CORRELATION OF THE SHIFT OF THE AXIS OF THE TIBIA WITH THE KNEE INSTABILITY

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THE TIBIA WITH THE KNEE INSTABILITY

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CHAPTER I

INTRODUCTION

Rotary instability of the knee is a continuing problem to the physician treating knee injuries and is explained as pathologically increased outward rotation of the tibia on femur. The clinical basis for recognizing instability of the patient relies upon symtoms observed in their knees, and the explanation given by the patient about the circumstance in which he was involved during the time of the injury. Thus, the attending physician has to depend much on his experience, which will vary from one physician to other. Without a set of objective criteria to identify the offending ligament(s) responsible for the instability, it would be a problem in precisely repairing the injured structure(s). Because of its anatomic and functional characteristics, the knee is predisposed to injury in sports. The knee lacks inherent bony stability and therefore, is particularly vulnerable in a contact sport in which large demands are place on the supporting ligamentous structure. Orthotic devices cannot replace the stabilizing function of the ligaments without detracting from performance.

Injuries, to the knee ligaments may lead to chronic instability if healing is imperfect. The appropriate treatment of such instability depends on specifying exactly the damagaged ligament(s). This identification of the damaged ligament(s), has been done traditionally using "Drawer tests" which are developed and employed by Nicholas (16), Hughston (7, 8), etc.

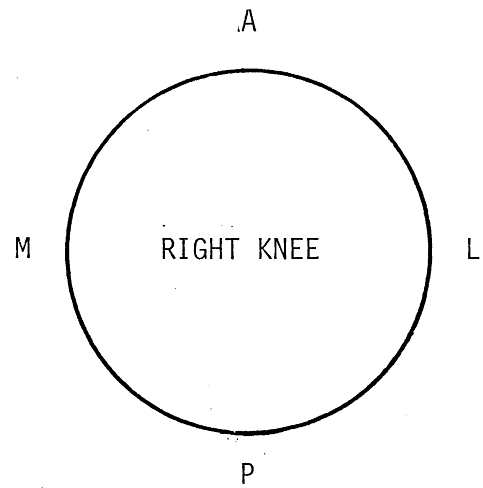
Based on the motion of the knee joint, there are four simple types of motions which a knee joint may execute when the knee is unstable. These simple motions contribute to four straight instabilities: 1. anterior instability, 2. posterior instability, 3. lateral instability, and 4. medial instability. When two of these simple motions are executed simultaneously, the knee joint is expected to have rotary instability. Discounting the cases of combined straight instabilities (A-P, L-M) as done by Nicholas (16) and Hughston (7, 8), we obtain four cases of rotary instabilities: 1. Antero-Lateral, 2. Antero-Medial, 3. Postero-Lateral, and 4. Postero-Medial. These four classes of rotary instabilities may be combined to obtain "combined-(dual) instabilities: 1. Antero-Lateral, Postero-Lateral, 2. Antero-Lateral, Antero-Medial, 3. Antero-Lateral, Postero-Medial, 4. Antero-Medial, Postero-Medial, 5. Postero-Lateral, Postero-Medial, and 6. Antero-Medial, Posterio-Lateral. Similarly, possible combinations of "combined triple instabilities" will yield additional three classes of instabilities: 1. Postero-Lateral, Antero-Lateral, Antero-Medial, 2. Antero-Lateral, Postero-Medial, Postero-Lateral, 3. Postero-Medial, Antero-Lateral, Antero-Medial.

Thus combining the straight, rotary, combined dual rotary, and combined triple and quadruple rotary instabilities, one is expected to obtain a total of twenty classes of knee instabilities. The number of classes of instabilities is expected to be more if one also counts the cases of antero-postero and lateral-medial instabilities. However, Nicholas classification scheme will provide a possible set of twenty classes of instabilities and Hughston classification scheme will provide only ten classes of instabilities. Since Hughston based on his clinical observation avaids the inclusion of poster-medial instabilities.

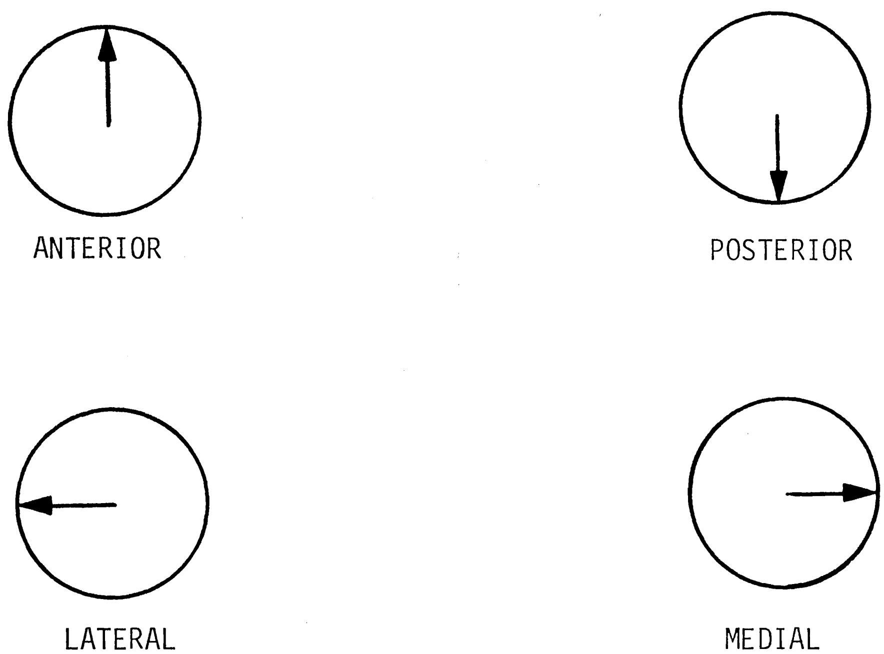
The primary objective of classifying the different types of instabilities is to associate the ligamentous injuries with these classes of instabilities and to arrive at suitable clinical tests to identify these ligamentous injuries. Despite the elaborate scheme of classifying the knee instabilities, there is a wide variety of opinions in identifying the ligamentous injuries. For example Kennedy (21) has stated that in antero-medial instability, the primary pathology is in the medial capsular ligamentsm while Marshall (17) attributes this instability to the more superficial tibial collateral ligament. Walker and Wang (2) felt that rotary stability was controlled by the collateral ligaments and menisci. Shaw and Murray (15), however stated that the cruciates stabilize but do not control motion of tibia on femur. On the other hand, O'Donoghue (18) has said that rotary instability is one clinical presentation of instability resulting from injury to both cruciate and collateral ligaments. Nicholas (16) has attempted to correlate the different types of rotary instabilities with the location of the horizontal axis (also called the longitudinal axis of rotation) in the tibial plateau. According to Shaw and Murray (15), the longitudinal axis of rotation in it's neutral position passes through the medial intercondylar tubrcle of the tibial plateau. For the anterolateral rotary instability, the longitudinal axis shifts to antero-medial position to the position describing rotary instability, the outward or inward rotation of tibia over femur also correspondingly increases. The basic hypothesis of the shift of the longitudinal axis is based on clinical tests conducted by Nicholas.

The existing literature cites the clinical tests for determining the different types of instabilities. These are the drawer tests as described in depth by Hughston (7, 8). Kennedy (21) has designed a stress machine which permits him to determine quantitatively the medial and anterior instabilities. Apart from the study by Walker (2, 4), Markof et al. (22), Hallen et al. (20) and Kennedy (44) the effects of torsional, compressive, adductional, and abductional loads in producing increased laxity there are no reported studies which describe quantitatively the criteria for in-vivo knee instabilities. Because of a lack of experimenation, the existing literature does not contain adequate information to determine quantitatively the types of instabilities, the interactive role of ligaments in knee instability, and the degree of damage to each of the knee ligaments and supportive structure in producing each type of instability. As a consequence, there is a wide range of opinions and procedures in clinically managing the knee instability (2, 3, 7, 8, 12, 15, 18, 21, 35, 36).

Table I presents an extension of the basic scheme of classification as proposed by Nicholas (16) and Hughston (7, 8). Assuming the existence of posterio-medial rotary instability, we note that a total of twenty classed of knee stability will exist. The knee joint moves about transverse axis to execute flexion-extension motion and longitudinal axis to execute rotary motion of tibia about the femur. The resultant of these two axes for each infinitesimal displacement of tibia with respect to femur will yield an instantaneous screw axis. Associated with the instantaneous screw axis is the pitch of the screw. The instantaneous screw axis and the pitch of the screw will uniquely



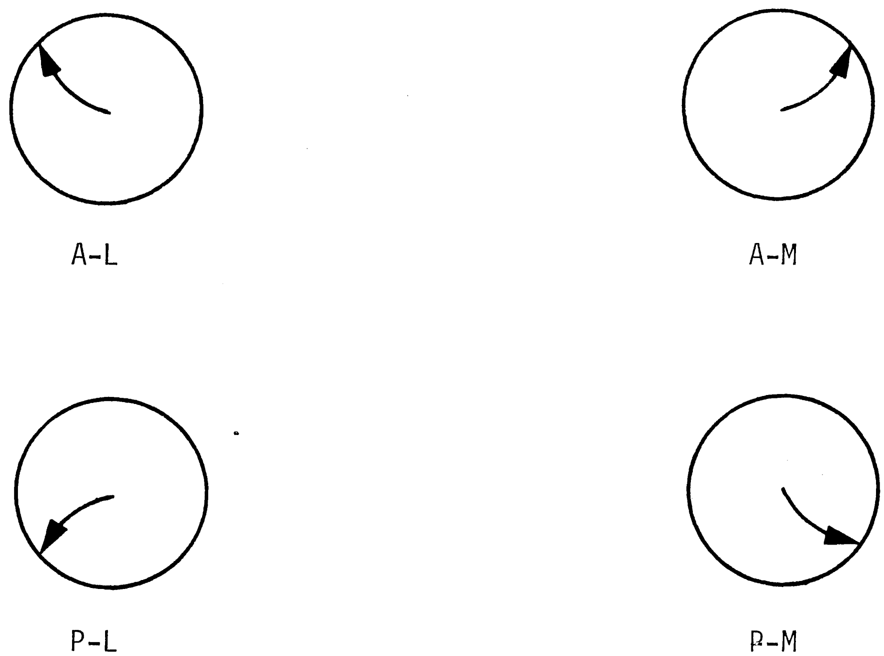
A Rationale Approach to Classify Knee Instability



Straight Instability

TABLE I

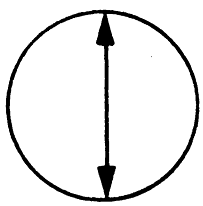
Knee Instabilities



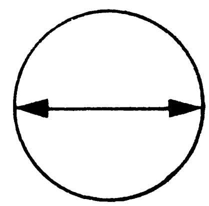
Simple Rotary Instability

TABLE I Continued

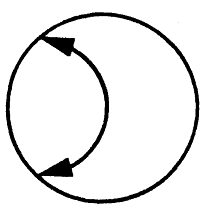
Combined Straight Instability



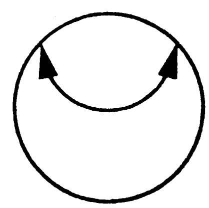
A-P



L-M



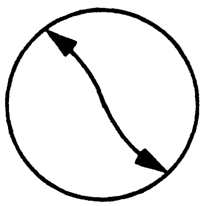
A-L, P-L



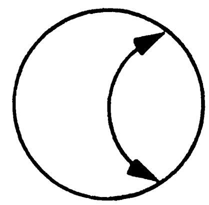
A-L, A-M

Dual Rotary Instability

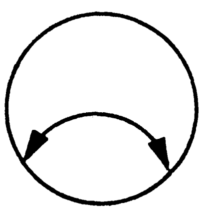
TABLE I Continued



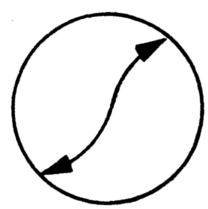
A-L, P-M



A-M, P-M



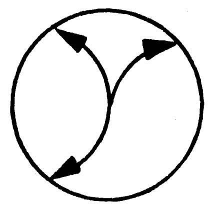
P-L, P-M



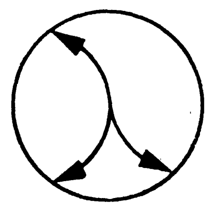
A-M, P-L

Dual Rotary Instability

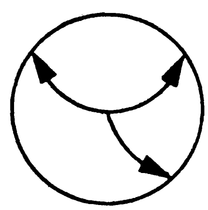
TABLE I Continued



P-L, A-L, A-M

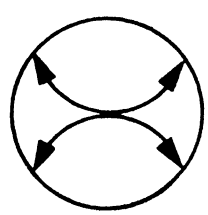


A-L, P-M, P-L



P-M, A-L, A-M

Triple Rotary Instability



Quadruple Rotary Instability

TABLE I Continued

define the relative motion of tibia over femur at each instant. As tibia executes its normal mode of motion, depending upon the geometric properties of the knee joint, the instantaneous screw axis will occupy different location in space and the corresponding associated pitch values will also change. The locus of the instantaneous screw axis will generate an axode. Using the Euler-Savary Equation (26) for rigid body motion in space, it is possible to calculate the conjugate axode. The axode and its conjugate will then describe uniquely the motion executed by tibia over femur. As the axode rolls and slides along the instantaneous screw axis common to its conjugate, the tibia will successively execute its motion relative to femur. An intersection of the axode with a plane parallel to the tibial plateau will yield the successive location of the horizontal or longitudinal axis of rotation of tibia in tibial plateau.

Much of the information presented in Table I in classifying the knee instability and it's relationship with the progressice shift in the location of the horizontal axis of rotation of tibia with respect to femur are neither clinically nor experimentally verified. The objective of this investigation is to examine this hypothesis for two classes of rotary instabilities. These two classes are:

1. Antero-Medial (right knee)
2. Antero-Lateral (left knee)

Such examinations will be carried out by (1) developing the necessary knee testing fixture. (2) developing the linkage transducer to measure motion of the tibia with respect to femur, and (3) developing the analytical method of analysis of these data.

Chapter II presents the fundamentals of knee anatomy. Chapter

III examines the kinematics of the knee joint, Chapter IV presents the design of the experiment. Chapter V presents the methods of data collection and analysis. Conclusion and summary of the present investigation are presented in Chapter VI.

CHAPTER II

THE KNEE JOINT ANATOMY

Understanding of the normal anatomy is fundamental to the diagnosis mentioned in Chapter I.

The knee joint is placed in between two long lever arms referred to as the FEMUR and TIBIA. It receives and absorbs vigorous stresses, such as the body weight, sudden impact from the bottom surface, or from lateral direction. Further, it plays significant role in contributing a wide range of motion (45) of the knee joint.

At the knee joint, femur and tibia bear one against the other, with the ingeneously created condyle surfaces. The femoral condyle rotates and slides on the surface of the tibial condyle as the leg assumes different position of flexion and extension in its normal motion. These two bones are held together by a ligamentous structure, and the knee capsule.

The capsule is the fibrous lining of the knee lying adjacent to its synovial encasement. Anteriorly the capsule of the knee is reinforced by the quadriceps, patella, patellar tendon and retinaculum.

Medially, the capsule thickens to form the three portions of the medial capsular ligament anterior, medial and posterior. The medial portion is the deep layer of the medial collateral ligament and the posterior portion is the same structure which Hughston (7, 8) has called the posterior oblique ligament. The tibial collateral ligament medially reinforces the medial capsular ligament, and is the same structure as the superficial part of the medial collateral ligament.

Laterally, there is also a capsular ligament which for convenience is divided into three portions. The posterior third is reinforced by the fibular collateral ligament, arcuate ligament, biceps femoris and popliteus tendon. The anterior two-thirds of the capsular ligament are reinforced by the iliotibial band.

Posteriorly, the capsule is thickened by the arcuate ligament, oblique popliteal ligament and the meniscofemoral ligaments.

The cruciate ligaments lying within the capsule of the knee but extra synovially connect the tibia to the femur. The anterior is attached to the anterior medial tibial plateau and extends up and back to the lateral femoral condyle. The posterior cruciate ligament extends toward and up from the posterior lateral tibial plateau to the medial femoral condyle.

This summary is well accepted and points out the complexity of the ligamentous structure of the knee. This complexity compounds the problem of diagnosis following injury.

The menisci of the knee may also provide a stabilizing function in that they act as shock absorbers when the knee is hyperflexed or hyperextended. They also act as cushions to varus or valgus stress. While the menisci do provide a more congruous surface for articulation they do not deepen the joint much. Consequently, stability must be provided by the surrounding ligaments, capsule and muscles.

FEMUR: (thigh bone) is the longest and the strongest bone in the body. The shaft of the femur is almost cylindrical in most of its length and bowed with a forward convexity. The upper portion of the femur is in the form of a rounded articular head. The distal portion is more massive, like a double knuckle joint - or condyles, which articulates with the tibia. The shaft of the femur is narrowest at the middle, expands as it is traced upwards, but it widens appreciably near the lower end of the bone. The lower end of the femur, is widely expanded providing a good bearing surface for the transmission of the weight of the body to the top of the tibia. It consists of two condyles, which are partially covered by a large articular surface. The articular surface forms a broad inverted 'U' shaped area for articulation with the patella above and the tibia below. Figure (1) following illustrates the transverse section of the left knee joint to show the relations of the joint.

TIBIA: is the second largest bone in the body. It is prismoid in section in it's shaft, and has expanded extremities. The lower end of the tibia is smaller than the upper. The anterior border of the tibial shaft is conspicuous, sharp crest, which curves medially at the lower end, towards the medial malleoulus. The upper end of the tibia is expanded in the transverse plane of the body. The main purpose of this is to provide an adequate bearing surface - for the body weight, transferred through the lower end of the femur. The upper end mainly consists of two condyle, namely medial and lateral condyle, and a smaller projection in the middle - the tuberosity of the tibia. The shaft of the tibia is triangular in shape with medial, lateral, and posterial surface (45).

FIBULA: (the lateral bone of the leg) is much more smaller than the tibia, and does not play any role in transferring the body weight.

The knee articular cartilage which are closely attached to joint

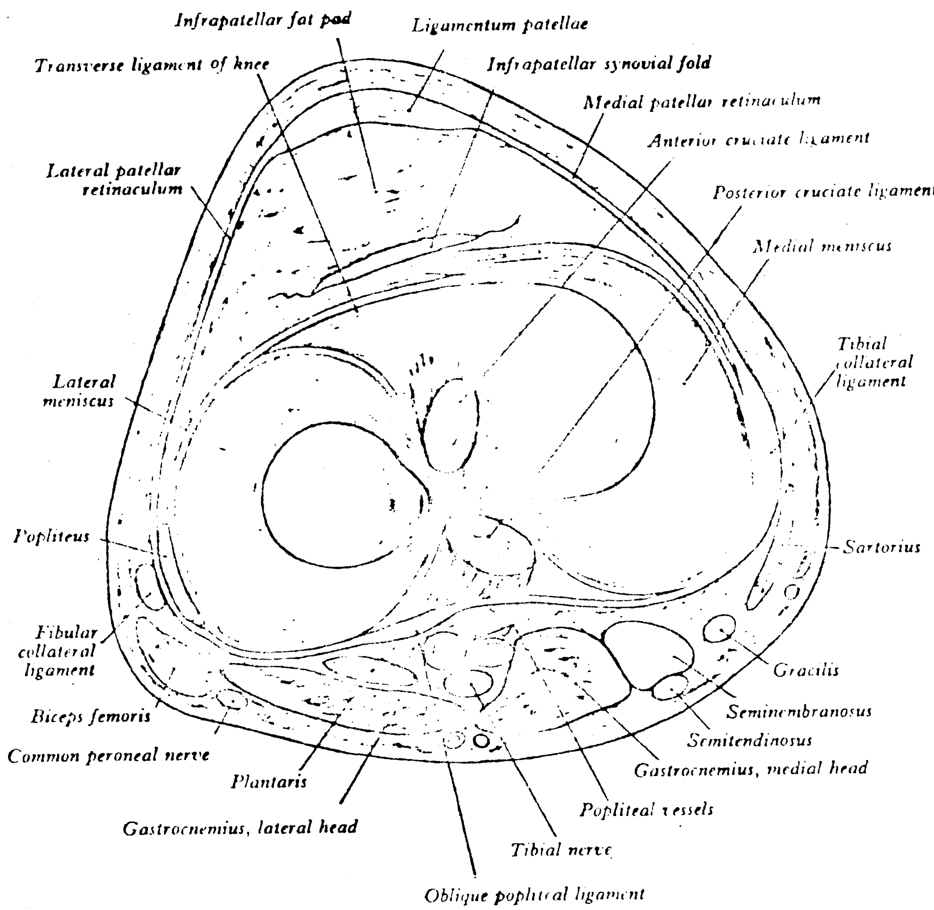


Figure 1. A Transverse Section of the Left Knee Joint, Superior Aspect, to Show the Relations of the Joint.

surfaces provides a wear resistant, low friction lubricated surface, both slightly compressible and elastic, which is ideally constructed for ease of movements over a similar surface but able to accomodate the relatively enormous compressive and shear forces generated during the muscle action (45). The thickness of the articular cartilage varies considerably (2-7 mm to 5-7 mm) in the large joints. These cartilage appear as white, smooth and glistening to the naked eye. This is the case with young and healthy cartilage. But aging cartilage are thinner, less cellular, firmer, more brittle with less regular surface, and with a yellowish tint. Though this surface looks too smooth to naked eye, its roughness is estimated to be varying between 30×10^{-6} (center line average of the undulations) to 200×10^{-6} inch - when lubricated with synovial fluid, the surface exibits an extremely low coefficient of friction (<.002).

The synovial fluid is found in the cavities of the synovial joints - such as knee joint. It is a pale yellow, viscous, glaring fluid. Its viscosity, color and volume is estimated to be, less than .5 ml in a large joint like knee. The physical properties of synovial fluid show viscous, elastic and plastic components. The functions of the synovial fluid is to provide a neutritive source for the articular cartilage, discs, and mensci, and to provide the necessary joint lubrication (45).

Ligaments (45, 46) Numerous ligaments support the knee joint. These ligaments are muscular in structure, and arranged around the knee joint in such a fashion, that it provides the necessary support, as well as the stability to the knee joint. The main ligaments which are to be considered in the knee joint are:

(a) The Cruciates:

(1) Anterior

(2) Posterior

(b) The Collaterals:

(1) The medial or tibial collateral

(2) Thes lateral or fibular collateral

The cruciate ligaments are of considerable strength, and situated a little posterior to the center of the joint. They are so called because they cross each other and the names are derived from the position of their attachment to the tibia (45).

The medial collateral ligament, is a broad flat band, nearer to the back than the front of the joint and is attached above to the medial epicondyle of the femur immediately below the adductor tubercle and, below to the medial condyle and medial surface of the shaft of the tibia. Its anterior part is a flattened band about 10 cm long.

The fibular collateral ligament is a strong rounded cord attached above to the lateral epicondyle of the femur and below to the head of the fibula in front of its apex.

The menisci (medial mensicus and the lateral meniscus - semilunar cartilage) are two crescentric lamellae which deepen the surfaces of the upper end of the tibia in articulation with the femorla condyles. The peripheral attached border of each meniscus is thick and convex, the free border is thin and concave. The upper surface of the menisci are smooth and concave and in contact with the condyle of the femur, and the lower surfaces are smooth and flat and rest upon the tibia.

CHAPTER III

THE KNEE MECHANISM

A. General Description

There are three perpendicular planes to be considered in analyzing the motion of a knee joint. They are:

(1) Transverse Plane

(2) Frontal Plane

(3) Sagittal Plane

which is illustrated in Figure (2) following.

The transverse axis of the joint is perfectly horizontal and lies in the transverse plane. It will remain horizontal both in extension and flexion.

In the frontal plane the angulation of the axes of the femur and the tibia are shown in the Figure (3) following.

The axis of the femur and the tibia form an angle of 171° laterally. Under normal conditions femur is oblique, and the tibia stands perfectly vertical. This angle is called as the femoro-tibial angle as seen from the Figure (3) following, it is not bisected by the horizontal axis, as femur makes an angle of 81° with the horizontal and the tibia makes an angle of 90° with the horizontal.

But the mechanical axis which runs from the center of the head of the femur to the center of the knee joint makes an angle of 87° with the transverse axis. Because of this obliquity of the Anatomical axis,

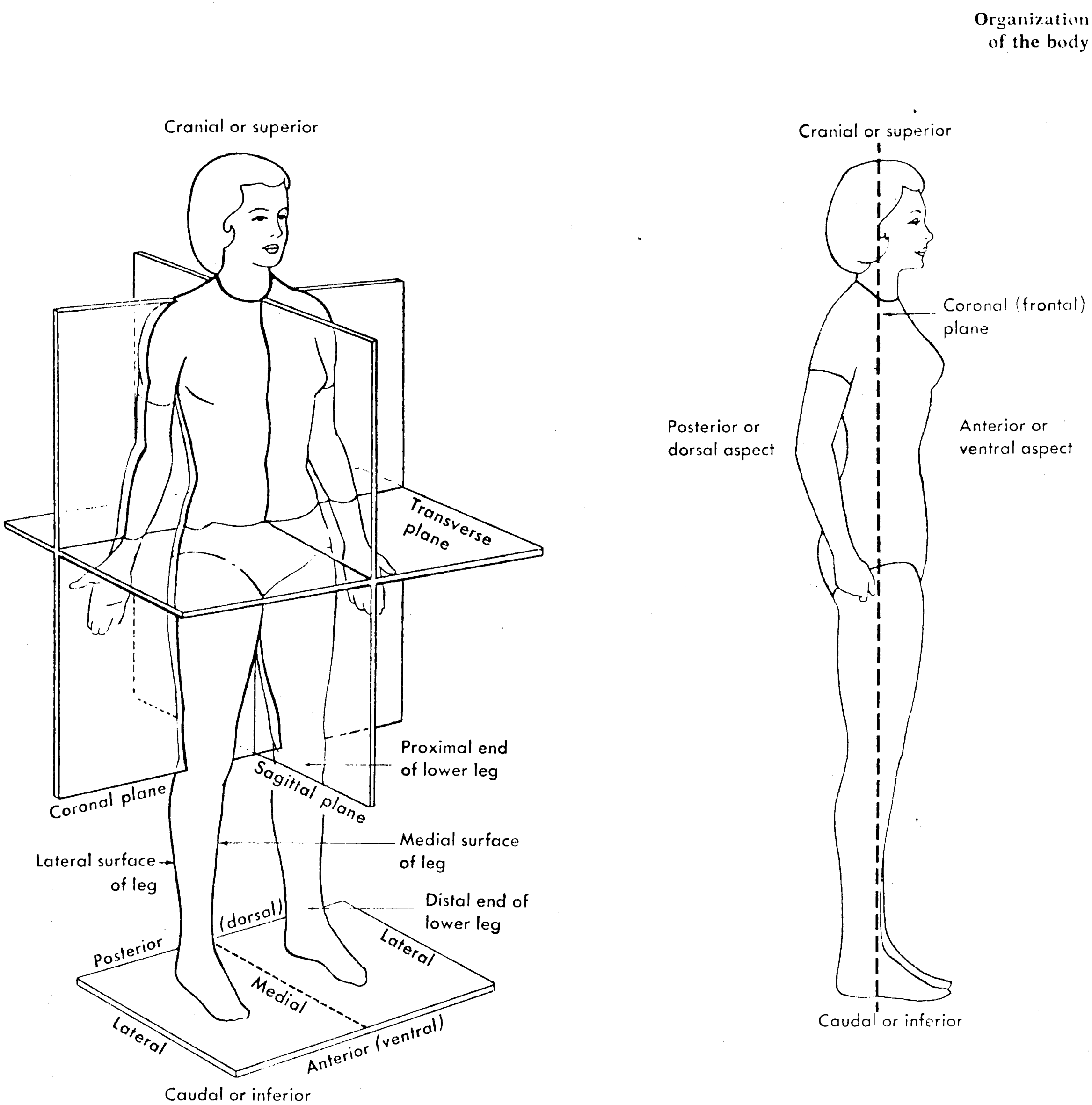


Figure 2. Anterior and Lateral View of the Human Figure

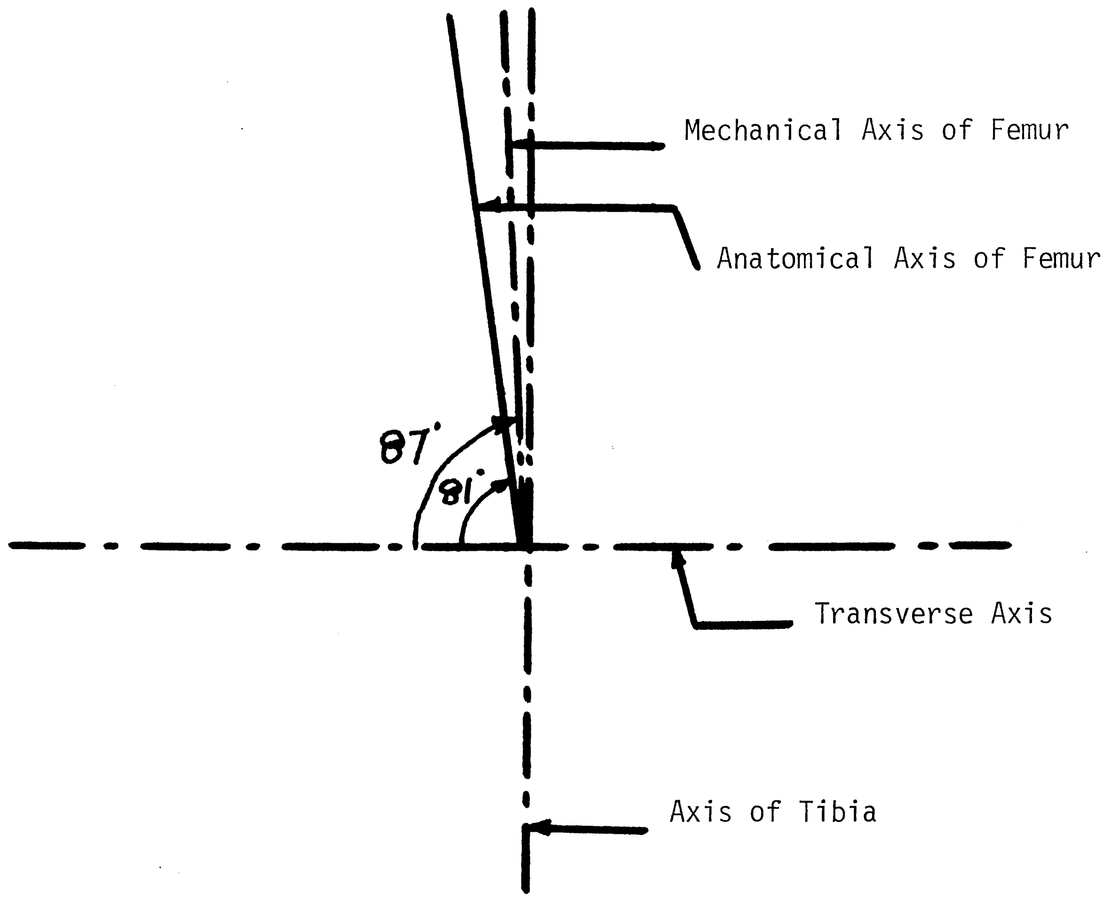

Mechanical Axis of Femur
Anatomical Axis of Femur
87°
81°
Transverse Axis
Axis of Tibia

Figure 3.

greater amount of pressure is born by the lateral condyles, and greater amount of stress is sustained by the medial structures such as medial collateral ligaments and the medial capsule. Depending upon the position of the mechanical axis the femur may bend towards the lateral side or towards the medial side. These two cases are referred to as Genu valgum or Genu-varum which is shown in Figure (4) following.

Looking at the "Motion" which a knee performs, it is understood that it represents a combination of two types of motion which are:

(1) True rocking motion-where equidistant point of the femur contact equidistant points of the tibia or vice versa.

(2) Slinding motion,-where the contact of tibia with femur is a localized area or a point-which "Sweeps" over the whole contour of the other part.

But in the sagittal plane, (46) the length of the femorol joint curve is estimated to be 10 cm and that of the tibia 8 cm. Hence, the radii of contacting surfaces are different - i.e., of the tibia more than the femur. As a result of this, there is neither a constant sliding as in the case of equal radii surfaces contacting each other, nor there is constant rocking motion as in the case of curved surface contacting more plain surface. As a result of this, combination of the above two types of motion occurs. Analysis has shown that - on the medial side from 180° extension to 170° or 165° extension (i.e., over 10-15° range) a pure rolling motion occurs. After this the contact of the tibia gradually narrows down to a point and the motion becomes a sliding one (46). On the lateral side - rolling occurs for 20° and then the sliding, hence on the lateral side rocking is more than sliding and on the medial side sliding is more than rocking. Thus during

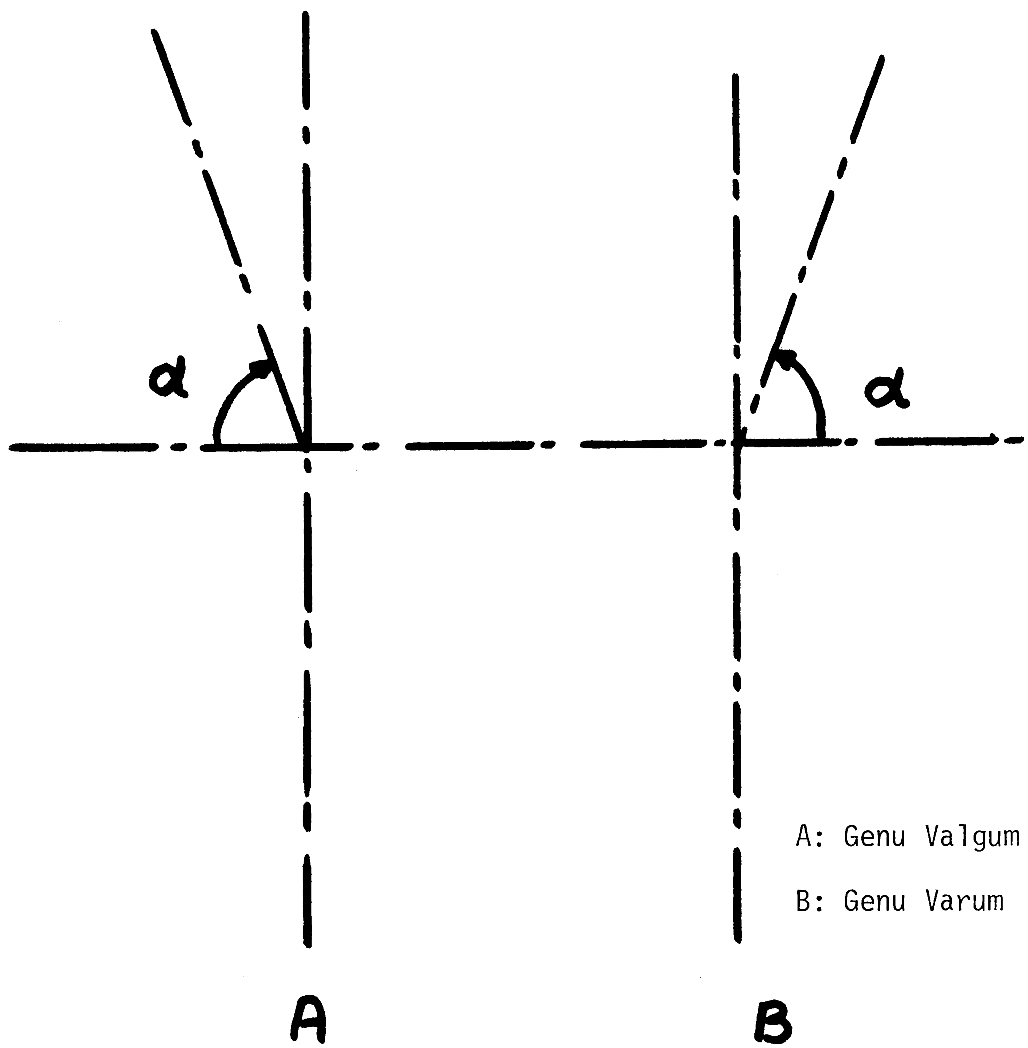


Figure 4.

rocking motion (say about 20° of flexion) the knee is stiffer than the rest of its motion.

B. Total Motion Between Tibia and Femur and Measurement of the Motion

It is presumed that a total of six components of motions are permitted in a human knee joint. Hence, while studying the total motion between the femur and tibia - 6 different parameters are to be measured. A spatial linkage, with the seven links and six pin joint is used for this purpose. The information provided by this linkage can be used to locate the position of a point either on the tibia or on the femur relative to each other at any given instant. To define the overall motion of the knee joint i.e., tibia relative to femur or vice versa motion is considered as a series of discrete displacement. Each of these discrete displacements can be explained as a rotation about a unique axis called as the "Serew Axis" and the translation along the same axis. The relative motion between two rigid bodies should be studied in a continuous mode. However the data collection procedure will require us to adopt a discrete mode simulating the motion in a continuous mode.

C. On Classification of the Rotary Instability

One way of classifying the knee instabilities is to examine the mobility of the knee joint and relate this motion with the principles of classification of kinematic pairs (42). A knee joint has six components of motion. These six components of motion consist of three rotational components (W_x, W_y, W_z) and three translation components (T_x, T_y, T_z) along a set of three (X, Y, Z) mutually perpendicular fixed axes. Since the knee joint has a constrained motion there exists a functional relationship between the six components of the knee joint motion. This functional relationship provides one degree of freedom to the knee joint which in its natural mode executes flexion - extension type of motion. When a knee joint has developed instability it can be hypothesized that the knee joint has acquired two or more degrees of freedom and that there are two or more independent functional relationship relating the six components of motion. The degree of instability will be directly related to the additional degree of freedom and the functional relationship between the components of motion acquired by the knee joint. Thus the Class I instability will mean that the knee joint has two degrees of freedom and Class II instability will mean that the knee joint has three degrees of freedom, etc. We note that based on this hypothesis of degrees of freedom of the knee joint and its relationship to knee instability, we can have at most five classes of instabilities. The Class V instability will then mean total dislocation of the joint.

The six components of motion and their interrelationship for a stable knee can be determined using a linkage transducer (42) shown in Figure (5) following. As the knee is executing flexion-extension type of motion, the stable knee joint will provide angular displacement at each of the six potentiometers of the linkage transducer. The relationship between the six components of motion at the knee joint is then expressed as the relationship between the six angular displacements of the potentiometers. Under this condition, the knee joint is assumed

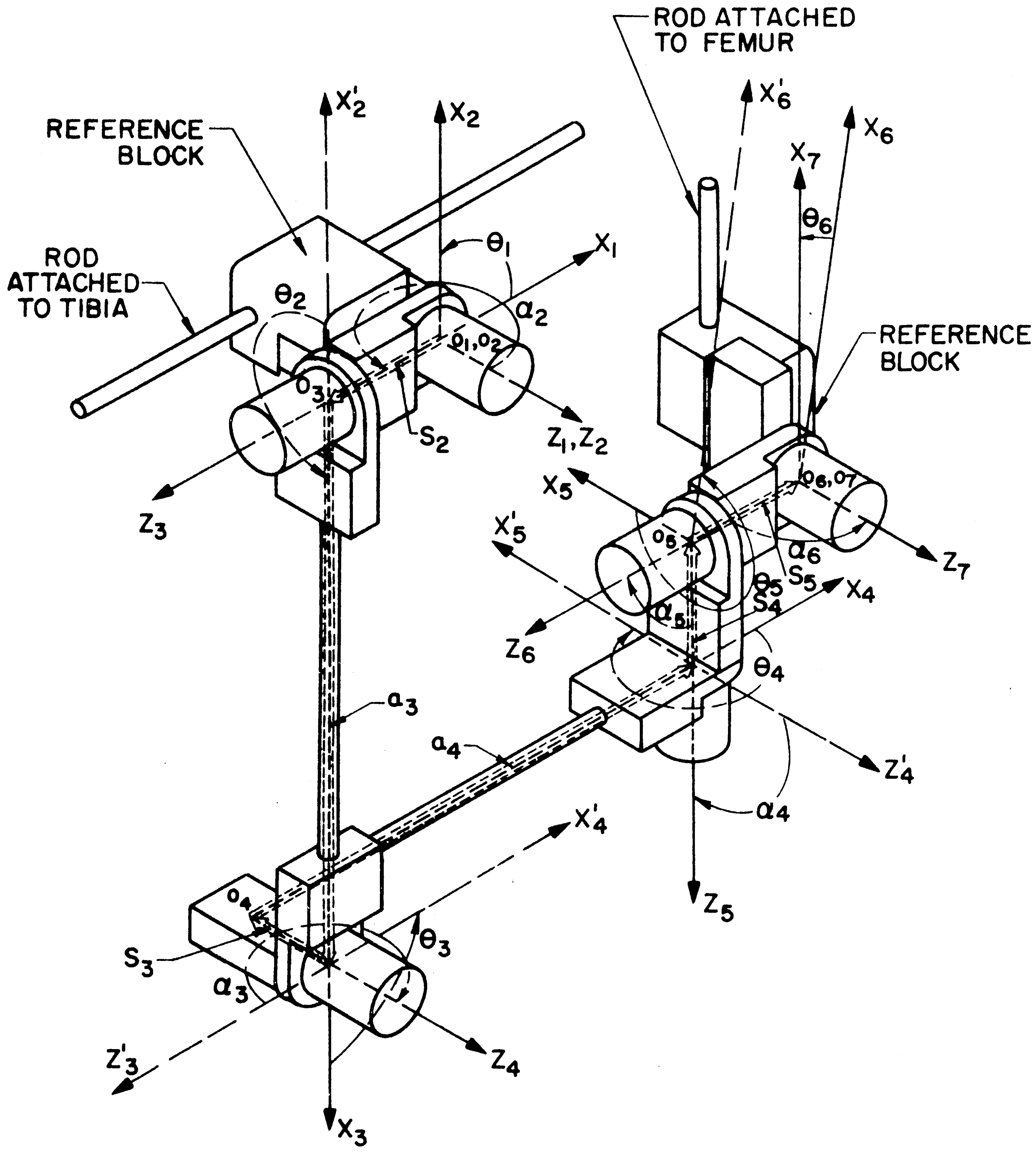


Figure 5. SCHEMATIC REPRESENTATION OF THE MECHANISM TRANSDUCER

to have one degree of freedom and the knee joint is considered to be a stable joint.

Since the linkage transducer has six potentiometers and the joint is providing constrained motion to the transducer, the total system consisting of the transducer and the knee joint constututes a mechanism having seven joints, seven links, and one degree of freedom according to Kutzbach's mobility criteria (25). Using this mobility criteria, we can also state that the total system consisting of the linkage transducer and the knee joint will continue to provide constrained output (displacement) at the potentiometers as long as the total degrees of freedom of all the joints including rotary potentiometers and knee joint is seven. Thus when the joint has acquired two degrees of freedom (instability of Class I) the total number of potentiometers needed in the linkage transducer will be five to obtain a constrained output motion from the total system including the knee joint. Similarly when the knee joint has acquired Class II instability, the total number of potentiometers required in the linkage transducer will be four. This rationale between the class of instability and type of transducer can be extended in a similar manner for other classes of instabilities.

It is assumed that regardless of the class instability, the total number of components of the motion of a knee joint will always be six. The functional relationship between these components of motion will be changing, however, for each class of instability. In order to obtain a quantitative measure of such a functional relationship we need to obtain the instantanedus screws of motion of the knee joint and the axode generated by these instantaneous screws (26).

The charcteristic parameters (27) associated with the geometric properties of the axode describe uniquely the axode and in turn the characteristic range and pattern of motion of the knee joint. The axodes will be different for each constrained system of linkage transducers and the knee joint. However as stated above to produce a constrained motion and to obtain the axode from a knee joint having Class I intability, we need to use a linkage transducer having five rotary potentiometers.

To study the kinematics of knee instabilities in a laboratory experiment, one is required to design an experiment and suitable loading arrangement to produce such instabilities. One possible avenue for achieving such an objective is to test cadaver knees in a testing apparatus capable of applying different types of loads.

The characteristic parameters of an axode are the scalar number describing geometric properties in terms of curvature and rate of change of curvature of a ruled surface such as an axode.

Referring to the Figure (6) following, the moving rigid body traverses with respect to the fixed rigid body from position 1 to position 2. The co-ordinates of any point such as Q in position 1 is completely known. Thus this motion can be considered as a combination of rotation and translation about an axis. This axis is located in the fixed body, which is called as the SCREW AXIS.

A screw axis and the corresponding motion about this axis is represented in the Figure (7) following.

Referring to Figure (7) the moving body travels from position 1 to position 2 by translating a distance 'T' along and rotating through an angle ϕ about the screw axis. The displacement of the rigid body is completely defined when:

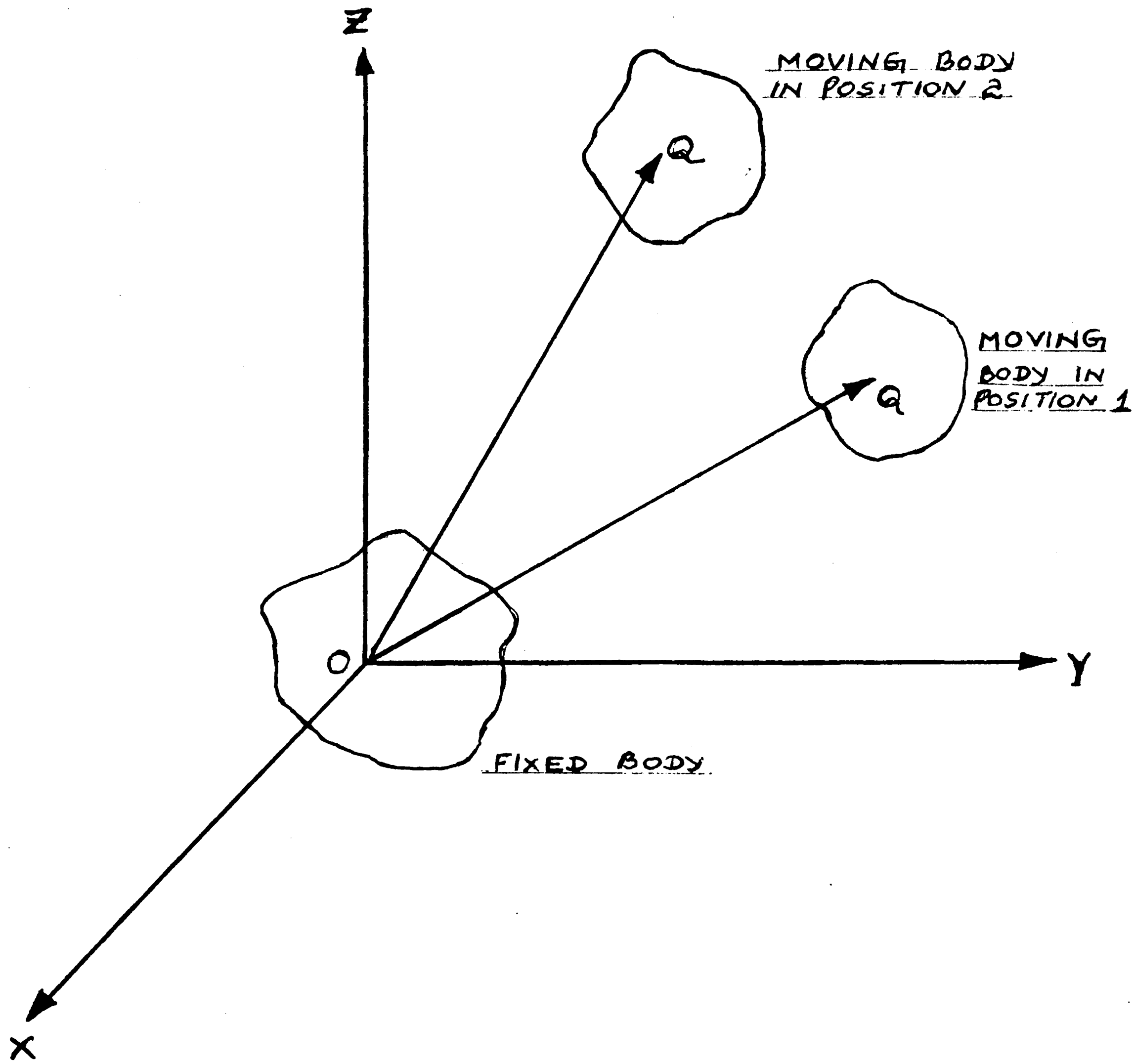


Figure 6. General Representation of Two Rigid Bodies in Space.

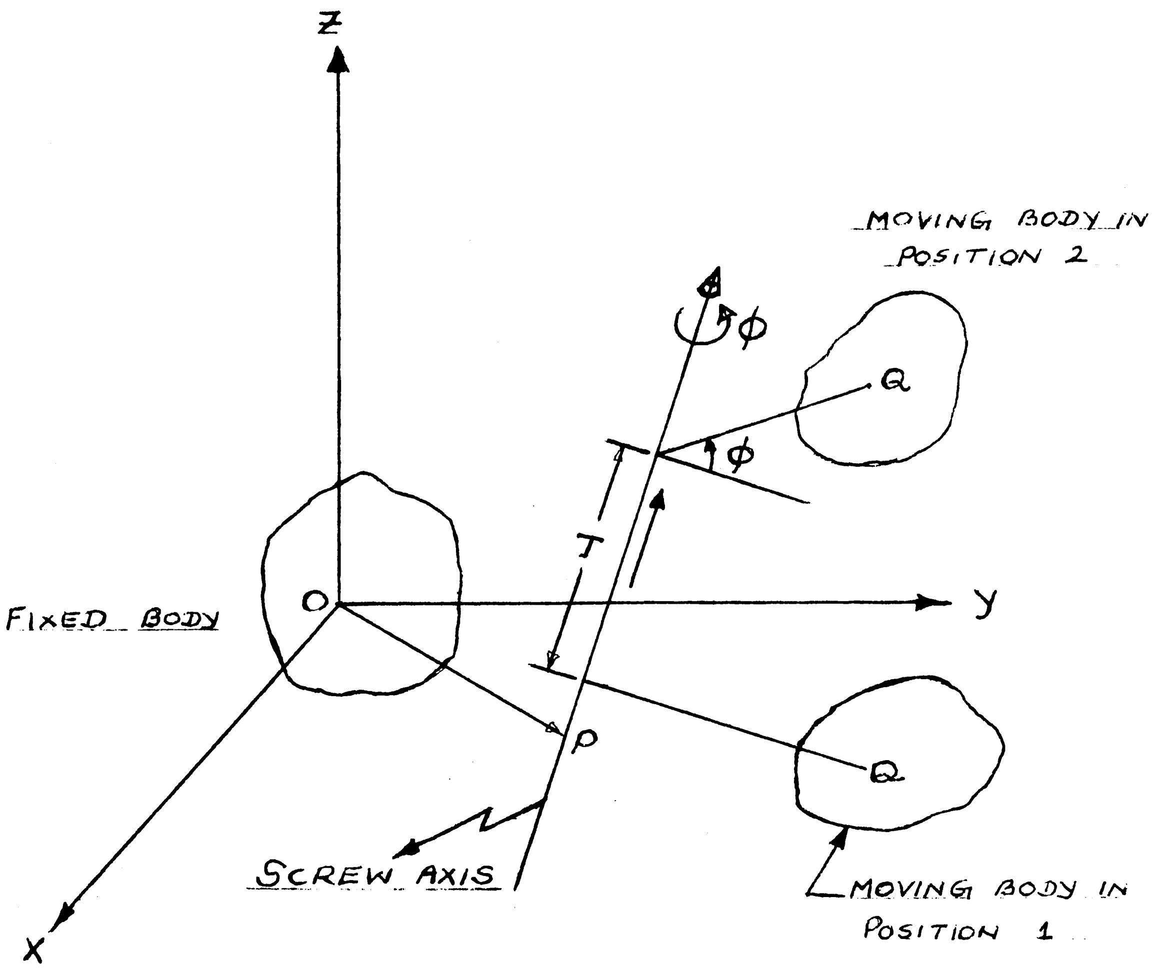


Figure 7. Screw Axis and Screw Motion. The moving body travels from position 1 to position 2 by rotating about the screw axis an amount Ø and by translating T along the screw axis.

1. The location of the screw axis with respect to the origin fixed somewhere in the fixed body.
2. Inclination of the screw axis.
3. The rotation angle ϕ of the moving body about the screw axis.
4. Translation along the screw axis is completely known. That is, it is necessary to define six parameters which are:
   (a) Two - for the location of the screw axis.
   (b) Two - for the inclination of the screw axis.
   (c) One - for the translation of the rigid body.
   (d) One - for the rotation angle.

Let X_1, Y_1, Z_1, be the co-ordinates of the point Q in position 1, and X_2, Y_2, Z_2 be the co-ordinates of the points Q in position 2. Then position 1 can be related to position 2 by the following equations:

$$X_2 = m_{11} X_1 + m_{12} Y_1 + m_{13} Z_1 + X_0$$

$$Y_2 = m_{21} X_1 + m_{22} Y_1 + m_{23} Z_1 + Y_0$$

$$Z_2 = m_{31} X_1 + m_{32} Y_1 + m_{33} Z_1 + Z_0 \tag{1}$$

which does the co-ordinate transformation from moving body to the fixed body. The equation set in (1) can be rewritten as:

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} M \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_2 \end{bmatrix} + \begin{bmatrix} r_0 \end{bmatrix}$$

where

$r_0 = (X_0, Y_0, Z_0)$

'M' is the rotation matrix

If the equation 1=1 is included in the set of equations (1) then the result will be a 4x4 matrix.

i.e.,

$$\begin{bmatrix} 1 \\ X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ X_0 & m_{11} & m_{12} & m_{13} \\ Y_0 & m_{21} & m_{22} & m_{23} \\ Z_0 & m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} 1 \\ X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \quad (2)$$

i.e.,

$$\left[P_2\right] = \left[M\right]\left[P_1\right]$$

where

$\left[P\right]_2$ = represents the position 2 of the moving rigid body.

$\left[P\right]_1$ = represents the position 1 of the moving rigid body.

$\left[M\right]$ = represents the transformation matrix.

If the matrix (M) is known, then the components of any vector can be determined in terms of the fixed co-ordinate system. In other words, determining the position of the moving body with respect to the fixed body is equivalent to finding the components of the matrix $\left[M\right]$. For each successive position of the moving rigid body a new matrix $\left[M\right]$ is determined, in order to locate the instantaneous screw axis and its parameters.

Matrix represented in (2) above can be rewritten as:

$$\begin{bmatrix} 1 \\ X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \left[\begin{array}{c|c} I & 0 \\ \hline S & R \end{array}\right] \begin{bmatrix} 1 \\ X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \quad (3)$$

where

$$\begin{bmatrix} S \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}$$

$$\begin{bmatrix} I \end{bmatrix} = \begin{bmatrix} 1 \end{bmatrix}$$

$$\begin{bmatrix} 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}$$

and

$$\begin{bmatrix} R \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}$$

where

$\begin{bmatrix} R \end{bmatrix}$ represent the rotation matrix about the screw axis.

If U_x, U_y, and U_z are the direction cosines of the screw axis and ϕ is the rotational angle, then $\begin{bmatrix} R \end{bmatrix}$ is given by:

$$\begin{bmatrix} R \end{bmatrix} = \begin{bmatrix} (U_x^2 \text{vers}\phi + \cos\phi) & (U_x U_y \text{vers}\phi - U_2 \sin\phi) & (U_x U_z \text{vers}\phi + U_y \sin\phi) \\ (U_x U_y \text{vers}\phi + U_2 \sin\phi) & (U_y^2 \text{vers}\phi + \cos\phi) & (U_y U_z \text{vers}\phi - U_x \sin\phi) \\ (U_z U_x \text{vers}\phi - U_y \sin\phi) & (U_y U_z \text{vers}\phi + U_z \sin\phi) & (U_z^2 \text{vers}\phi + \cos\phi) \end{bmatrix}$$

$\begin{bmatrix} S \end{bmatrix}$ will locate the screw axis, and the translation along the same.

Referring back to matrix 2 which can be rewritten as follows:

$$\begin{bmatrix} P \end{bmatrix}_2 \begin{bmatrix} P \end{bmatrix}_1^{-1} = \begin{bmatrix} M \end{bmatrix}$$

As the matrix $\begin{bmatrix} P \end{bmatrix}_1$ and $\begin{bmatrix} P \end{bmatrix}_2$ is formed by non coplanar points.

Now, consider a case where the screw axis passes through the origin and another screw axis parallel to this axis. As shown in Figure (8) following.

These two screw axes will determine the orientation of the screw axis, and the rotation angle ϕ. Consider the point 'X' in two positions about the screw axis as shown in the Figure (8) following.

Then, the transformation representing the pure rotation is given by:

$$\left[r_{x_1}\right] = \left[R\right]\left[r_{x_2}\right]$$

If 'X' is located on the screw axis which is the limiting case, then there is no rotation, i.e.:

$$X_1 = X_2$$

i.e.,

$$\left[r_x\right] = \left[R\right]\left[r_x\right]$$

or

$$\left[0\right] = \left[R\ \right]$$

or $$\left[0\right] = \left[R-I\right]\left[v_x\right] \tag{4}$$

The determinant of the matrix $\left[R-I\right] = 0$, hence there is a nontrivial solution for the vector V_x, i.e., V_x lies along the axis of rotation, which can be found out by the relation (3), but this does not uniquely determine the length of r_x.

Let

$$\bar{U} = \bar{r}_x = \text{unity}$$

Then the components of $\bar{U}$ becomes the direction co-sines of the screw axis.

Hence writting the matrix $\left[R\right]$ as in (3) and if $\bar{U} = \bar{r}_x$ equation (4) on expanding becomes:

$$\begin{bmatrix} m_{11}-1 & m_{12} & m_{13} \\ m_{21} & m_{21}-1 & m_{23} \\ m_{31} & m_{32} & m_{33}-1 \end{bmatrix} \begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

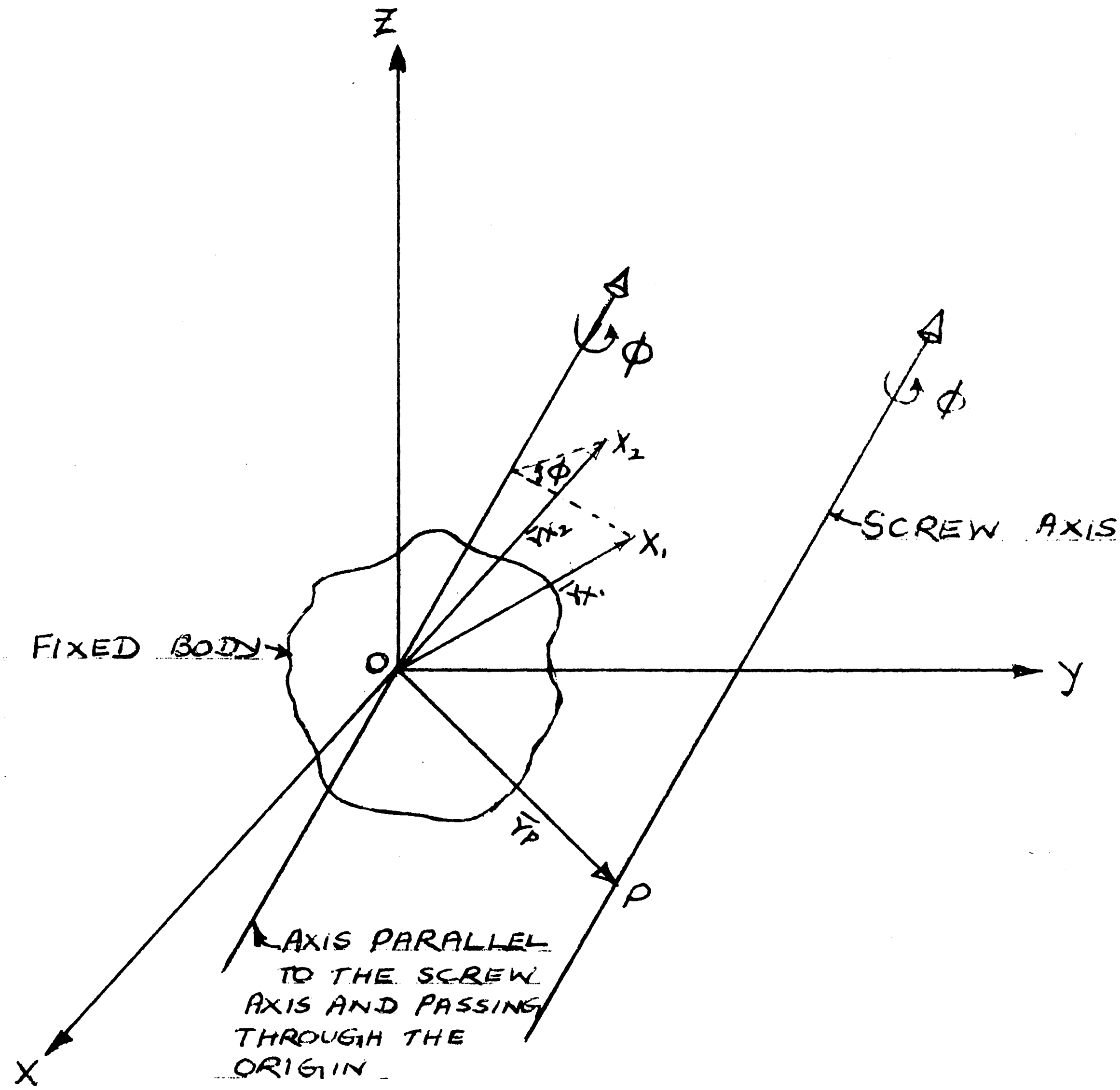


Figure 8. Pure Rotation of a Point X About an Axis Parallel to the Screw Axis but Passing Through the Origin of the Coordinate System.

Then the values which satsify U_x, U_y, U_z, in equation (5) can be written as:

$$U_x = U_x$$

$$U_y = \frac{U_x}{A} \quad m_{23}\, m_{31} - m_{21}\, (m_{33}-1)$$

$$U_z = \frac{U_x}{A} \quad m_{21}\, m_{32} - m_{31}\, (m_{22}-1) \qquad (6)$$

where

$$A = (m_{22}-1)\,(m_{33}-1) - m_{23}\, m_{32}$$

and the vector $\bar{U}$ with unit magnitude can be written as:

$$U_x^2 + U_y^2 + U_z^2 = 1 \qquad (7)$$

The two equations (6) and (7) will be sufficient to find the direction co-sines of the screw axis.

Once the direction cosines are determined the rotation angle ϕ can be determined using equation (8) which is:

$$\phi = \cos^{-1}\left[\frac{m_{11} - U^2}{1 - U_x^2}\right] \qquad (8)$$

Hence, the direction cosines, and the roation angle ϕ will uniquely determine the screw axis.

CHAPTER IV

DESIGN OF THE EXPERIMENT

To fulfill the objectives of the proposed study the below mentioned activities are undertaken:

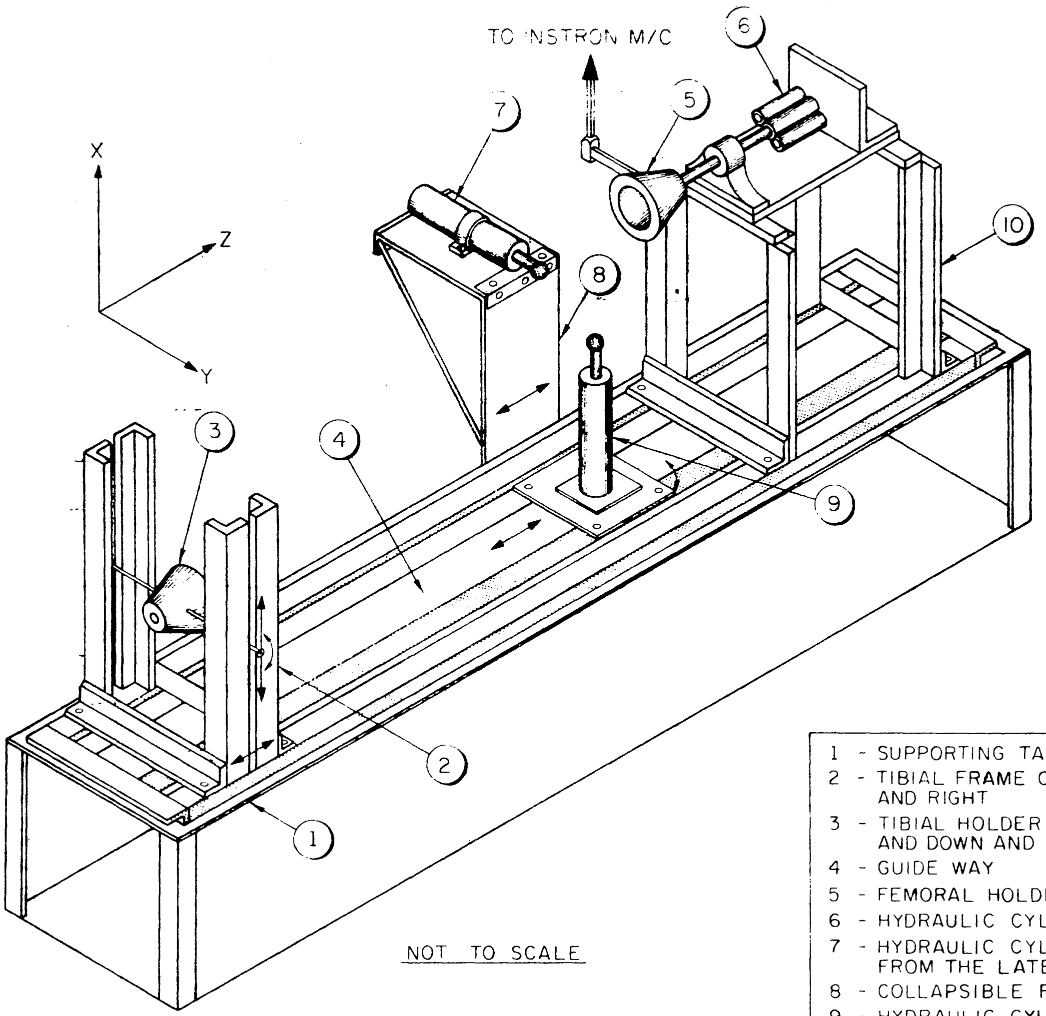
A. Design of a Suitable Knee Fixture

The knee shown in Figure (9) is in a position to:

1. Apply such external load as T_z.
2. To hold and maintain the knee specimen at a desired flexion angle.
3. To permit easy mounting and easy removal of the knee specimen.
4. To withstand any impact or cyclic load conditions.

Description of the Fixture

The fixture, shown in Figure (9) following, mainly consists of a table having guideways on it. The tibial frame will be in a position to move either towards the femoral frame or away from it thus facilitating the knee to have a different angle of flexion. The tibial frame will also be in a position to be fixed at any place on the guidewaus be means of bolts and nuts. The tibial frame has vertical slots cut in its two pillars. These vertical slots act as a guideway to the supporting pins of the tibial holder and the tibial holder can be moved up and down on these guideways, and can be fixed in this slot with the tibia so that the tibia can be fixed in different angles of flexion.



1 - SUPPORTING TABLE
2 - TIBIAL FRAME CAPABLE OF MOVING LEFT AND RIGHT
3 - TIBIAL HOLDER CAPABLE OF MOVING UP AND DOWN AND ROTATING
4 - GUIDE WAY
5 - FEMORAL HOLDER CAPABLE OF ROTATING
6 - HYDRAULIC CYLINDER
7 - HYDRAULIC CYLINDER TO APPLY FORCE FROM THE LATERAL DIRECTION
8 - COLLAPSIBLE FRAME
9 - HYDRAULIC CYLINDER TO APPLY FORCE IN THE SAGITTAL PLANE
10 - FEMORAL FRAME

Figure 9. "KNEE FIXTURE" (ONE SCHEMATIC WAY OF LOADING.)

The tibial holder is free to move in a vertical plane about these pins, which has a conial hole on one side where the tibia enters (this hole provides space for the free movement of the tibia on either side of its reference axis) and receives a bolt on the other side which positions the tibia and holds it in the fixture. The femoral holder is in the shape of a hollow truncated cone. The smaller end of this conical holder is connected to the piston head of the hydraulic compressor so that conpressive load can be applied to the femur directly. On the surface of the conical holder a moment arm is welded which is connected to the Instron cross head so that cyclic torsional load can be applied to the femur.

B. Design of a Suitable Linkage Transducer

One objective of the displacement transducer is to locate the successive position of the tibia in a fixed reference frame as the tibia executes motion relative to femur. Once the successive positions of rigid body (tibia in case of knee) moving relative to a fixed frame of reference (femur in case of knee) are determined, the motion characteristics of a selected point within the moving rigid body can be determined using an appropriate mathematical transformation which is explained in Chapter III. This information can be utilized to calculate elongation in any of the ligaments of the knee. Thus, the displacement transducer will provide the data for calculating instantaneous screw axis and translational motion along the direction parallel to the screw axis. The successive positions of the rigid body and the corresponding screws will provide the moving axode. The fixed axode or conjugate of the moving axode can be calculated using Euler's Equation (26). The fixed and the moving axodes together will provide the complete information describing the characteristic motion of the knee joint. The geometric properties of the axode and its conjugate will change as the knee is being subjected to different loads for different cycles and at different rates. As the knee instability is produced in a test specimen, the corresponding axode properties will also change. However since in the case of knee instability the functional relationship between six components is also expected to change, the mechanism transducer must be correspondingly adjusted to produce a constrained motion from the unstable knee joint. Thus, the requirements in the design of the mechanism transducer are:

1. To provide displacement data at each of the six, five, four, three, or two (depending upon the type of instability) potentiometers connected by rigid links.

2. To provide interference - free motion of the knee joint.

3. To have minimum error in the measurements of the knee joint motion.

4. To provide data in continuous as well as discrete mode.

5. To provide adjustability in constraining the motion of the knee joint when it is unstable.

One possible configuration of a mechanism transducer is shown in Figure (10) following. It consists of six rotary potentiometers and seven links. Figure (10) also shows a possible way of mounting such a mechanism transducer on a knee specimen. The mechanism parameters involving link lengths, and offset distances, are obtained by trial and error so that there is no interference with the motion of the knee specimen.

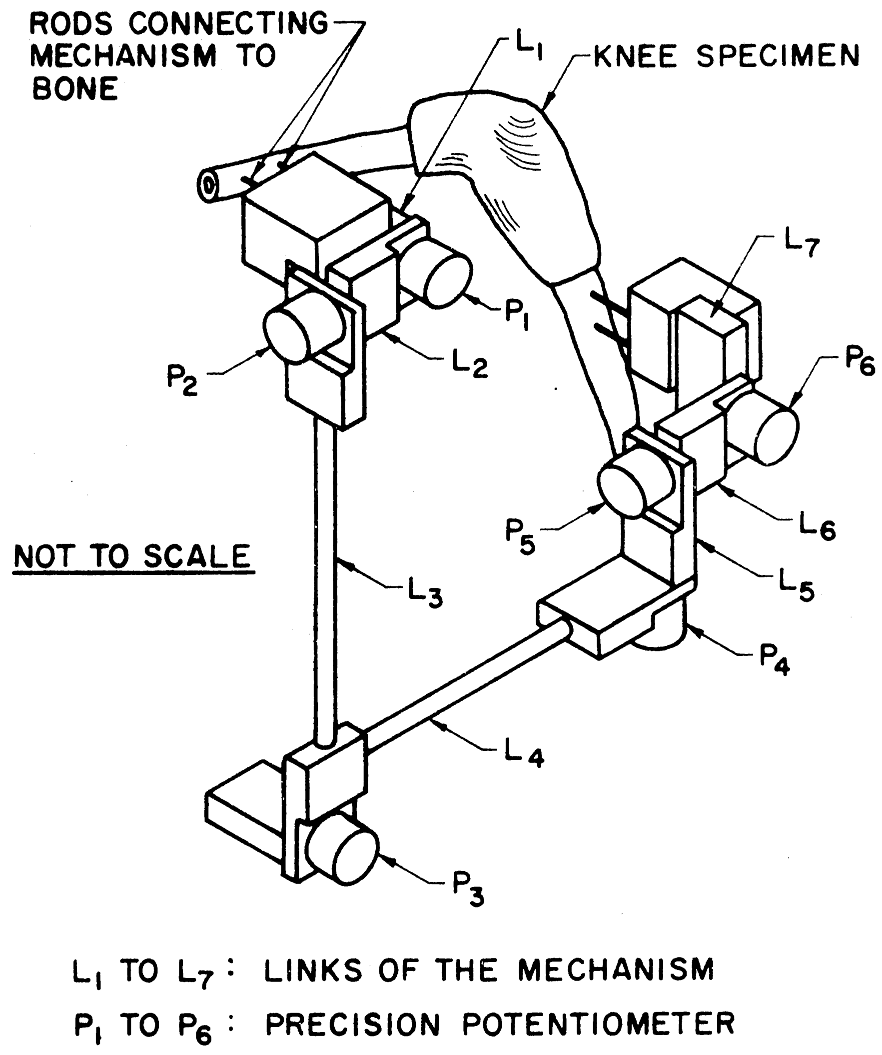


Figure 10. SCHEMATIC ARRANGEMENT SHOWING THE MECHANISM TRANSDUCER INSTALLED ON A KNEE SPECIMEN

C. Preparation of the Knee Specimens

Autopsy knee joint specimens are tested to arrive at the criteria of knee instability. The bones are cut about fifteen centimeters above and below the joint. The knee capsule, quadriceps tendon, and ligamentous structure are preserved. Before testing the specimen for producing knee instability, the specimen is examined using clinical procedures including A-P and lateral X-rays, drawer tests, and mobility of the knee joint using the mechanism transducer to check for the integrity of the knee joint. Kirchner's pins 10 cm long, 3 mm in diameter are inserted in tibia and femur to locate the ends of each ligament. Whenever the available specimens are not tested within a few hours of their availability, the specimens are stored at 30°C.

D. Testing Procedure

In testing the knee specimens, the basic objective is to produce adequate ligamentous damage which will include permanent elongation or tear of ligaments in a progressive manner to simulate condition similar to those found in knee with chronic or acute instability.

The stepwise procedure to test a knee specimen will be as follows:

1. Mount the specimen on the knee fixture.

2. Perform kinematic test to obtain data for the axode and to examine the pattern of motion of tibia moving relative to the femur.

3. Select the load and its loading condition.

4. Apply the selected load in a cyclic manner for n number of cycles at each step of testing ($n \leq 5$). The decision to stop or continue testing for n ($n > 5$) number of cycles will depend upon the ligamentous damage quantitatively analyzed during the testing.

5. Plot load deflection data for each cycle.

6. Perform kinematic analysis to obtain the instantaneous screws.

7. After testing for n number of cycles, stop the test and check for any visible tear in supporting structure.

8. Perform the drawer tests to check for instability.

9. Apply the kinematic test to check for unconstrained motion of the knee joint.

10. If the kinematic test is negative, increase the load to the next higher value.

11. Repeat steps 5 through 10 until knee instability of Class V is achieved.

Disect the knee specimen to examine for visual tear of the ligaments and supporting structure. This step will conclude the testing for each specimen.

CHAPTER V

DATA COLLECTION AND ANALYSIS

The stepwise procedure in collecting the data are as follows:

A. Preparation of the Specimen

1. Medullary canal of the tibia and femur are cleaned and filled with Methyl Metha Crylate.

2. The reference pins to hold the linkage transducer are fixed on the tibia and femur.

3. Anterior-Posterior, and Lateral x-rays are taken with the transducer mounted on the specimen.

B. Experimental Procedure

1. The femur is fixed in the femoral holder.

2. The linkage transducer is fitted on the specimen.

3. (a) The tibia is moved in steps of 15° from full extension to 90° flexion (i.e., from 0° to 90°) and the linkage transducer data are noted down in each position, which establishes the normal motion of the intact knee.

   (b) The tibia is moved from its extreme internal position to the extreme outward position each time noting down the transducer data.

4. The tibia is fixed in the tibial holder, at the desired flexion angle.

5. The netrual position of the femur is noted down (angular).

6. Load increasing:

(a) Increase the torsional load, thus rotating the femur in steps of 1°.

(b) The following readings are noted down.

(1) Load

(2) 6 potentiometer readings

(3) Angular position of the femur

The angular positions of the femur, the readings of the six potentiometers, and the load which are noted down in steps 3 (a), (b) and 6 (b) are tabulated in Appendix C.

7. Load decreasing:

The same steps as described in 6 (a) and (b) are followed.

8. Continue loading and unloading until marked looseness as diagnosed by clinical tests is found in the knee joint.

9. The loading of the tibia is stopped, and 1, 2, 3, . . . potentiometers are frozen, depending upon the type of instability and the steps described in 3 (a) and (b) are performed, which concludes the testing.

Data Analysis

The data which are collected can be analysed in many different ways to unfold the underlying theories of the human knee joint instability. As stated earlier in introduction the motion data and their analysis available regarding the human knee joints are mostly clinical. They appear to be more subjective.

The main objective of the analysis of these data is to develop criteria correlating the type of the knee instability with the shift of the horizontal axis of the tibia when it is subjected to a cyclic torsional load.

In their clinical practive Nicholas and Hughston has observed this shift of the axis of the tibia. These observations have led them to propose 20 types of knee instability mentioned in Table I of the introduction. But this has not been quantitatively verified by anybody. Within the scope of this present investigation, only two types of knee instability are examined, namely 1. Antero-Lateral (left knee) and 2. Antero-Medial (right knee). This has been achieved by the calculation of the Instantaneous Screws and their parameters and plotting the path traced by these screws in a plane parallel to the tibial plateau for each cycle of loading and unloading.

The screw has the following parameters:

1. U_x, U_y, U_z - the three direction cosines.
2. X, Y, Z - the co-ordinates of any point 'P' on the screw axis.
3. I - the translation along the screw axis.
4. ϕ - Rotation about the screw axis which are described in Chapter III.

The screw will uniquely describe the rigid body motion of the tibia relative to femur in a fixed frame of reference. These parameters of successive screws are obtained for each knee, for the following cases and tabulated in the Tables 2, 3, and 4 following.

1. Flexion - extension of the intact knee.
2. Each cycle of loading and unloading.
3. 1, 2, 3 . . . "Revolute pair' (potentiometer) locked and the constrained output data.

From these tables, X, Y, Z co-ordinates are chosen, and plotted in a transverse plane formed at the base of the reference pins parallel to the tibial plateau. This plane intersects all the screw axes (longitudinal axis of the tibia) which will represent the path followed by the screw axes. In Appendix D a pictorial representation of this is shown. By observing the graphs on pages 47, 48 it is found that the neutral position of the longitudinal axis of the tibia of the left knee is somewhere in the lower middle region of the postero-Medial compartment. When the load is increasing this position is found to shift first towards the origin i.e., towards the geometric center of the tibial plateau, and then towards the Antero-Medial compartment. When the load is decreaseing, it starts journeying backwards, but this time following an entirely different path, and the last position which marks the end of the first cycle was found to have shifted towards the Antero-Medial compartment. This phenomenon was observed in each cycle of loading and unloading, and the neutral position of the axis was found to have shifted progressively towards the Antero-Medial compartment. This indicates that, this knee was developing Antero-Lateral instability, which was further confirmed by the clinical drawer tests conducted. This shift of the longitudinal axis of the tibia towards the Antero-Medial compartment for the Antero-Lateral instability fully confirms with the Nicholas's clinical observation. Hence, it can be concluded that it is possible to exactly identify the type of the knee instability by looking at the shift of the longitudinal axis of the tibia. The same phenomenon was observed for the right knee also which establishes the Antero-Medial instability. These results lead us to believe that it is possible to quantitatively correlate all the 20 classes of knee

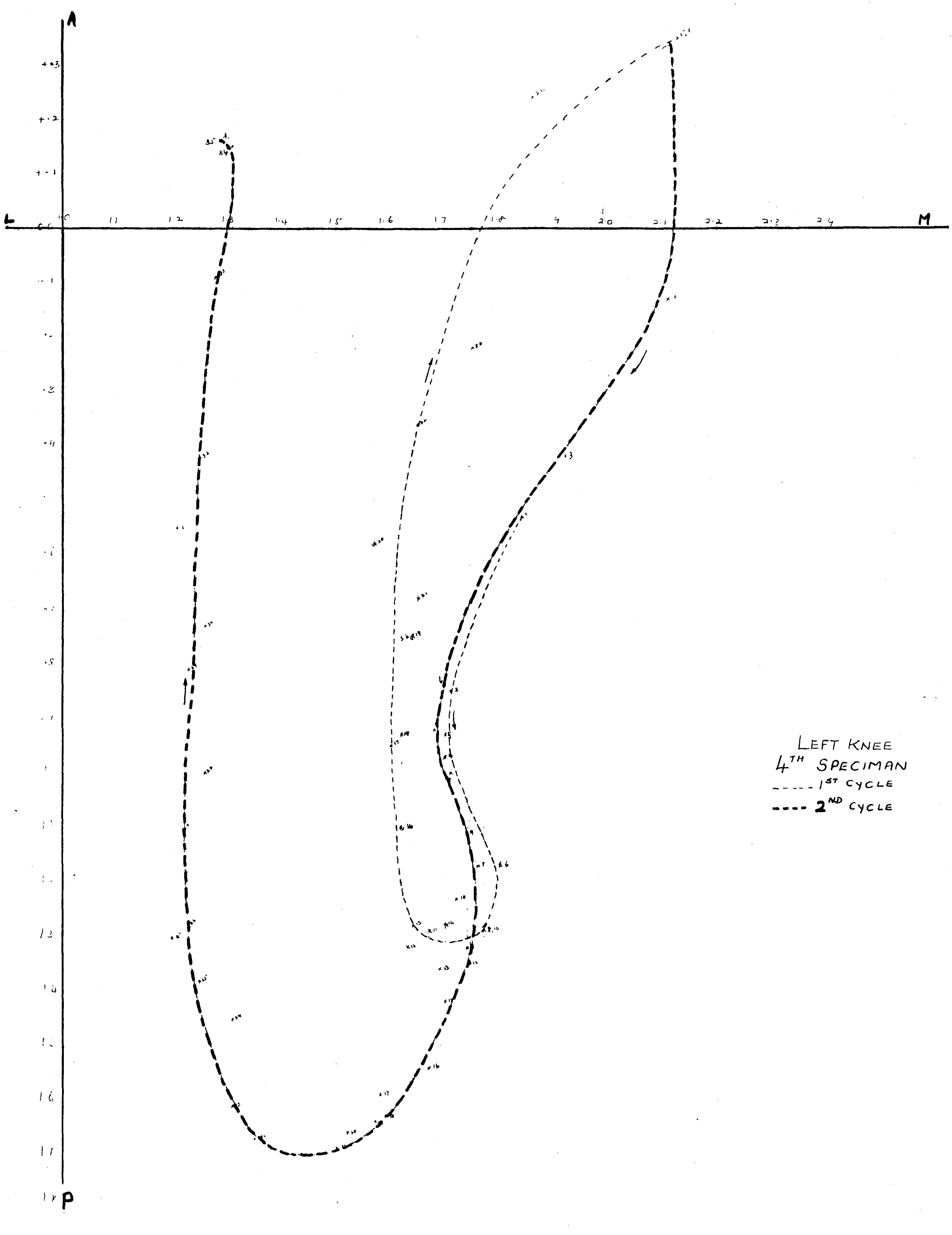


Figure 11.

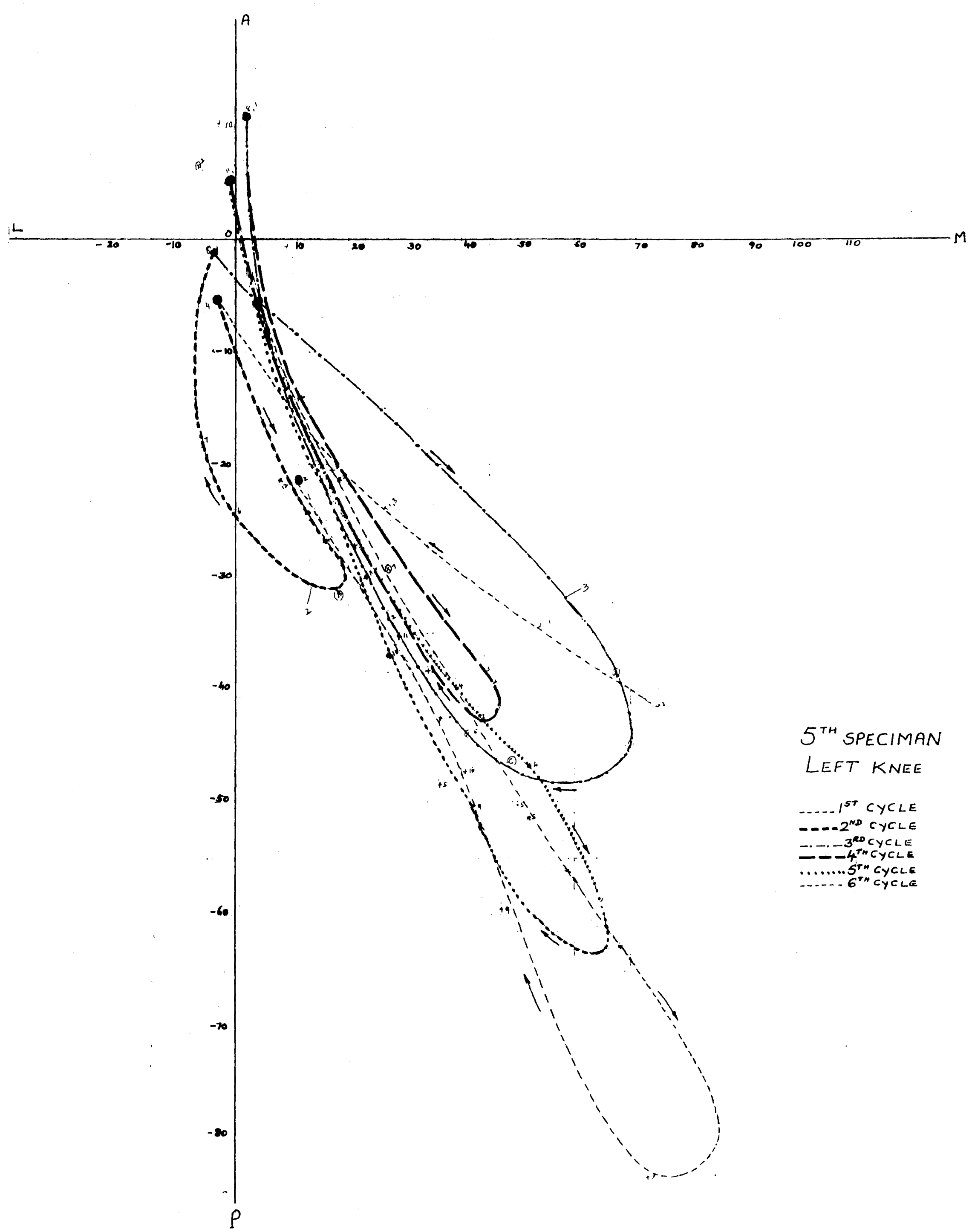

A
L
M
P
5TH SPECIMAN
LEFT KNEE
1ST CYCLE
2ND CYCLE
3RD CYCLE
4TH CYCLE
5TH CYCLE
6TH CYCLE

Figure 12.

instabilities with the shift of the axis of the tibia discussed in introduction provided the knee is subjected to all combinations of loadings along and about the three mutually perpendicular axes. Such an in-depth analysis to investigate other 18 classes of knee instability is beyond the scope of the present study.

The external load applied to the femur VS external rotation of the femur (Load VS θ) is found to be in the form of a hysteresis loop (refer to graph on page 51). These loops were found to be the same in shape for all the knees tested. It is interesting to note from these graphs that when the load was increasing, the curve constantly increased for about $1/3^{rd}$ of the load increasing cycle, and remained almost paralledl to the y-axis for the next $1/3^{rd}$ portion and again started increasing for the remainder of the cycle. This phenomenon is known as passing from primary laxity region to secondary laxity region, and the straight line portion of these loops indicate that the ligaments were tight, offered resistance to the external rotation of the femur thus preventing it from rotating, until they gave up. In other words, there is no rotation of the femur, even though the load was increasing at this stage.

The graph on page 52 shows the relationship between the external rotation of the femur and internal rotation of the longitudinal axis of the tibia. It is interesting to note from this graph that when the external rotation of the femur was increasing the internal rotation of the tibial axis was more than when the external rotation of the femur was decreasing. This may be attributed to the fact, that the "holding and supporting structures" of the tibia and femur were stiffer while the external rotation was increasing than while the external rotation of the femur was decreasing. This correlates with the shift of the axis of the tibia discussed earlier in this study.

The graph on page 53 shows the relationship between the external rotation of the femur, and the translation of the tibial axis. This graph shows that the translation of the tibial axis was more while the external rotation of the femur was increasing than while it was decreasing. This also establishes the fact that the "holding and supporting structures" of the knee were stiffer and were offering more resistance to the relative motion between femur and tibia, when the external rotation of the femur was increasing than while it was decreasing. This is because of the fact, that the supporting structures became loose, once they passed the primary laxity region and the relative motion between tibia and femur was not the same.

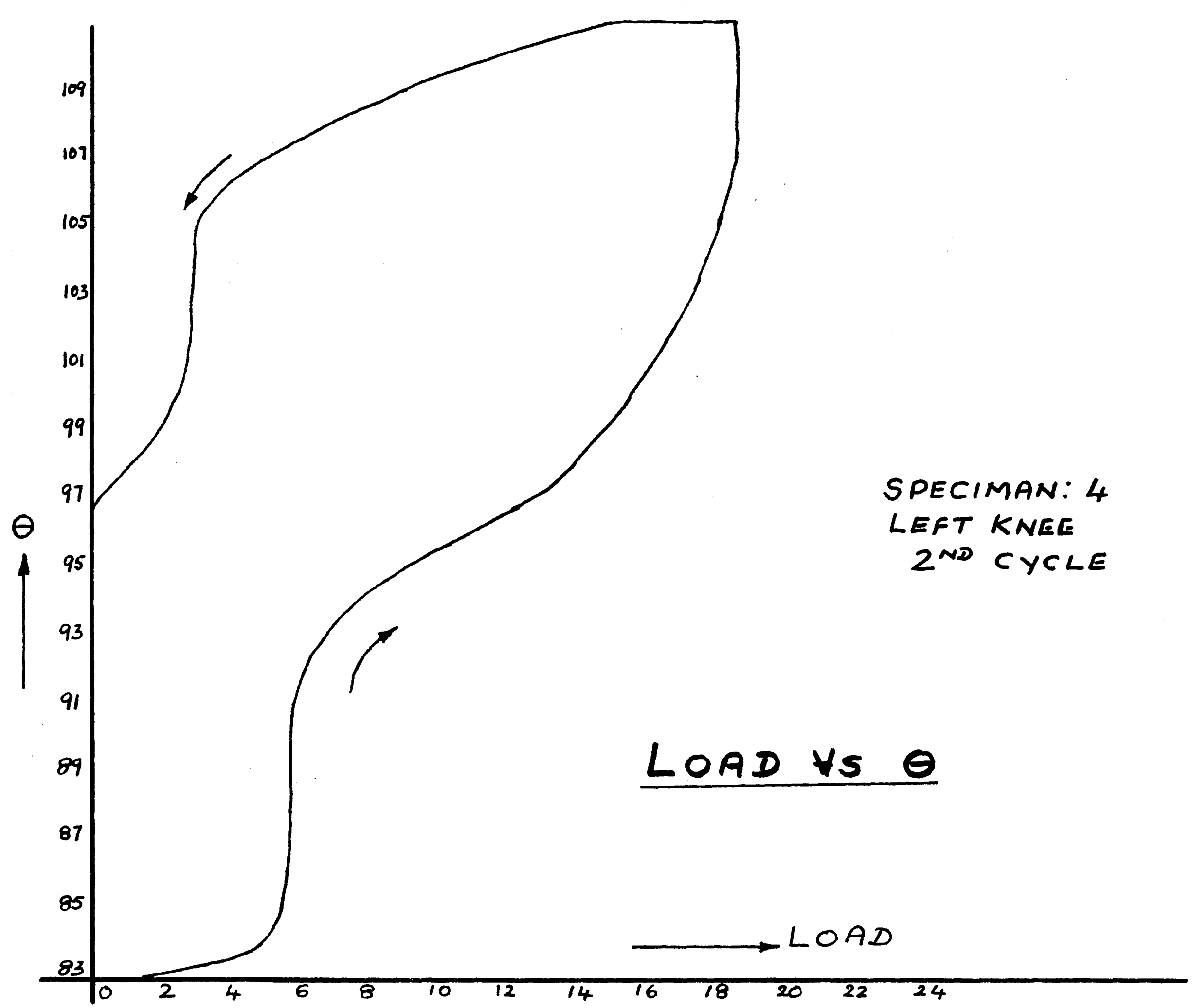

SPECIMAN: 4
LEFT KNEE
2ND CYCLE
LOAD VS Θ
LOAD
Θ
83
85
87
89
91
93
95
97
99
101
103
105
107
109
0
2
4
6
8
10
12
14
16
18
20
22
24

Figure 13.

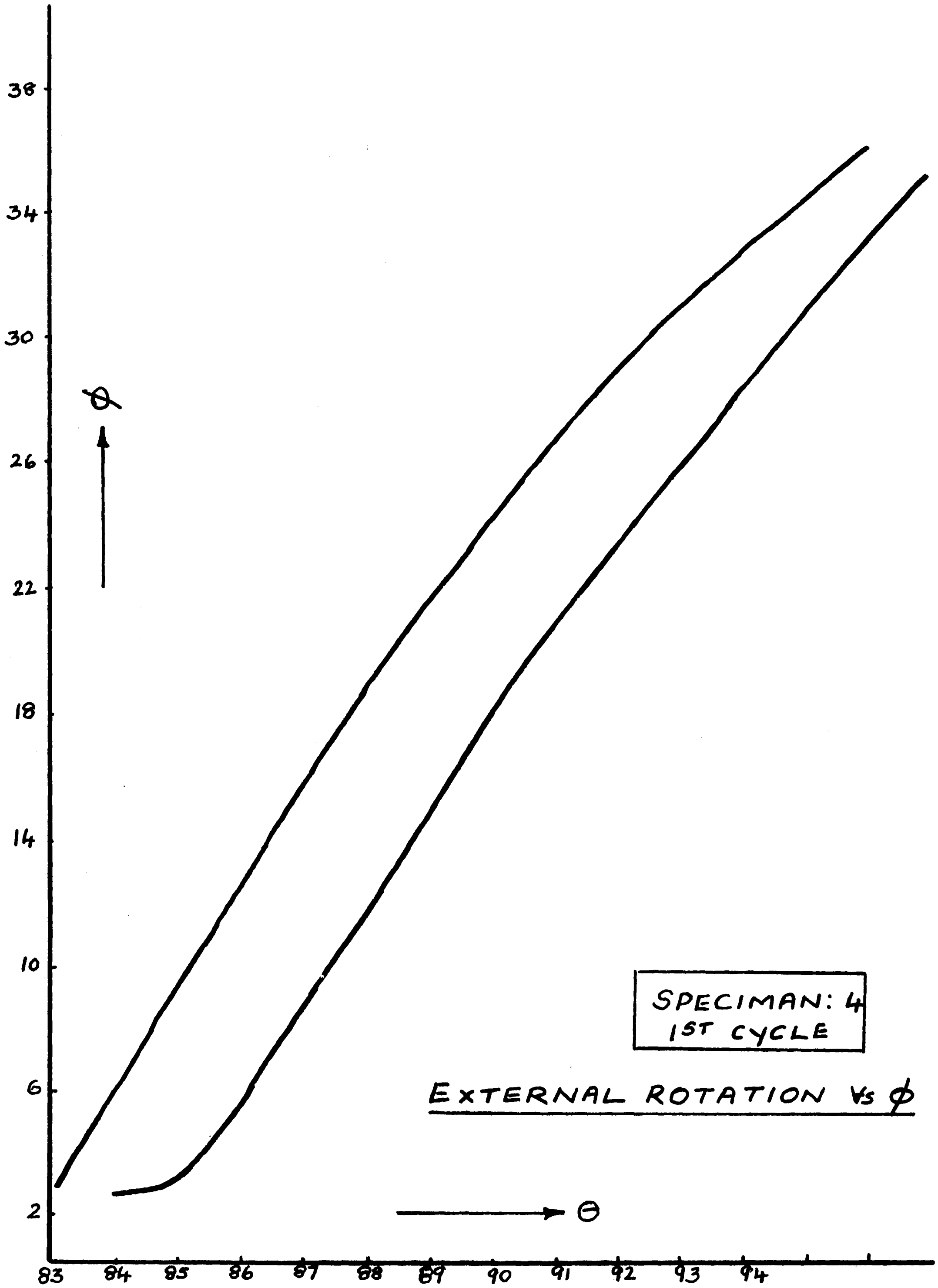
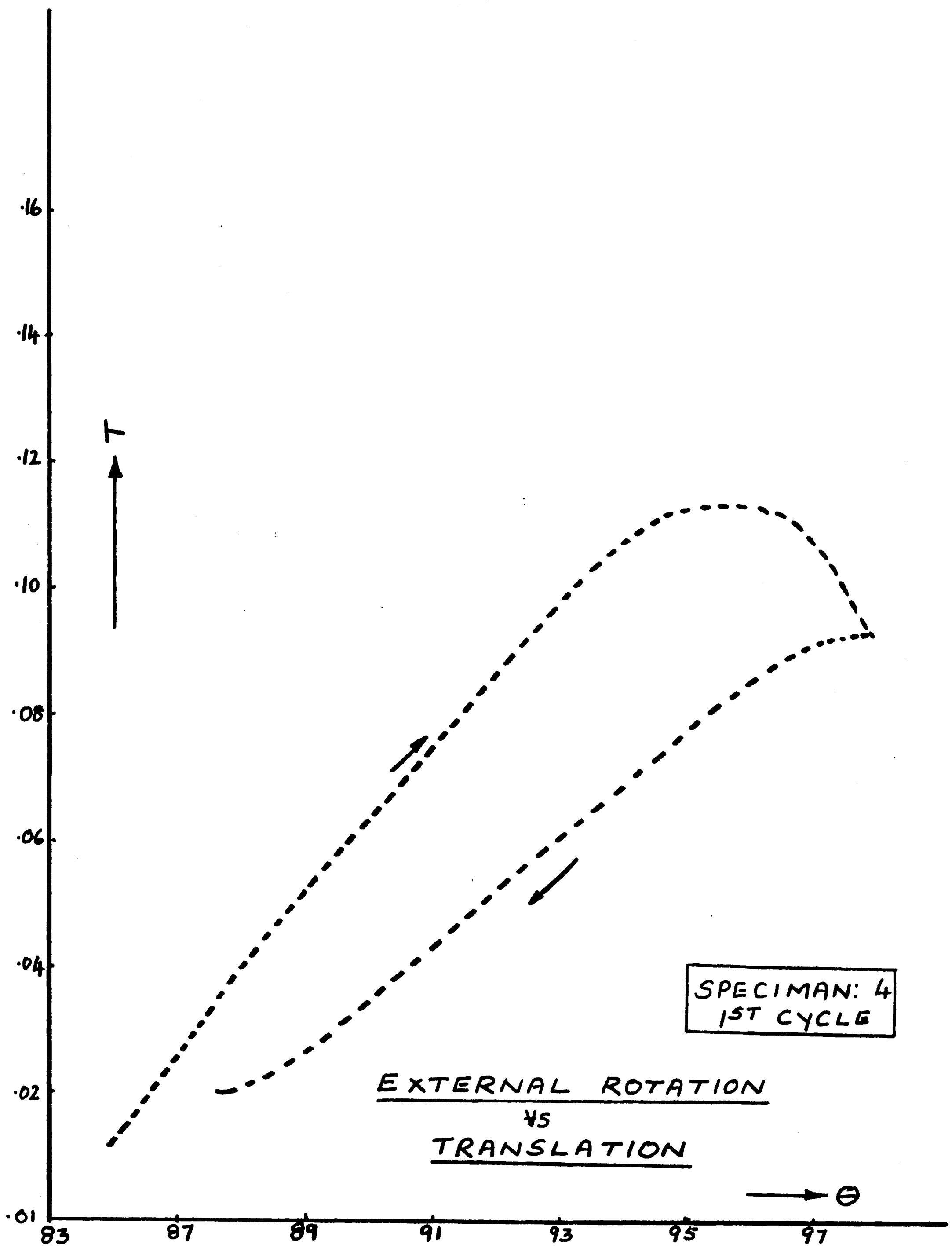

38
34
30
26
22
18
14
10
6
2
ϕ
θ
83
84
85
86
87
88
89
90
91
92
93
94
SPECIMAN: 4
1ST CYCLE
EXTERNAL ROTATION Vs ϕ

Figure 14.



·16
·14
·12
·10
·08
·06
·04
·02
·01
T
83
87
89
91
93
95
97
θ
SPECIMAN: 4
1ST CYCLE
EXTERNAL ROTATION
VS
TRANSLATION

Figure 15.

CHAPTER VI

SUMMARY AND CONCLUSION

Three left and two right knees which were tested by applying the cyclic torsional load, were dissected after the testing. The left knees tested indicated that:

1. Capsular ligaments were completely torn.
2. Fibular collateral ligament, arcuate complex, lateral capsular ligament, were translucent and their fibers were stretched and separated.

From the above two observations it can be concluded that the present loading system is in a position to damage only these portions of the left knee. The cruciates, and the medial collateral ligaments were intact, indicating that when the knee is subjected to a torsional load forcing the femur to rotate internally there by causing the tibia to rotate externally, no damage could be done to these structures. This also leads us to the conclusion that the femur should be twisted to its maximum internal position and to its maximum external position from its neutral position by applying the torsional load, since in the present study it was only psosible to twist the femur to its maximum internal position from its neutral position for left knees, and to its maximum external position from its neutral position for right knees. Loading may have to be done from the lateral and medial directions to cause damage to the cruciates.

From observing graphs on pages 47, 48 it is seen that the neutral position of the longitudinal axis of the tibia which was in the Postero-Lateral compartment progressively shifted towards the Antero-Medial compartment indicating that the knee was developing Antero-Lateral instability (left knee), which was further confirmed by the clinical drawer tests. After freezing three 'potentiometers' out of the six potentiometers, (after locking the three revolute pairs) and producing the constrained motion of the linkage transducer, it was observed that the knee was almost stable, which leads us to the conclusion that:

1. By providing a proper protection to these structures of the intact knee, these injuries (instability) can be avoided in human beings.

2. After the injury has occurred, by providing a suitable external device, the knee can be made stable.

The present study leads us to the conclusion that:

1. Instability in a knee joint is associated with the shift in the location of the horizontal axis.

2. A particular type of loading is responsible for a particular type of damage in the human knee.

3. A damaged knee can be made stable by providing a suitable external device.

4. It is possible to identify the class of instability and the associated structures, by the use of a linkage transducer data.

5. Instrumented linkage transducer can be used to study the property of the human knees.

6. There is a need for loading the knee in all possible ways to cause damage to different structures, there by producing different knee instabilities.

7. There is a need for continuously monitoring the linkage transducer data, as this will give more clear, precise pictures of the instabilities of the knee and the associated properties.

8. "Drawer Tests" which were conducted to identify the type of knee instability should be modified to a suitable "Mechanical Test" to prevent the human error which will be involved while conducting these tests.

9. Too much of a damage to the knee in too little a time will not give the correct picture of the type of instability, and that the testing should be done in a slow, regular manner, reaching the maximum load, in about 10 cycles.

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APPENDIXES

APPENDIX A

GLOSSARY

GLOSSARY

ABDUCT:	To move away from the middle line of the body, on one of its parts.
ADDUCT:	To draw toward on beyond the median line of the body on one of its parts.
ANTERIOR:	In front of or in the front part of.
CARTILAGE:	A translucent elastic tissue characterized by its scanty blood supply.
CONDYLE:	A rounded surface at the extremity of a bone.
DISTAL:	Farthest from the central point of the body.
DORSAL:	Relating to the back.
FEMUR:	Thigh bone.
FIBULA:	Smaller of the two bones in the calf.
FLEX:	To bend a limb.
LATERAL:	On the side (outside) opposite of medial.
LIGAMENT:	A band on sheet of fibrous tissue connecting two or more bones, and providing the integraity of the joint.
MEDIAL:	Relating to the middle on center.
MENISCUS:	A crescent or disk shaped cartilage found in certain joints.
PATELLA:	Knee cap.
POSTERIOR:	Behind - in the back opposite of Anterior.
SYNOVIA:	A clean viscus fluid secreted by a synovial membrane.
TIBIA:	Larger of the two bones of the calf.
TRANSVERSE:	Crosswise - lying across the long axis of the body.

APPENDIX B

LISTING OF THE COMPUTER PROGRAM

```
      C*************************************************************************
      C*                                                                       *
      C*             P R O G R A M   F O R   D E T E R M I N I N G             *
      C*                                                                       *
      C*                         S C R E W   A X I S                           *
      C*                                                                       *
      C*                         P A R A M E T E R S                           *
      C*                                                                       *
      C*************************************************************************
      C
      C      THIS PROGRAM CALCULATES THE DIRECTION COSINES, TRANSLATION ALONG,
      C
      C      ROTATION ABOUT, AND THE CO-ORDINATES OF ANY POINT 'P' ON THE SCREW AXIS.
      C
      C*************************************************************************
      C
      C      EXPLANATION OF A FEW SELECTED VARIABLE NAMES USEDIN THE PROGRAM
      C
      C*************************************************************************
      C      N *********DEFINES THE NO. OF PAIRS OF DATA CARDS TO BE READ.
      C
      C      KK *********ARRAY SUBSCRIPT.
      C
      C      A(I) *******ARRAY CONTAINING THE LINK LENGTHS.
      C
      C      ALPHI(I) ***ARRAY CONTAINING THE TWIST ANGLES.
      C
      C      S(I) *******ARRAY CONTAINING KINK LENGTHS.
      C
      C      THETA1(I,J) **ARRAY CONTAINING THE VOLTAGES READ BY THE SIX
      C                                                           POTENTIOMETERS.
      C*************************************************************************
      C
      C      INPUT DATA ::::::::::::::::::::::::::::
      C
      C*************************************************************************
      C      1ST CARD :::LINK LENGTHS.
      C
      C      2ND CARD ::: TWIST ANGLES.
      C
      C      3RD CARD ::: KINK LENGTHS.
      C
      C      4TH CARD ::: CHECK NO.
      C
      C      5TH CARD ONWARDS:: VOLTAGES READ BY THE SIX POTENTIOMETERS.
      C
      C*************************************************************************
      C
0001         DIMENSION A(6),ALPHA(6),ALPH(6),THET(6),THETA(200,6)     ,
           $S(6),AA(3,3),
           $ B(6,4,4),BBB(4,4),AAA(4,4),CCC(4,4),DD(2,4,4),AMULT(4,4),
           $ ADJINV(4,4),WKAREA(30),AINV(4,4),SKMAT(4,4),A1(6),A2(6),A3(6),
           $ A4(6),A5(6),A7(6),A8(6),A9(6),A10(6),A11(6),A6(6) ,
           $TPX1(123),TPY1(125),TPZ1(125),SUX(125),SUY(125),ST(125),
      &    $SPHI(125),  SUZ(125),
           $THETA1(200,6)
      C*************************************************************************
0002         N=2
```

```
              KK=1
              READ(5,1)(A(I),I=1,6)
              READ(5,1)(ALPHA(I),I=1,6)
              READ(5,1)(S(I),I=1,6)
              READ(5,2) IFLAG,PZ1
      1       FORMAT(6F10.0)
      2       FORMAT(I10,F10.0)
     C*************************************************************************
              DO 1445 KKK=1,N
              READ (5,3) ((THETA1(I,J),J=1,6),I=1,2)
      3       FORMAT (6F10.0)
              DO 201 I=1,2
              DO 201 J=1,6
     C*************************************************************************
     C
     C        CONVERTS THE VOLTAGES INTO ANGLES IN DEGREES.
     C
     C*************************************************************************
      201     THETA (I,J)=THETA1(I,J)*57.15
     C*************************************************************************
              FACT1=3.1415926  /180.0
              FACT2=180.0  /3.1415926
              DO 10 I=1,2
              DO 20 J=1,6
              ALPH(J)=ALPHA(J)*FACT1
              THET(J)=THETA(I,J)*FACT1
     C*************************************************************************
     C
     C        FINDS THE COMPONENTS  OF THE TRANSFORMATION MATRIX
     C
     C*************************************************************************
              A1(J)=-A(J)* COS(THET(J))
              A2(J)=A(J)* SIN(THET(J))
              A3(J)=-S(J)
              A4(J)= COS(THET(J))
              A5(J)=- SIN(THET(J))
              A6(J)= COS(ALPH(J))* SIN(THET(J))
              A7(J)= COS(ALPH(J))* COS(THET(J))
              A8(J)=- SIN(ALPH(J))
              A9(J)= SIN(ALPH(J))* SIN(THET(J))
              A10(J)= SIN(ALPH(J))* COS(THET(J))
              A11(J)= COS(ALPH(J))
     C*************************************************************************
              DO 40 II=1,4
              DO 50 JJ=1,4
              B(J,II,JJ)=0.0
      50      CONTINUE
      40      CONTINUE
     C*************************************************************************
     C
     C        FORMS THE TRANSFORMATION MATRIX
     C
     C*************************************************************************
              B(J,1,1)=1.0
              B(J,2,1)=A1(J)
              B(J,3,1)=A2(J)
              B(J,4,1)=A3(J)
              B(J,2,2)=A4(J)
```

```
      B(J,3,2)= A5(J)
      B(J,2,3)=A6(J)
      B(J,3,3)=A7(J)
      B(J,4,3)=A8(J)
      B(J,2,4)=A9(J)
      B(J,3,4)=A10(J)
      B(J,4,4)=A11(J)
   20 CONTINUE
C*****************************************************************************
C
C      IN THIS SECTION THE SIX MATRICES IN THE 1ST POSITION OF THE
C      RIGID BODY ARE MULTIPLIED TOGETHER TO YIELD A RESULTANT MATRIX
C
C*****************************************************************************
      J=1
      DO 70 II=1,4
      DO 80 JJ=1,4
      BBB(II,JJ)=B(J,II,JJ)
   80 CONTINUE
   70 CONTINUE
  210 DO 220 II=1,4
      DO 230 JJ=1,4
      AAA(II,JJ)=B(J+1,II,JJ)
  230 CONTINUE
  220 CONTINUE
      CALL  VMULFF(AAA,BBB,4,4,4,4,4,CCC,4,IER)
      DO 90 II=1,4
      DO 200 JJ=1,4
      BBB(II,JJ)=CCC(II,JJ)
  200 CONTINUE
   90 CONTINUE
      J=J+1
      IF(J.LT.6) GO TO 210
      DO 240  II=1,4
      DO 250  JJ=1,4
      DD(I,II,JJ)=BBB(II,JJ)
  250 CONTINUE
  240 CONTINUE
   10 CONTINUE
      DO 260  II=1,4
      DO 270  JJ=1,4
      AMULT(II,JJ)=DD(2,II,JJ)
     ADDINV(II,JJ)=DD(1,II,JJ)
  270 CONTINUE
  260 CONTINUE
      IDGT=0
C*****************************************************************************
C
C      IN THE FOLLOWING SECTION THE MATRIX OBTAINED IN POSITION '1' IS INVERTED
C      AND MULTIPLIED BY THE THE MATRIX OBTAINED IN POSITION '2' YIELDING
C      THE TRANSFORMATION MATRIX'SKMAT'.
C
C*****************************************************************************
C
      CALL  LINV2F(ADDINV,4,4,AINV,IDGT,WKAREA,IER)
      CALL  VMULFF(AMULT,AINV,4,4,4,4,4,SKMAT,4,IER)
C
C*****************************************************************************
```

```
C
      SX=SKMAT(2,1)
      SY=SKMAT(3,1)
      SZ=SKMAT(4,1)
C
C***********************************************************************
C
C     SUB MATRIX  AA(II,JJ) CONTAINS THE INFORMATION REGARDING THE PURE
C     ROTATION ABOUT THE SCREW AXIS.
C
C***********************************************************************
C
      DO 280  II=1,3
      DO 290  JJ=1,3
      AA(II,JJ)= SKMAT(II+1,JJ+1)
  290 CONTINUE
  280 CONTINUE
C
C
      DEN=(AA(2,2)-1)*(AA(3,3)-1)-AA(2,3)*AA(3,2)
      C1=(AA(2,3)*AA(3,1)-AA(2,1)*(AA(3,3)-1))/DEN
      C2=(AA(2,1)*AA(3,2)-AA(3,1)*(AA(2,2)-1))/DEN
C
C***********************************************************************
C
C     CALCULATES THE DIRECTION COSINES OF THE SCREW AXIS.
C
C***********************************************************************
C
      UX=-1.0/SQRT(1.0+C1*C1+C2*C2)
      UY=C1*UX
      UZ=C2*UX
C
      DN=(AA(1,1)-UX*UX)/(1.0-UX*UX)
      AN=(UX*UY*(1.0-DN)-AA(1,2))/UZ
C***********************************************************************
C
C     CALCULATES THE ROTATICN ANGLE 'PHI' OF THE SCREW AXIS.
C
C***********************************************************************
      PHI= ATAN2(AN,DN)*FACT2
C
C
      C12=AA(1,2)/(AA(1,1)-1.0)
      C13=AA(1,3)/(AA(1,1)-1.0)
C
      DNN=(AA(2,2)-1.0)*(AA(1,1)-1.0)-AA(1,2)*AA(2,1)
      C23=(AA(2,3)*(AA(1,1)-1.0)-AA(1,3)*AA(2,1))/DNN
      D1=UX/(AA(1,1)-1.0)
      E1=-SX/(AA(1,1)-1.0)
      D2=(UY*(AA(1,1)-1.0)-UX*AA(2,1))/DNN
      E2=(SX*AA(2,1)-SY*(AA(1,1)-1.0))/DNN
      D3=UZ-AA(3,1)*UX/(AA(1,1)-1.0)-(AA(3,2)-AA(3,1)*AA(1,2)/(AA(1,1)-
     $ 1.0))*(UY*(AA(1,1)-1.0)-UX*AA(2,1))/DNN
      E3=SX*AA(3,1)/(AA(1,1)-1.0)-SZ-(AA(3,2)-AA(3,1)*AA(1,2)/(AA(1,1)-
     $ 1.0))*(SX*AA(2,1)-SY*(AA(1,1)-1.0))/DNN
C
C***********************************************************************
```

```
C
C      FINDS THE TRANSLATION ALONG THE SCREW AXIS
C
C*****************************************************************************
       T=-E3/D3
C
C*****************************************************************************
C
C      CALCULATES THE CO-ORDINATES OF ANY POINT 'P' ON THE SCREW AXIS.
C
C*****************************************************************************
C
       IF(IFLAG.EQ.1) GO TO 400
       PZ1= ((D2*T +E2)*(UX*C12-UY)-UX*(D1*T+E1))/(UZ-UY*C23+UX*(C12*
     $ C23-C13))
 400   PY1=D2*T+E2-C23*PZ1
       PX1=D1*T+E1-C12*PY1-C13*PZ1
      TPX1(KK)=PX1
      TPY1(KK)=PY1
      TPZ1(KK)=PZ1
      ST(KK)=T
      SPHI(KK)=PHI
      SUX(KK)=UX
      SUY(KK)=UY
      SUZ(KK)=UZ
      KK=KK+1
 1445  CONTINUE
C
C*****************************************************************************
C
C      WRITES THE RESULTS.
C
C*****************************************************************************
C
       WRITE (6,137)
 137   FORMAT(12X,'UX',13X,'UY',13X,'UZ',13X,'PHI',13X,'T',13X,'TPX1',
     $13X,'TPY1',13X,'TPZ1',/)
C
       WRITE (6,103) (SUX(KK),SUY(KK),SUZ(KK),SPHI(KK),ST(KK),TPX1(KK),
     $ TPY1(KK),TPZ1(KK),KK=1,N)
 103   FORMAT(5X,F10.4,5X,F10.4,5X,F10.4,5X,F10.4,5X,F10.4,5X,F10.4,
     $5X,F10.4,5X,F10.4,/)
       STOP
       END
```

APPENDIX C

EXPERIMENTAL DATA

TABLE II

POTENTIOMETER READINGS							
Angle (Deg)	1	2	3	4	5	6	Load (Lb)
0	2.14	7.71	6.09	0.00	0.84	1.50	0
15	2.26	7.72	6.03	0.01	0.90	1.41	0
30	2.48	7.62	5.94	0.02	0.98	1.15	0
45	2.58	7.67	5.85	0.01	1.05	0.62	0
60	2.58	7.63	5.81	0.10	1.02	0.23	0
75	2.59	7.57	5.78	0.21	0.93	0.01	0
90	2.86	7.62	5.63	0.28	1.01	9.87	0
First Cycle							
81	2.42	7.80	6.12	0.01	0.93	0.88	0
83	2.10	7.71	6.07	0.15	0.87	0.47	3
84	2.13	7.72	6.08	0.13	0.88	0.49	4
85	2.17	7.73	6.08	0.11	0.89	0.55	5.5
86	2.22	7.75	6.09	0.08	0.91	0.62	5.75
87	2.26	7.76	6.10	0.05	0.91	0.67	6.00
88	2.30	7.77	6.10	0.01	0.92	0.72	6.00
89	2.34	7.79	6.11	0.11	0.93	0.78	6.00

TABLE II (Continued)

First Cycle	1	2	3	4	5	6	Load (Lb)
90	2.37	7.80	6.11	0.01	0.93	0.81	6.00
91	2.40	7.81	6.13	0.01	0.93	0.87	6.5
92	2.45	7.83	6.14	0.01	0.94	0.92	8.25
93	2.48	7.84	6.15	0.01	0.94	0.97	9.75
94	2.51	7.5	6.15	0.01	0.94	1.0	11
95	2.54	7.85	6.16	0.01	0.94	1.04	12
96	2.58	7.87	6.16	0.01	0.95	1.08	13.5
97	2.62	7.88	6.16	0.02	0.95	1.13	15.00
97	2.59	7.88	6.16	0.00	0.96	1.09	12.75
95	2.56	7.87	6.16	0.02	0.95	1.05	11.00
94	2.52	7.86	6.15	0.01	0.95	1.00	9.5
93	2.48	7.85	6.13	0.01	0.95	0.94	8.00
92	2.45	7.83	6.12	0.01	0.95	0.89	8.00
91	2.40	7.82	6.12	0.01	0.95	0.83	6.00
90	2.37	7.81	6.11	0.01	0.94	0.78	4.50
89	2.33	7.80	6.10	0.01	0.94	0.72	2.50

TABLE II (Continued)

First Cycle	1	2	3	4	5	6	Load (Lb)
88	2.28	7.78	6.10	0.05	0.93	0.67	2.50
87	2.25	7.76	6.09	0.07	0.92	0.62	2.25
86	2.22	7.75	6.09	0.08	0.91	0.58	2.00
85	2.17	7.73	6.08	0.10	0.89	0.52	1.50
84	2.14	7.72	6.08	0.12	0.88	0.49	1.00
83	2.10	7.70	6.08	0.15	0.86	0.42	0.50
Second Cycle							
84	2.08	7.70	6.08	0.15	0.85	0.41	5.00
85	2.17	7.74	6.09	0.11	0.89	0.52	5.50
86	2.23	7.76	6.10	0.09	0.91	0.59	5.75
87	2.28	7.78	6.10	0.05	0.95	0.67	5.75
88	2.33	7.81	6.11	0.01	0.94	0.73	5.75
89	2.36	7.82	6.12	0.01	0.94	0.77	5.75
90	2.40	7.83	6.13	0.01	0.95	0.82	5.75
91	2.45	7.85	6.14	0.01	0.95	0.88	5.75
92	2.47	7.85	6.15	0.01	0.95	0.92	6.50
93	2.49	7.86	6.15	0.01	0.95	0.95	6.75
94	2.53	7.88	6.16	0.01	0.95	1.00	8.00
95	2.55	7.88	6.17	0.01	0.95	1.04	9.00

TABLE II (Continued)

Second Cycle	1	2	3	4	5	6	Load (Lb)
96	2.59	7.90	6.18	0.02	0.95	1.08	11.50
97	2.62	7.91	6.18	0.01	0.95	1.12	13.00
98	2.64	7.92	6.19	0.01	0.95	1.15	14.00
99	2.68	7.93	6.20	0.02	0.95	1.20	15.25
100	2.70	7.95	6.21	0.02	0.95	1.23	16.00
101	2.73	7.96	6.20	0.02	0.95	1.28	17.00
102	2.74	7.96	6.21	0.01	0.95	1.30	17.50
103	2.76	7.97	6.21	0.02	0.95	1.32	17.50
104	2.78	7.98	6.21	0.01	0.95	1.35	18.25
105	2.79	7.98	6.21	0.01	0.95	1.37	18.50
111	2.87	8.01	6.20	0.01	0.95	1.45	18.75
111	2.86	8.01	6.10	0.01	0.96	1.42	15.50
110	2.84	8.00	6.18	0.01	0.97	1.38	12.00
109	2.81	7.98	6.17	0.01	0.97	1.34	8.50
108	2.79	7.98	6.15	0.02	0.98	1.30	7.75
107	2.76	6.14	6.14	0.02	0.99	1.25	5.50
106	2.72	6.12	6.12	0.02	0.99	1.18	3.50
105	2.68	6.12	6.12	0.01	0.99	1.13	3.00
104	2.66	6.10	6.10	0.01	0.99	1.08	3.00
103	2.64	6.10	6.10	0.01	0.99	1.05	3.00
102	2.60	6.08	6.08	0.01	0.99	0.99	3.00

TABLE II (Continued)

Second Cycle	1	2	3	4	5	6	Load (Lb)
101	2.55	7.84	6.07	0.01	0.98	0.93	2.50
100	2.53	7.82	6.06	0.01	0.98	0.89	2.25
99	2.49	7.80	6.06	0.01	0.97	0.84	2.00
98	2.46	7.78	6.05	0.01	0.96	0.79	1.00
97	2.44	7.78	6.05	0.01	0.96	0.77	0.00
Third Cycle							
86	1.72	7.71	6.23	0.38	0.70	0.12	0.00
91	1.89	7.75	6.20	0.30	0.78	0.28	6.50
96	2.05	7.77	6.20	0.19	0.83	0.46	7.00
101	2.28	7.81	6.20	0.05	0.89	0.70	7.50
106	2.43	7.85	6.22	0.01	0.92	0.88	9.50
111	2.57	7.89	6.22	0.02	0.93	1.06	11.00
116	2.68	7.94	6.22	0.01	0.94	1.19	13.50
121	2.78	7.98	6.24	0.02	0.94	1.34	19.50
126	2.83	8.00	6.25	0.02	0.93	1.43	22.00
131	2.89	8.03	6.25	0.02	0.92	1.52	23.00
136	2.90	8.04	6.26	0.02	0.92	1.55	23.00

TABLE II (Continued)

With 3R -- Locked -- Flexion -- Extension -- Data	1	2	3	4	5	6	Load (Lb)
0	2.21	7.71	7.97	0.02	0.86	1.63	0.00
15	2.38	7.71	7.97	0.02	0.92	1.59	0.00
30	2.58	7.71	7.97	0.02	1.02	1.21	0.00
45	2.76	7.71	7.97	0.02	1.10	0.64	0.00
60	2.81	7.71	7.97	0.02	1.13	0.19	0.00
75	2.88	7.71	7.97	0.02	1.09	0.00	0.00
90	3.03	7.71	7.97	0.02	1.10	0.01	0.00

TABLE III

Speciman: 4

Flexion -- Extension

UX	UY	UZ	PHI	T	X	Y	Z
-0.0277	0.8166	-0.5766	- 5.9588	-0.2025	0.0	-58.7636	45.4824
-0.1443	0.6653	-0.7325	- 18.7848	-0.5806	0.0	- 6.2539	11.0543
-0.1167	0.4540	-0.8833	- 38.2346	-0.9797	0.0	- 6.0343	19.0980
-0.0943	0.2993	-0.9495	- 53.3748	-1.0931	0.0	- 4.9528	26.0448
-0.0914	0.1928	-0.9770	- 64.6371	-1.1581	0.0	- 2.5890	27.8600
-0.1707	0.1744	-0.9698	-100.2643	-1.7103	0.0	- 0.1205	16.5776

TABLE IV

Speciman: 4

First Cycle

UX	UY	UZ	PHI	T	X	Y	Z
-0.6621	0.0419	0.7483	- 1.9914	-0.0236	0.0	2.1440	-0.0774
-0.5598	0.1073	0.8217	- 5.1762	-0.0122	0.0	1.8452	-0.5384
-0.5272	0.1292	0.8399	- 9.4341	-0.0285	0.0	1.7187	-0.8590
-0.5399	0.1002	0.8358	- 12.7429	-0.0424	0.0	1.8570	-0.8213
-0.5271	0.1298	0.8398	- 16.5955	-0.0316	0.0	1.7166	-0.8548
-0.5272	0.1311	0.8396	- 19.1740	-0.0490	0.0	1.7049	-0.9765
-0.5356	0.1336	0.8338	- 20.7484	-0.0401	0.0	1.7016	-0.9389
-0.5293	0.1088	0.8414	- 23.2577	-0.0796	0.0	1.8028	-1.1871
-0.5382	0.1188	0.8344	- 25.9845	-0.0953	0.0	1.7619	-1.1809
-0.5352	0.1143	0.8370	- 28.1780	-0.1099	0.0	1.7779	-1.2936
-0.7471	0.0730	0.6607	- 20.1679	0.0306	0.0	2.0796	-0.7522
-0.5463	0.1178	0.8293	- 31.3808	-0.1137	0.0	1.7701	-1.2930
-0.5458	0.1380	0.8265	- 33.6051	-0.1074	0.0	1.6717	-1.2939
-0.5475	0.1458	0.8240	- 35.5530	-0.0923	0.0	1.6334	-1.3270
-0.5437	0.1428	0.8371	- 34.6505	-0.1070	0.0	1.6464	-1.2860
-0.5462	0.1313	0.8273	- 32.1497	-0.1156	0.0	1.7046	-1.2880
-0.4922	0.1375	0.8596	- 32.9527	-0.0919	0.0	1.6018	-1.7920

TABLE IV (Continued)

UX	UY	UZ	PHI	T	X	Y	Z
-0.5384	0.1488	0.8295	- 27.4697	-0.0669	0.0	1.6236	-1.1-69
-0.5470	0.1563	0.8224	- 25.0021	-0.0510	0.0	1.6057	-0.9503
-0.5402	0.1517	0.8277	- 22.3033	-0.0684	0.0	1.6219	-0.9372
-0.5484	0.1505	0.8226	- 20.1793	-0.0508	0.0	1.6446	-0.7554
-0.5486	0.1694	0.8188	- 17.6041	-0.0402	0.0	1.5748	-0.5749
-0.5464	0.1497	0.8241	- 13.5783	-0.0488	0.0	1.6511	-0.6755
-0.5777	0.1595	0.8006	- 10.5027	-0.0309	0.0	1.6535	-0.3648
-0.5974	0.1390	0.7898	- 8.3456	-0.0378	0.0	1.7535	-0.2228
0.6486	0.1234	0.7510	- 4.7168	-0.0214	0.0	1.8543	-0.2491
-0.7183	0.0495	0.6939	- 2.5157	-0.0238	0.0	2.1166	-0.3481
Second Cycle							
-0.6402	0.0494	0.7666	- 4.6999	-0.9450	0.0	2.1106	-0.1323
-0.6012	0.0952	0.7934	- 8.7647	-0.0595	0.0	1.9209	-0.4231
-0.5334	0.1971	0.8226	- 13.5485	-0.0559	0.0	1.4269	-0.7287
-0.5374	0.1502	0.8299	- 18.2019	-0.654	0.0	1.6369	-0.7434
-0.5415	0.1340	0.8300	- 20.0864	-0.0820	0.0	1.7065	-0.8440
-0.5452	0.1377	0.8269	- 22.3655	-0.0983	0.0	1.6889	-0.9292
-0.5494	0.1317	0.8251	- 25.4148	-0.1090	0.0	1.7164	-1.0003
-0.5470	0.1233	0.8280	- 26.8755	-0.1252	0.0	1.7495	-1.1190

TABLE IV (Continued)

UX	UY	UZ	PHI	T	X	Y	Z
-0.3524	0.9208	0.1671	-165.5215	-0.2370	0.0	13.8727	-0.5878
-0.5432	0.1270	0.8300	- 30.9362	-0.1331	0.0	1.7245	-1.2324
-0.5413	0.1222	0.8319	- 32.4108	-0.1493	0.0	1.7430	-1.3286
-0.5465	0.1215	0.8286	- 34.4514	-0.1644	0.0	1.7492	-1.3540
-0.5447	0.1322	0.8282	- 36.6255	-0.1551	0.0	1.6947	-1.3659
-0.5434	0.1300	0.8293	- 38.1232	-0.1752	0.0	1.7019	-1.4255
-0.5235	0.2116	0.8253	- 39.4454	0.0775	0.0	1.2854	-1.3063
-0.5421	0.1315	0.8300	- 41.9465	-0.2098	0.0	1.6876	-1.5496
-0.9702	-0.0982	-0.2216	- 24.6281	-0.2419	0.0	2.6747	2.2356
-0.5350	0.1489	0.8316	- 43.9816	-0.1731	0.0	1.5893	-1.5997
-0.5349	0.1470	0.8321	- 45.0911	-0.1951	0.0	1.5978	-1.6302
-0.5357	0.1511	0.8308	- 45.9075	-0.1895	0.0	1.5763	-1.6425
-0.5322	0.1596	0.8314	- 47.6431	-0.1848	0.0	1.5263	-1.6670
-0.5305	0.1629	0.8319	- 48.3434	-0.1799	0.0	1.5059	-1.6956
-0.5320	0.1916	0.8248	- 52.4957	-0.1320	0.0	1.3556	-1.6758
-0.5331	0.2003	0.8220	- 51.3506	-0.1158	0.0	1.3175	-1.6092
-0.5384	0.2045	0.8175	- 47.3132	-0.0806	0.0	1.3173	-1.4595
-0.5366	0.2188	0.8150	- 45.3829	-0.0412	0.0	1.2505	-1.3865
-0.5408	0.2260	0.8102	- 42.8636	-0.0274	0.0	1.2318	-1.2829
-0.5478	0.2337	0.8033	- 39.6732	-0.0105	0.0	1.2247	-1.1040

TABLE IV (Continued)

UX	UY	UZ	PHI	T	X	Y	Z
-0.5509	0.2285	0.8027	- 37.4672	-0.0018	0.0	1.2624	-1.0333
-0.5628	0.2434	0.7900	- 35.1469	-0.0404	0.0	1.2348	-1.8191
-0.5716	0.2413	0.7843	- 33.4584	0.0342	0.0	1.2656	-0.7382
-0.5762	0.2595	0.7750	- 30.5973	0.0692	0.0	1.2180	-0.5563
-0.5798	0.2602	0.7721	- 27.6572	0.0818	0.0	1.2401	-0.4259
-0.3540	-0.9183	0.1774	-161.8726	-1.8603	0.0	13.7164	-0.7801
-0.6059	0.2686	0.7488	- 23.2172	0.0827	0.0	1.2873	-0.0994
-0.6260	0.2773	0.7288	- 20.8931	0.0929	0.0	1.3177	0.1491
-0.6211	0.2816	0.7314	- 20.0493	0.0869	0.0	1.2997	0.1662
Third Cycle							
-0.6211	0.2816	0.7314	- 20.0493	0.0869	0.0	1.2997	0.1662
-0.5883	0.3607	0.7237	24.9706	-0.3079	0.0	1.3108	1.1967
-0.5836	0.4940	0.6445	13.8270	-0.2095	0.0	1.1098	1.4564
-0.1788	0.9743	-0.1371	5.6915	0.1414	0.0	-7.5672	3.7649
-0.5385	-0.1400	0.8309	- 16.2896	-0.3010	0.0	3.0793	-1.6169
-0.5587	-0.0092	0.8293	- 25.9066	-0.3115	0.0	2.3961	-1.3838
-0.5589	0.0589	0.8272	- 33.8009	-0.2641	0.0	2.0659	-1.4319
-0.5529	0.1102	0.8259	- 40.7480	-0.2388	0.0	1.8070	-1.4663
-0.5437	0.1303	0.8291	- 47.4150	-0.2580	0.0	1.6902	-1.6756

TABLE IV (Continued)

UX	UY	UZ	PHI	T	X	Y	Z
-0.5364	0.1372	0.8327	- 51.4200	-0.2637	0.0	1.6410	-1.8084
-0.5295	0.1539	0.8342	- 55.7537	-0.2444	0.0	1.5381	-1.9021
-0.5242	0.1538	0.8376	- 57.1224	-0.2692	0.0	1.5279	-1.9887

TABLE V

Speciman: 4

3-R-Results

UX	UY	UZ	PHI	T	X	Y	Z
-0.5144	-0.6773	0.5260	- 77.7802	-3.2628	0.0	8.5418	-2.6387
-0.5759	-0.5463	0.6082	- 84.2071	-3.5102	0.0	6.9221	-2.9001
-0.5833	-0.6713	0.4573	- 72.6683	-2.0332	0.0	8.1191	-2.5403
-0.5780	-0.7694	0.2717	- 66.6161	-0.5202	0.0	9.1010	-1.8252
-0.5137	-0.8543	0.0797	- 63.9556	0.7380	0.0	10.6114	-0.6174
-0.4880	-0.8727	0.0152	- 66.0854	1.2817	0.0	11.0130	-0.0152
-0.5385	-0.8418	0.0382	- 68.4822	1.2979	0.0	9.9754	-0.4282

TABLE VI

Speciman: 5

Flexion -- Extension

UX	UY	UZ	PHI	T	X	Y	Z
-0.1681	0.0841	-0.9822	22.9540	0.0696	0.0	1.0328	- 2.9469
-0.1070	0.0704	-0.9918	38.8839	-0.0035	0.0	1.3318	- 8.7793
-0.0526	0.0460	-0.9976	52.3995	-0.1726	0.0	1.6663	- 22.5485
-0.0129	0.0090	-0.9999	67.6514	-0.4003	0.0	1.4855	-111.9867
-0.0092	0.0288	0.9995	- 82.3880	0.6302	0.0	4.8230	155.4093
-0.0063	0.0329	0.9994	- 87.2495	0.6899	0.0	7.8650	229.2479
-0.0113	0.0352	0.9993	- 96.7944	0.8027	0.0	5.4313	146.1334
-0.0107	0.0207	0.9997	-103.6274	0.9241	0.0	4.2090	189.6930
-0.0150	0.0085	0.9999	-106.6742	1.0443	0.0	1.6507	161.9712

TABLE VII

Speciman: 5

UX	UY	UZ	PHI	T	X	Y	Z
First Cycle							
-0.2282	0.9155	-0.3312	-0.8228	0.0103	0.0	24.4656	-24.1186
-0.0879	0.9704	-0.2249	-1.5210	-0.0554	0.0	75.3814	-41.4225
-0.2282	0.9155	-0.3312	-0.8228	0.0103	0.0	24.4656	-24.1186
-0.4768	0.8531	0.2119	-0.9095	0.0264	0.0	- 3.9525	- 5.2425
Second Cycle							
-0.4768	0.8531	0.2119	-0.9095	0.0264	0.0	- 3.9525	- 5.2425
-0.1917	0.9573	-0.2165	-0.6847	-0.0005	0.0	11.7688	-14.2757
-0.2838	0.9524	-0.1111	-1.3964	0.0655	0.0	12.1927	-24.1250
-0.1450	0.9881	-0.0507	-1.9751	-0.0110	0.0	15.8484	-26.7099
-0.1322	0.9691	-0.2083	-1.9548	-0.0096	0.0	64.2171	-45.0336
-0.2622	0.9641	0.0427	-1.8444	0.0807	0.0	- 0.3277	-24.5795
-0.2364	0.9684	0.0789	-1.5612	0.0343	0.0	- 6.2588	-18.9520
-0.9434	-0.3049	0.1386	-0.6685	-0.5906	0.0	- 4.1934	- 1.2566

TABLE VII (Continued)

Third Cycle							
UX	UY	UZ	PHI	T	X	Y	Z
-0.9434	-0.3049	0.1306	-0.6685	-0.5906	0.0	- 4.1934	- 1.2566
-0.3423	0.9162	-0.2082	-0.7938	-0.0165	0.0	- 6.5675	6.5171
-0.1187	0.9522	-0.2815	-1.6524	-0.0365	0.0	71.3714	-45.8525
-0.1570	0.9545	-0.2537	-2.0870	0.0230	0.0	63.9877	-48.2897
-0.1557	0.9840	-0.0863	-1.9640	0.0529	0.0	41.1714	-44.9227
-0.2141	0.8778	-0.4285	-2.0342	0.2005	0.0	104.6025	-95.3680
-0.1322	0.9691	-0.2083	-1.9548	-0.0096	0.0	64.2171	-45.0336
-0.2720	0.9032	-0.3320	-1.4714	0.0548	0.0	27.7262	-29.8719
-0.6652	0.0009	-0.7467	-1.0631	-0.1553	0.0	1.8603	12.0072
Fourth Cycle							
-0.6652	0.0009	-0.7467	-1.0631	-0.1553	0.0	1.8603	12.0072
-0.3236	0.8582	-0.3985	-1.8205	0.1268	0.0	28.8730	-33.8718
-0.1742	0.9631	-0.2054	-1.8374	0.0160	0.0	44.2208	-38.2991
-0.1823	0.9721	-0.1477	-2.1511	0.0657	0.0	39.5426	-39.9687
-0.2058	0.9609	-0.1855	-2.2166	0.1496	0.0	50.9116	-50.1944
-0.2436	0.8010	-0.5469	-2.6746	0.3358	0.0	91.4304	-98.8554
-0.3200	0.8666	-0.3829	-2.2456	0.3721	0.0	53.8226	-62.0750

TABLE VII (Continued)

UX	UY	UZ	PHI	T	X	Y	Z
-0.2033	0.9600	-0.1925	-2.2811	0.1036	0.0	43.4529	-42.6047
-0.2974	0.8845	-0.3596	-2.2132	0.1896	0.0	38.9407	-43.1927
-0.3608	0.8889	-0.2824	-1.9231	0.1167	0.0	16.2169	-22.3595
-0.4731	0.7822	-0.4053	-1.5460	0.1418	0.0	13.0134	-20.1359
-0.6003	0.6661	-0.4426	-0.9908	-0.0565	0.0	- 1.0630	5.4701
Fifth Cycle							
-0.6003	0.6661	-0.4426	-0.9908	-0.0565	0.0	- 1.0630	5.4701
-0.3387	0.8519	-0.3995	-1.8860	0.0781	0.0	18.7675	-22.5904
-0.3068	0.9093	-0.2811	-2.0273	0.1202	0.0	21.9876	-27.1193
-0.2037	0.9374	-0.2824	-2.2707	0.0987	0.0	52.8125	-46.6026
-0.2511	0.8944	-0.3702	-2.7132	0.2038	0.0	52.6233	-51.6358
-0.2421	0.8896	-0.3872	-2.9763	0.2443	0.0	59.1155	-56.7699
-0.2228	0.8210	-0.5256	-3.5005	0.3667	0.0	91.1172	-92.0723
-0.2826	0.8712	-0.4014	-3.0140	0.4743	0.0	65.5027	-68.9518
-0.2363	0.9011	-0.3635	-2.7608	0.2736	0.0	67.2968	-63.3655
-0.3412	0.8521	-0.3969	-2.5168	0.3680	0.0	42.2995	-50.9871
-0.3404	0.9069	-0.2482	-2.3135	0.2804	0.0	27.2365	-37.0328
-0.3885	0.8290	-0.4022	-2.4534	0.2564	0.0	23.1301	-30.9693

TABLE VII (Continued)

UX	UY	UZ	PHI	T	X	Y	Z
-0.4875	0.8628	-0.1337	-1.6028	0.2217	0.0	8.7875	-22.7615
-0.5048	0.7832	-0.3630	-1.4614	0.0309	0.0	4.0841	- 5.8516
Sixth Cycle							
-0.5048	0.7832	-0.3630	-1.4614	0.0309	0.0	4.0841	- 5.8516
-0.3268	0.8886	-0.3219	-2.2384	0.0958	0.0	17.2445	-21.3133
-0.2942	0.8800	-0.3729	-2.5850	0.1979	0.0	34.9305	-38.4780
-0.2421	0.8896	-0.3872	-2.9763	0.2443	0.0	59.1155	-56.7699
-0.2522	0.8877	-0.3851	-2.9148	0.3219	0.0	64.7082	-63.5191
-0.3563	0.8930	-0.2750	-3.1377	0.6377	0.0	36.6735	-48.6504
-0.2049	0.8709	-0.4467	-3.5089	0.3172	0.0	89.3802	-80.5431
-0.2856	0.7990	-0.5292	-3.8303	0.6520	0.0	73.3992	-83.4555
-0.3258	0.7486	-0.5774	-3.6977	0.8496	0.0	70.6443	-90.7175
-0.2721	0.8083	-0.5221	-3.6612	0.5928	0.0	78.1192	-86.1710
-0.3661	0.8211	-0.4379	-3.3928	0.7351	0.0	47.3514	-59.6083
-0.3132	0.8896	-0.3323	-2.9804	0.4046	0.0	40.9844	-47.3253
-0.3139	0.9053	-0.2862	-2.6266	0.2470	0.0	29.1136	-35.4329
-0.4223	0.8861	-0.1909	-2.4661	0.2533	0.0	11.1810	-21.5798

TABLE VII (Continued)

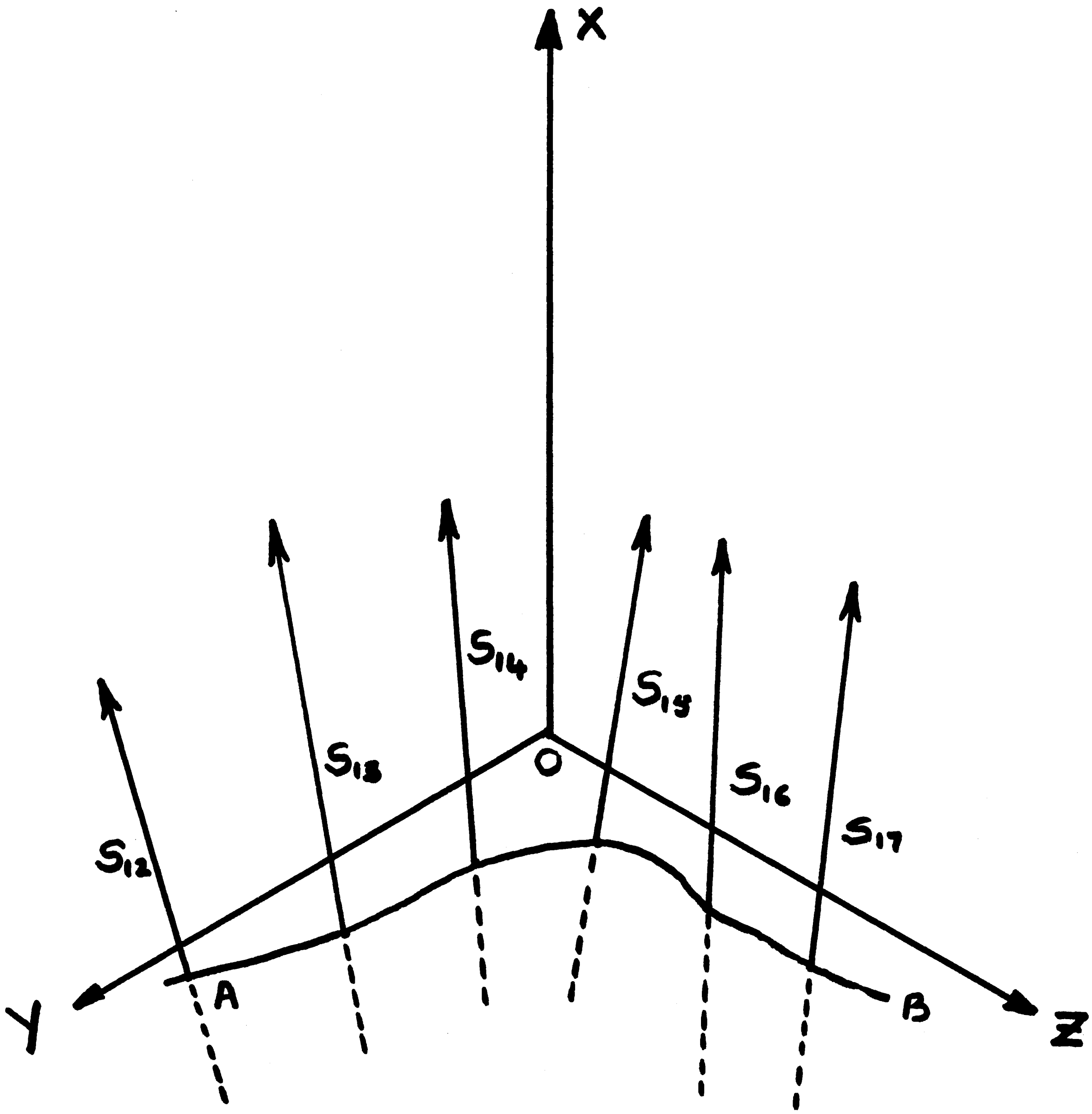
Seventh Cycle							
UX	UY	UZ	PHI	T	X	Y	Z
-0.4223	0.8861	-0.1909	-2.4661	0.2533	0.0	11.1810	-21.5798
-0.2294	0.9362	-0.2662	-2.8449	0.1179	0.0	34.9856	-34.4745
-0.2788	0.8623	-0.4226	-3.6107	0.4281	0.0	54.5459	-57.3160
-0.2618	0.8422	-0.4713	-4.0441	0.5258	0.0	68.2776	-70.6724
-0.2955	0.7973	-0.5263	-4.3832	0.7166	0.0	63.9520	-73.6544
-0.2914	0.8433	-0.4517	-4.1671	0.8081	0.0	70.1244	-75.6422
-0.3726	0.7650	-0.5253	-4.6059	1.1479	0.0	53.0600	-69.4936
-0.4195	0.7135	-0.5612	-4.6926	1.4419	0.0	48.4964	-70.7954
-0.3398	0.6598	-0.6702	-5.3809	1.2656	0.0	61.7146	-92.0342
-0.3854	0.6539	-0.6511	-5.6101	1.5992	0.0	53.7059	-83.0396
-0.4237	0.5834	-0.6929	-6.1926	1.8931	0.0	43.8744	-78.1764
-0.4151	0.5734	-0.7063	-6.2209	1.9232	0.0	46.0034	-83.1732
-0.4234	0.5820	-0.6943	-6.3469	2.0470	0.0	45.4226	-80.9138
-0.4644	0.5414	-0.7009	-6.3986	2.2122	0.0	37.5150	-73.3909
-0.4681	0.6379	-0.6115	-5.9283	2.1258	0.0	40.6995	-67.5163
-0.4243	0.7084	-0.5640	-5.3179	1.7769	0.0	49.1147	-71.8688
-0.4411	0.7487	-0.4949	-4.9490	1.7619	0.0	45.6221	-65.1954
-0.4205	0.7635	-0.4901	-4.8876	1.4662	0.0	44.7218	-61.8904

TABLE VII (Continued)

UX	UY	UZ	PHI	T	X	Y	Z
-0.4234	0.8036	-0.4183	-4.7572	1.3072	0.0	38.2434	-52.4151
-0.3225	0.9050	-0.2774	-4.2242	0.8158	0.0	41.2183	-49.4582
-0.1811	0.9630	-0.1994	-4.5235	0.2676	0.0	46.0832	-40.6192
-0.3531	0.9235	-0.1498	-4.3786	0.6162	0.0	16.9787	-30.2945
-0.2821	0.9541	-0.1003	-4.1329	0.3347	0.0	14.2578	-27.0717
-0.3236	0.9439	-0.0661	-4.2394	0.3720	0.0	8.1121	-23.1552

APPENDIX D

PICTORIAL VIEW OF THE PATH FOLLOWED BY THE TIBIAL AXIS

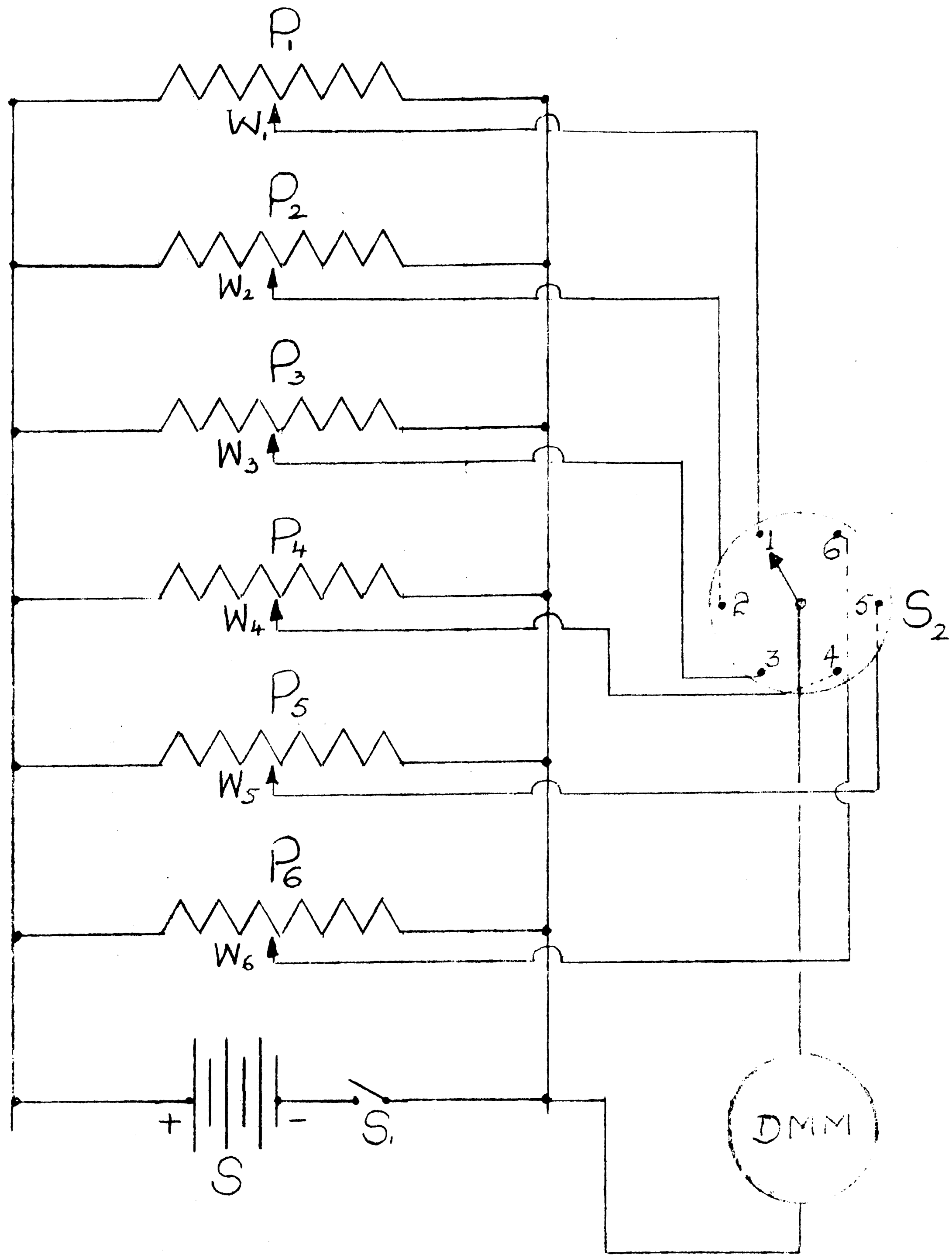


S_{12} - S_{17} : Screw Axes

AB : Path Followed by the Tibial Axis in the Tibial Plateau

APPENDIX E

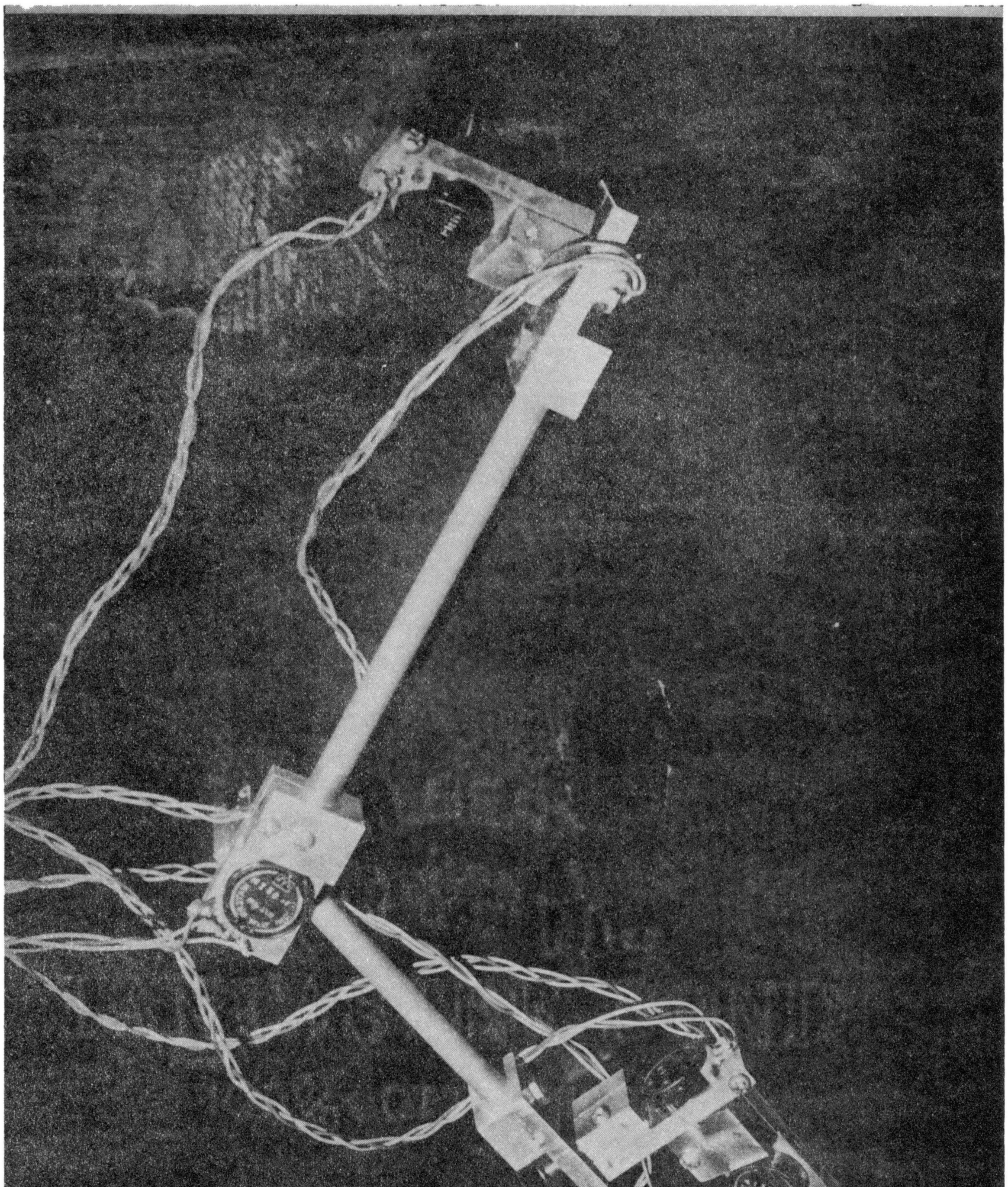
CIRCUIT DIAGRAM OF THE INSTRUMENTED LINKAGE TRANSDUCER



P1 to P6	:	Potentiometers
S	:	Power Supply
S1	:	Main Switch
S2	:	6-Pole Rotary Switch
DMM	:	Digital Multimeter

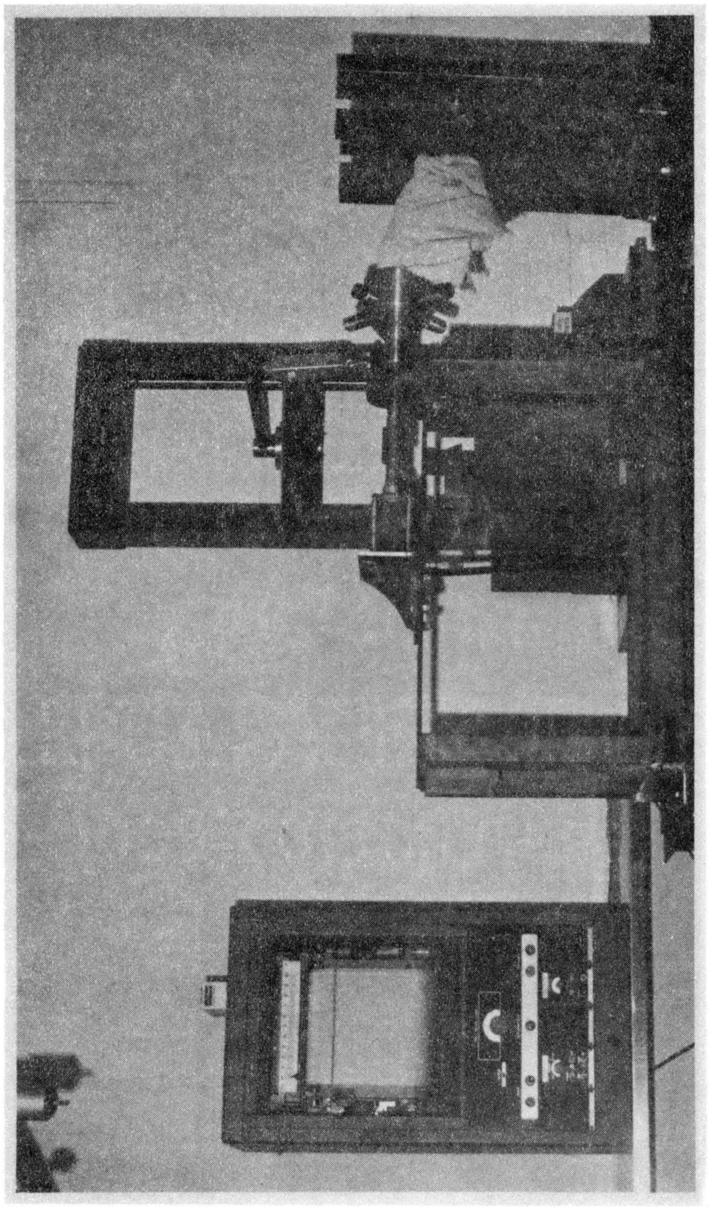
APPENDIX F

INSTRUMENTED LINKAGE TRANSDUCER USED IN THE EXPERIMENT



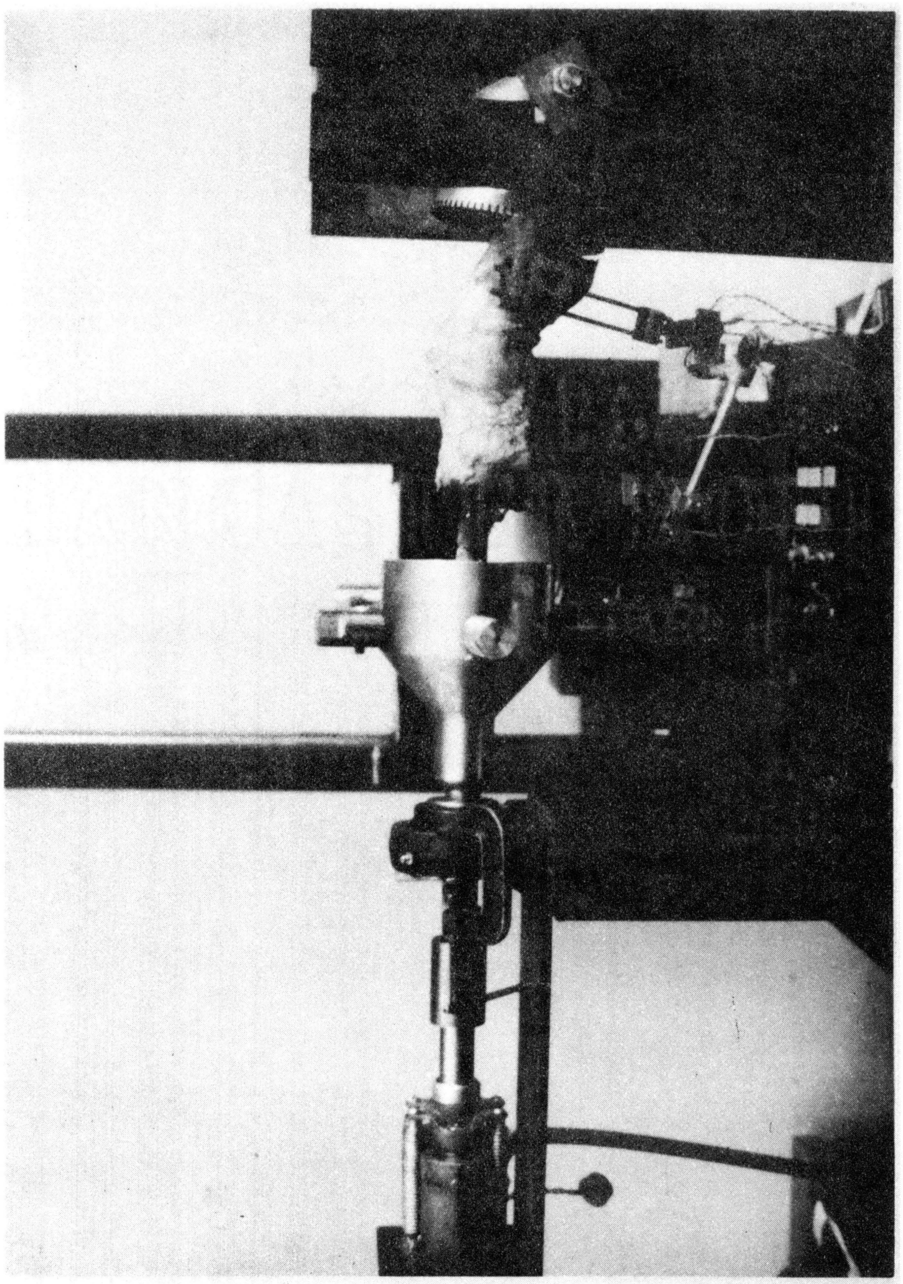
APPENDIX G

SET UP USED IN THE EXPERIMENT



APPENDIX H

THE EXPERIMENT IN PROGRESS



VITA

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