# QUANTITATIVE PARAMETERS DESCRIBING KNEE MOTION AND LIGAMENTOUS DAMAGE

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QUANTITATIVE PARAMETERS DESCRIBING KNEE

MOTION AND LIGAMENTOUS DAMAGE

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## PREFACE

This study investigates ligament reactions in the human knee joint when torsional loads are applied to the tibia. A method for clinical diagnosis of chronic knees is demonstrated for external rotation of the tibia on the femur at a 45 degree flexion angle.

I would like to express my humble gratitude to the Lord Jesus Christ for the opportunity He has given me to study and glimpse a bit more of the order of His creation.

My sincere thanks are extended to my major adviser, Dr. Soni, for his support and encouragment not only throughout the course of this research, but also in many other areas of my plan of study. Thanks to Dr. Grana for his continuing support of this research program. My appreciation is expressed to Dr. Shively who also was of great assistance in completing this study.

I'm grateful to David Jones and John Perault for their advice and patience, particularly in facilitating the use of the Interdata Mini-Computer for data collection and processing.

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I thank my friends Susie Schroeder, Jeff Laughlin, Artie Henderson and Pat Tillson for their continued support and fellowship throughout the course of my studies. Without the assistance of Barbara Byers and Karla Burge, this manuscript would still be in ball-point pen. Thank you.

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Finally, I thank my parents, my brothers Jim and Dave and also Gary and Amy Blobaum for their love and support which have continued to be sources of comfort and encouragement to me throughout my years of study.

## TABLE OF CONTENTS

| Chapter | Page |
| --- | --- |

LIST OF TABLES

LIST OF FIGURES

# CHAPTER I

## INTRODUCTION

A clinical problem exists in quantitatively analyzing chronic knee injuries. A knee injury or damaged knee will, in this study, be classified as a knee having ligamentous damage.

Knee injuries are divided into two categories; acute and chronic. When a ligament is damaged, discoloration occurs for a period of time in the damaged area. While the discoloration and tenderness around the injured ligament exists, the injury is said to be acute. If an orthopedic surgeon is consulted soon after an injury occurs (within a week), the surgeon can note what part of the knee seems to be loose and in opening up that area, he can visually diagnose which ligament was damaged and suture that ligament back together.

If however, the patient doesn't seek help soon after the injury, the ligament discoloration disappears and the damaged ligament becomes more difficult to identify. The knee may no longer be sensitive and a localized area of pain may no longer exist. Yet, with laxity in the ligaments, a knee may be very unstable and tend to "give out" on the patient. The knee injury would now be considered a chronic condition. The acute knee injury is more easily diagnosed than is the chronic. In the chronic condition, a surgeon can no longer identify ligament damage by discoloration. He also has the difficulty of knowing how much a ligament needs to be tightened because ligament damage no longer exists as a "tear", but rather as a "stretch" of that ligament. A reconstruction may be necessary but if the ligaments are shortened too much, knee motion will be restricted and if they are not shortened enough, the joint will remain unstable.

Currently, stress tests and drawer tests are being used to clinically identify knee instabilities and ligament damage. Hughston (6) reviews the use and application of these tests. Briefly, forces are manually applied to the knee joint and the resulting motion is categorized and statistically related to ligament damage. The problem with these tests is in obtaining quantitative data regarding knee motion and ligamentous damage. The tests are subject to variance of application and interpretation. Gradations of severity which have been proposed for evaluating the degree of instability demonstrated during stress testing, are stated here.

> A mild (1+) instability indicates that the joint surfaces separate five millimeters or less; a moderate (2+) instability, that they separate between five and ten millimeters; and a severe (3+) instability, that they separate ten millimeters or more. . . . In the knees with a 3+ clinical abduction stress test or a 3+ clinical anterior drawer test, the displacements certainly seemed much greater then ten millimeters in most instances (and often were greater), but measurements at operation confirmed that the actual separation was not in excess of ten millimeters in many knees even though the severity had been graded 3+ preoperatively (6, p. 160).

It is evident that a quantitative way to clinically determine ligament damage would be a great improvement over the qualitative methods currently being used.

To quantitatively determine ligamentous damage of a clinical knee, the following research must be conducted:

1. Establish a means to quantitatively descrive knee motion.
2. Establish a means to quantitatively describe ligament damage.

3. Determine the relationship between knee motion and ligament damage.

Three methods were investigated for classifying knee motion. They are:

1. Shift of the screw axis during loading.
2. Drawer tests (not for quantitative data, but for comparison with current research).
3. Tibia rotation at a given flexion angle.

The loading condition of a knee-joint is a critical problem. A torsional load may be applied about the mechanical axis or about the anatomical axis of the tibia or femur. Maiya (13) used the loading conditions originally proposed by Walker (18). The present investigation uses an alternative loading condition. A torsional load is applied to the anatomical tibial axis and a U-joint is mounted approximately 21 inches from the condyles, on the anatomical femoral axis. The U-joint provides two of the three degrees of rotational freedom normally supplied by a hip joint. A restraint is made on the third degree of rotational freedom to allow application of a torsional load to the knee joint.

Shift of the screw axis during loading of the knee joint was observed by plotting the intersection of the screw axis with a plane defined by the tibia plateau.

Drawer tests were conducted before and after loading by Dr. Grana or Dr. Shiveley. These tests were used as a means for comparison of current clinical analysis with the current quantitative research being conducted.

As torsional loads were applied to the tibia at a 45 degree flexion angle of the knee joint, rotation of the tibia on the femur was recorded. This data provided a third means for classifying knee motion.

Also needed is a quantitative method for determining ligamentous damage, to which knee motion data may be related. Two parameters used to describe ligament damage are:

1. Ligament stretch
2. Ligament twist.

After testing, the knee was dissected for a visual check of which ligaments were damaged.

The present investigation involved collection and processing of data for six knees (three left and three right). Using these six knees, the three methods of classifying knee motion and the two parameters describing ligament damage as stated above, were examined.

## CHAPTER II

## TESTING PROCEDURE

The apparatus and instrumentation developed by Jones (8) was used in this investigation. Appendix B lists the equipment used. Appendix C describes the mounting procedure used to prepare the knee joint for testing. Figure 1 is a flow chart of the procedure used for conducting knee tests.

After the knee joint has been mounted in the test stand, the linkage transducer is used to locate ligament endpoints. Dr. Grana or Dr. Shively first mounts the linkage on the tibia to locate ligament endpoints on the tibia in the tibia reference system. He then mounts the linkage on the femur to locate the other ends of the ligaments in the femur reference system. Ligaments located at this time are given in Table I.

Figure 2 shows the ligament endpoints as located by Dr. Grana and Dr. Shively. As the ligament endpoints were located, the linkage length was calculated and displayed on the CRT screen. This length was checked manually with a pair of dividers and a ruler to verify the potentiometer readings being collected. The linkage is mounted between the tibia and the femur to yield the relative position of these two bodies to each other. Potentiometer voltages from the linkage transducer are read by the Interdata Mini-Computer through the analoque to digital converter. Voltages of each potentiometer

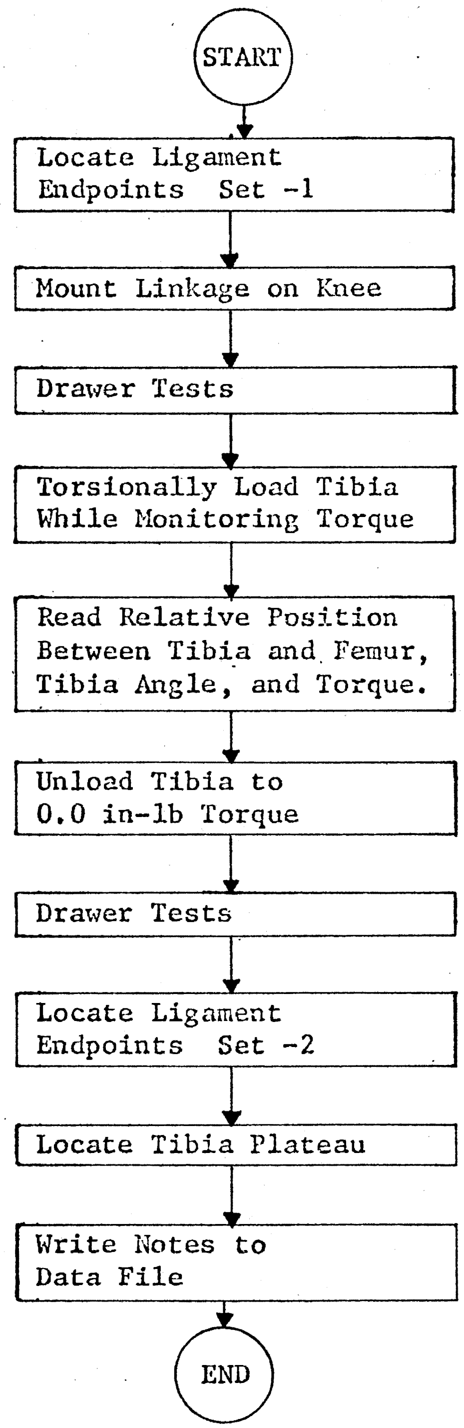
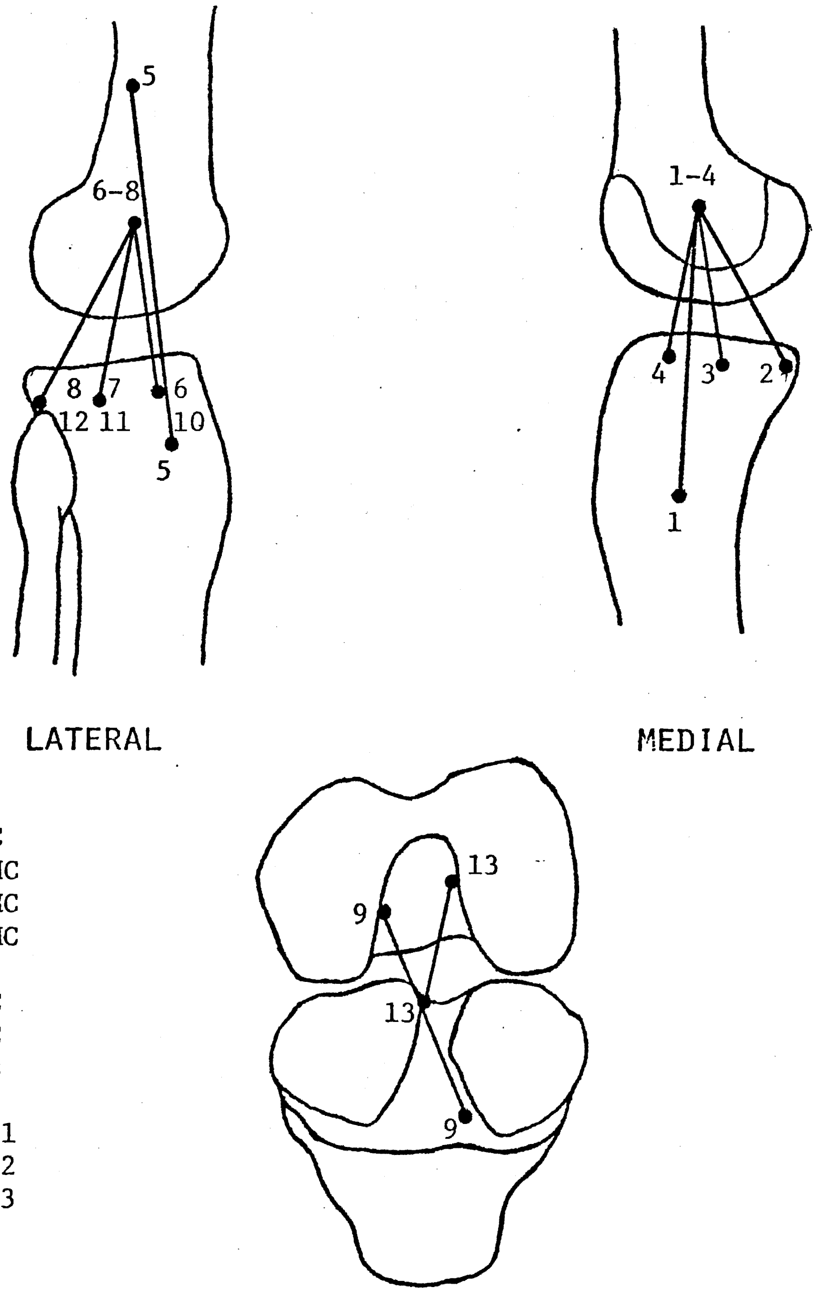



Figure 1: Flow Chart of Testing Procedure

TABLE I

LIGAMENTS LOCATED BEFORE LOADING

| Number | Name | Abbreviation |
|---|---|---|
| 1 | Superficial Medial Capsular Ligament | SMCL |
| 2 | Superficial Medial Capsular Ligament | SMCL |
| 3 | Anterior Deep Medial Capsular Ligament | ADMCL |
| 4 | Miodle Deep Medial Capsular Ligament | MDMCL |
| 5 | Posterior Deep Medial Capsular Ligament | PDMCL |
| 6 | Illiotibial Band | IB |
| 7 | Illiotibial Band | IB |
| 8 | Anterior Lateral Capsular Ligament | ALCL |
| 9 | Middle Lateral Capsular Ligament | MLCL |
| 10 | Posterior Lateral Capsular Ligament | PLCL |




1 - SMC
2 - ADMC
3 - MDMC
4 - PDMC
5 - IB
6 - ALC
7 - MLC
8 - PLC
9 - AC
10 - DLC1
11 - DLC2
12 - DLC3
13 - PC

Figure 2. Ligament Endpoint Locations

are multiplied by a calibration factor to yield potentiometer rotation in degrees, and a correction factor is added to each reading to provide the angle of the given potentiometer, relative to a previously initialized position. These potentiometer angles are stored on disk for later processing, to obtain ligament length and twist data.

At 90 degree flexion, Dr. Grana or Dr. Shively conducted drawer tests at a neutral position, with internal rotation of tibia on femur and with external rotation of tibia on femur. Potentiometer angles from the linkage transducer were also recorded on disk for these knee configurations.

With the linkage transducer still mounted on the knee joint, an Instron testing machine was used to apply a torque through a torque transducer, to the tibia. Direction of the torque caused external rotation of the tibia on the femur. The Instron was controlled by the Mini-Computer through a Universal Logic Interface (ULI). Knees were cyclically loaded to a maximum torque specification (TMAX) by increments of TMAX/10.0 in-lbs and then unloaded to 0 in-lbs. Unloading was done by incrementing the angle of rotation of the tibia as shown in Table II. Cyclic loading was repeated for TMAX specifications as given in Table III.

Potentiometer voltages and angles, as read by the computer, were listed on the lineprinter during loading for each position of the knee joint. In this way, erroneous potentiometer readings caused by mechanical failure could be noticed and corrected.

A potentiometer was used to record rotation of the tibia during the test. The computer stored on disk the potentiometer angles from the linkage transducer, the potentiomer angle for tibia rotation,

TABLE II

TIBIA ANGLE INCREMENTS USED DURING UNLOADING

| Knee Number | Degrees |
| --- | --- |
| 19 | 2.0 |
| 20 | 0.8 |
| 21 | 0.8 |
| 22 | 0.4 |
| 23 | 0.4 |
| 24 | 1.0 |

TABLE III

MAXIMUM TORQUE SPECIFICATIONS FOR LOADING CYCLES

| Knee Number | TMAX Specifications (in-lbs) |
| --- | --- |
| 19 | 30, 60, 90, 120 |
| 20 | 30, 60, 90, 120, 150 |
| 21 | 8, 24, 42, 175, 200 |
| 22 | 30, 60, 90, 120, 150, 180 |
| 23 | 30, 60, 90, 120, 150, 180 |
| 24 | 30, 60, 90, 120 |

and the applied torque.

When the loading portion of the test was completed drawer tests were again conducted. Tests performed after loading were compared with those done before loading to correlate change in motion of the knee joint, with instabilities developed during loading.

A second set of ligaments as specified in Table IV and shown in Figure 2 were then located. The knee was dissected without removing the linkage mounting blocks from either the tibia or the femur. Ligament endpoints were located on the tibia and on the femur in the same way as was the first set of ligaments. Since the relative position between tibia and femur has already been obtained, this information does not need to be collected again.

The last step of the procedure being described, was to locate three points on the tibia plateau. Screw axis parameters were related to the plane defined by these points and are explained further in the section of this document related to knee motion.

Three left and three right knee joints were tested. All knees were above knee (AK) after below knee (BK) amputees of ages 60+ years old and were amputated for peripheral vascular disease. Notes including drawer test information and knee integrity were written to a designated portion of the data file by the knee test computer program, before the file was closed.

All muscles were passive during this investigation and their contribution to knee stability was not considered.

TABLE IV

LIGAMENTS LOCATED AFTER LOADING

| Number | Name | Abbreviation |
|---|---|---|
| 1 | Superficial Medial Capsular Ligament | SMCL |
| 2 | Anterior Deep Medial Capsular Ligament | ADMCL |
| 3 | Middle Deep Medial Capsular Ligament | MDMCL |
| 4 | Posterior Deep Medial Capsular Ligament | PDMCL |
| 5 | Anterior Cruciate | AC |
| 6 | Illiotibial Band | IB |
| 7 | Anterior Deep Lateral Capsular Ligament | DLC1 |
| 8 | Middle Deep Lateral Capsular Ligament | DLC2 |
| 9 | Posterior Deep Lateral Capsular Ligament | DLC3 |
| 10 | Posterior Cruciate | PC |

# CHAPTER III

# KNEE MOTION

Determine the motion and change in motion of the human knee, resulting from forced external rotation of the tibia on the femur, at a 45 degree flexion angle.

## A. Relative Motion Between Tibia and Femur

Relative motion between tibia and femur is given as rotation about and translation along a screw axis. Maiya (13) describes the procedure for obtaining direction cosines of the screw axis, rotation about and translation along that axis, and a point on the line locating that axis is the fixed body. A way of comparing screw location from knee to knee is to plot the intersection of the screw axis with the tibia plateau. Location of the origin of the tibia plateau coordinate system and of the orientation of that coordinate system with respect to anatomical landmarks such as the tibial eminence, is important for comparing results from knee to knee. The X, Y, Z tibial plateau coordinate system was established by first locating three points on the tibia plateau as seen in Figure 3. Point one was located on the left edge of the left condyle and point two was located on the right edge of the right tibial condyle. Point three was located anterior to points 1 and 2 and also on the tibia plateau. X, Y, Z coordinates of these points were obtained using the same

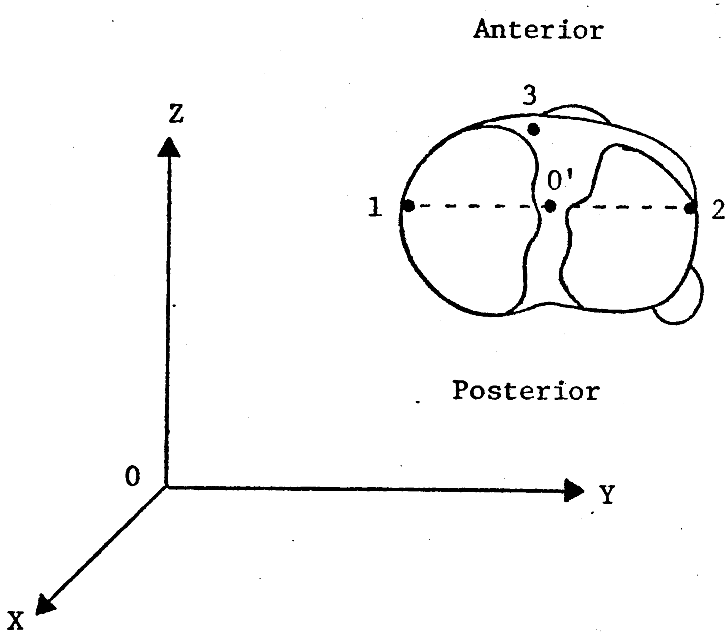



Figure 3. Locating Points to Define Tibia Plateau

method as Jones (8) used to locate ligament endpoints on the fixed body. X, Y, Z coordinates of the point halfway between points one and two are given by equation 1, 2 and 3.

$$0'_X = \frac{X_1 + X_2}{2} \tag{1}$$

$$0'_Y = \frac{Y_1 + Y_2}{2} \tag{2}$$

$$0'_Z = \frac{Z_1 + Z_2}{2} \tag{3}$$

Now we define two vectors

$$\overrightarrow{0'1} = \overrightarrow{0\,1} - \overrightarrow{0\,0'} \tag{4}$$

and

$$\overrightarrow{0'3} = \overrightarrow{0\,3} - \overrightarrow{0\,0'} \tag{5}$$

By crossing vectors $\overrightarrow{0'3}$ and $\overrightarrow{0'1}$ we obtain a vector perpendicular to the tibia plateau, which will be the Z axis of the tibia plateau coordinate system. Vector $\overrightarrow{0'1}$ is the new Y axis and by crossing vector $\overrightarrow{0'1}$ with the vector describing the new Z axis, we obtain the X axis of the new coordinate system. The tibia plateau coordinate system is shown in Figure 4. Direction cosines of the screw in the new coordinate system are obtained by multiplying the direction cosines in the fixed reference system by a transformation matrix[1].

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[1]Coordinates transformation procedures are well documented by Kinzel (11), Maiya (13), and Jones (8) and will not be repeated in this document.

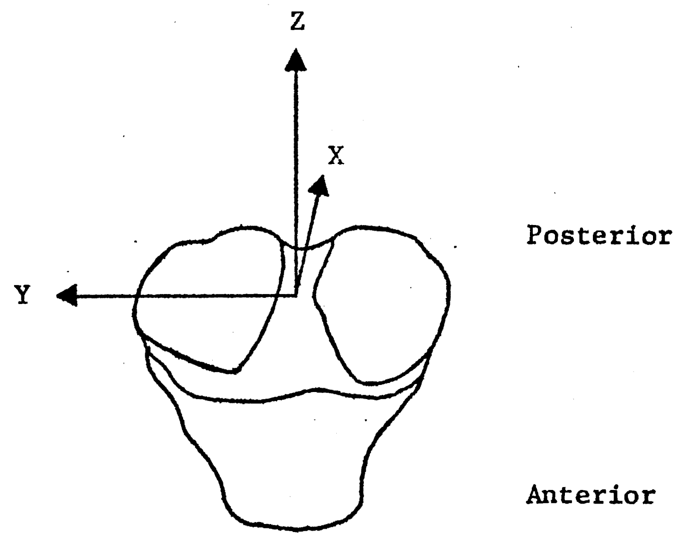



Figure 4. Tibia Plateau Coordinate System

A parametric equation of the line describing the screw axis is

$$X' = X_o + U_x t \qquad (6)$$

$$Y' = Y_o + U_y t \qquad (7)$$

$$Z' = Z_o + U_z t \qquad (Z_o = 0.0) \qquad (8)$$

Point (Xo, Yo, 0) is the point of intersection of the screw with the tibia plateau. Coordinates of the new point P are X', Y' and Z'. Then,

$$t = -Z'/U_z \qquad (9)$$

$$X_o = X' - U_x * t \qquad (10)$$

$$Y_o = Y' - U_y * t \qquad (11)$$

The line describing the screw axis in the tibial plateau coordinate system is obtained from that in the fixed coordinate system, via the transformation matrix.

## B. Screw Axis Shift

Change in motion of the human knee is given by the screw axis parameters, describing the motion of the tibia with respect to the femur.

Location of the screw axis is given by its intersection with the tibia plateau. Change in motion of the human knee is observed as the screw shifts and hence as this point of intersection shifts. The pattern of this shift will be referred to as the screw patterns for torsional loads applied to the tibia. With the exception of knees 21 and 24, cyclic loads were applied to the joints in increments of 30 in-lbs. Figures 5 through 10 are screw patterns for six knees having had external torsional loads applied to the tibia.

Shift of the screw axis during loading of the tibia is summarised in Table V. Under zero load, the screw is located in the fourth quadrant for the left knees (22, 23 and 24) and in the third quadrant for right knee number 21. Screws of the primary component of rotation of these four knees passed through the medial intercondylar tubercle of the tibia plateau. Direction of shift of the screws during loading, and rotation about the screws are shown in Table V. If more knees were tested and their screw patterns examined, the shift of the screws under load could be related to specific ligamentous damage. Ligament damage could then be clinically determined by observing screw shifts for small torsional loads, and by relating these shifts to ligament damage as determined experimentally.

Knees 19 and 20 differ from the other four knees in the location of their screws under no load. Knee 20 has a two-direction, back and forth shift of the screw over a distance in the X-direction of twice the magnitude of the other knees (Figure 6). Shaw and Murray (16, p. 1609) observed that, ". . . increased limberness of the freshly amputated joints resulted in patterns with greater irregularity than that observed in patterns obtained from joints from cadaver." It is possible that as ligament properties change with age, older joints display a more defined pattern of motion than do fresher specimens. Shaw and Murray go on to state that, ". . . a definite center of rotation for both cadavera and fresh joints could be determined in all instances in which the cruciate ligaments were intact". Their comments are in reference to

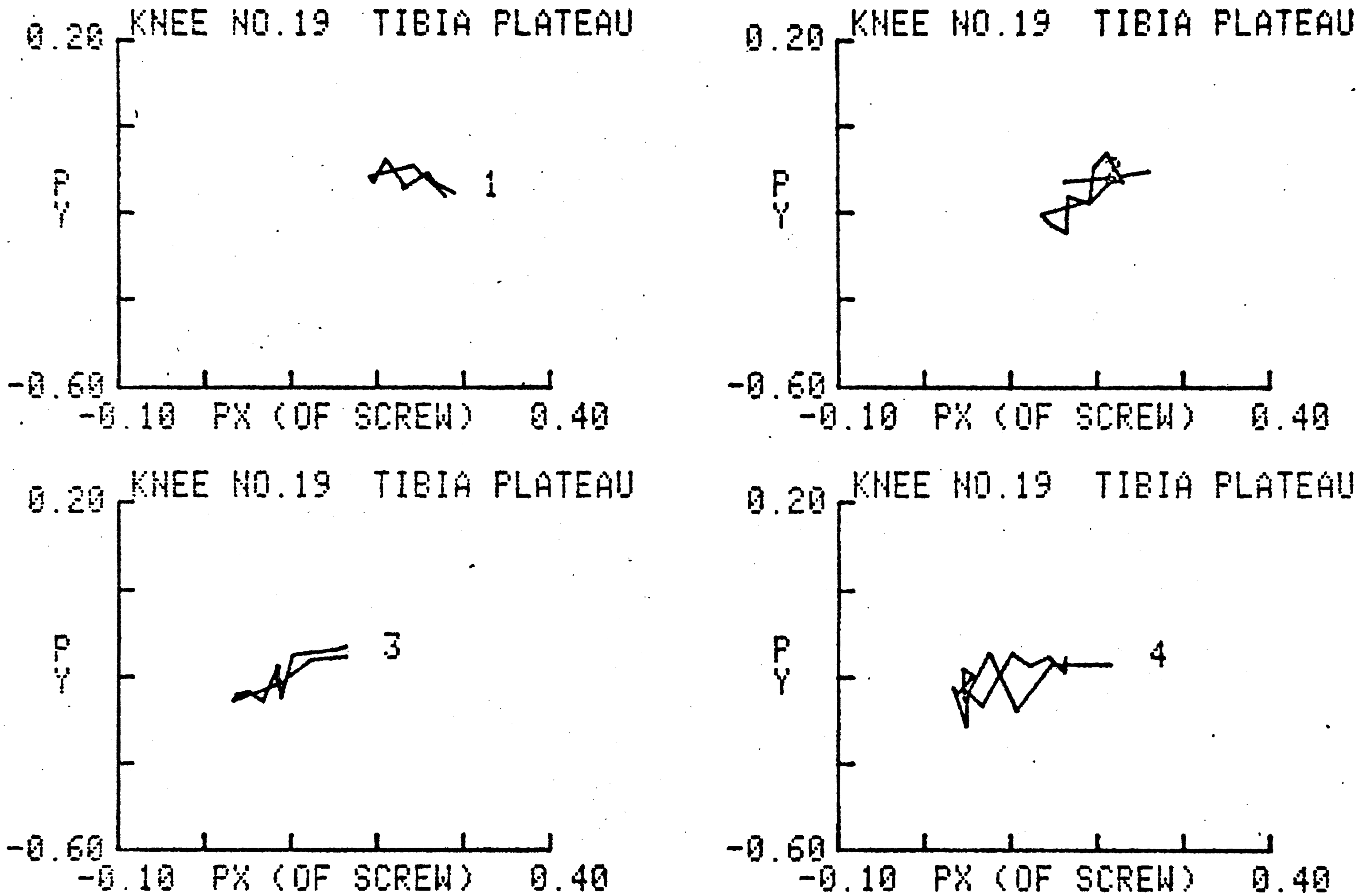



Figure 5. Knee 19 Screw Patterns During Loading

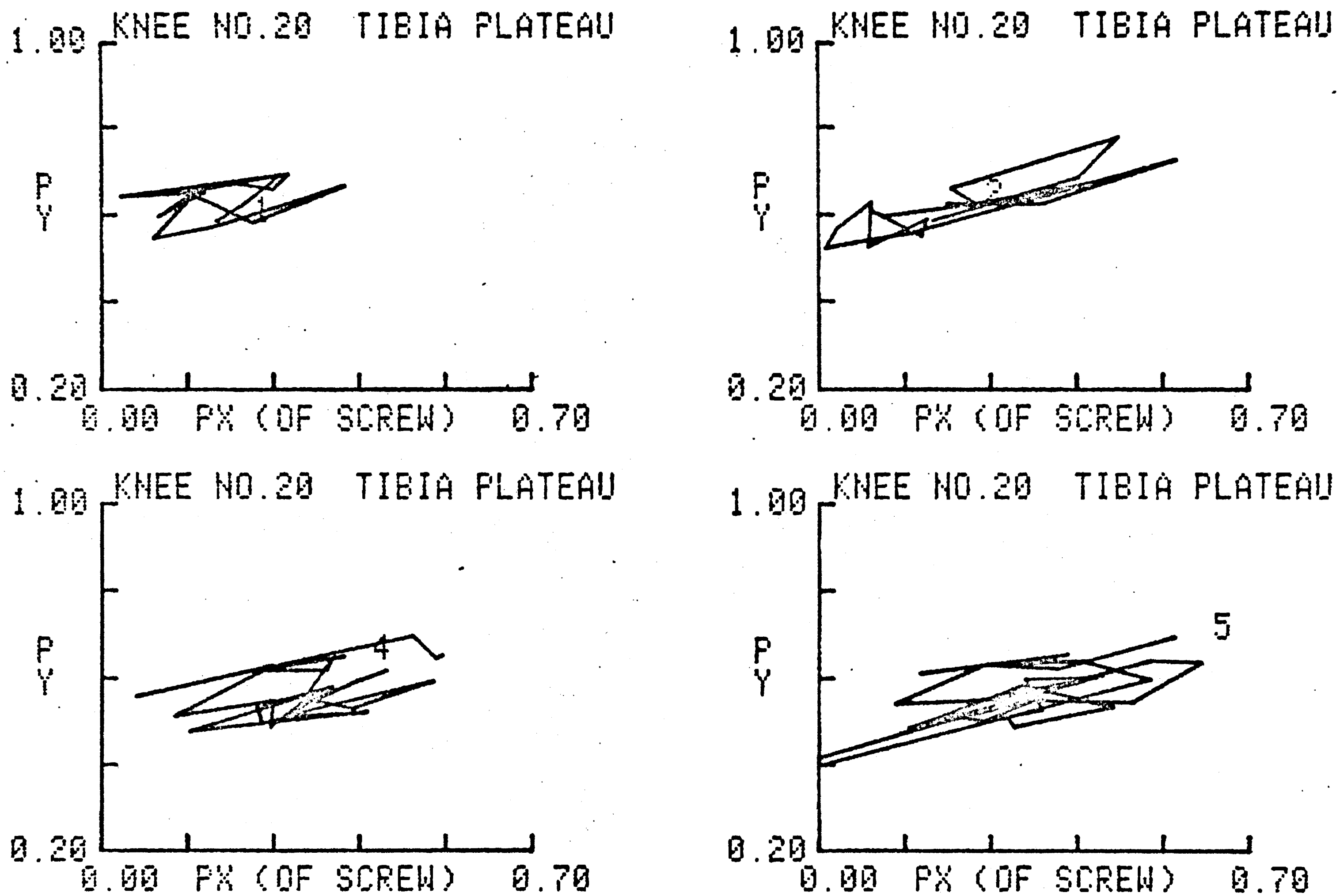



Figure 6. Knee 20 Screw Patterns During Loading

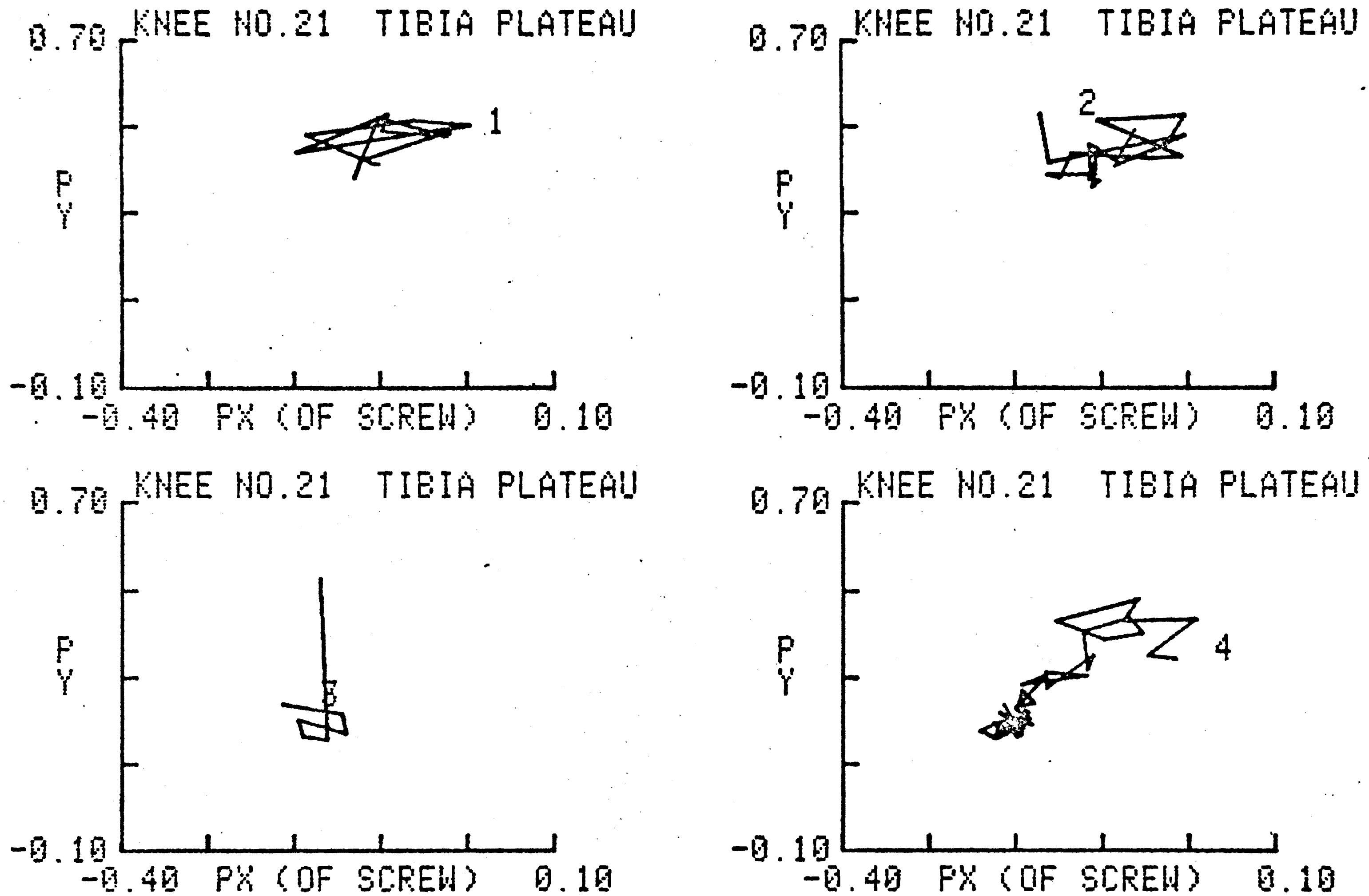



Figure 7. Knee 21 Screw Patterns During Loading

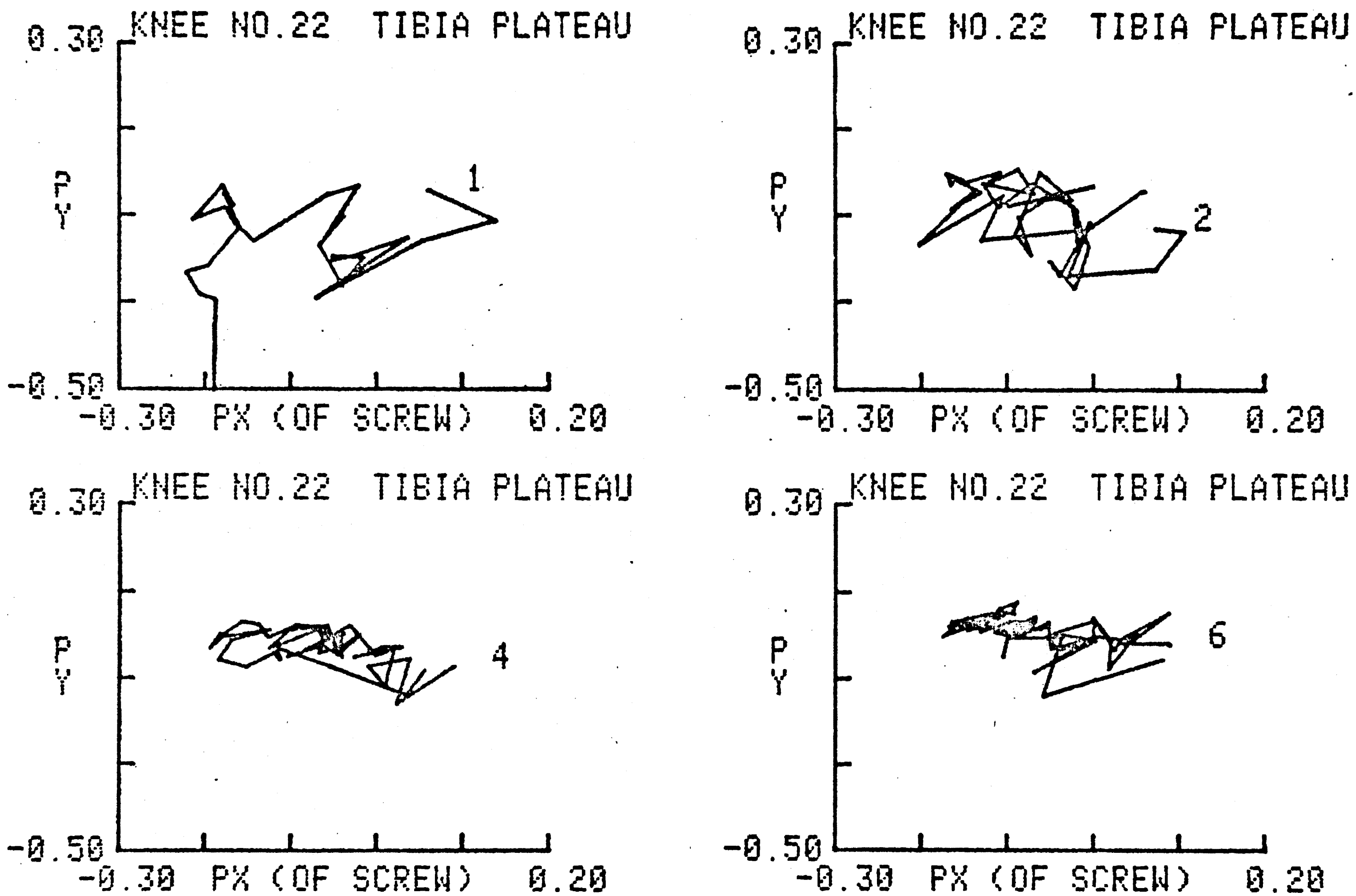



Figure 8. Knee 22 Screw Patterns During Loading

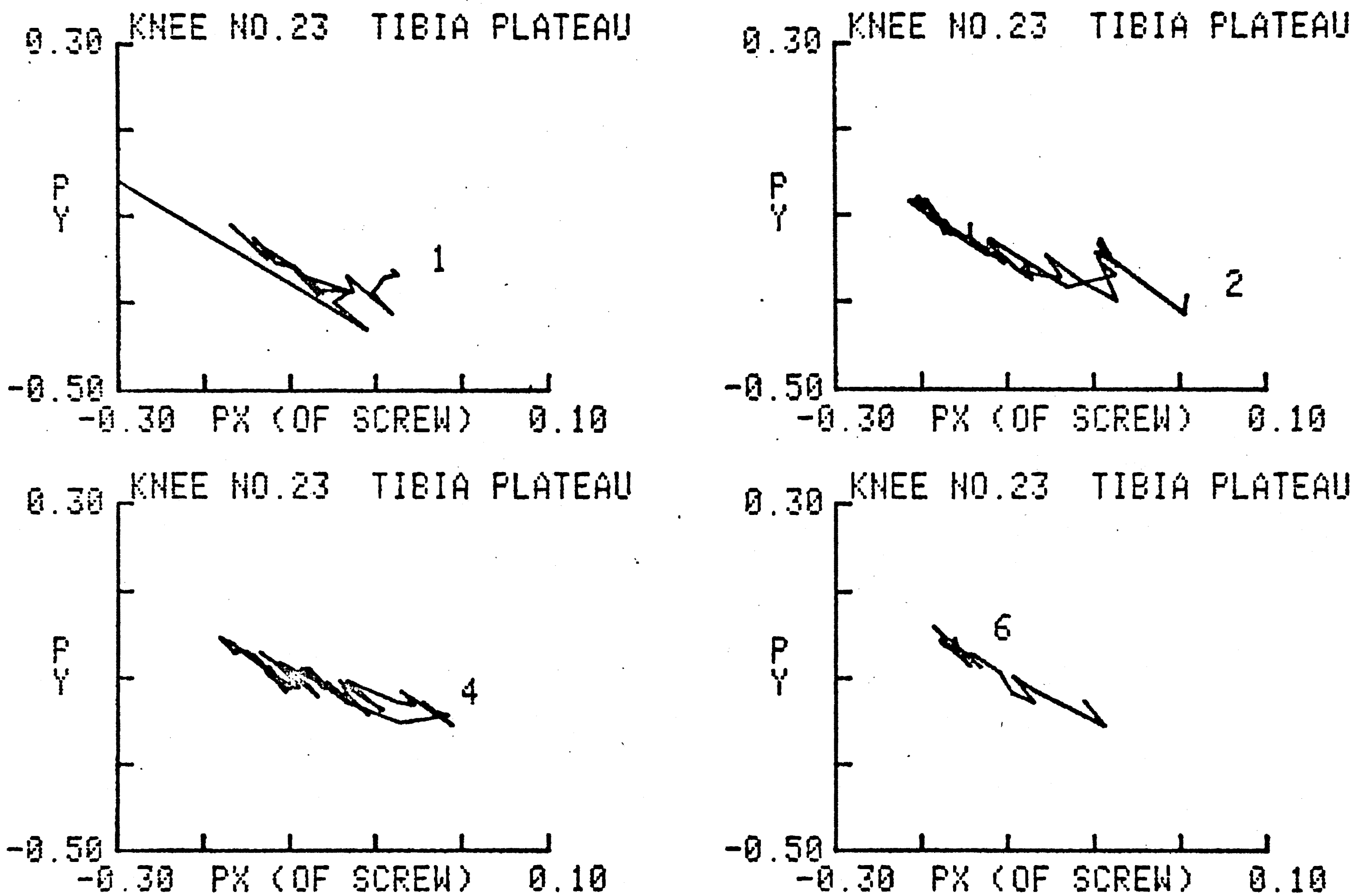



Figure 9. Knee 23 Screw Patterns During Loading

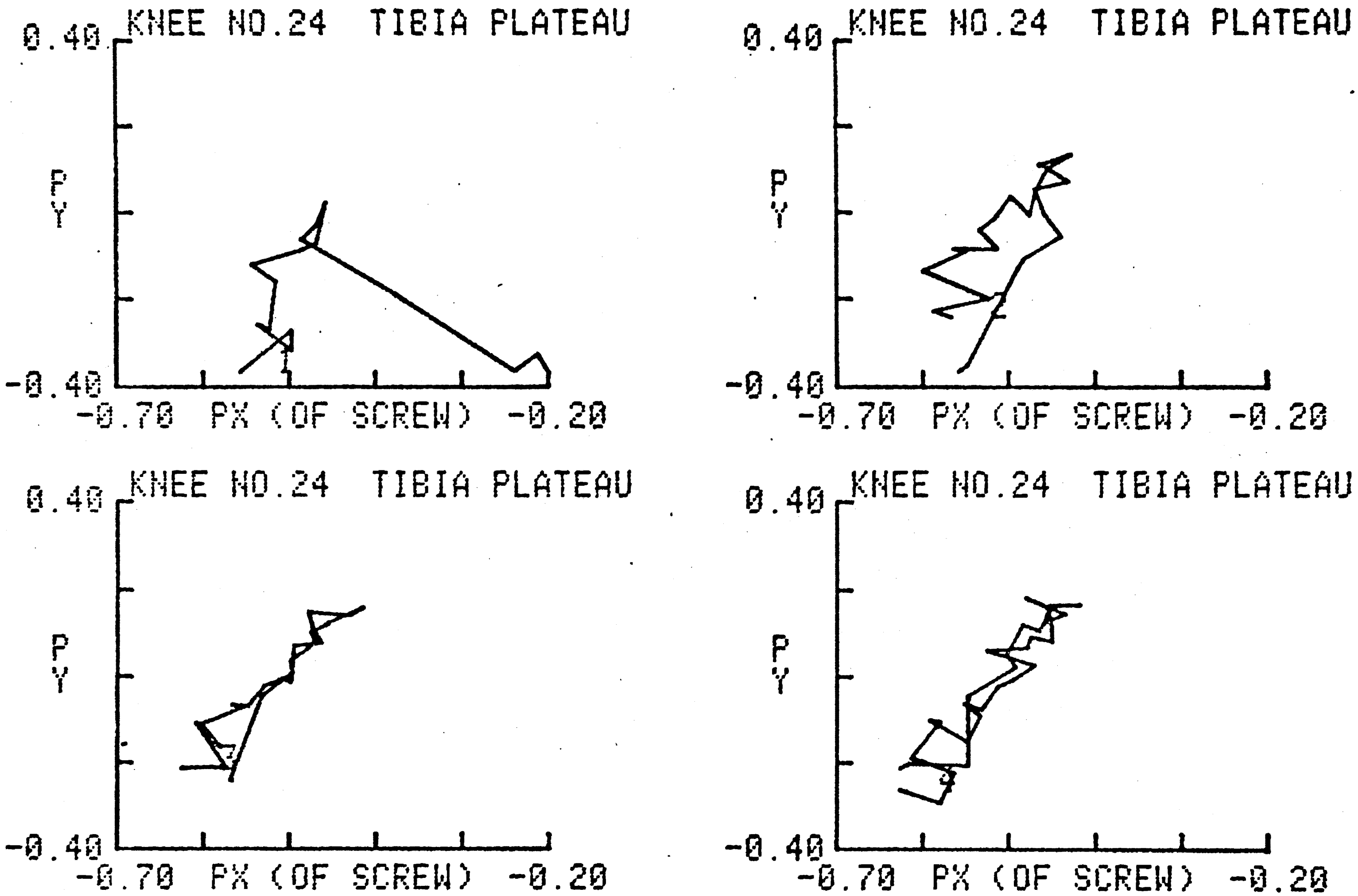
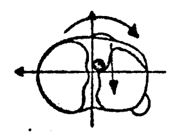
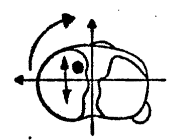
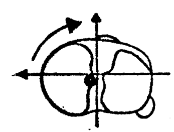
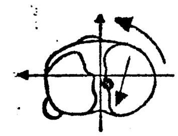
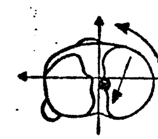
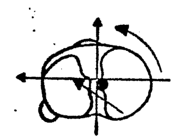



Figure 10. Knee 24 Screw Patterns During Loading

TABLE V

SUMMARY OF SCREW AXIS SHIFT DURING LOADING

| Knee Number | Type | Tibia Plateau |
| --- | --- | --- |
| 19 | Right |  |
| 20 | Right |  |
| 21 | Right |  |
| 22 | Left |  |
| 23 | Left |  |
| 24 | Left |  |

● Location of screws describing primary component of rotation

Direction of rotation of tibia

Direction of shift of screw axis during loading rotation of the tibia on the femur with the anterior cruciate ligament severed, as the knee approaches full extension. Markolf (14) showed that the knee joint has greater rotational laxity at 45 degree flexion than at 0 degree flexion. With the greater laxity present, even with the cruciates intact one could expect to see a variation in screw patterns between fresh and aged specimens. Knee 20 was in significantly better condition than the other specimens tested. This might explain the increased randomness of its screw patterns. Inversely, this also suggests that a "larger" screw pattern may be indicative of a "fresh" or good knee speciman.

Torsional loading sequence of knee 21 varied from that of the other knees because of technical problems related to computer control of the Instron loading machine. The long straight line seen in cycle 3 of Figure 7 corresponds to a single step torsional load from 0 in-lb to 175 in-lb torque. Since the testing procedure for this knee differed significantly from the others, a variance in screw patterns is expected.

## CHAPTER IV

## KNEE INSTABILITY

This chapter describes the use of two methods for determining knee instability. The methods investigated are drawer tests and tibia range of rotation at a given flexion angle.

### A. Drawer Tests

Before and after torsional loading, clinical drawer tests were conducted by Dr. Grana or Dr. Shively to determine the integrity of the given knee joint. Straight anterior drawer, internal rotation of tibia on femur and external rotation of tibia on femur were performed. Range of rotation of tibia on femur both before and after loading, was recorded. This data along with the maximum torque as applied to each specimen is given in Table VI. Chapter VI details the results of these tests.

### B. Tibia Rotation at a Given Flexion Angle

Markolf and Menach (14) have tabulated tibia range of rotation data for 35 intact knee joints in 6 flexion positions. At 90 degree flexion and applying a torque of 8 newton meters, they observed a laxity of 24.3 degrees, with a standard deviation of 4.7 degrees. Two standard deviations produce a "standard" range of rotation of $24.3 \pm 9.4$ degrees. This data is not adequate for determining the

TABLE VI

RANGE OF ROTATION OF TIBIA ON FEMUR AND MAXIMUM
TORQUE APPLIED DURING LOADING

| Knee Number | Before Loading (Degrees) | After Loading (Degrees) | Max. Torque (In-lbs) |
|---|---|---|---|
| 24 | 31 | 40 | 120 |
| 23 | 30 | NA | 180 |
| 22 | 32 | NA | 180 |
| 21 | 28 | 37 | 200 |
| 20 | 33 | 49 | 150 |
| 19 | 51 | 56 | 120 |

stability of an injured knee joint. Since tibia rotation ranges vary from person to person as this large deviation of ± 9.4 degrees indicates, comparision of a patient's injured knee with the patient's good knee would most accurately reflect the extent of the damage to the injured joint. By noting the tibia range of rotation at various flexion angles, a complete motion pattern can be established. Variations of that pattern between left and right knees can be related to quantitative ligament damage information.

Chapter VI explains and demonstrates the relationship between variations of external tibia rotation to ligament damage, at a 45 degree flexion of the knee joint.

CHAPTER V

LAGAMENTOUS DAMAGE

Ligamentous damage will be described in terms of two parameters, change in length ($\Delta$), and twist ($\gamma$), of the individual ligaments.

A. Ligament Stretch

Jones (8) describes a method for determining ligament endpoints on the tibia and corresponding coordinates of the ligament endpoints on the femur. In knowing the location of the endpoints of ligaments in each successive position of the knee joint, he was able to calculate percentage strain in the ligaments with respect to their initial length. Percent strain is dependent on initial length of a given ligament. Four variables affecting determination of initial length are:

1. Anatomical geometry of the given knee such as size, shape, and points of attachment of the ligaments.
2. Error in the linkage transducer (Appendix D.)
3. Variation as to what part of the ligament is defined as the endpoint. Ligaments in general do not have single point attachments to the boney structures, but are only "modeled" as such.
4. Variation between individuals in locating ligaments. Dr. Grana located ligament endpoints on knees up to and

including knee 20. Dr. Shively worked with knees 21 to 24.

Wang (18) and Erkman (4) stated ligament lengths for the AC, PC, Medial Collateral (MC) and lateral colateral (LC) ligaments. Another set of ligament lengths can be obtained from the X, Y, Z coordinates for these four ligaments (AC, PC, MC and LC) at a 0 degree flexion, as given by Edwards, Lafferty and Lange (2). These data are given in Table VII. Table VIII lists initial ligament length plus or minus one standard deviation for the six knees tested during the course of the research being presented.

Change in length of the ligaments will be plotted as a function of torque. These plots are shown in Appendix E for all ligaments of knee 24 as listed in TableVIII, and for the AC, PC, SMC, and MLC ligaments of knees 19 through 23. Ligament numbers on these figures correspond to those given in Table VII. Numbers at the ends of the curves are cycle numbers corresponding to maximum torque specifications given in Table III. Further observations regarding figures given in Appenxix E and ligament change in length are made in Chapter VI, subheading C, of this report.

## B. Ligamentous Twist

Ligamentous twist is the second parameter used to investigate ligament damage. As Markolf's (14) investigation shows, there is a certain amount of rotary laxity in all positions of the knee joint. At a fixed flexion angle and as the tibia rotates on the femur, the knee joint tends to tighten, Upon medial rotation of the tibia with respect to the femur, the crucitate ligaments twist or "wrap" on themselves. Conversely, they "unwrap" with external rotation of the tibia on the

TABLE VII

LIGAMENT LENGTHS FOR 0 DEGREE FLEXION

| Ligaments | Erkman and Walker (inches) | Edwards, Laferty and Yang (inches) | Wang, Walker and Wolf (inches) |
|---|---|---|---|
| AC | 1.26 | 1.00 | 1.13 |
| PC | 1.34 | 1.43 | 1.31 |
| MC | 2.17 | 3.98 | 2.6 |
| LC | 1.65 | 3.5 | 2.14 |

TABLE VIII

INITIAL LIGAMENT LENGTHS

| No. | Ligament | Abbreviation | Ligament Length (IN) $\pm\sigma$ for 6 knees |
|---|---|---|---|
| 1 | Superficial Medial Capsular | (SMC) | 2.58 $\pm$ 0.30 |
| 2 | Anterior Deep Medial Capsular | (ADMC) | 1.65 $\pm$ 0.31 |
| 3 | Middle Deep Medial Caps | (MDMC) | 1.75 $\pm$ 0.27 |
| 4 | Posterior Deep Medial Caps | (PDMC) | 2.21 $\pm$ 0.40 |
| 5 | Illiotibial Band | (IB) | 4.46 $\pm$ 0.42 |
| 6 | Anterior Laterial Caps | (ALC) | 1.60 $\pm$ 0.10 |
| 7 | Middle Lateral Caps | (MLC) | 1.80 $\pm$ 0.14 |
| 8 | Posterior Lateral Caps | (PLC) | 2.15 $\pm$ 0.06 |
| 9 | Anterior Cruciate | (AC) | 1.00 $\pm$ 0.19 |
| 10 | Deep Lateral Caps | (DLC1) | 4.3 $\pm$ 0.84 |
| 11 | Deep Lateral Caps | (DLC2) | 2.02 $\pm$ 0.26 |
| 12 | Deep Lateral Caps | (DLC3) | 2.47 $\pm$ 0.63 |
| 13 | Posterior Crucitate | (PC) | 1.33 $\pm$ 0.25 |

femur. Hence, the angle of twist of ligaments, particularly cruciates, influences stress and damage to the ligaments. Calculation of ligamentous twist is demonstrated in Appendix F.

As a rubber band "tightens" when it is twisted, so it can be expected that ligaments tighten as they are twisted. Hence, it is conceivable that ligament length could actually decrease, while the stress in the ligament may increase. Both change in length and twist must be considered in qualifying ligament damage. Table IX compares cruciate ligament twist ($\gamma$) to rotation of the tibia with respect to the femur ($\phi$).

## C. Dissection

When all testing of the knee joint was completed, Dr. Grana or Dr. Shively dissected the joint and visually investigated the integrity of individual ligaments. Table X contains a summary of observations made through clinical drawer tests and visual inspection.

TABLE IX

TIBIA ROTATION VERSUS CRUCIATE LIGAMENT TWIST

| Knee No. | Internal Tibia Rotation (Deg.) $\phi$ | Twist of Ant. Cruc. (Deg.) $\gamma_A$ | Twist of Post. Cruc. (Deg.) $\gamma_P$ |
|---|---|---|---|
| 19 | 24.34 | 23.4 | 22.3 |
| 20 | 21.9 | 16.6 | 21.5 |
| 21 | 30.02 | 21.3 | 28.8 |
| 22 | 31.92 | 26.7 | 31.9 |
| 23 | 32.69 | 31.5 | 32.1 |
| 24 | 39.52 | 34.9 | 36.4 |
| 18* | 10.55 | 7.5 | 8.3 |
| 17* | 14.33 | 4.9 | 10.9 |
| 16* | 14.00 | 0.1 | 5.3 |

* David Jones's Loading Conditions. (Torsional load applied to femur with tibia fixed). Knees 19 through 24 had torsional loads applied to the tibia with a U-joint mounted on the femoral axis.

TABLE X

OBSERVATIONS FROM DRAWER TESTS AND DISSECTION

| Knee Number | | Before | After | Dissection |
|---|---|---|---|---|
| 19 | Right | 2+ Ant. inst. with ant. med. and ant. lat. rotary inst. | Same as before but worse | Gross ant. cruc. inst. and deep capsular laxity on medial side |
| 20 | Right | Stable | 2+ Valgus inst. | Laxity of superficial medial collateral and deep medial capsular |
| 21 | Right | 1+ ant. drawer rotary stability | 3+ ant. drawer anterolateral inst. | Laxity of superficial medial collateral, deep capsular ligs. and laxity of ant. cruc. and lateral capsular ligaments |
| 22 | Left | Stable to ant/post and Varus-Valgus | 1+ inst. with Valgus stresses at $30^{\circ}$ & no. inst. with Varus 1+ ant. drawer at neutral, anterolateral rotary inst. & questional anteromedial | Laxity of deep and superficial layers of medial collateral ligs. and of lateral collateral and ant. cruciate |
| 23 | Left | Stable | 1+ Valgus inst. at $30^{\circ}$ 2+ ant. drawer at neutral & internal rotation | Laxity of superficial and deep medial collateral & laxity of ant. cruciate |
| 24 | Left | 1+ ant. drawer and mild anterolateral inst. | 2+ ant. drawer 1+ Varus Valgus at $30^{\circ}$ anterolateral & anteromedial inst. | Laxity of deep medial and lateral caps. ligs. and of the ant. cruc. |

# CHAPTER VI

## KNEE INSTABILITY VERSUS LIGAMENTOUS DAMAGE

Observations relating knee instability to ligament data, are given here.

### A. Drawer Tests

Knees 22 and 23 were both stable before testing. Maximum torque applied to these knees were 160 and 178 in-lb. At these loads, ligament reactions and knee instabilities were observed as given in Table XI. Drawer tests indicated a 1+ valgus instability. This is in agreement with the laxity of the superficial and deep medial collateral ligaments observed visually during dissection. It also reflects the significant change in length of medial ligaments when loaded. Clinical observations of 1+ and 2+ anterior drawer are in agreement with the laxity of the AC as observed during dissection. A stretch of 0.1 to 0.2 inches and a ligament twist of 26.7 to 31.5 degrees was enough to cause AC damage. Knee 22 has a 1+ anterior drawer and anterolateral instability corresponding to damage of the anterior cruciate and the lateral collateral ligaments. Knee 23 had a 2+ anterior drawer with lateral collaterals intact. It is evident that a torsional load applied to the tibia cannot be assumed to cause identical ligamentous damage from knee to knee. Medial ligaments were damaged in all six knees to which an external torsional load was applied to the tibia.

TABLE XI

LIGAMENT REACTIONS OF KNEES 22 AND 23

| Knee | (in-lb) torque | Tibia rotation (Deg.) | AC rotation (Deg.) | PC rotation (Deg.) | AC $\Delta/L$ | PC $\Delta/L$ | SMC $\Delta/L$ | MLC $\Delta/L$ | MDMC $\Delta/L$ | DLC $\Delta/L$ | Inst. | Ligament Damage |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 22 | 160 | 31.92 | 26.7 | 31.9 | $\frac{0.2}{0.9}$ | $\frac{0.0}{1.1}$ | $\frac{0.2}{3.0}$ | $\frac{0.35}{2.0}$ | $\frac{0.4}{1.8}$ | $\frac{0.2}{2.1}$ | 1+ valgus at 30 degrees 1+ ant. at neut. antero-lateral | PMC, SMC LC, AC |
| 23 | 178 | 32.69 | 31.5 | 32.1 | $\frac{0.1}{1.0}$ | $\frac{0.1}{1.3}$ | $\frac{0.4}{2.9}$ | $\frac{0.5}{2.2}$ | $\frac{0.2}{1.8}$ | $\frac{0.3}{2.4}$ | 1+ valgus at 30 degrees 2+ ant. at neut. & Int. | PMC, SMC AC |

However, damage to the anterior cruciate and also to the lateral ligament varied from knee to knee. Upon dissection, significant anterior cruciate damage was observed in five of these six knees. Damage to lateral ligaments varied from knee to knee.

Two explanations can be given for variations observed in data collected. First, no two knee joints are identical in size, shape or ligament strength. Hence, no two knee joints will react identically under a given loading condition. Second, the importance of establishing the integrity of a knee joint before testing is critical. Three of the six knees tested indicated anterior instability before testing and therefore, could not be expected to react as would a stable knee joint. In future research, knees having any clinical instability should not be tested.

## B. Screw Patterns

Knee instability as given by drawer tests and by the screw patterns may be used to specify ligamentous damage. For screw patterns to be effective in this application, a larger scale investigation involving stable knees would have to be conducted. Similarities in direction and initial location of the screw patterns of knees 22 and 23 were observed. A difference between these two is that the screw pattern of knee 22 was located closer to the orgin of the tibia plateau coordinate system, than was the screw pattern of knee 23. Ligament damage as given in Table X corresponds to screw patterns noted here.

## C. Tibia Rotation

At a 45 degree flexion angle a knee joint has a certain amount of rotational laxity. Therefore, it is difficult to determine a standard neutral position of the knee, from which tibia rotation measurements can be made and compared from knee to knee. A 15 in-lb torque externally applied to the tibia, may cause a 5 - 15 degree rotation of the tibia, depending on where the neutral position was chosen. Also, variation in motion from specimen to specimen can be expected. To minimize these factors, motion comparison of a patient's right and left knees can be made.

A patient's damaged knee can be analyzed as follows:

1. Determine range of tibia rotation of the patient's undamaged knee at specific flexion angles.
2. Determine range of tibia rotation of the patient's damaged knee at the same flexion angles.
3. Relate the difference in rotation ranges of the two knees to quantitative ligament damage information.

Quantitative information must therefore be available relating knee motion to ligament damage. The method used to obtain this information, and the use of the data collected is presented here.

A knee joint was mounted as explained in Appendix C. A 15 in-lb torque was applied in external rotation of the tibia. This position was assumed to be the normal limit of external rotation of the tibia (it will be referred to as the "original" position of the tibia). Ligament lengths as recorded at this position were considered to be the "original" lengths of the ligaments. Torque was increased and ligament lengths and tibia rotation were recorded at specified torque intervals. Change in ligament length and percent starain of the ligaments (based on the "original" lengths) were plotted as a function of tibia rotation, as seen in Figures 11 and 12. It is noted that tibia rotation is the rotation of the tibia from its "original" position. Tibia rotation is therefore analogous to the difference in rotation range of a damaged and undamaged knee joint. Charts such as those given in Figures 11 and 12 can be used to clinically diagnose an unstable knee.

When a difference in range of external rotation of a patient's damaged and undamaged knees is noticed, damaged ligaments must first be identified. By consulting the percent strain curves (Figure 11), the relative damage to each ligament can be determined. For a 10 degree difference in external rotation of the tibia, the percent strain curves indicate that the anterior deep medial capsular ligament has incurred the most serious damage (approximately 8.6% strain). Change in length curves are then consulted (Figure 12) to determine the extent of the damage. For 10 degree rotation, the ADMCL has stretched 0.14 in. One may note that at 10 degree rotation, a 0.04 inch change in length of the AC represents only a 4½% strain (Fig's. 11 and 12). This is true because the original length of the AC (1.0 inch) is less than half the original length of the SMC (2.98 inches).

Trent, Walker and Wolf (17) plot percent increase and percent decrease of cruciate lengths for a 40 in-lb torque applied to the tibia in internal and external rotation, as shown in Figure 13. Figures 11 and 12 both indicate little or no change in PC length for external

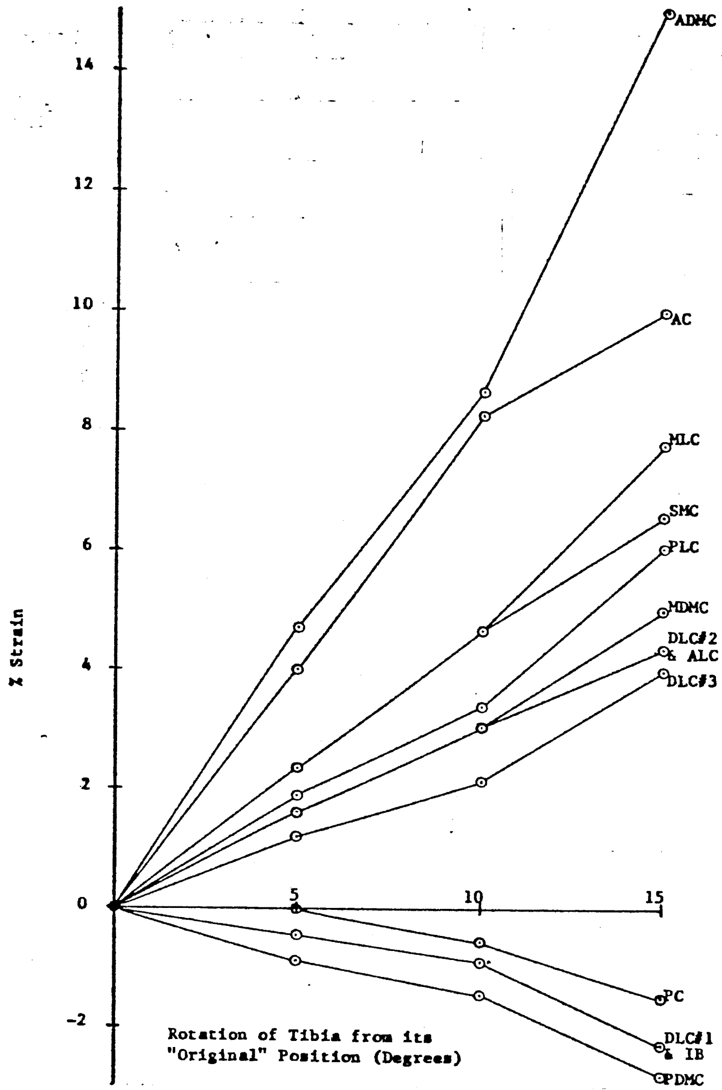



Figure 11. Ligament Percent Strain Versus External Rotation of Tibia on Femur at a 45 Degree Flexion Angle. (Average Values of Knees 21, 22, 23, 24)
Note: 0 Degree Rotation Corresponds to the Tibia Position with 15 in-lb Torque Applied to the Tibia.

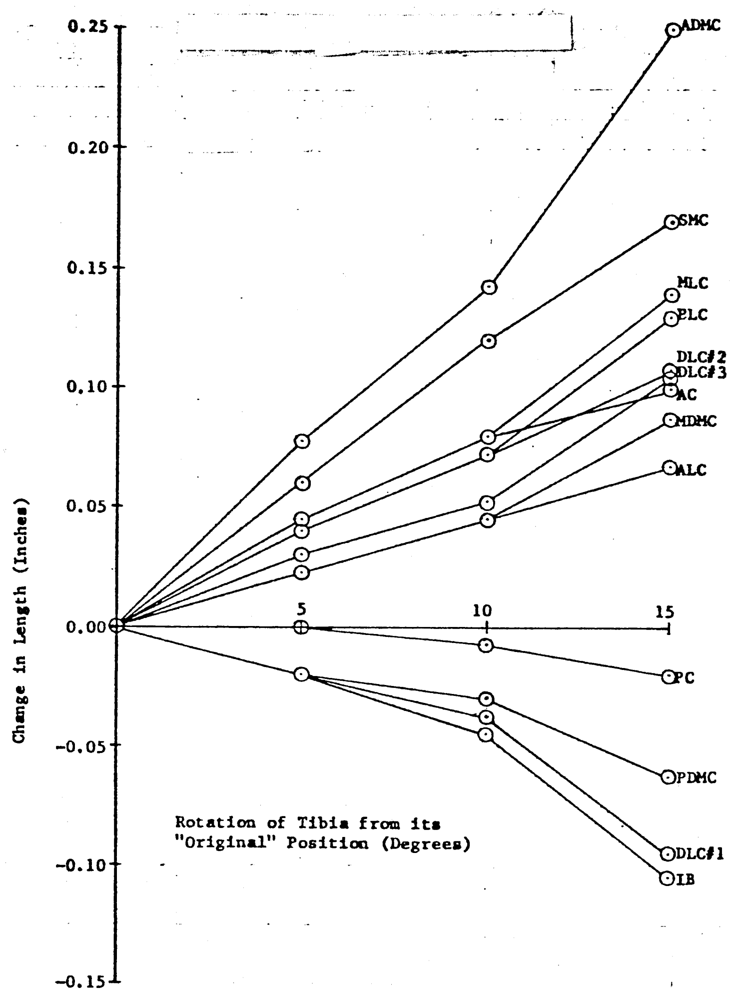



Figure 12. Ligament Change in Length Versus External Rotation of Tibia on Femur at a 45 Degree Flexion Angle. (Average Values of Knees 21, 22, 23, 24) Note: 0 Degree Rotation Corresponds to the Tibia Position with 15 in-lb Torque Applied to Tibia.

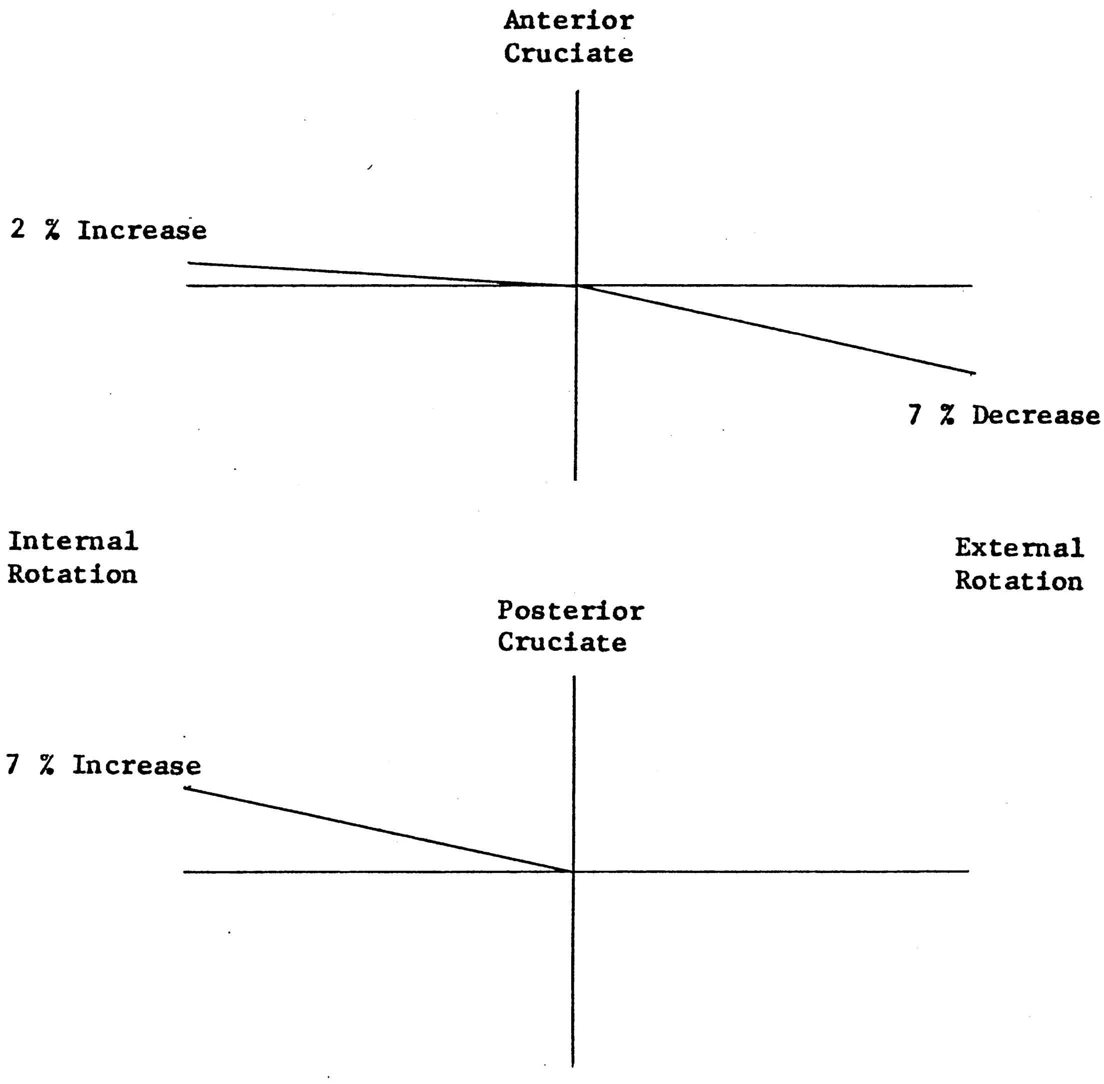



Figure 13. Percentage Change in Length of Ligaments with Internal and External Rotation of Tibia on Femur at a 45 Degree Flexion Angle as Given by Trent (17, p. 268). Note: Tibia was Torsionally Loaded with 40 in-lb Torque.

rotation of the tibia. Figures in Appendix E show that the AC ligament (ligament no. 9) of knees 20, 21 and 24 did initially shorten in length. When the 15 in-lb torque was applied to the tibia, ligaments were stressed, removing the laxity or "looseness" of the joint and drawing the condyles closer together. At this point, the AC was shorter than before the torque was applied and this decreases in length is what was observed by Trent, Walker and Wolf. However, as torque was increased, the AC increased in length from this original position (the position of 15 in-lb torque), and from this point on, the AC ligament increased in length. This increase in length is shown in Figure 12.

Figures 11 and 12 demonstrate a quantitative method for determining ligamentous damage. These charts are for external rotation of the tibia at a 45 degree flexion angle. A complete set of charts for both internal and external tibia rotation ranges is needed to give a complete picture of ligamentous damage.

# CHAPTER VII

# CONCLUSIONS

Numerous difficulties are encountered in relating ligamentous reactions due to a torsional load applied to the tibia, to the instability of the knee. Included is the complication of deducing and stating a "general" or "expected" reaction for all stable knees. Some of the variables encountered are listed here.

1. Fresh, stable specimens are needed to obtain results which can be related back to the clinical case.
2. Variation of knee reactions can be expected between specimens from males and females.
3. Race, sex, age and weight of a person affect knee motion (16).
4. Variation has been observed between matched right and left specimens (14).
5. Any variation in the testing procedure as to loading and unloading speeds and maximum applied loads affects the ligament reactions and hence the knee instability.

These difficulties are responsible for variation from knee to knee, of the data collected.

The effectiveness of each of the five parameters noted in the abstract of this report, is given here.

### A. Screw Patterns From Loading and Unloading the Tibia

Shift of the screw axis during loading indicated a definite trend as knee instability increased. Through a large scale investigation, this shift could be directly related to specific ligamentous damage.

### B. Drawer Test

Drawer tests were effective in subjectively determining knee instability. Difficulties arise in maintaining consistency of application and interpretation of such tests. Drawer tests conducted in this investigation provided a clinical means of verification of knee joint stability before and after testing. They did not, however, yield quantitative data with regard to ligamentous damage.

### C. Tibia Rotation at a Given Flexion Angle

Tibia rotation has been shown to have great potential as a clinical tool for identifying knee instabilities. A method for relating tibia rotation to quantitative ligament damage information has been demonstrated. It is recommended that further research be conducted to examine internal and external tibia rotation at flexion angles other than 45 degrees, and to relate this data to quantitative ligament damage information. This would provide a complete diagnostic tool for the orthopedic surgeon.

### D. Ligament Stretch

Ligament change in length can be effectively used to quantitatively indicate ligament damage. The correlation of excess tibia rotation to ligament stretch has been demonstrated in this report to be a useful tool both for identifying damaged ligaments and also for determining the amount of damage incurred by those ligaments.

## E. Ligament Twist

Ligament twist is of particular importance in describing cruciate damage. Ligament twist calculation is demonstrated in Appendix F. Further research must be conducted to determine the functional relationship between cruciate ligament twist and cruciate ligament damage.

## F. Dissection

Dissection clearly indicated which ligament had been damaged and was used to check experimental findings. No quantitative data was collected during dissection. Dissection was used for validating hypotheses regarding knee instability and ligamentous damage.

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APPENDIXES

# APPENDIX A

# GLOSSARY

# GLOSSARY

| | |
|---|---|
| ABDUCT: | To move away from the middle of the body, on one of its parts. |
| ADDUCT: | To draw toward or beyond the median line of the body or 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 extrimity of a bone. |
| EXTEND: | To straighten out a limb. |
| FEMUR: | Thigh bone. |
| FLEX: | To bend a limb. |
| LATERAL: | On the side (outside) opposite of medial. |
| LIGAMENT: | A band or sheet of fibrous tissue connecting two or more bones, and providing the integrity of the joint. |
| MEDIAL: | Relating to the middle or center. |
| POSTERIOR: | Behind - in the back opposite of Anterior. |
| SCREW HOME MECHANISM: | Knee motion characteristic causing rotation of the tibia about the tibial axis as full extension of the knee joint is approached. |
| TIBIA: | Larger of the two bones of the calf. |
| TIBIAL EMINENCE: | Protrussion between tibial condyles. |
| TRANSVERSE: | Crosswise - lying across the long axis of the body |
| TUBERCLE: | A bump or protrusion such as the tibial eminence. |
| VALGUS: | Contact between lateral condyles is lost. |
| VARUS: | Contact between medial plateau is lost. |

APPENDIX B

INSTRUMENTATION AND EQUIPMENT ASSEMBLY

INSTRUMENTATION AND EQUIPMENT ASSEMBLY

1. Lebow 1104S Rotating Strain Gauge Torque Transducer.

2. Datronic Transducer Amplifier with Type 90 Strain Gauge Module and Type P Galvonometer Driver.

3. Potentiometer mounted to torque transducer (indicating tibia rotation) Usable range - 0 to 192 degrees.

4. Seven-bar Linkage Transducer including six potentiometers.

5. Interdata 7/16 Minicomputer System including

   A) Universal Logic Interface (ULI)

   B) 10 Bit Analog to Digital converter (A/D)

   C) CDC Hawk disk drive

   D) Centronics Lineprinter

   E) ADM CRT Terminal

6. Harrison Model 865C power supply 25V source used to drive relays controlling Instron testing machine.

7. Kepco power supply 10V source used to excite potentiometers.

8. Instron testing machine.

The following figure is a schematic representation of the testing equipment used.

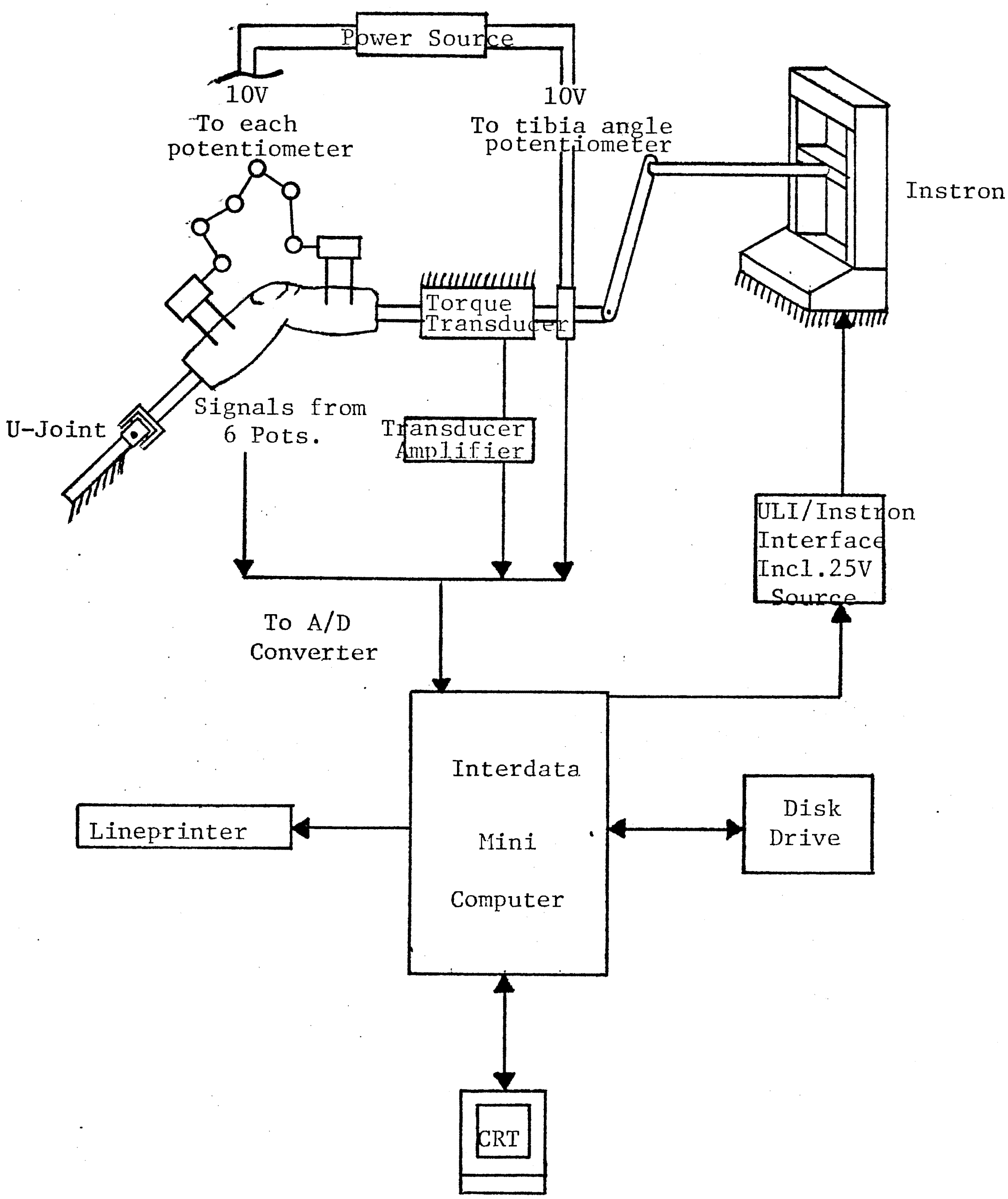


Figure 14. Instrumentation Assembly Schematic

APPENDIX C

PREPARING AND MOUNTING

THE KNEE JOINT

## PREPARING AND MOUNTING THE KNEE JOINT

1) Remove knee from freezer and place in sink with warm running water for 2 hours.

2) Drill femur and tibia with ½" bit. Clean holes with test tube cleaner and water, and dry the hole using paper towels.

3) Cement long aluminum arbor in femur and short arbor in tibia. Position shafts and allow bone cement to cure without moving shafts in bone.

4) Insert threaded pins on medial side of knee to mount linkage transducer. Positioning of pins is accomplished using a spacing block. Pins should extend 1¼" beyond the knee surface.

5) Drill fibula end, insert pin into hole and fasten pin to the shaft in the tibia, using a hose clamp.

6) Keep knee moist during the course of the experiment. A plastic bag around the knee accomplishes this.

# APPENDIX D

# TRANSDUCER ERROR ANALYSIS

TRANSDUCER ERROR ANALYSIS

A statistical approach was used to investigate the accuracy of the linkage transducer. For 100 different configurations of the transducer, the X, Y, Z coordinates of a known point as given by the transducer, were recorded.

X, Y, Z coordinates were averaged and standard deviations from those averages are given in Table XII.

TABLE XII

STANDARD DEVIATIONS FROM AVERAGE
X, Y, Z COORDINATES

| Parameter | Average Value (in.) | Standard Deviation $\sigma$ (in.) |
|---|---|---|
| X | -0.90 | 0.08 |
| Y | 6.49 | 0.05 |
| Z | -2.61 | 0.08 |
| $\ell$ | 7.06 | 0.056 |
| D | | 0.121 |

Parameter $\ell$ is average length as given by

$$\ell = \left| \sum_{i=1}^{100} \sqrt{x_i^2 + y_i^2 + z_i^2} \right| \Big/ 100 \qquad (12)$$

equation C1. $\sigma_o$ is the standard deviation from the point located. If X, Y, Z coordinates of a point P are known and $X_i$, $Y_i$, $Z_i$ are coordinates given by the linkage transducer in locating point P, then $X_i$, $Y_i$, $Z_i$ actually describe a point P' (Figure 33). The distance (D) between P and P' is the error incurred by the linkage transducer in locating point P.

$$D_i = \sqrt{(X - X_i')^2 + (Y - Y_i')^2 + (Z - Z_i')^2} \qquad (13)$$

$$\sigma_D = \sqrt{\frac{(D_1 - 0)^2 + (D_2 - 0)^2 + \ldots + (D_{100} - 0)^2}{100-1}} \qquad (14)$$

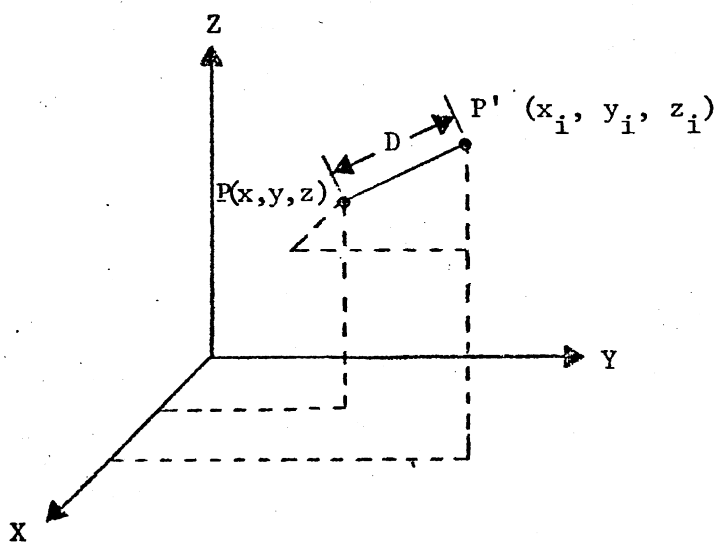


Figure 15 . Linkage Error

Standard deviations from the known values of X, Y, Z coordinates of Point P are given in Table XIII.

TABLE XIII

STANDARD DEVIATION FROM KNOWN X, Y, Z COORDINATES

| Parameter | Known Value (in.) | Standard Deviation $\sigma$ (in.) |
|---|---|---|
| X | -0.95 | 0.12 |
| Y | 6.48 | 0.08 |
| Z | -2.55 | 0.12 |
| $\ell$ | 7.03 | 0.085 |
| D | | 0.190 |

Known values of X, Y, and Z coordinates were obtained using a vernier caliper.

In Tables XII and XIII for zero error, D would have a value of zero. So, $\sigma$ is the deviation from the zero error condition.

APPENDIX E

LIGAMENT STRETCH VERSUS TORQUE

# LIGAMENT STRETCH VERSUS TORQUE

Ligament numbers shown on Table VIII and reproduced in Table XIV are those used to identify ligaments on figures 16 to 24. Numbers shown in the plots of figures 16 to 24 identify maximum loading points of each loading cycle of the given knee joints.

TABLE XIV

LIGAMENT NUMBERS AND ABBREVIATIONS

| Lig. No. | Abbreviation | Lig. No. | Abbreviation |
|---|---|---|---|
| 1 | SMC | 8 | PLC |
| 2 | ADMC | 9 | AC |
| 3 | MDMC | 10 | DLC1 |
| 4 | PDMC | 11 | DLC2 |
| 5 | IB | 12 | DLC3 |
| 6 | ALC | 13 | PC |
| 7 | MLC | | |

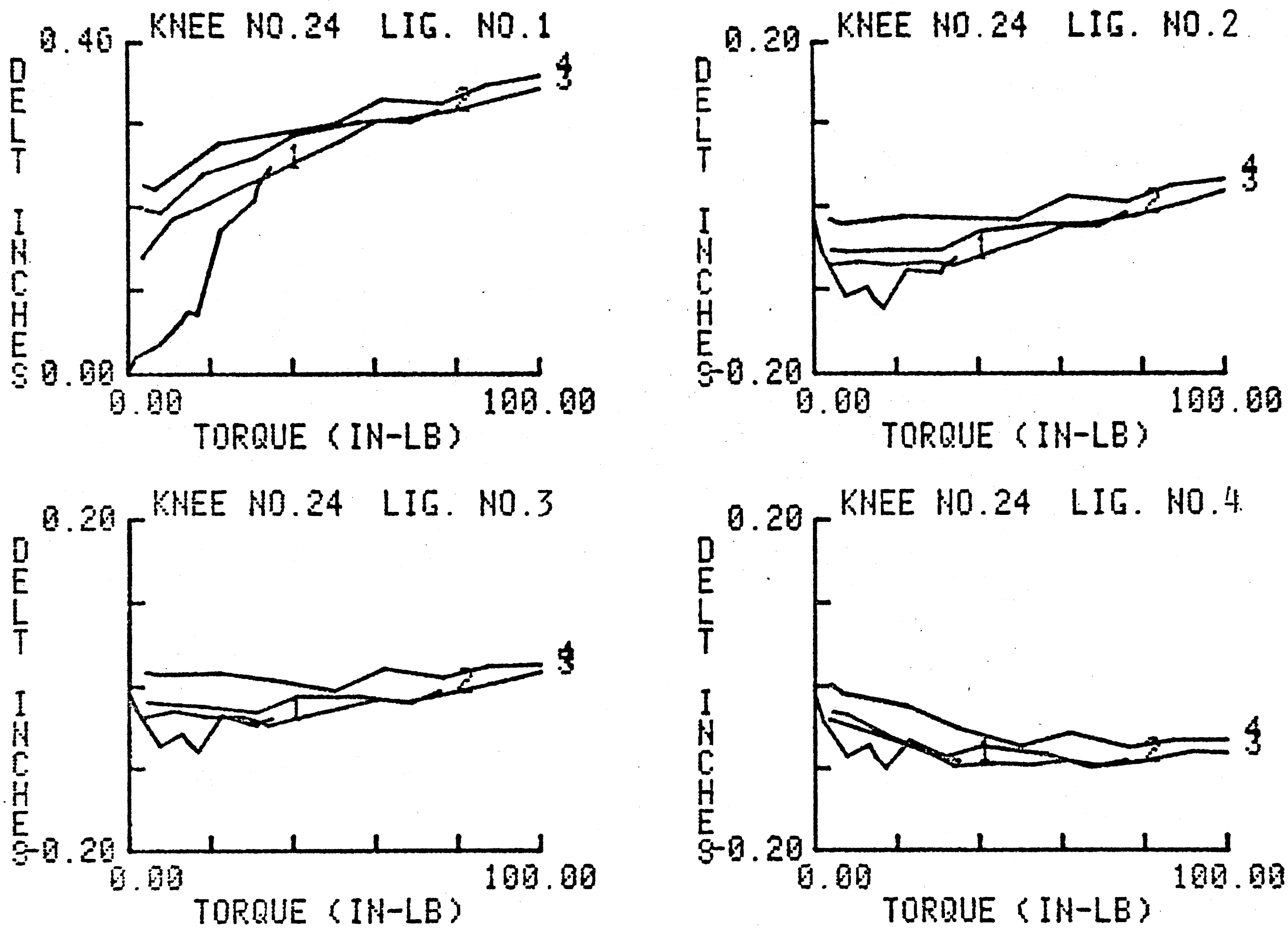


Figure 16. Knee 24 SMC, ADMC, MDMC and PDMC Ligament Stretch Versus Torque

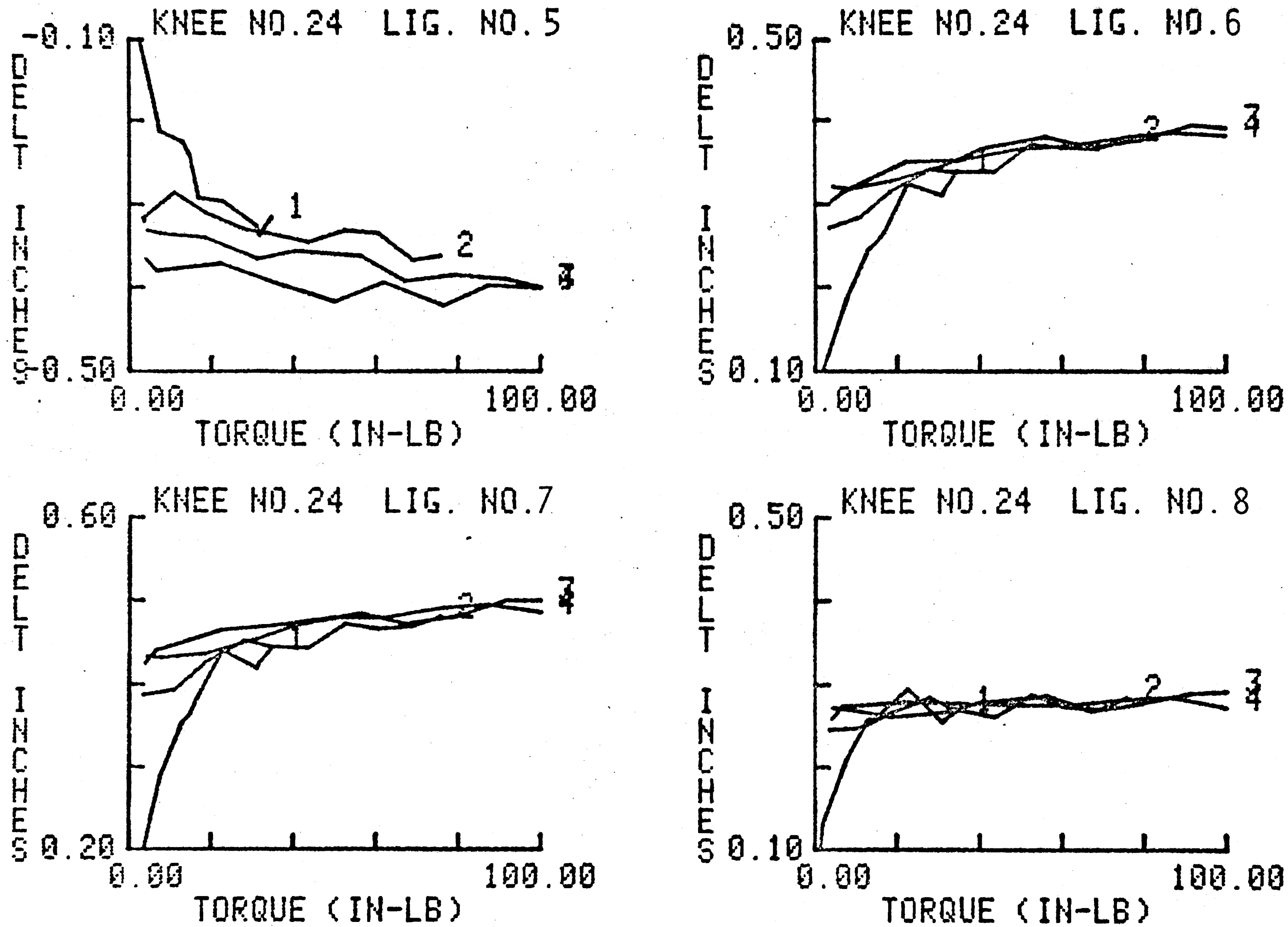


Figure 17. Knee 24 IB, ALC, MLC and PLC Ligament Stretch

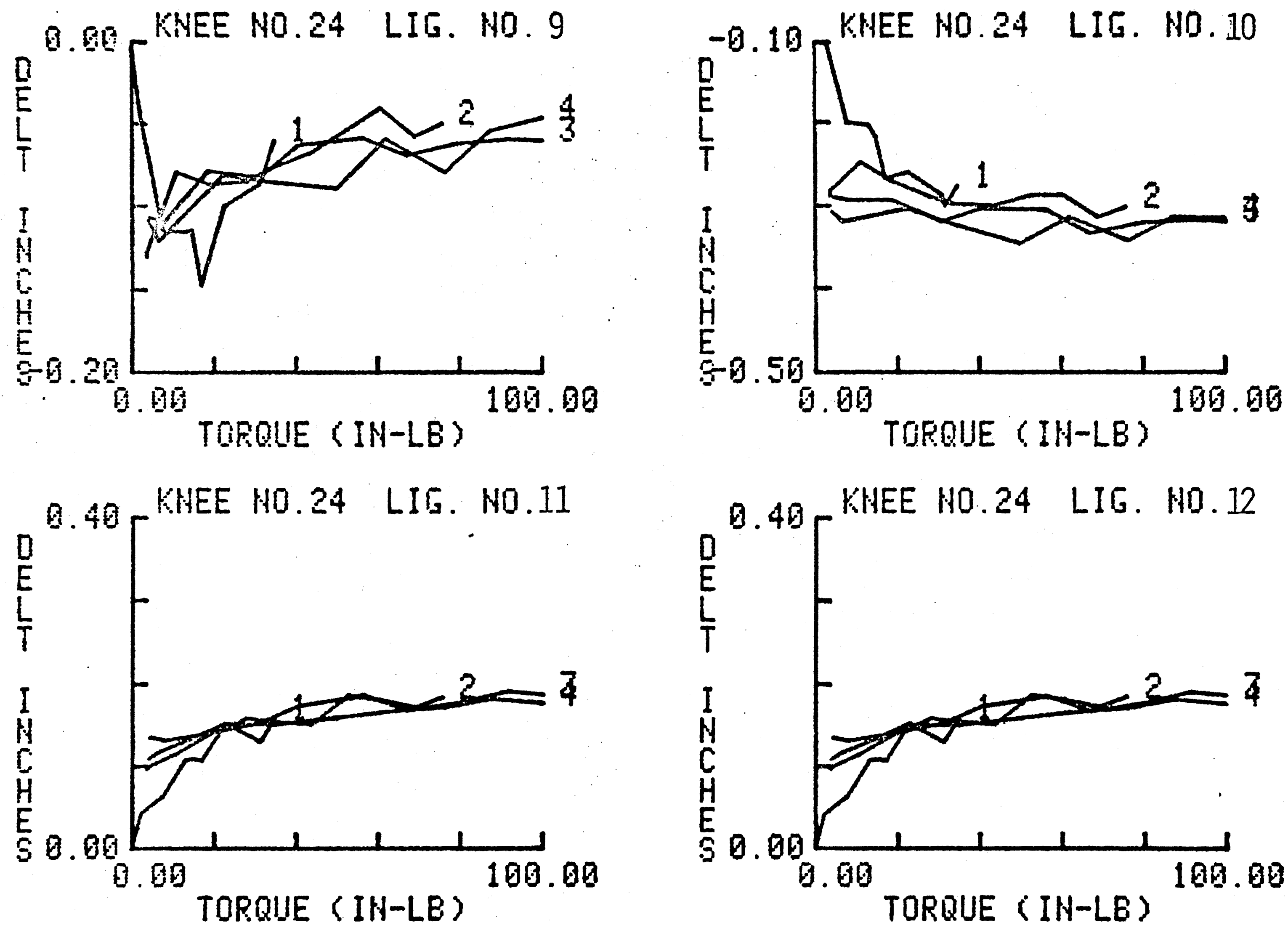


Figure 18. Knee 24 AC, DLC1, DLC2, DLC3 Ligament Stretch

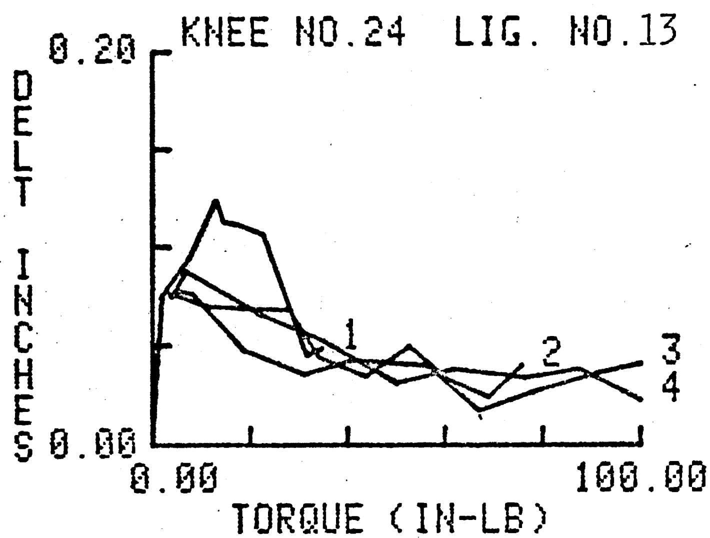


Figure **19**. Knee 24 PC Ligament Stretch

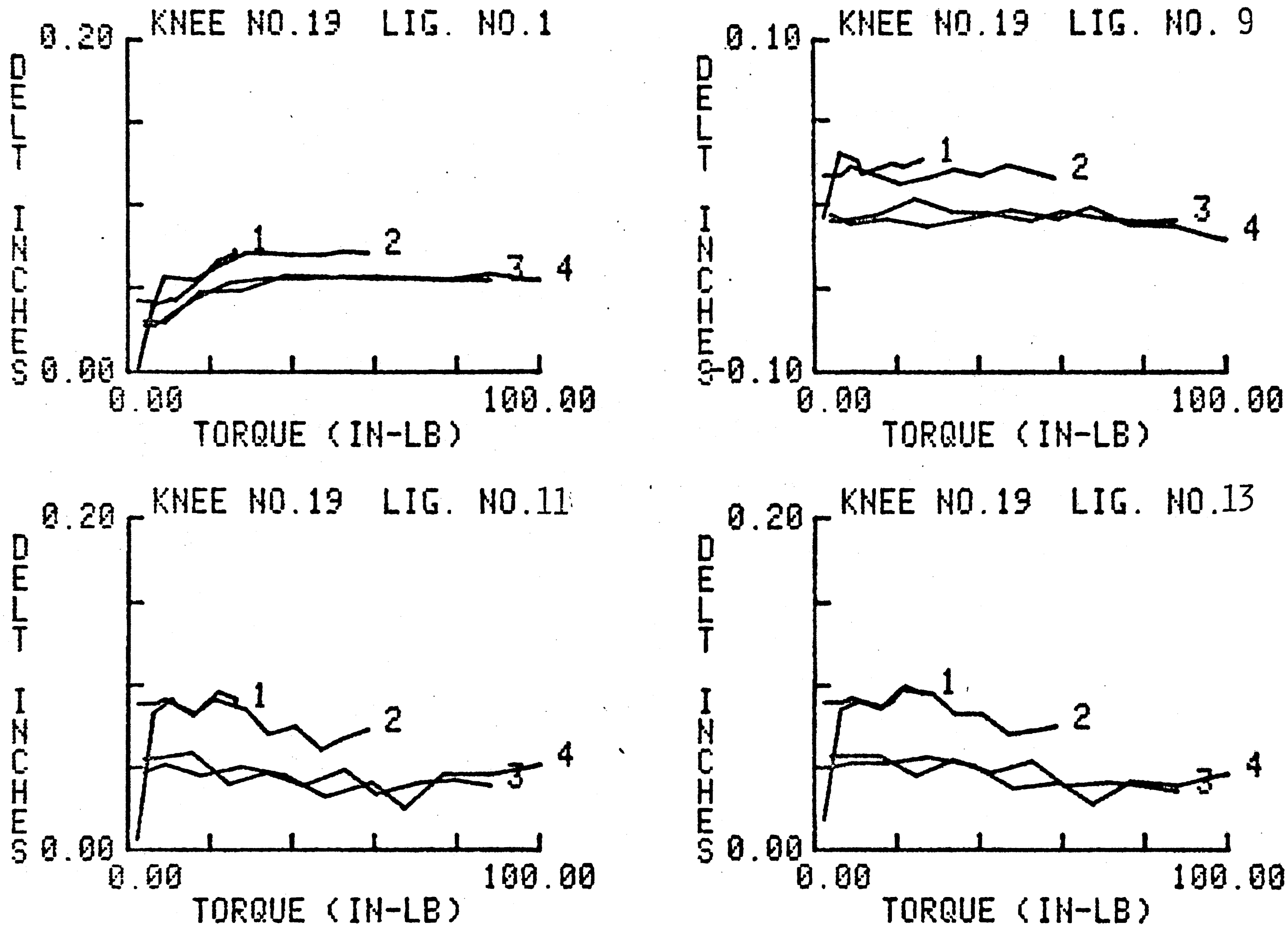


Figure 20. Knee 19 AC, PC, SMC and MLC Ligament Stretch

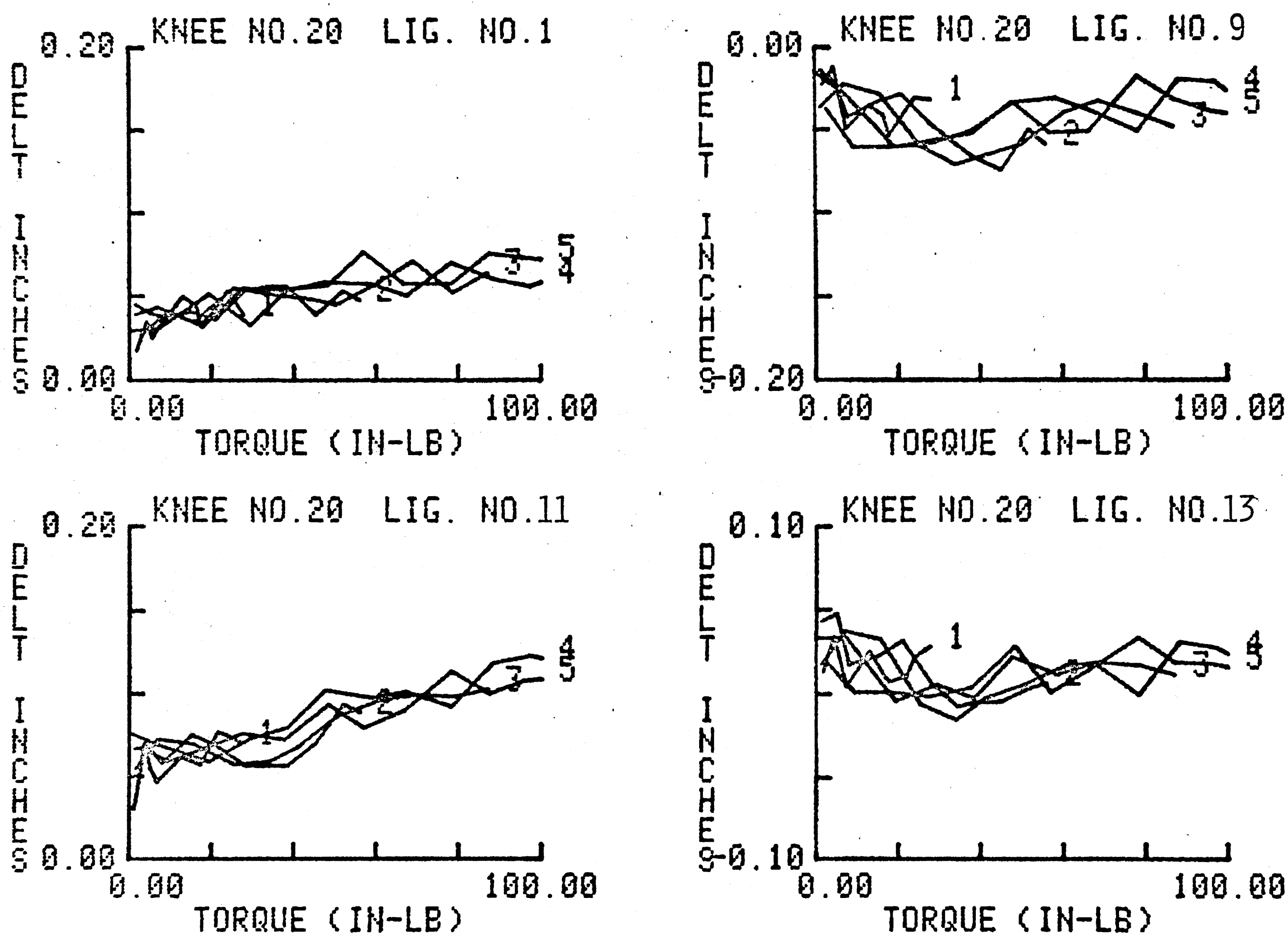


Figure 21. Knee 20 AC, PC, SMC and MLC Ligament Stretch

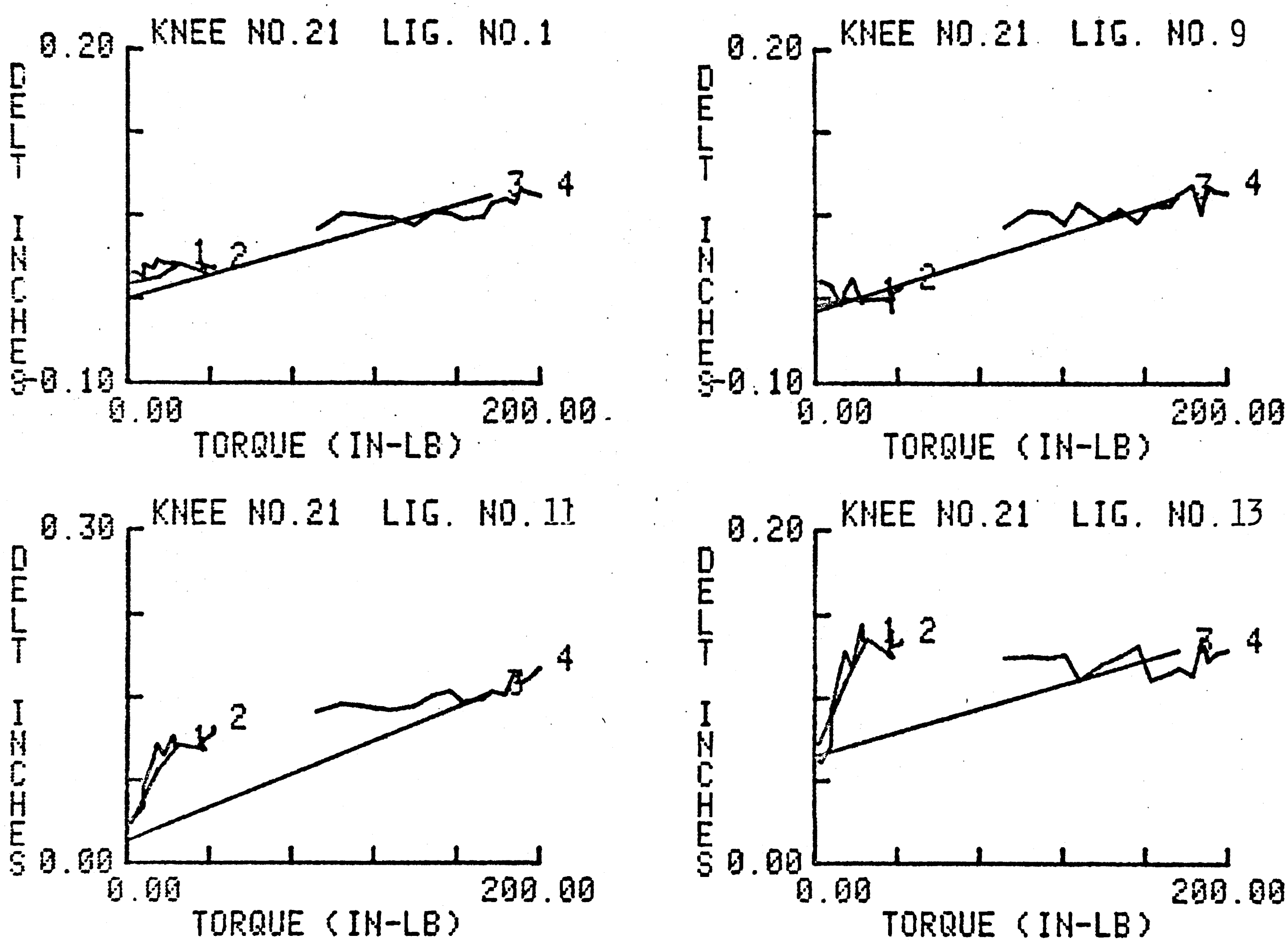


Figure 22. Knee 21 AC, PC, SMC and MLC Ligament Stretch

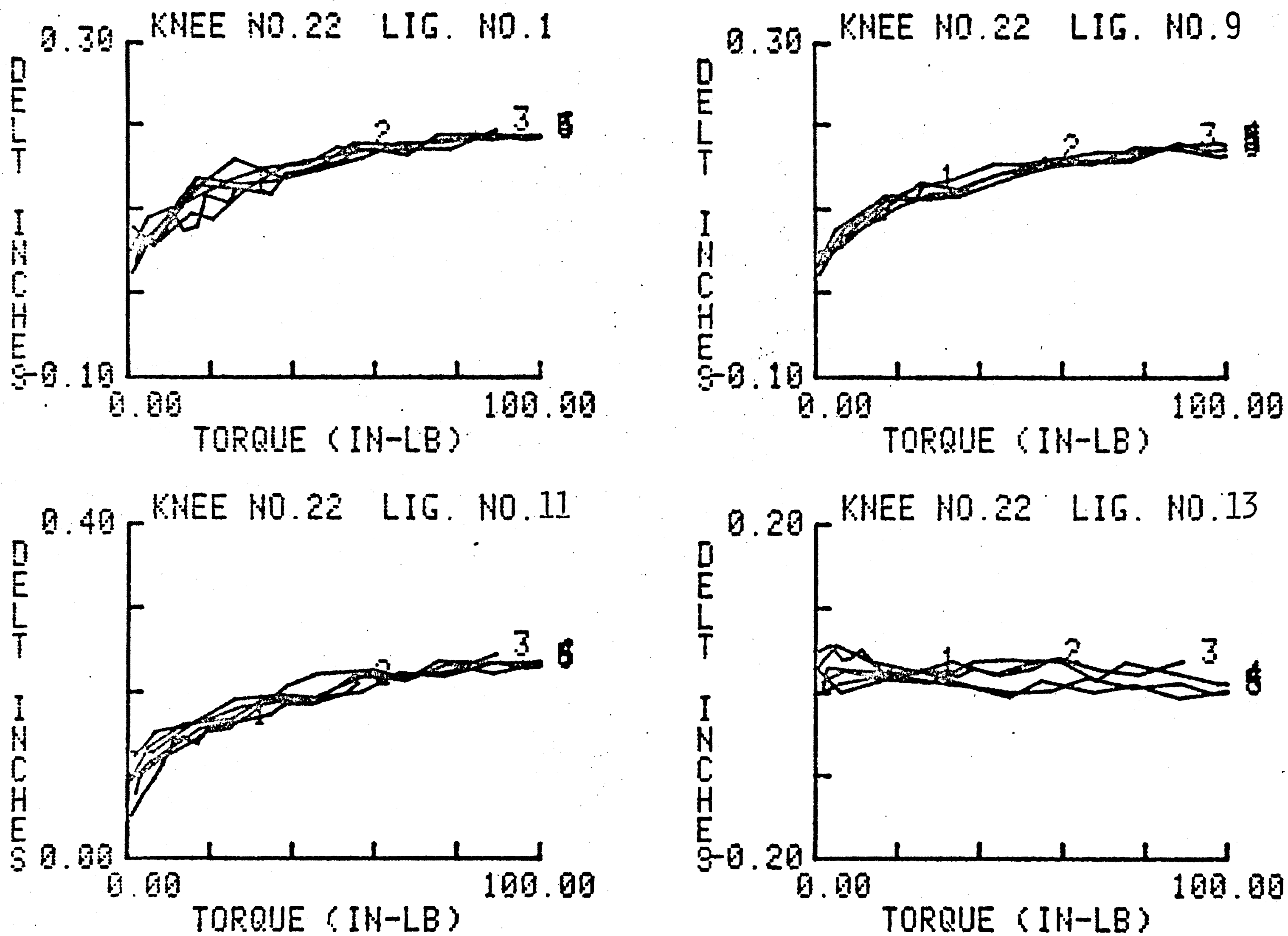


Figure 23. Knee 22 AC, PC, SMC and MLC Ligament Stretch

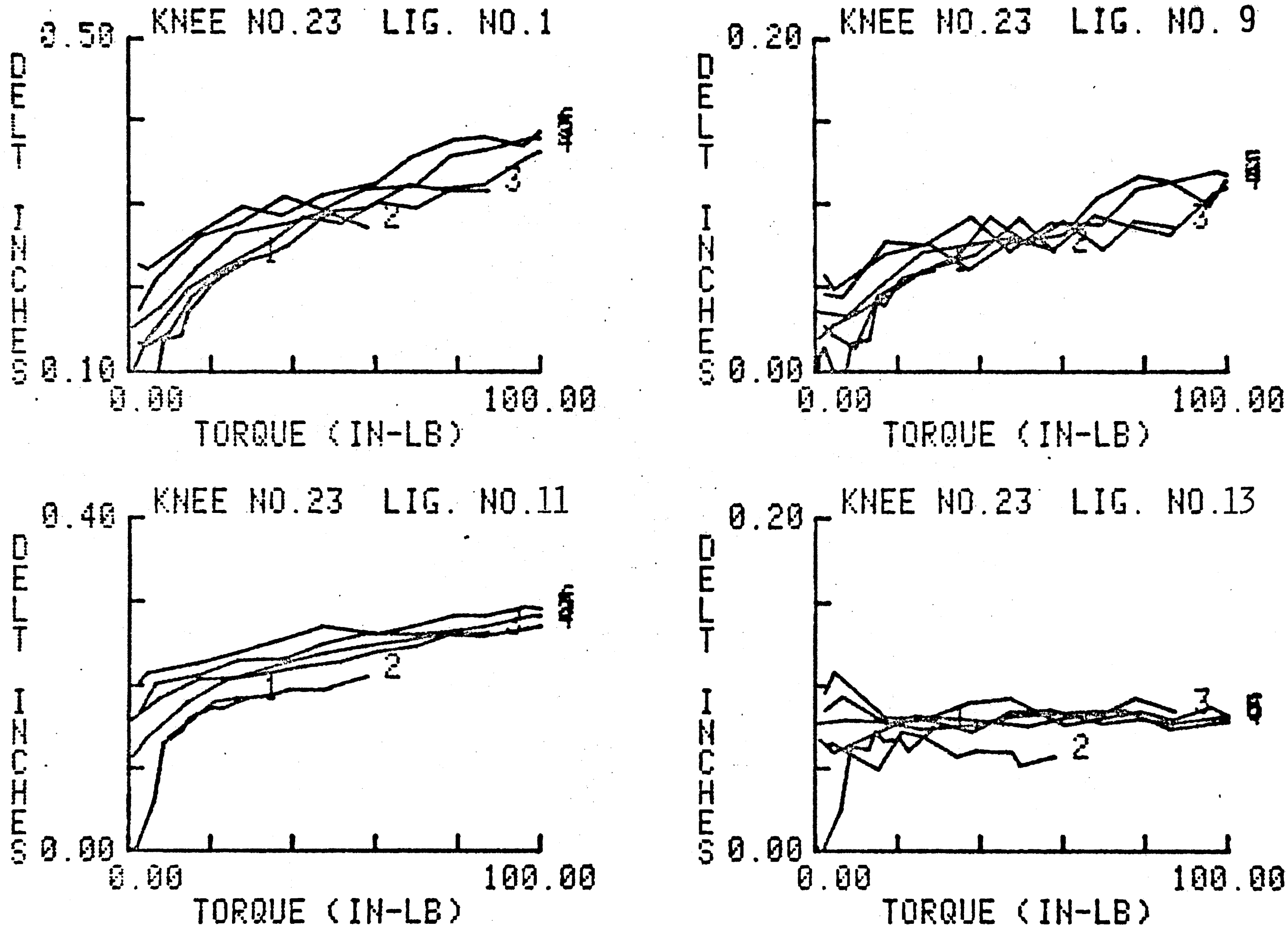


Figure 24. Knee 23 AC, PC, SMC and MLC Ligament Stretch

# APPENDIX F

# LIGAMENT TWIST CALCULATIONS

# LIGAMENT TWIST CALCULATIONS

If direction cosines of a screw axis defining motion between two bodies, and rotation about that axis are given, then rotation about any other axis can be determined. Directions cosines ($U_x$, $U_y$, $U_z$) of the screw axis defining motion of the knee joint and rotation ($\phi$) about that axis, are known (12). It is desired to find the twist ($\gamma$) of a ligament for a given rotation $\phi$ between tibia and femur.

Referring to Figure 25, T and $F_1$ are initial locations of ligament endpoints on the tibia and femur of a knee joint. $F_2$ is the location of the same ligament endpoint on the femur, after the femur has rotated about the screw axis $\phi$ degrees, to its second position. Ligament twist ($\gamma$) is the rotation of the ligament about its initial axis, $\overrightarrow{TF_1}$. Distance $d_1F_1$ has no influence on $\gamma$ for given $U_x$, $U_y$, $U_z$ and $\phi$. That is, if U were to pass through point T having direction cosines $U_x$, $U_y$, $U_z$ and rigid body rotation $\phi$, ligament twist $\gamma$ would be the same as if U was located as depicted in Figure 25. Furthermore, the distance d describes a translation of the femur with respect to the tibia and does not influence ligament twist.

For simplification of calculations, U is assumed to pass through T and a new coordinate system is set up as shown in Figure 26. To find the twist of the ligament about its initial axis $\overrightarrow{TF_1}$, calculate the rotation of a vector on the moving body (femur), in the plane

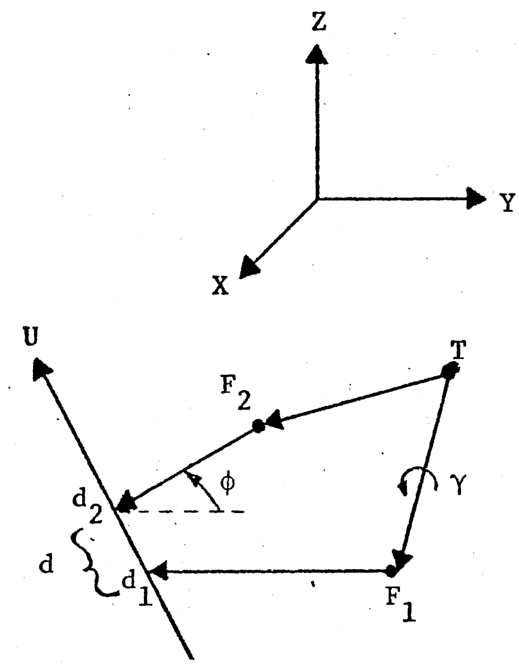


Figure 25. Ligament Twist Schematic

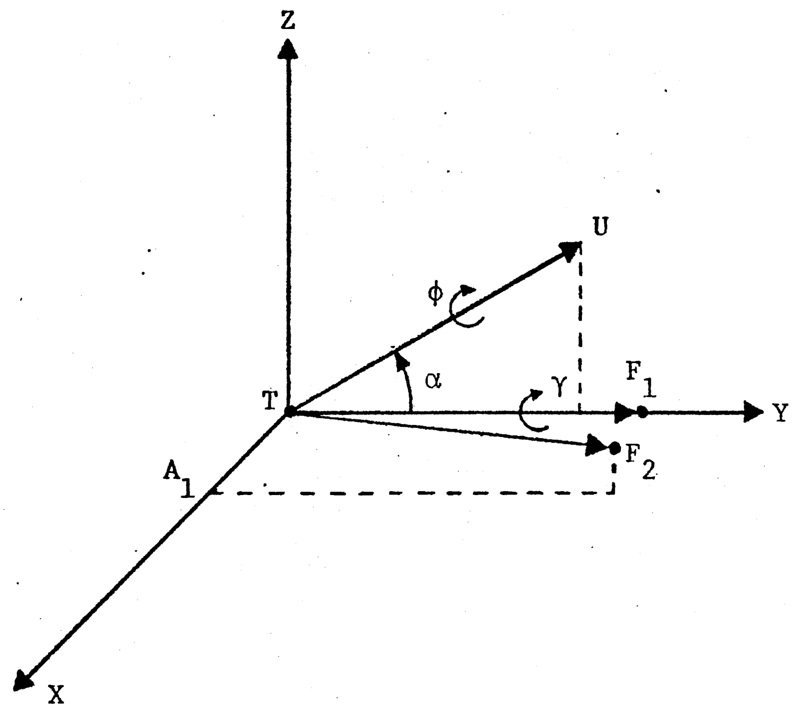


Figure 26. Screw Axis Repositioned

perpendicular to $TF_1$. For the coordinate system shown in Figure 26, point A, is assumed to be on the femus and has coordinates (1, 0, 0). Point A, is defined by vector $\overrightarrow{TA_1}$.

A rotation matrix R is now needed to determine ligament end-point coordinates on the femur, after rotating $\phi$ degrees.

$$\left[TA_2\right] = \left[R\right] \left[TA_1\right] \tag{15}$$

Rotation matrix R is a matrix product of three matrices which rotate $TA_1$ through $-\alpha$ degrees about the X-axis, $\phi$ degrees about the Y-axis and than $\sigma$ degrees about the X-axis.

$$\left[R\right] = \left[R\right]_{\alpha,x} \left[R\right]_{\phi,y} \left[R\right]_{-\alpha,x} \tag{16}$$

$$\left[R\right]_{-\alpha,x} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(-\alpha) & -\sin(-\alpha) \\ 0 & \sin(-\alpha) & \cos(-\alpha) \end{bmatrix} \tag{17}$$

$$\left[R\right]_{\phi,y} = \begin{bmatrix} \cos\phi & 0 & -\sin\phi \\ 0 & 1 & 0 \\ \sin\phi & 0 & \cos\phi \end{bmatrix} \tag{18}$$

$$\left[R\right]_{\alpha,x} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \tag{19}$$

$$\left[R\right] = \begin{bmatrix} \cos\phi & \sin\phi\ \sin\alpha & -\sin\phi\ \cos\alpha \\ -\sin\alpha\ \sin\phi & \cos^2\alpha + \cos\phi\ \sin^2\alpha & \sin\alpha\ \cos\alpha(1-\cos\phi) \\ \sin\phi\ \cos\alpha & \sin\alpha\ \cos\alpha\ (1-\cos\phi) & \sin^2\alpha + \cos\phi\ \cos^2\alpha \end{bmatrix} \tag{20}$$

Knowing that $\left[TA_1\right] = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$, $\left[TA_2\right]$ is found using equations C2 and C7

$$\left[TA_2\right] = \begin{bmatrix} \cos\phi \\ -\sin\alpha\ \sin\phi \\ \sin\phi\ \cos\alpha \end{bmatrix} \tag{21}$$

Ligament twist ($\gamma$) is the rotation of $\overrightarrow{TA_1}$ about the Y-axis as seen in Figure 27. $\gamma$ then is the angle between $\overrightarrow{TA_1}$ and $\overrightarrow{TA_2}'$ where $\overrightarrow{TA_2}'$ the projection of $\overrightarrow{TA_2}$ into the X - Z plane.

$$\left[TA_2'\right] = \begin{bmatrix} \cos\phi \\ 0 \\ \sin\phi\cos\alpha \end{bmatrix} \qquad (22)$$

Since $\overrightarrow{TA_1}$ lies on the X-axis, $\gamma$ is the angle between $\overrightarrow{TA_2}$ and the X-axis.

$$\gamma = \tan^{-1}\left(\frac{\sin\phi\ \cos\alpha}{\cos\phi}\right) \qquad (23)$$

It should be noted that $\overrightarrow{TA_1}$ must not only be perpendicular to the ligament axis defined by $\overrightarrow{TF_1}$, but also to the screw axis. The case when the screw axis is perpendicular to the ligament axis verifies this. In this case, if $\overrightarrow{TA_1}$ is perpendicular to those two axes, then a rotation $\phi$ about the screw axis will not cause a rotation about the ligament axis. That is if $\alpha = 90^\circ$ the Z coordinate of $\overrightarrow{TA_2}$ will always be zero (eq. C9).

In summary, ligament twist ($\gamma$) is dependent on two parametner; the rotation $\phi$ about the screw axis, and the angle ($\alpha$) between the screw axis and the ligament axis. Angle $\alpha$ is given by the dot product between the screw axis and the ligament axis.

$$\cos\alpha = \frac{\vec{U} \cdot \overrightarrow{TF_1}}{|U|\ |TF_1|}$$

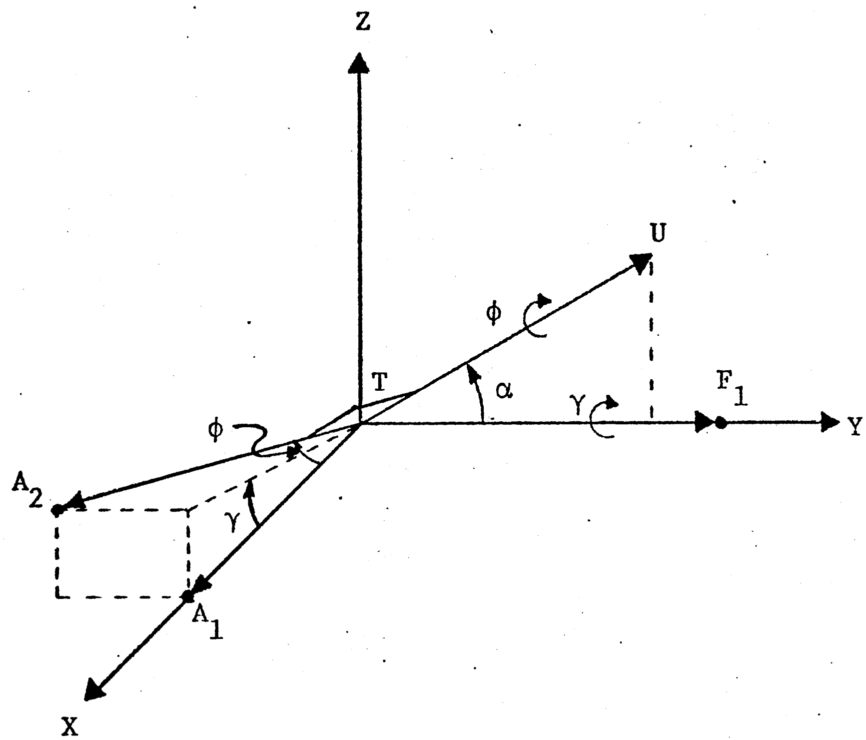


Figure 27. Ligament Rotation

APPENDIX G

COMPUTER PROGRAMS

```
$DBUG
$LAB= DJLG
C.............................................................
C
C      CALCULATES LIGAMENT TWIST FOR EACH LIGAMENT.
C      THE FOLLOWING STEPS SHOULD BE TAKEN TO
C      RUN THIS PROGRAM.
C          1)  *SE PA 1/F700
C          2)  *LD DJLG.LDM
C          3)  *AS 1,KNEEXXB.DAT
C              *AS 2,KXXTWST.DAT               (I,80)
C              *AS 5,CON:
C          4)  *ST
C
C..............................................................
C
       IMPLICIT INTEGER*2 (I-N)
       INTEGER*2 BUF1(64),BUF2(64),BUF3(64),BUF4(64),BUF5(64),
     &           BUF6(64),BUF7(64),BUF8(64),BUF9(64),BUF10(64),
     &           IN(64),OUT(64),OUT1(40)
C
       DOUBLE PRECISION ALPHA(6),A(6),S(6),THETA(6),P(3),U(3),
     &           TEMP(4),BPRD(4,4),ZETA(6,20),PSI(6,20),PNT1(6),
```

```
     &          PNT2(6),PNT3(6),PNT4(6),PNTM(4),PNTF(4),D,PHI,
     &          TRFORM(4,4),STRAIN(20),ALNGTH(20),TEMP2(4),
     &          TEMP1(4),T,GAM(20),CFIX(4,20),CMINF(4,20),CMOV(4,20)
C
      DIMENSION UO(3),PO(3),STRANO(20),GAMO(20)
C
      EQUIVALENCE (BUF3(1),ZETA(1,1)),
     &            (BUF4(1),ZETA(1,6)),
     &            (BUF5(1),PSI(1,1)),
     &            (BUF6(1),PSI(1,6)),
     &            (BUF7(1),ZETA(1,11)),
     &            (BUF8(1),ZETA(1,16)),
     &            (BUF9(1),PSI(1,11)),
     &            (BUF10(1),PSI(1,16))
C
      EQUIVALENCE (IN(1),THETA(1)),
     &            (IN(13),ANGPOS),
     &            (IN(15),TORQUE),
     &            (IN(61),NCY),
     &            (IN(62),NTP),
     &            (IN(63),NUD)
C
      EQUIVALENCE (OUT(1),STRANO(1)),
     &            (OUT(41),ANGPO),
     &            (OUT(43),TORQO),
     &            (OUT(45),PO(1)),
     &            (OUT(51),UO(1)),
     &            (OUT(57),PHIO),
     &            (OUT(59),DO),
     &            (OUT(61),NCYO),
     &            (OUT(62),NTPO),
     &            (OUT(63),NUDO)
      EQUIVALENCE (OUT1(1),GAMO(1))
C
      DO 10 I=1,64
```

```
      BUF1(I)=0
      BUF2(I)=0
      BUF3(I)=0
      BUF4(I)=0
      BUF5(I)=0
      BUF6(I)=0
      BUF7(I)=0
      BUF8(I)=0
      BUF9(I)=0
      BUF10(I)=0
      IN(I)=0
      OUT(I)=0
10    CONTINUE
20    NUMREC=1
      REWIND 1
      REWIND 2
      READ(1) BUF1
      WRITE(2) BUF1
      DO 30 I=1,3000
      READ(1,END=50,ERR=40) Z
30    NUMREC=NUMREC+1
40    PAUSE
      GO TO 20
50    IF (NUMREC.LE.62) GO TO 999
      NUMREC=NUMREC-1
C
C     GRAB THAT DATA
C
      CALL READER(BUF1,1,1)
      CALL READER(BUF2,2,1)
      CALL READER(BUF3,3,1)
      CALL READER(BUF4,4,1)
      CALL READER(BUF5,5,1)
      CALL READER(BUF6,6,1)
      CALL READER(BUF7,7,1)
      CALL READER(BUF8,8,1)
```

```
      CALL READER(BUF9,9,1)
      CALL READER(BUF10,10,1)
C
C     ALIGN IT
C
      CALL EQUATE(ALPHA,BUF1,6,1,5)
      CALL EQUATE(A,BUF1(13),6,1,5)
      CALL EQUATE(S,BUF1(25),6,1,5)
      CALL EQUATE(PNTF,BUF1(37),4,1,5)
      CALL EQUATE(PNTM,BUF1(45),4,1,5)
C
      CALL EQUATE(PNT1,BUF2,6,1,5)
      CALL EQUATE(PNT2,BUF2(13),6,1,5)
      CALL EQUATE(PNT3,BUF2(25),6,1,5)
      CALL EQUATE(PNT4,BUF2(37),6,1,5)
      CALL DROUND(ALPHA,6,3)
      CALL DROUND(A,6,3)
      CALL DROUND(S,6,3)
      CALL DROUND(PNTF,4,3)
      CALL DROUND(PNTM,4,3)
      CALL DROUND(PNT1,6,3)
      CALL DROUND(PNT2,6,3)
      CALL DROUND(PNT3,6,3)
      CALL DROUND(PNT4,6,3)
C
C     DEFINE IT
C
      DO 60 J=1,16,5
      CALL UNPACK(ZETA(1,J),30,3)
60    CALL UNPACK(PSI(1,J),30,3)
C
C     GET THE TRANSFORMATION MATRIX FROM OLDREF TO NEWREF
C
      CALL NEWREF(ALPHA,A,S,PNTF,PNT1,PNT2,PNT3,TRFORM)
```

```
C
      NLGMNT=20
      NOUT=1
      NCYO=1
      M=1
      DO 80 NREC=63,NUMREC
      CALL READER(IN,NREC,1)
      IF (NTP.EQ.0) GO TO 80
      NCYO=NCY
      NUDO=NUD
      NTPO=NTP
      ANGPO=ANGPOS
      TORQO=TORQUE
      CALL UNPACK(THETA,6,2)
      CALL SCREWD(ALPHA,A,S,THETA,U,P,D,PHI,M)
      IF(M.EQ.1) CALL STRND(ALPHA,A,S,THETA,ALNGTH,STRAIN,
     &   CFIX,CMINF,CMOV,PNTF,NLGMNT,ZETA,PSI,M)
      CALL LGTWSD(CFIX,CMINF,GAM,NLGMNT,M,U,PHI)
      CALL EQUATE(STRANO,STRAIN,20,1,4)
      CALL EQUATE(TEMP1(2),P,3,1,3)
      TEMP1(1)=1.0D0
      CALL PRODDT(TRFORM,TEMP1,TEMP2,4,4,1)
      CALL EQUATE(P,TEMP2(2),3,1,3)
      CALL EQUATE(TEMP1(2),U,3,1,3)
      TEMP1(1)=0.0D0
      CALL PRODDT(TRFORM,TEMP1,TEMP2,4,4,1)
      CALL EQUATE(U,TEMP2(2),3,1,3)
      IF (U(3).EQ.0.0D0) GO TO 70
      T=-P(3)/U(3)
      P(1)=P(1)+U(1)*T
      P(2)=P(2)+U(2)*T
      P(3)=0.0D0
      CALL EQUATE(UO,U,3,1,4)
      CALL EQUATE(PO,P,3,1,4)
      PHIO=SNGL(PHI)
      DO=SNGL(D)
70    CONTINUE
```

```
      CALL EQUATE(GAMO,GAM,20,1,4)
      CALL WRITER(OUT1,NOUT,2)
      NOUT=NOUT+1
      M=2
      WRITE(5,75) NREC
75    FORMAT(I4)
80    CONTINUE
C
999   STOP
      END
$DBUG
$LAB= LGTWSD
C.........................................................
C
C  ** DOUBLE PRECISION **
C  CALCULATES TWIST AROUND EACH LIGAMENT FOR A
C  GIVEN TWIST AROUND THE SCREW.
C
C  GIVEN:  CFIX - FROM SUBROUTINE STRND
C         CMINF - FROM SUBROUTINE STRND
C        NLGMNT - NO. OF LIGAMENTS
C             M - A FLAG THAT MUST BE 1 UPON FIRST ENTRY
C             U - FRON SUBROUTINE SCREWD (DIRECTION COSINES
C                 OF SCREW AXIS)
C           PHI - FROM SUBROUTINE SCREWD (RIGID BODY ROTATION
C                 AROUND THE SCREW)
C
C  RETURNED:
C           GAM - AN ARRAY CONTAINING THE TWIST IN DEGREES
C                 AROUND EACH OF THE LIGAMENTS.
C
C..........................................................
C
      SUBROUTINE LGTWSD(CF1X,CMINF,GAM,NLGMNT,M,U,PHI)
      IMPLICIT INTEGER*2 (I-N)
      DOUBLE PRECISION CFIX(4,20),CMINF(4,20),VFM(3,20),
```

```
     &         PHIR,COSA,SINA,
     &         AMAGFM(20),AMAGU,D,GAM(20),ALPHA,S,C,U(3),PHI
      WRITE(6,660)
660   FORMAT(9X,'U',27X,'PHI',7X,'VFM',25X,'ALPHA',7X,'GAM')
      DO 100 I=1,NLGMNT
      IF(M.NE.1) GO TO 20
      DO 10 K=1,3
10    VFM(K,I)=CMINF(K+1,I)-CFIX(K+1,I)
      AMAGFM(I)=DSQRT(VFM(1,I)*VFM(1,I)+VFM(2,I)*VFM(2,I)+
     &                 VFM(3,I)*VFM(3,I))
      GAM(I)=0.0D0
      GO TO 100
20    AMAGU=DSQRT(U(1)*U(1)+U(2)*U(2)+U(3)*U(3))
      D=AMAGU*AMAGFM(I)
      IF(D.NE.0.0D0) GO TO 30
      GAM(I)=270.0D0
      GO TO 100
C
C    PHI - RIGID BODY ROTATION AROUND THE SCREW AXIS
C ALPHA - ANGLE BETWEEN THE SCREW AND THE LIGAMENT AXIS
C    GAM - THE TWIST AROUND THE LIGAMENT AXIS
C
30    COSA=(VFM(1,I)*U(1)+VFM(2,I)*U(2)+VFM(3,I)*U(3))/D
      SINA=(1.0D0-COSA*COSA)
      ALPHA=DATAN2(SINA,COSA)
      PHIR=PHI/57.29578D0
      S=DSIN(PHIR)*DCOS(ALPHA)
      C=DCOS(PHIR)
      GAM(I)=DATAN2(S,C)*57.29578D0
      WRITE(6,600) U,PHI,(VFM(K,I),K=1,3),ALPHA,GAM(I)
600   FORMAT(9F10.3)
100   CONTINUE
      RETURN
      END
```

## VITA

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