pbmom
ENTER THE FORCE FILE CONTAINING COP,REACTION FORCE
AND REACTION TORQUE INFORMATION FROM THE PBCOP
PROGRAM.
dhp2.fce
ENTER THE MOTION FILE CONTAINING THE PHALANGEAL
TARGET LOCATIONS.
dhp2ph.pos
ENTER THE MOTION FILE CONTAINING THE PILL BOTTLE
TARGET LOCATIONS.
dhp2pb.pos
ENTER THE NAME OF THE OUTPUT MOMENT FILE.
dhp2.mom
ENTER THE FIRST FRAME NUMBER OF THE __.TED FILE.
1
ENTER THE FRAME NUMBER THE DYNAMOMETER WAS
TRIGGERED ON.
5
ENTER THE FRAME NUMBER TO BEGIN MOMENT CALCULATIONS.
5
ENTER THE LAST FRAME NUMBER OF MOMENT CALCULATIONS.
100
ENTER THE VERTICAL HEIGHT FROM THE PILL BOTTLE
TARGETS TO THE TOP SURFACE OF THE CAP.
.08

Figure 45: Input Portion Of PBMOM Program

**Figure 46: Phalangeal Joint Moments**

and the flexion/extension axis for each type of functional strength test. The greatest moments were generated in the grasp test followed in decreasing order by thumb opposition and pinch. In each type of test, the moments existing about the flexion/extension axis approximate 87% of the total moment about the approximate joint center.

VII. CONCLUSIONS:

This methodology for testing functional hand strength has numerous clinical applications.

Although functional strength is one of the fundamental determinants in hand activities, this factor has not been given enough attention in the treatment and rehabilitation of hand patients as compared to other parameters such as pain, manipulative ability, joint alignment and sensibility.²⁴

The pill bottle dynamometer and its adapters could be used to measure hand strength in various patient populations; cerebral palsy, Charcot-Marie Tooth syndrome, carpal tunnel syndrome and other compression neuropathies, rheumatoid arthritis, osteoarthritis and hand joint replacement patients.

Areas of analysis include determining the magnitudes of effective versus non-effective forces generated when performing various functional strength tests, observing movement of the COP and vector orientations as a measure of coordination and stability of the hand, the percent contribution of force exerted by each digit relative to overall hand strength in grasp tests to determine individual digit weakness and the resultant force magnitudes generated by the hand when performing various functional strength tests as a test for general hand strength.

Other applications include measuring the forces and torques required to open a child-proof cap, a pop-off cap

and a standard twist off cap in comparison to the forces and torques various patient populations are able to generate. Phalangeal joint loading at pain thresholds could be determined in arthritic patients. Percent loading about the flexion/extension axis of the joint could be analyzed to determine the effectiveness of the joint orientation when performing various tasks. The adequacies of artificial joints could be assessed by measuring the applied moments about them. Longitudinal studies of patients using this methodology would allow physicians to keep track of a patients progress. Accurate preoperative assessment and postoperative evaluations can be performed for objective treatment and care of disabled and handicapped hand patients²⁴.

VIII. FUTURE RECOMMENDATIONS:

Future areas of interest should include;

- 1) Developing an overall hand grasp dynamometer.
- 2) Altering the current design of the adapters to allow adjustable spacings between opposing sides of the hand.
- 3) Collecting normative data of different aged populations for comparison with patient populations.
- 4) Collecting patient data of various diseased populations in order to establish general trends associated with each population.
- 5) Creating a mathematical model of the hand capable of determining the outcomes of predictive surgeries.

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APPENDIX

C THE PURPOSE OF THIS PROGRAM IS TO CALCULATE COP, GRT AND GRF FOR THE PILL
 C DYNAMOMETER; A SIX LOAD COMPONENT TRANSDUCER. THE INPUT FILE
 C FOR THIS PROGRAM IS A .DEC2 FILE. IT CONTAINS EACH MILLISECOND
 C OF DATA IN THE FORM; FZ,FX,FY,MZ,MX,MY. THE PROGRAM CALCULATES
 C THE DIRECTION, MAGNITUDE AND THE POINT (OR POINTS) WHERE THE SCREW
 C AXIS PENETRATES THE SURFACE OF THE CAP. THESE CALCULATIONS ARE
 C DONE DIFFERENTLY DEPENDING ON WHICH TYPE OF TEST IS PERFORMED.
 C THUMB OPPOSITION CALCULATES THE COP AS THE POINT WHERE THE SCREW
 C AXIS PENETRATES THE TOP SURFACE OF THE CAP. THE GRASP TESTS AND
 C PINCH TESTS CALCULATE THE COP'S USING A POLAR COORDINATE SYSTEM.
 C IN THESE TYPES OF TESTS THE FINGERS OR THUMB PUSH AGAINST THE SIDE
 C OF THE CAP RATHER THAN THE TOP SURFACE. THEREFORE, THE Z COORDINATE
 C OF THE COP IS NOT A CONSTANT. THE ONLY CONSISTENCY IS THE RADIUS
 C OF THE CAP. IN THE GRASP TESTS AN EXTENSION IS ADDED TO THE SIDE
 C OF THE CAP WHICH CHANGES THE RADIUS OF THE CAP FROM 20MM TO 30MM.
 C THE FORCE COMPONENTS AND THE PARALLEL MOMENT COMPONENTS OF THE SCREW
 C ARE ALSO CALCULATED. THEY ARE THEN SCALED PROPORTIONAL TO THEIR
 C MAGNITUDES AND IMAGED. THIS PROGRAM CAN ALSO IMAGE THE RAW MOMENT
 C AND FORCE DATA FROM THE DYNAMOMETER FOR CAP OPENING AND CLOSING TESTS.
 C THE PILL BOTTLE STRUCTURE HAS BEEN IMAGED IN ACCURATE PROPORTIONS
 C WITH CORRECT ORIENTATIONS OF ITS AXES.

 C PROGRAM PIMAGE

```

REAL  X,Y,Z,RADIUS,ANGLE,VPX,VPY,VPZ,CPX1G,CPY1G,CPZ1G
REAL  CPX2G,CPY2G,CPZ2G,SCFX1,SCFY1,SCFZ1,SCMX1,SCMY1,SCMZ1
REAL  SCFX2,SCFY2,SCFZ2,SCMX2,SCMY2,SCMZ2
REAL*8  FZ,FX,FY,MZ,MX,MY,FXZ,FYZ,FXYZ,CPZ1,CPX1
REAL*8  CPY1,MPX,MPY,MPZ,RS,FXR,RSQ,RFYSQ,RFXSQ,MZP
REAL*8  MZPSQ,STHET1,STHET2,CPY2,CTHET1,CTHET2,CPX2
REAL*8  MYP,MXP,CPZ2,SCALEF,SCFX1,SCFY2
INTEGER MSI,MSF,TEST,MS,RTRF
CHARACTER*32  FILEIN
  
```

C -----
 C X- THE X COORDINATE OF THE IMAGED SPACE
 C Y- THE Y COORDINATE OF THE IMAGED SPACE
 C Z- THE Z COORDINATE OF THE IMAGED SPACE
 C RADIUS- THE RADIUS OF THE CAP USED IN IMAGING
 C ANGLE- THE ANGLE (IN RADIANS) OF A POINT IN SPACE RELATIVE TO THE X
 C AXIS OF THE DYNAMOMETER
 C VPX- X COORDINATE POSITION OF THE VIEWER WITH RESPECT TO THE BOTTLE
 C VPY- Y COORDINATE POSITION OF THE VIEWER WITH RESPECT TO THE BOTTLE
 C VPZ- Z COORDINATE POSITION OF THE VIEWER WITH RESPECT TO THE BOTTLE
 C CPX1G- IMAGED X COORDINATE POSITION OF COP NUMBER 1
 C CPY1G- IMAGED Y COORDINATE POSITION OF COP NUMBER 1
 C CPZ1G- IMAGED Z COORDINATE POSITION OF COP NUMBER 1
 C CPX2G- IMAGED X COORDINATE POSITION OF COP NUMBER 2
 C CPY2G- IMAGED Y COORDINATE POSITION OF COP NUMBER 2
 C CPZ2G- IMAGED Z COORDINATE POSITION OF COP NUMBER 2
 C SCFX1- IMAGED AND SCALED X POSITION OF THE RXN FORCE RELATIVE TO CPX1G
 C SCFY1- IMAGED AND SCALED Y POSITION OF THE RXN FORCE RELATIVE TO CPY1G
 C SCFZ1- IMAGED AND SCALED Z POSITION OF THE RXN FORCE RELATIVE TO CPZ1G
 C SCFX2- IMAGED AND SCALED X POSITION OF THE RXN FORCE RELATIVE TO CPX2G
 C SCFY2- IMAGED AND SCALED Y POSITION OF THE RXN FORCE RELATIVE TO CPY2G
 C SCFZ2- IMAGED AND SCALED Z POSITION OF THE RXN FORCE RELATIVE TO CPZ2G
 C SCMX1- IMAGED AND SCALED X POSITION OF THE RXN TORQUE RELATIVE TO CPX1G
 C SCMY1- IMAGED AND SCALED Y POSITION OF THE RXN TORQUE RELATIVE TO CPY1G
 C SCMZ1- IMAGED AND SCALED Z POSITION OF THE RXN TORQUE RELATIVE TO CPZ1G
 C SCMX2- IMAGED AND SCALED X POSITION OF THE RXN TORQUE RELATIVE TO CPX2G
 C SCMY2- IMAGED AND SCALED Y POSITION OF THE RXN TORQUE RELATIVE TO CPY2G
 C SCMZ2- IMAGED AND SCALED Z POSITION OF THE RXN TORQUE RELATIVE TO CPZ2G
 C FZ- RAW Z FORCE COMPONENT
 C FX- RAW X FORCE COMPONENT
 C FY- RAW Y FORCE COMPONENT
 C MZ- RAW Z MOMENT COMPONENT
 C MX- RAW X MOMENT COMPONENT

```

C MY-      RAW Y MOMENT COMPONENT
C FXY-      (FX) SQUARED + (FY) SQUARED
C FXZ-      (FX) SQUARED + (FZ) SQUARED
C FYZ-      (FY) SQUARED + (FZ) SQUARED
C FXYZ-      (FX) SQUARED + (FY) SQUARED + (FZ) SQUARED
C RS-      RADIUS OF THE CAP USED IN CALCULATIONS
C FXR-      (FX) SQUARED * (RS) SQUARED
C RSQ-      (RS) SQUARED
C RFYSQ-      (RS) SQUARED * (FY) SQUARED
C RFXSQ-      (RS) SQUARED * (FX) SQUARED
C MZP-      PERPENDICULAR MZ COMPONENT
C MYP-      PERPENDICULAR MY COMPONENT
C MXP-      PERPENDICULAR MX COMPONENT
C MPZ-      PARALLEL MZ COMPONENT
C MPX-      PARALLEL MX COMPONENT
C MPY-      PARALLEL MY COMPONENT
C MZPSQ-      (MZP) SQUARED
C CPZ1-      CALCULATED Z COMPONENT OF COP1
C CPX1-      CALCULATED X COMPONENT OF COP1
C CPY1-      CALCULATED Y COMPONENT OF COP1
C CPZ2-      CALCULATED Z COMPONENT OF COP2
C CPX2-      CALCULATED X COMPONENT OF COP2
C CPY2-      CALCULATED Y COMPONENT OF COP2
C STHET1-    THE SINE ANGLE OF THE FIRST COP RELATIVE TO X AXIS
C STHET2-    THE SINE ANGLE OF THE SECOND COP RELATIVE TO X AXIS
C CTHET1-    THE COSINE ANGLE OF THE FIRST COP RELATIVE TO X AXIS
C CTHET2-    THE COSINE ANGLE OF THE SECOND COP RELATIVE TO X AXIS
C SCALEF-    MULTIPLICATIVE FACTOR OF IMAGED FORCE OR MOMENT VECTORS
C MSI-      BEGINNING TIME TO START IMAGE
C MSF-      END TIME TO STOP IMAGE
C TEST-      NUMERICAL VALUE SIGNIFYING TYPE OF TEST PERFORMED
C MS-      TIME COLUMN FROM RAW DYNAMOMETER DATA
C RTRF-      NUMERICAL VALUE SIGNIFYING FORCE OR TORQUE IMAGE
C FILEIN-    INPUT FORCE FILE (__.DEC2)
C -----
C INPUT DATA
      PRINT*, 'ENTER THE FORCE FILE (EX:FILENAME.DEC2)'
      READ (*,6) FILEIN
6      FORMAT (A32)
      OPEN (10,FILE=FILEIN,STATUS='OLD')
      PRINT*, 'ENTER THE BEGINNING TIME IN MILLISECONDS'
      READ (*,*) MSI
      PRINT*, 'ENTER THE END TIME IN MILLISECONDS'
      READ (*,*) MSF
      PRINT*, 'ENTER THE TYPE OF TEST PERFORMED.'
      PRINT*, '0 -THUMB OPPOSITION TEST'
      PRINT*, '1 -PINCH TEST (LATERAL,2-POINT,3-POINT)'
      PRINT*, '2 -GRASP TEST'
      PRINT*, '3 -BOTTLE OPENING OR CLOSING TEST'
      READ (*,*) TEST
      PRINT*, 'ENTER THE TYPE OF IMAGE PERFORMED.'
      PRINT*, '0- REACTION FORCE'
      PRINT*, '1- REACTION TORQUE'
      READ (*,*) RTRF
      PRINT*, 'ENTER THE VECTOR SCALE FACTOR'
      READ (*,*) SCALEF
      PRINT*, 'ENTER THE X COORDINATE VIEWPOINT '
      READ (*,*) VPX
      PRINT*, 'ENTER THE Y COORDINATE VIEWPOINT '
      READ (*,*) VPY
      PRINT*, 'ENTER THE Z COORDINATE VIEWPOINT '
      READ (*,*) VPZ
      VPX= VPX * 100
      VPY= VPY * 100
      VPZ= VPZ * 100
C -----

```

```

C  INITIAL PARAMETERS
    CALL GRSTRT (4105,1)
    call zpersp
    CALL MILLIM
    call viewt
    CALL SCAXYZ (3.0,3.0,3.0)
    call wind3d (-193.5,193.5,-147.6,147.6,-147.6,147.6)
    call vwpt3d (-193.5,193.5,-147.6,147.6,-147.6,147.6)
    call rotxyz (90.0,0.0,0.0)
    call trnxyz (0.0,0.0,60.0)
    CALL EYEBAL (VPX,VPY,VPZ)

C  -----
C  DRAW THE Y AXIS
    call linclr (2)
    call move3d (0.0,0.0,-36.4)
    CALL DRAW3D (0.0,40.0,-36.4)

C  -----
C  DRAW THE ARROWHEAD ON THE Y AXIS
    CALL MOVE3D (3.0,40.0,-36.4)
    CALL DRAW3D (-3.0,40.0,-36.4)
    CALL DRAW3D (0.0,43.0,-36.4)
    CALL DRAW3D (3.0,40.0,-36.4)

C  -----
C  LABEL THE Y AXIS
    CALL MOVE3D (0.0,52.0,-36.4)
    CALL TXQUAL (4)
    CALL TXICUR (5)
    CALL TEXT (1,'Y')

C  -----
C  DRAW THE X AXIS
    CALL MOVE3D (0.0,0.0,-36.4)
    CALL DRAW3D (40.0,0.0,-36.4)

C  -----
C  DRAW THE ARROWHEAD ON THE X AXIS
    CALL MOVE3D (43.0,0.0,-36.4)
    CALL DRAW3D (40.0,3.0,-36.4)
    CALL DRAW3D (40.0,-3.0,-36.4)
    CALL DRAW3D (43.0,0.0,-36.4)

C  -----
C  LABEL THE X AXIS
    CALL MOVE3D (52.0,0.0,-36.4)
    CALL TXQUAL (4)
    CALL TXICUR (5)
    CALL TEXT (1,'X')

C  -----
C  DRAW THE Z AXIS
    CALL MOVE3D (0.0,0.0,-36.4)
    CALL DRAW3D (0.0,0.0,-7.6)

C  -----
C  DRAW THE ARROWHEAD ON THE Z AXIS
    CALL MOVE3D (-3.0,0.0,-7.6)
    CALL DRAW3D (0.0,0.0,-4.6)
    CALL DRAW3D (3.0,0.0,-7.6)
    CALL DRAW3D (-3.0,0.0,-7.6)

C  -----
C  LABEL THE Z AXIS
    CALL MOVE3D (0.0,0.0,5.6)
    CALL TXQUAL (4)
    CALL TXICUR (5)
    CALL TEXT (1,'Z')

C  -----
C  DRAW THE BASE OF THE BOTTLE
    call linclr (5)
    RADIUS= 25.0
    Z= -31.4
    DO 30 B= 1,51

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```

        ANGLE=0.0
        CALL MOVE3D (25.0,0.0,Z)
        DO 20 C= 1,48
            ANGLE= ANGLE+0.272
            X= 25.0 * COS(ANGLE)
            Y= 25.0 * SIN(ANGLE)
            CALL DRAW3D (X,Y,Z)
20      CONTINUE
        Z= Z + 1.3
30      CONTINUE
C -----
C  DRAW THE NECK OF THE BOTTLE
    call linclr (5)
    RADIUS=17.0
    Z= -46.4
    DO 70 D= 1,10
        ANGLE=0.0
        CALL MOVE3D (17.0,0.0,Z)
        DO 60 E= 1,24
            ANGLE= ANGLE + 0.272
            X= 17.0 * COS(ANGLE)
            Y= 17.0 * SIN(ANGLE)
            CALL DRAW3D (X,Y,Z)
60      CONTINUE
        Z= Z+ 1
70      CONTINUE
C -----
C  DRAW THE FUNNEL OF THE BOTTLE
    RADIUS=17.0
    Z=-36.4
    DO 90 F=1,5
        ANGLE=0.0
        RADIUS= RADIUS + 1.5
        CALL MOVE3D (RADIUS,0.0,Z)
        DO 80 G=1,24
            ANGLE= ANGLE + 0.272
            X= RADIUS * COS(ANGLE)
            Y= RADIUS * SIN(ANGLE)
            CALL DRAW3D (X,Y,Z)
80      CONTINUE
        Z= Z + 1
90      CONTINUE
C -----
C  DRAW THE CAP OF THE BOTTLE
    CALL LINCLR (4)
    RADIUS= 20.0
    Z= -58.4
    DO 110 H= 1,2
        ANGLE= 0.0
        CALL MOVE3D (20.0,0.0,Z)
        DO 100 I=1,24
            ANGLE= ANGLE + 0.272
            X= 20 * COS(ANGLE)
            Y= 20 * SIN(ANGLE)
            CALL DRAW3D (X,Y,Z)
            CALL DRAW3D (X,Y,-46.4)
            CALL MOVE3D (X,Y,Z)
100     CONTINUE
        Z= Z+12
110     CONTINUE
C -----
C  DRAW THE VERTICAL LINES ON THE BOTTLE CAP
    CALL LINCLR (7)
    CALL MOVE3D (20.0,0.0,-58.4)
    CALL DRAW3D (20.0,0.0,-46.4)
    CALL MOVE3D (-20.0,0.0,-58.4)

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```

CALL DRAW3D (-20.0,0.0,-46.4)
CALL MOVE3D (0.0,20.0,-58.4)
CALL DRAW3D (0.0,20.0,-46.4)
CALL MOVE3D (0.0,-20.0,-58.4)
CALL DRAW3D (0.0,-20.0,-46.4)
C -----
C  DRAW THE DASHED LINES ON THE CAP SURFACE
  call linclr (7)
  CALL DASHPT (3)
  CALL MOVE3D (20.0,0.0,-58.4)
  CALL DRAW3D (-20.0,0.0,-58.4)
  CALL MOVE3D (0.0,20.0,-58.4)
  CALL DRAW3D (0.0,-20.0,-58.4)
C -----
C  INITIAL CALCULATIONS FOR ALL TESTS
  DO 120 J= 1,MSI
    READ (10,*)
120    CONTINUE
121    DO 150 K= MSI,MSF
      READ (10,*) MS,FZ,FX,FY,MZ,MX,MY
      FZ= FZ/2.048
      FX= FX/2.048
      FY= FY/2.048
      MZ= MZ/2.048
      MX= MX/2.048
      MY= MY/2.048
      FXY= (FX**2) + (FY**2)
      FXZ= (FX**2) + (FZ**2)
      FYZ= (FY**2) + (FZ**2)
      FXYZ= (FX**2) + (FY**2) + (FZ**2)
      IF (FXYZ .LT. 2) THEN
        GOTO 121
      ENDIF
C -----
C  THUMB OPPOSITION SELECTION
  IF (TEST .EQ. 0) THEN
    CPZ1= -0.0584
    CPX1= (CPZ1*FX*FXYZ) - (MY*FXZ) + (MX*FX*FY) + (MZ*FY*FZ)
    CPX1= CPX1/ (FZ*FXYZ)
    CPY1= (CPZ1*FY*FXYZ) + (MX*FYZ) - (MY*FX*FY) - (MZ*FX*FZ)
    CPY1= CPY1/ (FZ*FXYZ)
    MPX= FX*(MX*FX + MY*FY + MZ*FZ)
    MPX= MPX/FXYZ
    MPY= FY*(MX*FX + MY*FY + MZ*FZ)
    MPY= MPY/FXYZ
    MPZ= FZ*(MX*FX + MY*FY + MZ*FZ)
    MPZ= MPZ/FXYZ
    CPX1G= CPX1*1000
    CPY1G= CPY1*1000
    CPZ1G= CPZ1*1000
    CALL LINCLR (3)
    CALL MOVE3D (CPX1G,CPY1G,CPZ1G)
    CALL DRAW3D (CPX1G,CPY1G,CPZ1G)
    CALL LINCLR (6)
    IF (RTRF .EQ. 0) THEN
      SCFX1= CPX1G - SCALEF*FX
      SCFY1= CPY1G - SCALEF*FY
      SCFZ1= CPZ1G - SCALEF*FZ
      CALL MOVE3D (CPX1G,CPY1G,CPZ1G)
      CALL DRAW3D (SCFX1,SCFY1,SCFZ1)
    ELSEIF (RTRF .EQ. 1) THEN
      SCMX1= CPX1G - SCALEF*MPX
      SCMY1= CPY1G - SCALEF*MPY
      SCMZ1= CPZ1G - SCALEF*MPZ
      CALL MOVE3D (CPX1G,CPY1G,CPZ1G)
      CALL DRAW3D (SCMX1,SCMY1,SCMZ1)
    
```

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      ENDIF
      ELSEIF (TEST .EQ. 1 .OR. TEST .EQ. 2) THEN
C -----
C PINCH TEST SELECTION
      IF (TEST .EQ. 1) THEN
        RS=0.02
C -----
C GRASP TEST SELECTION
      ELSEIF (TEST .EQ. 2) THEN
        RS= 0.03
        RADIUS= 30.0
        CALL LINCLR (4)
        Z= -58.4
        DO 140, L=1,2
          ANGLE=0.0
          CALL MOVE3D (RADIUS,0.0,Z)
          DO 130, M=1,24
            ANGLE= ANGLE + 0.272
            X= 30 * COS(ANGLE)
            Y= 30 * SIN(ANGLE)
            CALL DRAW3D (X,Y,Z)
          130 CONTINUE
            Z= Z + 12
          140 CONTINUE
          CALL LINCLR (7)
          CALL MOVE3D (30.0,0.0,-58.4)
          CALL DRAW3D (30.0,0.0,-46.4)
          CALL MOVE3D (-30.0,0.0,-58.4)
          CALL DRAW3D (-30.0,0.0,-46.4)
          CALL MOVE3D (0.0,30.0,-58.4)
          CALL DRAW3D (0.0,30.0,-46.4)
          CALL MOVE3D (0.0,-30.0,-58.4)
          CALL DRAW3D (0.0,-30.0,-46.4)
          CALL LINCLR (7)
          CALL MOVE3D (30.0,0.0,-58.4)
          CALL DRAW3D (-30.0,0.0,-58.4)
          CALL MOVE3D (0.0,30.0,-58.4)
          CALL DRAW3D (0.0,-30.0,-58.4)
        ENDIF
C -----
C CALCULATIONS FOR PINCH AND GRASP TESTS
      FXR= (FX**2) * (RS**2)
      RSQ= RS**2
      RFYSQ= RSQ* (FY**2)
      RFXSQ= RSQ* (FX**2)
      MZP= (MZ*FX) - (MX*FX*FZ) - (MY*FY*FZ)
      MZP= MZP/FXYZ
      MZPSQ= MZP**2
      STHET1= (-2*MZP*FX*RS) + (2*RS*FY*(FXR-MZPSQ+RFYSQ)**0.5)
      STHET1= STHET1/(2*RSQ*FX)
      STHET2= (-2*MZP*FY*RS) - (2*RS*FX*(FXR-MZPSQ+RFYSQ)**0.5)
      STHET2= STHET2/(2*RSQ*FY)
      CPY1= RS*STHET1
      CPY2= RS*STHET2
      CTHET1= (2*MZP*FY*RS) + (2*RS*FX*(RFYSQ-MZPSQ+RFXSQ)**0.5)
      CTHET1= CTHET1/(2*RSQ*FX)
      CTHET2= (2*MZP*FX*RS) - (2*RS*FY*(RFYSQ-MZPSQ+RFXSQ)**0.5)
      CTHET2= CTHET2/(2*RSQ*FY)
      CPX1= RS*CTHET1
      CPX2= RS*CTHET2
      MYP= (MY*FXZ) - (MX*FX*FY) - (MZ*FY*FZ)
      MYP= MYP/FXYZ
      MXP= (MX*FYZ) - (MY*FX*FY) - (MZ*FX*FZ)
      MXP= MXP/FXYZ
      CPZ1= -(MXP*CTHET1+MYP*STHET1)/(-FX*STHET1+FY*CTHET1)
      CPZ2= -(MXP*CTHET2+MYP*STHET2)/(-FX*STHET2+FY*CTHET2)

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MPX= MX-MXP
MPY= MY-MYP
MPZ= MZ-MZP
CPX1G= CPX1*1000
CPX2G= CPX2*1000
CPY1G= CPY1*1000
CPY2G= CPY2*1000
CPZ1G= CPZ1*1000
CPZ2G= CPZ2*1000
CALL LINCLR (6)
CALL MOVE3D (CPX1G,CPY1G,CPZ1G)
CALL DRAW3D (CPX1G,CPY1G,CPZ1G)
CALL MOVE3D (CPX2G,CPY2G,CPZ2G)
CALL DRAW3D (CPX2G,CPY2G,CPZ2G)
IF (RTRF .EQ. 0) THEN
  SCFX1= CPX1G - SCALEF*FX
  SCFY1= CPY1G - SCALEF*FY
  SCFZ1= CPZ1G - SCALEF*FZ
  SCFX2= CPX2G - SCALEF*FX
  SCFY2= CPY2G - SCALEF*FY
  SCFZ2= CPZ2G - SCALEF*FZ
  SCFXY1= (SCFX1**2 + SCFY1**2)**0.5
  SCFXY2= (SCFX2**2 + SCFY2**2)**0.5
  IF (SCFXY1 .GT. SCFXY2) THEN
    CALL LINCLR (3)
    CALL MOVE3D (CPX1G,CPY1G,CPZ1G)
    CALL DRAW3D (SCFX1,SCFY1,SCFZ1)
  ELSEIF (SCFXY2 .GT. SCFXY1) THEN
    CALL LINCLR (5)
    CALL MOVE3D (CPX2G,CPY2G,CPZ2G)
    CALL DRAW3D (SCFX2,SCFY2,SCFZ2)
  ENDIF
ELSEIF (RTRF .EQ. 1) THEN
  SCMX1= CPX1G - SCALEF*MPX
  SCMY1= CPY1G - SCALEF*MPY
  SCMZ1= CPZ1G - SCALEF*MPZ
  SCMX2= CPX2G - SCALEF*MPX
  SCMY2= CPY2G - SCALEF*MPY
  SCMZ2= CPZ2G - SCALEF*MPZ
  CALL LINCLR (3)
  CALL MOVE3D (CPX1G,CPY1G,CPZ1G)
  CALL DRAW3D (SCMX1,SCMY1,SCMZ1)
  CALL LINCLR (5)
  CALL MOVE3D (CPX2G,CPY2G,CPZ2G)
  CALL DRAW3D (SCMX2,SCMY2,SCMZ2)
ENDIF

```

```

C -----
C CALCULATIONS BOTTLE OPENING AND CLOSING TESTS
  ELSEIF (TEST .EQ. 3) THEN
    CALL LINCLR (3)
    CALL MOVE3D (0.0,0.0,-58.4)
    IF (RTRF .EQ. 0) THEN
      SCFX1= 0.0 - SCALEF*FX
      SCFY1= 0.0 - SCALEF*FY
      SCFZ1= -58.4 - SCALEF*FZ
      CALL DRAW3D (SCFX1,SCFY1,SCFZ1)
    ELSEIF (RTRF .EQ. 1) THEN
      MXP= MX + 0.0584 * FY
      MYP= MY + 0.0584 * FX
      SCMX1= 0.0 - SCALEF*MXP
      SCMY1= 0.0 - SCALEF*MYP
      SCMZ1= -58.4 - SCALEF*MZ
      CALL DRAW3D (SCMX1,SCMY1,SCMZ1)
    ENDIF
  ENDIF
CONTINUE

```


CLOSE (10)
CALL GRSTOP
STOP
END

C -----

PROGRAM PBCOP

```

CHARACTER*32 FILEIN, FILEOUT, TYPE
REAL*8 FX, FY, FZ, MX, MY, MZ, FXZ, FYZ, FXYZ, CPX1, CPY1, CPZ1
REAL*8 MPX, MPY, MPZ, RS, RSQ, FXR, RFYSQ, RFXSQ, MZP, MZPSQ
REAL*8 STHET1, STHET2, CPX2, CPY2, CPZ2, FXY, MYP, MXP
REAL*8 RFX1, RFX2, RFY1, RFY2, RFX1, RFX2
INTEGER MS, MSI, MSF, TEST
C -----
C INPUT DATA
PRINT*, 'ENTER THE FORCE FILE (EX:FILENAME.DEC2)'
READ (*, 6) FILEIN
6 FORMAT(A32)
OPEN (10, FILE=FILEIN, STATUS='OLD')
PRINT*, 'ENTER THE BEGINNING TIME IN MILLISECONDS'
READ (*, *) MSI
PRINT*, 'ENTER THE END TIME IN MILLISECONDS'
READ (*, *) MSF
PRINT*, 'WOULD YOU LIKE AN OUTPUT FILE CONTAINING COP,'
PRINT*, 'PBRF AND PBRT DATA OR RESULTANT FORCE DATA?'
PRINT*, 'TYPE "COP" OR "RES".'
READ (*, 6) TYPE
IF (TYPE .EQ. 'COP') THEN
PRINT*, 'ENTER THE TYPE OF TEST PERFORMED.'
PRINT*, '0= THUMB OPPOSITION TEST'
PRINT*, '1= PINCH TEST (LATERAL, 2-POINT, 5-POINT)'
PRINT*, '2= GRASP TEST'
PRINT*, '3= BOTTLE OPENING OR CLOSING TEST'
READ (*, *) TEST
IF (TEST .EQ. 0) THEN
PRINT*, 'THE THUMB OPPOSITION OUTPUT FILE WILL CONTAIN'
PRINT*, 'COORDINATES OF THE COP, REACTION FORCE AND '
PRINT*, 'REACTION TORQUE.'
PRINT*, 'ENTER THE NAME OF THIS OUTPUT FILE (EX:FILENAME.TO)'
READ (*, 6) FILEOUT
ELSEIF (TEST .EQ. 1) THEN
PRINT*, 'THE PINCH TEST OUTPUT FILE WILL CONTAIN COORDINATES'
PRINT*, 'OF THE COP, REACTION FORCE AND REACTION TORQUE.'
PRINT*, 'ENTER THE NAME OF THIS OUTPUT FILE (EX:FILENAME.P2)'
READ (*, 6) FILEOUT
ELSEIF (TEST .EQ. 2) THEN
PRINT*, 'THE GRASP TEST OUTPUT FILE WILL CONTAIN COORDINATES'
PRINT*, 'OF THE COP, REACTION FORCE AND REACTION TORQUE.'
PRINT*, 'ENTER THE NAME OF THIS OUTPUT FILE. (EX:FILENAME.G1)'
READ (*, 6) FILEOUT
ELSEIF (TEST .EQ. 3) THEN
PRINT*, 'THE BOTTLE OPENING OR CLOSING TEST OUTPUT FILE WILL'
PRINT*, 'CONTAIN THE MOMENT COMPONENTS ABOUT THE CENTER OF'
PRINT*, 'THE CAPS TOP SURFACE.'
PRINT*, 'ENTER THE NAME OF THIS OUTPUT FILE (EX:FILENAME.CAP)'
READ (*, *) FILEOUT
ENDIF
OPEN (11, FILE=FILEOUT)
C -----
C READING THE INPUT FILE AND INITIAL CALCULATIONS FOR ALL TESTS
DO 20 I=1, MSI
READ (10, *) MS, FZ, FX, FY, MZ, MX, FY
20 CONTINUE
DO 60 I=MSI, MSF
READ (10, *) MS, FZ, FX, FY, MZ, MX, MY
FZ= FZ/2.048
FX= FX/2.048
FY= FY/2.048
MZ= MZ/2.048
MX= MX/2.048

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MY= MY/2.048
FXY= (FX**2) + (FY**2)
FXZ= (FX**2) + (FZ**2)
FYZ= (FY**2) + (FZ**2)
FXYZ= (FX**2) + (FY**2) + (FZ**2)
C -----
C THUMB OPPOSITION SELECTION
  IF (TEST .EQ. 0) THEN
    CPZ1= -0.0584
    CPX1= (CPZ1*FX*FXYZ) - (MY*FXZ) + (MX*FX*FY) + (MZ*FY*FZ)
    CPX1= CPX1 / (FZ*FXYZ)
    CPY1= (CPZ1*FY*FXYZ) + (MX*FYZ) - (MY*FX*FY) - (MZ*FX*FZ)
    CPY1= CPY1 / (FZ*FXYZ)
    MPX= FX*(MX*FX+MY*FY+MZ*FZ)
    MPX= MPX/FXYZ
    MPY= FY*(MX*FX+MY*FY+MZ*FZ)
    MPY= MPY/FXYZ
    MPZ= FZ*(MX*FX+MY*FY+MZ*FZ)
    MPZ= MPZ/FXYZ
    MPX= -MPX
    MPY= -MPY
    MPZ= -MPZ
    FX= -FX
    FY= -FY
    FZ= -FZ
    WRITE(11,50) MS,CPX1,CPY1,CPZ1,FX,FY,FZ,MPX,MPY,MPZ
50  FORMAT (I3,1X, 6(F8.4,1X), 3(F6.4,1X))
C -----
C PINCH OR GRASP TEST SELECTION
  ELSEIF (TEST .EQ. 1 .OR. TEST .EQ. 2) THEN
    IF (TEST .EQ. 1) THEN
      RS= 0.02
    ELSEIF (TEST .EQ. 2) THEN
      RS= 0.03
    ENDIF
    FXR= (FX**2) * (RS**2)
    RSQ= (RS**2)
    RFYSQ= RSQ * (FY**2)
    RFXSQ= RSQ * (FX**2)
    MZP= (MZ*FXY) - (MX*FX*FZ) - (MY*FY*FZ)
    MZP= MZP/FXYZ
    MZPSQ= MZP**2
    STHET1= (-2*MZP*FX*RS) + (2*RS*FY*(FXR-MZPSQ+RFYSQ)**0.5)
    STHET1= STHET1 / (2*RSQ*FXY)
    STHET2= (-2*MZP*FY*RS) - (2*RS*FX*(FXR-MZPSQ+RFYSQ)**0.5)
    STHET2= STHET2 / (2*RSQ*FXY)
    CPY1= RS*STHET1
    CPY2= RS*STHET2
    CTHET1= (2*MZP*FY*RS) + (2*RS*FX*(RFYSQ-MZPSQ+RFXSQ)**0.5)
    CTHET1= CTHET1 / (2*RSQ*FXY)
    CTHET2= (2*MZP*FX*RS) - (2*RS*FY*(RFYSQ-MZPSQ+RFXSQ)**0.5)
    CTHET2= CTHET2 / (2*RSQ*FXY)
    CPX1= RS*CTHET1
    CPX2= RS*CTHET2
    MYP= (MY*FXZ) - (MX*FX*FY) - (MZ*FY*FZ)
    MYP= MYP/FXYZ
    MXP= (MX*FYZ) - (MY*FX*FY) - (MZ*FX*FZ)
    MXP= MXP/FXYZ
    CPZ1= -((MXP*CTHET1+MYP*STHET1)/(-FX*STHET1+FY*CTHET1))
    CPZ2= -((MXP*CTHET2+MYP*STHET2)/(-FX*STHET2+FY*CTHET2))
C CALCULATING THE PARALLEL MOMENT
  MPX= MX-MXP
  MPY= MY-MYP
  MPZ= MZ-MZP
C DETERMINING WHICH COP IS THE CORRECT POINT OF PRESSURE OF PHALANGE
  RFX1= CPX1 - FX

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RFX2= CPX2 - FX
RFY1= CPY1 - FY
RFY2= CPY2 - FY
RFXY1= (RFX1**2 + RFY1**2)**0.5
RFXY2= (RFX2**2 + RFY2**2)**0.5
C CREATING THE REACTION FORCES AND MOMENTS FROM TRANSDUCER SENSED ONES
FX= -FX
FY= -FY
FZ= -FZ
MPX= -MPX
MPY= -MPY
MPZ= -MPZ
IF (RFXY2 .GT. RFXY1) THEN
  WRITE (11,52) MS,CPX2,CPY2,CPZ2,FX,FY,FZ,MPX,MPY,MPZ
ELSEIF (RFXY1 .GT. RFXY2) THEN
  WRITE (11,52) MS,CPX1,CPY1,CPZ1,FX,FY,FZ,MPX,MPY,MPZ
ENDIF
52 FORMAT (I3,1X, 6(F8.4,1X), 3(F6.4,1X))
C -----
C BOTTLE OPENING OR CLOSING TESTS
ELSEIF (TEST .EQ. 3) THEN
  CPX1= 0.0000
  CPY1= 0.0000
  CPZ1= -0.0584
  MPX= MX + 0.0584*FY
  MPY= MY + 0.0584*FX
  WRITE (11,54) MS,FX,FY,FZ,MPX,MPY,MZ
54 FORMAT (I3,1X, 6(F6.4,1X))
  ENDIF
60 CONTINUE
  ENDIF
C -----
C CALCULATING THE RESULTANT FORCE
IF (TYPE .EQ. 'RES') THEN
  PRINT*, 'ENTER THE NAME OF THE RESULTANT FORCE OUTPUT FILE.'
  PRINT*, ' (EX: FILENAME.RES)'
  READ (*,6) FILEOUT
  OPEN (11,FILE=FILEOUT)
  DO 80, N=1,MSI
    READ (10,*) MS,FZ,FX,FY,MZ,MX,MY
80 CONTINUE
    DO 90, P= MSI,MSF
      READ (10,*) MS,FZ,FX,FY,MZ,MX,MY
      FZ= FZ/2.048
      FX= FX/2.048
      FY= FY/2.048
      MZ= MZ/2.048
      MX= MX/2.048
      MY= MY/2.048
      RES= (FX**2 + FY**2 + FZ**2)**0.5
      WRITE (11,65) MS,RES
65 FORMAT (I3,1X, F10.4,1X)
90 CONTINUE
    ENDIF
    CLOSE (10)
    CLOSE (11)
    STOP
  END

```

PROGRAM PBMOM

```

CHARACTER*32 FFILE,PFILE,PBFILE,MFILE
INTEGER FFR,FPFR,IMFR,FMFR,DIFFA,DIFFB,DIFFC,CTR,TIM
REAL*8 HZ,MS,MEDX,MEDY,MEDZ,LATX,LATY,LATZ,AX,AY,AZ
REAL*8 BX,BY,BZ,CX,CY,CZ,CPX,CPY,CPZ,RFY,RFZ
REAL*8 RMPX,RMPY,RMPZ,ACX,ACY,ACZ,MAGX,XX,XY,XZ,RESM
REAL*8 ABX,ABY,ABZ,ZX,ZY,ZZ,MAGZ,YX,YY,YZ,POX,POY,POZ
REAL*8 PXP,PYP,PZP,MEDXP,MEDYP,MEDZP,LATXP,LATYP,LATZP
REAL*8 AXP,AYP,AZP,COPXP,COPYP,COPZP,SXP,SYP,SZP
REAL*8 PMX,PMY,PMZ,MAGFEP,FXEP,FEYP,FEZP,PMFE,BXP,BYP,BZP
C -----
C INPUT INFORMATION
PRINT*, 'ENTER THE FORCE FILE CONTAINING COP, REACTION FORCE'
PRINT*, 'AND REACTION TORQUE INFORMATION FROM THE PBCOP'
PRINT*, 'PROGRAM.'
READ (*, 6) FFILE
6 FORMAT (A32)
PRINT*, 'ENTER THE MOTION FILE CONTAINING THE PHALANGEAL'
PRINT*, 'TARGET LOCATIONS.'
READ (*, 6) PFILE
PRINT*, 'ENTER THE MOTION FILE CONTAINING THE PILL BOTTLE'
PRINT*, 'TARGET LOCATIONS.'
READ (*, 6) PBFILE
PRINT*, 'ENTER THE NAME OF THE OUTPUT MOMENT FILE.'
READ (*, 6) MFILE
PRINT*, 'ENTER THE FIRST FRAME NUMBER OF THE ____TED FILE.'
READ (*, *) FFR
PRINT*, 'ENTER THE FRAME NUMBER THE DYNAMOMETER WAS'
PRINT*, 'TRIGGERED ON.'
READ (*, *) FPFR
PRINT*, 'ENTER THE FRAME NUMBER TO BEGIN MOMENT CALCULATIONS.'
READ (*, *) IMFR
PRINT*, 'ENTER THE LAST FRAME NUMBER OF MOMENT CALCULATIONS.'
READ (*, *) FMFR
PRINT*, 'ENTER THE VERTICAL HEIGHT FROM THE PILL BOTTLE'
PRINT*, 'TARGETS TO THE TOP SURFACE OF THE CAP.'
READ (*, *) HZ
C -----
C OPENING OLD FILES, CREATING TEMPORARY FILES AND THE OUTPUT FILE
OPEN (10, FILE=FFILE, STATUS='OLD')
OPEN (11, FILE=PFILE, STATUS='OLD')
OPEN (12, FILE=PBFILE, STATUS='OLD')
OPEN (13, FILE=MFILE)
OPEN (14, FILE='TEMP1')
OPEN (15, FILE='TEMP2')
OPEN (16, FILE='TEMP3')
C -----
C READING THE MOTION FILES FROM FIRST FRAME TO THE FRAME PRIOR
C TO THE FORCE PLATE TRIGGER
DIFFA=FPFR - FFR
DO 20 A= 1,DIFFA
  READ (11,*)
  READ (11,*)
  READ (12,*)
  READ (12,*)
  READ (12,*)
20 CONTINUE
C -----
C READING THE MOTION FILES FROM THE FP TRIGGER FRAME TO THE FIRST
C SYNCHRONIZED FRAME AFTER THE INPUTED BEGINNING FRAME TO START
C THE MOMENT CALCULATIONS
DIFFB=IMFR - FPFR
CTR= 0
21 IF (CTR .LT. DIFFB) THEN
  DO 22 B=1,3

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      READ (11,*)
      READ (11,*)
      READ (12,*)
      READ (12,*)
      READ (12,*)
22      CONTINUE
      CTR= CTR + 3
      GO TO 21
    ENDIF
C -----
C   READING THE FORCE FILE TO THE FIRST SYNCHRONIZED FRAME AFTER
C   THE INPUTED BEGINNING FRAME FOR MOMENT CALCULATIONS
      CTR= CTR/3
      CTR= CTR * 5
      DO 23 C= 1,CTR
        READ (10,*)
23      CONTINUE
C -----
C   FORCE AND MOTION FILES ARE NOW SYNCHRONIZED AT THE FIRST FRAME
C   OF DATA TO CALCULATE MOMENTS.
C   READING EVERY SYNCHRONIZED FRAME OF MOTION DATA AND SENDING
C   THIS DATA TO A TEMPORARY FILE.
      DIFFC= FMFR - IMFR
      DIFFC= DIFFC - 2
      CTR=0
24      IF (CTR .LT. DIFFC) THEN
        READ (11,*) MS,LATX,LATY,LATZ,MS,MEDX,MEDY,MEDZ
        WRITE (14,25) MS,LATX,LATY,LATZ,MEDX,MEDY,MEDZ
25        FORMAT (F8.6,1X,6(F10.5,1X))
        READ (11,*)
        READ (11,*)
        READ (11,*)
        READ (11,*)
        READ (12,*) MS,AX,AY,AZ,MS,BX,BY,BZ,MS,CX,CY,CZ
        WRITE (15,26) MS,AX,AY,AZ,BX,BY,BZ,CX,CY,CZ
26        FORMAT (F8.6,1X,5(F10.5,1X),F10.5,5X,3(F10.5,1X))
        READ (12,*)
        READ (12,*)
        READ (12,*)
        READ (12,*)
        READ (12,*)
        READ (12,*)
        CTR= CTR + 3
        GO TO 24
      ENDIF
C -----
C   READING EVERY SYNCHRONIZED FRAME OF FORCE DATA AND WRITING
C   THIS DATA TO A TEMPORARY FILE
      CTR= CTR/3
      DO 29 D= 1,CTR
        READ (10,*) TIM,CPX,CPY,CPZ,RFX,RFY,RFZ,RMPX,RMPY,RMPZ
        WRITE (16,27) TIM,CPX,CPY,CPZ,RFX,RFY,RFZ,RMPX,RMPY,RMPZ
27        FORMAT (I3,1X, 6(F8.4,1X), 3(F6.4,1X))
        DO 28 E= 1,4
          READ (10,*)
28        CONTINUE
29      CONTINUE
      CLOSE (10)
      CLOSE (11)
      CLOSE (12)
C -----
C   READING THE SYNCHRONIZED TEMPORARY FORCE FILE AND MOTION
C   FILES AND PERFORMING ALL CALCULATIONS.
      REWIND (14)
      REWIND (15)
      REWIND (16)

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DO 31 F= 1,CTR
  READ (14,*) MS,LATX,LATY,LATZ,MEDX,MEDY,MEDZ
  READ (15,*) MS,AX,AY,AZ,BX,BY,BZ,CX,CY,CZ
  READ (16,*) TIM,CPX,CPY,CPZ,RFY,RFZ,RMPX,RMPY,RMPZ
  MEDX= MEDX/100
  MEDY= MEDY/100
  MEDZ= MEDZ/100
  LATX= LATX/100
  LATY= LATY/100
  LATZ= LATZ/100
  AX= AX/100
  AY= AY/100
  AZ= AZ/100
  BX= BX/100
  BY= BY/100
  BZ= BZ/100
  CX= CX/100
  CY= CY/100
  CZ= CZ/100

C -----
C   CREATING A UNIT COORDINATE SYSTEM ON THE PILL BOTTLE
  ABX= BX - AX
  ABY= BY - AY
  ABZ= BZ - AZ
  MAGX= (ABX**2 + ABY**2 + ABZ**2)**0.5
  XX= ABX/MAGX
  XY= ABY/MAGX
  XZ= ABZ/MAGX
  ACX= CX - AX
  ACY= CY - AY
  ACZ= CZ - AZ
  ZX= ACY*ABZ - ACZ*ABY
  ZY= ACZ*ABX - ACX*ABZ
  ZZ= ACX*ABY - ACY*ABX
  MAGZ= (ZX**2 + ZY**2 + ZZ**2)**0.5
  ZX= ZX/MAGZ
  ZY= ZY/MAGZ
  ZZ= ZZ/MAGZ
  YX= ZY*XZ - ZZ*XY
  YY= ZZ*XX - ZX*XZ
  YZ= ZX*XY - ZY*XX

C -----
C   COORDINATES OF MEDIAL PHALANGEAL TARGET IN PRIMED
C   SYSTEM
  MEDXP= (XX*MEDX)+(XY*MEDY)+(XZ*MEDZ)
  MEDYP= (YX*MEDX)+(YY*MEDY)+(YZ*MEDZ)
  MEDZP= (ZX*MEDX)+(ZY*MEDY)+(ZZ*MEDZ)

C -----
C   COORDINATES OF LATERAL PHALANGEAL TARGET IN PRIMED
C   SYSTEM
  LATXP= (XX*LATX)+(XY*LATY)+(XZ*LATZ)
  LATYP= (YX*LATX)+(YY*LATY)+(YZ*LATZ)
  LATZP= (ZX*LATX)+(ZY*LATY)+(ZZ*LATZ)

C -----
C   COORDINATES OF TARGET A IN THE PRIMED SYSTEM
  AXP= (XX*AX)+(XY*AY)+(XZ*AZ)
  AYP= (YX*AX)+(YY*AY)+(YZ*AZ)
  AZP= (ZX*AX)+(ZY*AY)+(ZZ*AZ)

C -----
C   COORDINATES OF TARGET B IN THE PRIMED SYSTEM
  BXP= (XX*BX)+(XY*BY)+(XZ*BZ)
  BYP= (YX*BX)+(YY*BY)+(YZ*BZ)
  BZP= (ZX*BX)+(ZY*BY)+(ZZ*BZ)

C -----
C   CALCULATING THE APPROXIMATE JOINT CENTER IN THE PRIMED SYS
  PKP= (MEDXP+LATXP)/2

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      PYP= (MEDYP+LATYP)/2
      PZP= (MEDZP+LATZP)/2
C -----
C COORDINATES OF THE TRANSDUCER CENTER IN THE PRIMED SYSTEM
      POX= (AXP+BXP)/2
      POY= (AYP + BYP)/2
      POZ= AZP - (HZ - 0.0584)
C -----
C COORDINATES OF THE COP IN THE PRIMED SYSTEM
      COPXP= CPX + POX
      COPYP= CPY + POY
      COPZP= CPZ + POZ
C -----
C CALCULATING THE DISTANCE BETWEEN THE PHALANGEAL JOINT
C CENTER AND THE COP IN THE PRIMED SYSTEM
      SXP= COPXP - PXP
      SYP= COPYP - PYP
      SZP= COPZP - PZP
C -----
C CALCULATING THE MOMENTS ABOUT THE PHALANGEAL JOINT CENTER
      PMX= (SYP*RFZ) - (SZP*RFY) + RMPX
      PMY= (SZP*RFX) - (SXP*RFZ) + RMPY
      PMZ= (SXP*RFY) - (SYP*RFX) + RMPZ
C -----
C CALCULATING THE RESULTANT MOMENT MAGNITUDE
      RESM= (PMX**2 + PMY**2 + PMZ**2)**0.5
C -----
C CALCULATING THE DIRECTION OF THE FLEXION-EXTENSION AXIS OF
C THE PHALANGEAL JOINT
      FEXP= MEDXP - LATXP
      FEYP= MEDYP - LATYP
      FEZP= MEDZP - LATZP
      MAGFEP= (FEXP**2 + FEYP**2 + FEZP**2)**0.5
      FEXP= FEXP/MAGFEP
      FEYP= FEYP/MAGFEP
      FEZP= FEZP/MAGFEP
C -----
C CALCULATING THE MOMENTS ABOUT THE FLEXION/EXTENSION AXIS
      PMFE= FEXP*PMX + FEYP*PMY + FEZP*PMZ
C -----
C WRITING THE COMPONENT MOMENTS ABOUT THE PHALANGEAL JOINT CENTER
C AND THE MOMENT ABOUT THE FLEXION/EXTENSION AXIS. (POSITIVE
C TORQUE= TENDENCY TO EXTEND, NEGATIVE TORQUE= TENDENCY TO FLEX)
      WRITE (13,30) TIM,RESM,PMFE
30      FORMAT (I3,1X,2(F9.4,1X))
      OPEN (17,FILE='TEMP4')
      WRITE (17,*) XX,XY,XZ,ZX,ZY,ZZ,YX,YY,YZ,MEDXP,MEDYP,MEDZP,
+      LATXP,LATYP,LATZP,AXP,AYP,AZP,BXP,BYP,BZP,PXP,PYP,PZP,
+      POX,POY,POZ,COPXP,COPYP,COPZP,SXP,SYP,SZP,PMX,PMY,PMZ,
+      RESM,MAGFEP,FEXP,FEYP,FEZP,PMFE
31      CONTINUE
      CLOSE (14)
      CLOSE (15)
      CLOSE (16)
      STOP
      END

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