AN ANALYSIS OF THE EFFECT OF THE ROTATIONAL, CONVEX, POLY-AXIAL, MECHANICAL KNEE BRACE (PROTOTYPE I) ON THE STABILITY AND DYNAMIC RANGE OF MOTION OF THE KNEE JOINT

by

CHRISTOPHER COOKE

B.A./B.P.H.E., Queen's University, 1973
B.Ed., Queen's University, 1974

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF PHYSICAL EDUCATION

in

THE SCHOOL OF PHYSICAL EDUCATION
AND RECREATION

We accept this thesis as conforming to the
required standard

THE UNIVERSITY OF BRITISH COLUMBIA

MARCH, 1977

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the Head of my Department or by his representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Graduate Studies, School of Physical Education and Recreation

The University of British Columbia
2075 Wesbrook Place
Vancouver, Canada
V6T 1W5

Date March 23, 1977

ABSTRACT

The functional loss of knee stability that results from soft tissue and ligamentous injury is a serious problem for the competitive athlete. Non-surgical attempts to restore femoro-tibial stability and function have been centered on the external application of supportive tape and athletic knee braces. Several athletic braces are available on the market today. The more substantial ones, however, have proven cumbersome and uncomfortable in their attempts to provide support for the unstable knee.

Prototype I of the rotational, convex, poly-axial, mechanical knee brace (Taylor Brace) was subjected to testing to determine its effect on knee stability and dynamic range of motion. Electrogoniometric recordings of knee function in three mutually perpendicular movement parameters were obtained from each subject at varying speeds of ambulation. Testing was conducted in the laboratory for unbraced and braced conditions using a 2 x 2 collapsible parallelogram chain electrogoniometer.

Instant center of rotation pathways and joint surface velocity angles were determined from roentgenogram analysis of the unstable knee for unbraced and braced conditions. Seven medial roentgenograms were taken of the knee with the femur fixed and the tibia moved from ninety degrees of flexion to zero degrees of flexion in

increments of fifteen to twenty degrees.

Stress analysis was carried out on the unstable knee using a mechanical stress machine. Regulated forces were applied to the knee joint and radiographic changes in the range of medial and anterior laxity recorded for the unbraced and braced knee. Subjective evaluation was also conducted in which subjects evaluated the Taylor Brace verbally, after each session of activity, and in an overall written assessement at the end of the study. Various aspects of brace construction and function were discussed under pre-determined criteria.

Electrogoniometric results showed that the Taylor Brace had a general restraining effect on unwanted internal-external rotation and varus-valgus movement of the knee. Reductions in the flexion-extension range were also recorded but were considered unimportant as a hindrance to total knee function. There was also an indication that the contra-lateral, unbraced knee pattern changed following bracing.

There were no consistent trends in the pattern or dispersion of the instant center of rotation pathways following bracing. A consistent shifting posteriorly and superiorly of the individual centers and a change in abnormal joint surface velocity angles, however, was noted following application of the Taylor Brace.

Subjective evaluation suggested several minor aspects of brace construction for improvement in future prototypes. Thigh cuff rigidity, tibial abraison and brace slippage were cited as areas for improvement. Knee joint range and articulation was considered excellent as well as ease of application, overall brace comfort, lightness and cosmetics of design.

ACKNOWLEDGEMENTS

Had it not been for the cooperation of Mr. George Taylor (G.F. Strong Rehabilitation Center) this study could not have taken place. His initial kindness in allowing the first prototypes of his brace to be tested and his subsequent help and advice throughout have made this study possible.

Thanks are due to Dr. Robert Hindmarch, Ms. Sue Fife, Dr. Ted Rhodes and Dr. David Harder for their criticisms and advice during the study. Thanks are also due to Dr. Frank Cox and Dr. T. Bridge (Workers' Compensation Board) for their advice on roentgenogtam technique; to Ms. Lefki Kriptos (G.F. Strong Rehabilitation Center) for her help with roentgenogram analysis; to Mr. Steve Cousins (Canadian Arthritis and Rheumatism Society) for his kind help and advice during electrogoniometric testing; and to the subjects, Bruce Goldsmid, Brian Barker and Doug Finlay for their time and cooperation. My thanks.

Finally, a special note of thanks to David Rankine and Bob Field for their excellent art work, and of course to L.C.

C.C.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure | Page

CHAPTER I

STATEMENT OF THE PROBLEM

Introduction

During normal activity, the ligaments of the knee joint are essential for the control, integrity and stability of the knee. The specific function of the individual ligaments (Wolf, 1973) and the functional loss that results from soft tissue and ligamentous injury, singly or in combination, has been well documented (Kennedy, 1971;1973; O'Donoghue, 1973; Slocum, 1974; Hughston et al, 1976; and Eriksson, 1976). Internal derangement, as a result of partial or complete lesions of the ligamentous structures of the knee has been clinically shown to produce exaggerated medial and anterior laxity and instability of the knee joint with resultant pain and loss of function (Kennedy and Fowler, 1971).

Attempts to restore femoro-tibial stability by the application of external support have been approached from two directions. Researchers interested in the non-surgical treatment of the athlete who wishes to return to athletic competition, have studied the effects of taping on the unstable knee (Roser, Miller and Clawson, 1971; Noonan and Cooke, 1976). Biomechanical and medical researchers (Lehmann, Warren and DeLateur, 1970; Roser, Miller and Clawson, 1971; Kennedy and Fowler, 1974) have been concerned with the effect of bracing on knee stability, motion and athletic function.

Nature and Scope of the Problem

Several athletic knee braces are available on the market today, the Lennox-Hill Derotation Brace[1] being one that has been shown, with proper application, to reduce chronic knee instability, pain and swelling in damaged knees (Kennedy, 1974). Although supportive for the correction of medio-lateral and antero-posterior movement, the nature of the application of the Lennox-Hill Brace, however, has tended to sacrifice comfort, lightness and flexibility for strength and support.

Often obstructive on quadriceps and hamstring bulk, and irritating through the popliteal region of the knee with active use, the Lennox-Hill Brace has proven cumbersome and uncomfortable.

---

[1]Information available on request from Hodgson Orthotics Ltd., 1650 West Broadway, Vancouver, B.C. V6J 1X6.

The straps for the brace attachment to the thigh and calf, the bi-lateral derotation straps and the metal frame of the brace itself are constrictive and can reduce circulation to the underlying tissues (Figure 1).

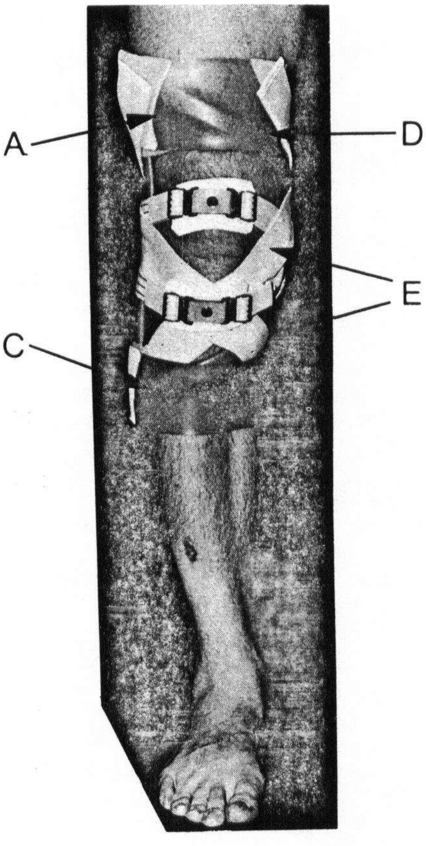


Figure 1. Lennox-Hill Derotation Brace showing (A) and (C) straps for brace attachment to the thigh and calf; (E) bi-lateral derotation straps and (D) metal brace frame.

To the athlete, obstruction of muscle function and numbness of the limb as a result of constriction of surface vessels, and the irritation on the skin can seriously hamper the duration of use and the efficiency of walking or running. The movement mechanics of the Lennox-Hill, "Bub" Duribilknit[2] and Palmer[3] Athletic Braces have been built into bi-lateral supportive struts in the form of single hinge and off-set hinge joints (See Figure 1 , Definition of Terms). Allowing planar movement in the fixed, single-axis direction of flexion and extension, conventional athletic brace joint designs have ignored the internal-external rotation and varus-valgus movement of the tibia and femur that takes place during normal knee motion.

Jesswein (1966) developed a polycentric knee joint that provided stability, at the same time allowing for a shifting of the knee brace axis with the angulation of the anatomical joint. Its one drawback for functional use was that it only allowed flexion with weight-bearing up to fifteen degrees. To date, no mention has been found in the literature of a device flexible enough in its design to simulate the anatomical functioning of the human knee joint, that is not restricting because of its weight, that is comfortable and that can provide the necessary knee stability, support and dynamic function.

---

[2] Manufactured by John B. Flaherty Co., Incorporated, New York, N.Y. Distributed by Sparlings Sporting Goods, 929 Granville St., Vancouver, B.C.

[3] Developed by Rex B. Palmer, M.D. of Seattle. Available from Quik-Cold Incorporated, Moberly, Missouri, U.S.A.

Knee Brace Description

The rotational, convex, poly-axial, mechanical knee brace (Taylor Brace) prototype consists of a lateral leg iron composed of two independently articulating metal extensions held together at the knee by a common, convex base (Figure 2). The leg iron is constructed of .072 inch tempered, high carbon (C1095) steel.

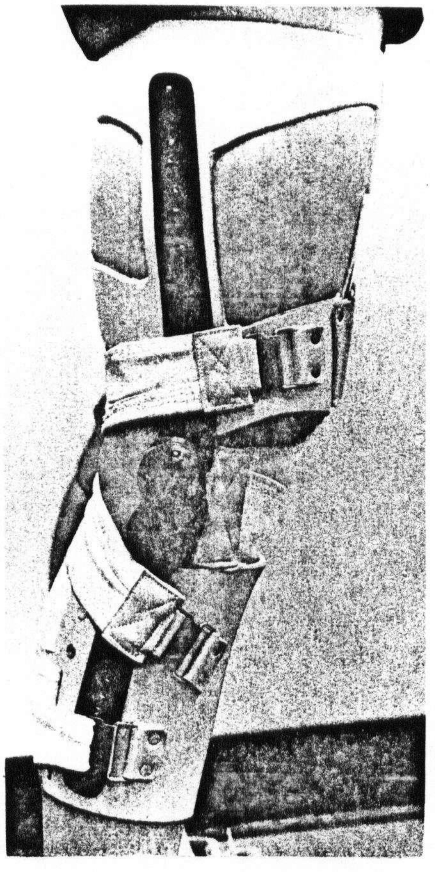


Figure 2. Taylor Brace, lateral view.

Articulation simulating an anatomical knee movement comes about by the geometric slotting on the joint ends of the extension arms moving simultaneously on the convex surface of the base. The pathway of the extension movement is governed by pins sliding in the slots. The nature of the convex surface of the base and the slope of the slots on the extension arms, allows rotation of the extensions to the inside and to the outside (Figure 3).

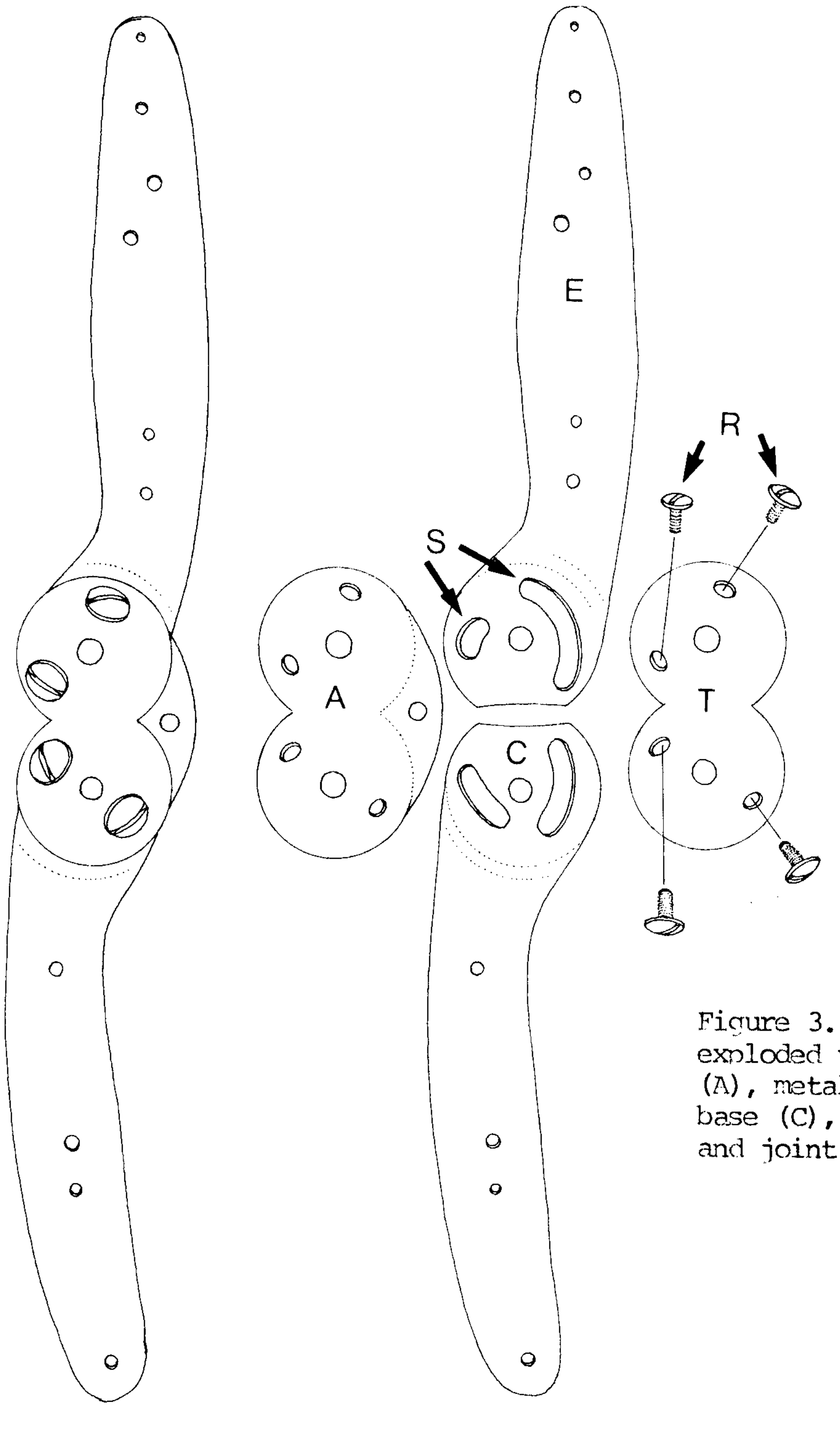


Figure 3. Taylor Brace Joint, exploded view showing convex base (A), metal extensions (E), extension base (C), metal pins (R), slots (S) and joint cover (T).

The lateral leg iron is secured to the leg by means of flexible, moulded thigh and calf cuffs. These cuffs are made of polyester resin, vacu-moulded from a positive cast of the leg. The moulded thigh and calf cuffs are lined with a foam padding to protect the skin in the area of application. The articulating joint lies close to the skin at the knee but is never in contact (Figure 4).

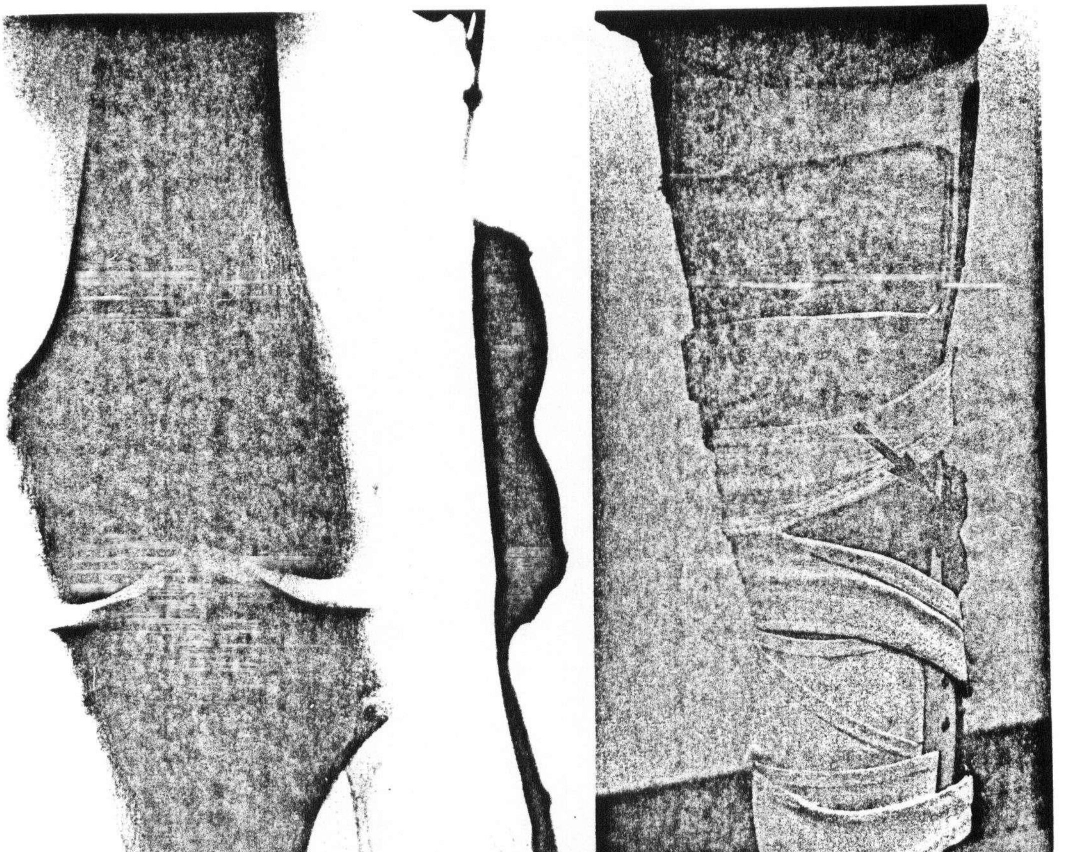


Figure 4. Posterior view of the knee with the Taylor Brace applied. Note the position of the brace joint relative to the femoro-tibial articulating surfaces. The arrow shows the location of the articulating joint close to the skin.

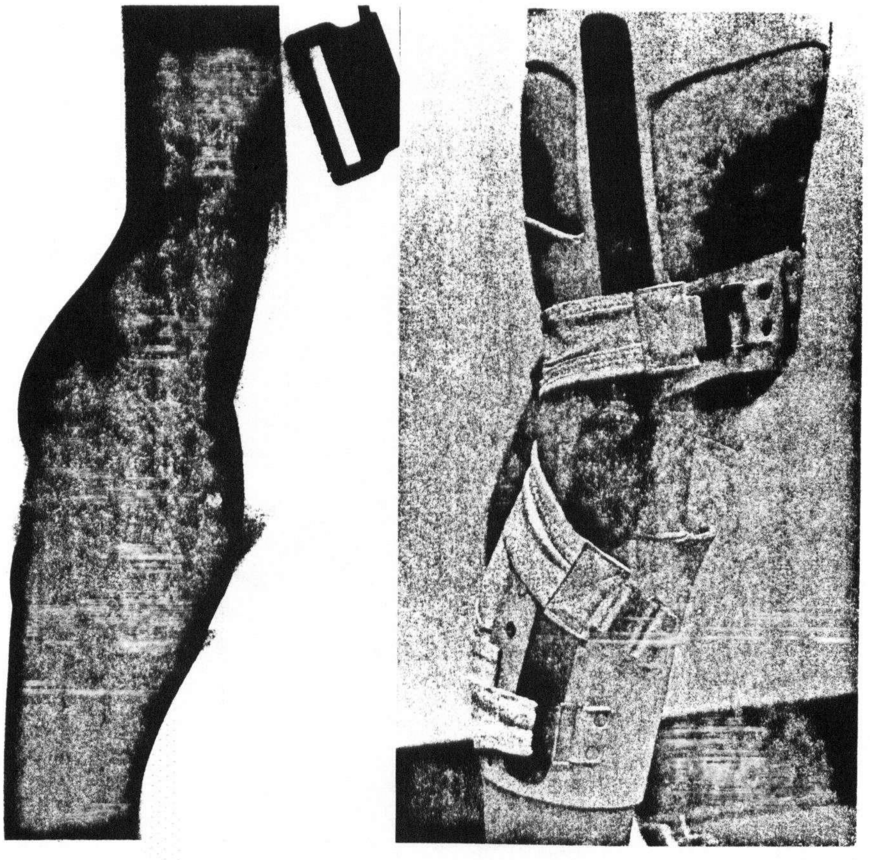


Figure 5. Lateral view of Taylor Brace applied. Note the location of the brace joint and the position of the extension arms relative to the shafts of the femur and tibia.

Additional medial support is provided by an elastic strap webbing extending from the lateral leg iron, over the patella, across the medial aspect of the knee and attaching to the fiberglass cuffs. The popliteal region of the knee is, therefore, not restricted (Figure 6).

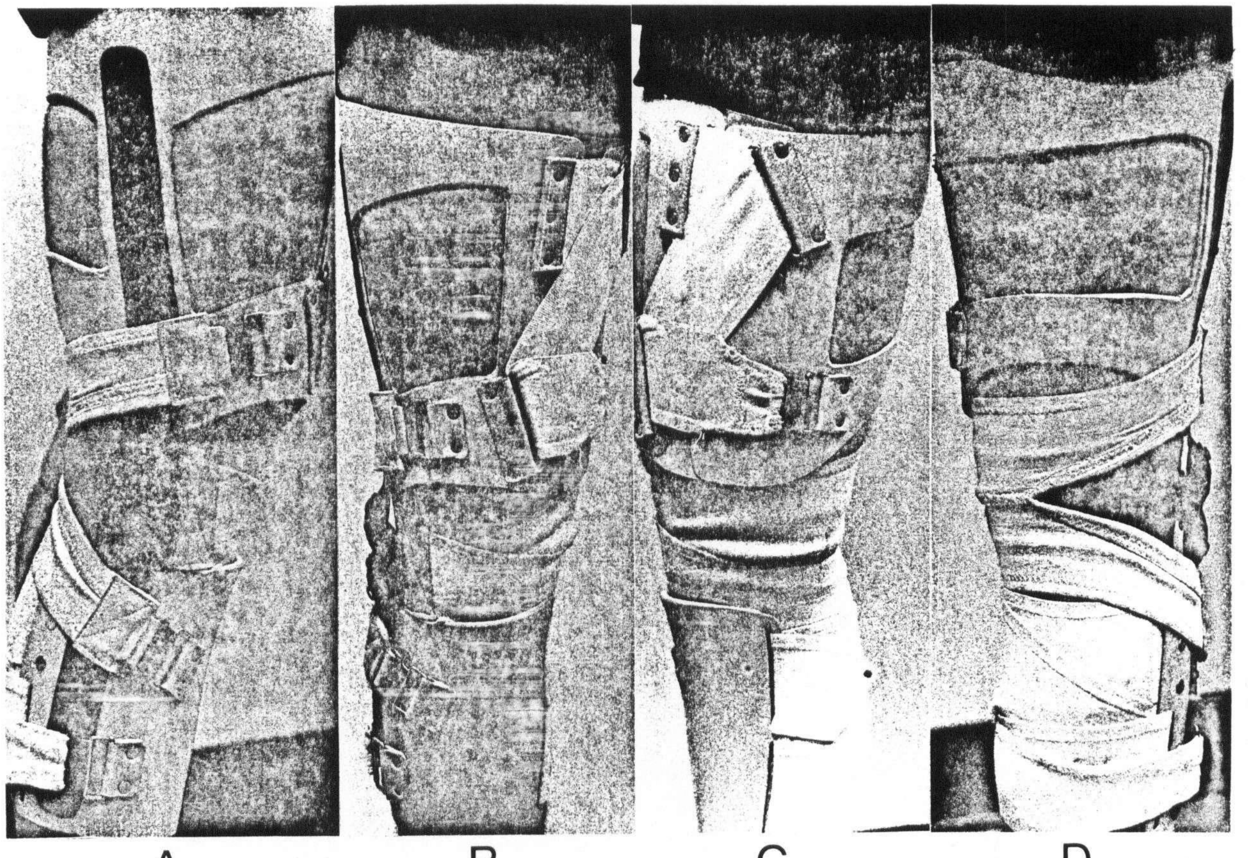


Figure 6. Sequence view of Taylor Brace applied showing (a) lateral view, (b) anterior view with medial support strap originating from lateral leg iron and crossing patella, (c) medial view and (d) posterior view showing free popliteal region.

Statement of the Problem

The purpose of this study is to determine the effect of the rotational, convex, poly-axial, mechanical knee brace (Taylor Brace) prototype on the stability and dynamic range of motion of the human knee joint.

Justification and Significance of the Study

The study is designed to apply the present work being done in the field of orthotic bracing to athletics. In particular, it is being done to evaluate the Taylor Brace under fairly natural conditions of walking and running. It is also intended to utilize new developments in the field of electrogoniometry to analyse normal and pathological knee function by determining pathological patterns in unstable knees and specifically of the effect of bracing on knee function.

The use of a roentgenogram technique for the determination of the instant center of rotation for the knee is also being investigated and the Taylor Brace is being used to evaluate the effect of bracing on that pattern. Stress analysis of joint laxity will be included to determine the effect of the brace on stability of the knee under force application. Electrogoniometric and roentgenogram analysis of the function of the braced knee can provide information useful to the orthopaedic surgeon, athletic trainer and rehabilitation therapist on the effect of the Taylor Brace design on the function of the abnormal knee.

Delimitations

The determination of normal and pathological knee function will be confined to the evaluation of dynamic clinical electrogoniometric data of the knee joint. All functions of walking and running are performed in the laboratory under controlled conditions. The recorded data can, therefore, only be interpreted from this restricted situation. The roentgenogram measurements for instant center of rotation calculation were performed in a lying position from ninety degrees of flexion to full extension. The non-weight-bearing nature of the evaluation cannot, therefore, be correlated with the function of the knee joint with weight-bearing. Roentgenogram stress analysis was carried out in the laboratory using mechanically simulated forces imposed at the knee joint. The results can only be considered from this restricted situation.

Assumptions and Limitations

In the analysis of electrogoniometric data, the following information is taken into consideration:

(a) elgon accuracy as determined by joint simulation reproduction will keep the recording of the data from knee function to within an error of four percent (Cousins, 1975:74).

In determining the instant center of rotation for the knee, the following points will be followed:

(a) two fixed points on the femur are considered sufficient (Frankel and Burstein, 1971:916).

(b) all medio-lateral and axial rotation movement of the knee is ignored and only flexion and extension will be used.

Definition of Terms

Definition of the following terms is necessary for the understanding of joint function and movement parameters (See Appendix A: Knee Axes of Rotation).

Flexion-extension

Movement about the knee joint in the saggital plane.

Internal-external Rotation

Inward and outward movement of the tibia about its long axis with respect to the femur.

Varus-valgus

Movement about the knee joint occurring in the coronal plane.

Internal Derangement of the Knee

An anatomical disturbance of the structures within the knee joint, both bony and soft tissue, resulting in changes in the mechanics of the joint.

Medial Laxity

The extent of the intra-articular gap or distance between the most distal portions of the sub-chondral bone of the medial femoral condyle and the most distally placed portions of the sub-chondral bone of the medial tibial condyle. In damaged knees, medial laxity increases with stress application as a result of ligamentous instability.

Anterior Laxity

The amount of forward displacement of the medial and lateral tibial condyles with respect to the medial and lateral femoral condyles. Anterior laxity increases with stress application as a result of ligamentous instability.

Offset Hinge Joint

A joint formed from two extensions of metal coming together in a common hinge, allowing independent articulation of the extensions in a fixed, single-axis direction through ninety degrees. The hinge is offset posteriorly from the line formed by the metal extensions (Figure 7).

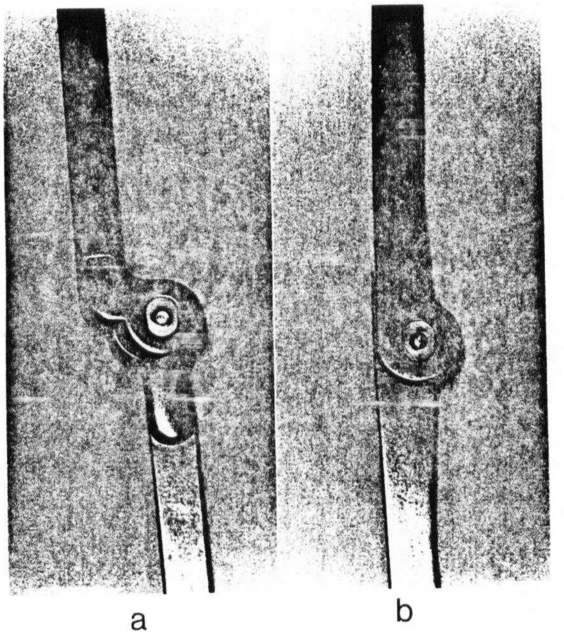


Figure 7: (a) Offset hinge joint and (b) hinge joint.

Hinge Joint

A joint formed from two extensions of metal coming together in a common hinge allowing independent movement of the extensions in a fixed, single-axis direction through ninety degrees. The hinge or point of articulation is in line with the metal extensions (Figure 7).

Poly-centric Joint

A joint formed through the geared articulation of two extensions of metal about each other on a common plane. This allows movement in a fixed-axis direction. The geared nature of the joint produces a driving action with the result that one metal extension is driven about the other producing two axes of rotation.

Poly-axial

A term used to define articulation in more than one plane or about more than one axis. The human knee joint is poly-axial in that the axis of rotation is constantly shifting or travelling during active knee function.

CHAPTER II

REVIEW OF THE LITERATURE

Electrogoniometric Studies

Electrogoniometry* measures motion using potentiometer transducers. There are recording techniques for measuring joint motion using closed-circuit video tape, strobascopic cinematography and motion analysis, but the techniques themselves are time consuming and the data must be reduced to useable numerical or graphical information. The electrogoniometer is externally worn by the subject and converts joint movement into voltage. The data produced is easily interpreted in direct graphical form.

Electrogoniometric evaluation of human joint motion has been divided into the research activities of the following three major groups:

(1) The investigations of Karpovich et al (1960, 1962, 1964, 1965) initiated the clinical use of the elgon. This device consisted of a potentiometer and two metal bars or lever arms, one attached to the potentiometer casing and one attached to the potentiometer shaft.

---

* "electro" refers to the voltage produced by the potentiometer motion transducer; "goniometry" comes from the Greek, gonia, which means angle and refers to angle movement. The device used is called an electrogoniometer, often referred to as an "elgon".

One lever arm was strapped above the joint and one below. By aligning the shaft of the potentiometer to the joint axis of rotation, joint motion in that plane could be measured. Angular joint rotation was converted to a voltage output by the potentiometer, which was then graphically recorded. Flexion-extension of the knee and ankle joints were measured for normal and pathological gaits during various, everyday and athletic activities. The work of Karpovich et al initiated research into dynamic movement evaluation by providing an instantaneous recording of joint motion. This work was limited, however, because:

(a) knee joint motion evaluation was limited to flexion-extension, ignoring the additional movement parameters of internal-external rotation and varus-valgus that take place coincident with the normal flexion-extension phase of knee articulation.

(b) most of the published data was for one leg only; the movement of the unmonitored leg and its effect on gait pattern was not considered.

(c) potentiometer alignment with the joint center of rotation was a matter of guesswork and could vary between successive applications to yield a significant source of error. The constantly shifting axis of the poly-axial anatomical knee joint could not be accurately accommodated by a fixed, single-axis mechanism.

(2) Johnson and associates advanced the work of Karpovich, evaluating the movement of the hip (Johnson, 1969) and knee joints (Kettlekamp and Johnson, 1970) during normal walking and of the knee during activities of daily living (Laubenthal and Kettlekamp, 1972). Johnson and Kettlekamp established the first electrogoniometric values for the three mutually perpendicular rotations of flexion-extension, varus-valgus and internal-external rotation of the knee. Laubenthal and Kettlekamp provided useful electrogoniometric data of knee function

during activities of climbing stairs, lifting objects and sitting down. Although their work contributed to the knowledge of joint motion, the solutions of Johnson and his associates were also restricted because:

(a) their measuring device was not self-aligning and had to be positioned for each trial within a given distance of the calculated joint center.

(3) Lamoreux (1971), in his studies of gait, set down the most extensive criteria for the evaluation of human joint motion. He developed and tested an exoskeleton device that simultaneously measured three dimensional motion of the pelvis and the major joints of the right lower extremity of a single, normal subject walking on a treadmill. Measurements were made at six different speeds. Results were presented in graphical form to permit visual interpretation of the effects of variations in speed on the patterns of motion.

Lamoreux's exoskeleton had self-aligning parallelogram linkages that made evaluation of poly-axial joints possible by the use of single-axis potentiometers. Although enhancing reproducibility by reducing re-alignment error, Lamoreux's device had the following limitations:

(a) the weight of the device (3.5 kilograms) made it quite cumbersome and did not allow more mobile activity than normal walking.

(b) the hip analog was not self-aligning, again introducing the error of alignment for successive trials.

(c) the complicated application of two self-aligning parallelogram linkages for evaluation of ankle motion produced a bulky device.

(d) the elaborate nature of application limited its use to a laboratory.

Recent Electrogoniometric Evaluation of Joint Motion

Recent work by Cousins (1975) has produced a parallelogram chain design capable of measuring, simultaneously, tri-axial movement of the hip, knee and ankle joints. As each parallelogram scissors "unwanted translations are absorbed while three mutually perpendicular rotations pass through the chain unchanged." This allows the device to be essentially self-aligning and evaluation of flexion-extension,internal-external rotation and varus-valgus movement can be carried out. The rotational movement passing through the chain is registered by potentiometers positioned along the axes of rotation and a permanent graphical record is obtained.

The device has been developed for easy, bi-lateral application, is light (1.7 kilograms) and non-restricting. It can be used for indoor or outdoor testing at varying rates of ambulation. Clinical application of the parallelogram chain device is currently being investigated for the evaluation of normal and pathological gaits.

Reproducibility of the electrogoniometer was measured by placing it on a normal subject and obtaining a graphical record of level walking. The equipment was then removed, replaced and tested again. This technique was repeated a number of times for various subjects until reproducibility was achieved.

Electrogoniometry of Abnormal Knee Patterns

Kettlekamp et al (1970) presented data on abnormal knee patterns from their studies of knee motion in normal gait. Electrogoniometric tracings of a patient with degenerative genu varum showed greater knee extension during the stance phase than during neutral stance. They also produced data from a patient with rheumatoid arthritis with a loss of bone from the lateral tibial plateau and increased valgus. Electrogoniometric patterns of the knee showed very little flexion-extension. The abduction-adduction patterns were grossly abnormal with the swing phase of the leg during normal walking being quite reduced.

Karpovich and Tipton (1965) in their studies of knee and ankle movements in pathologic gaits showed electrogoniometric data from patients recovering from internal derangements of the knee. They showed recordings from a patient recovering from an "industrial accident" which resulted in impaired extension of the right knee. As a result of this injury, flexion during the support phase of walking was absent and the patient walked stiff-legged. The second set of data was from a patient recorded four days after a right medial menisectomy. The patient walked with a limp and flexion in the right knee was limited to fourteen degrees as compared to sixty degrees in the left knee. The specific nature of the injuries, unfortunately, was not available. Their study was limited to two sets of tracings.

Functional Evaluation of Below-Knee Braces

Published data on the functional evaluation of braced limbs is not abundant in the literature. For the most part, it has been confined to minor references in studies of joint motion. Electrogoniometric evaluation of braced joint function began with the work of Karpovich and Tipton (1964). In their study of the clinical evaluation of the electrogoniometer, they included some information on the effect of wearing a below-knee, lower, left leg brace on the joint movement of a cerebral palsied individual. They found that a marked reduction in flexion occurred in the left knee range but little change occurred in the right knee pattern. Their observations were limited to flexion-extension evaluation of an isolated individual. The other movement parameters of internal-external rotation and varus-valgus of the knee were not included and no data was available for joint function before bracing. Information on the type of brace used was not available.

Rozin et al (1972) correlated electrogoniometric results of hip motion with electromyography of the muscles of the lower limb. A standard below-knee, drop-foot brace was used consisting of two side bars attached through a pivot joint to a heel stirrup. The drop-foot stop mechanism allowed ankle movement in the range of ten degrees of plantar flexion and free dorsi-flexion but eliminated the movements of abduction-adduction and inversion-eversion. The analysis was limited to normal subjects and the effect of bracing on pathological joint function was not considered. Electrogoniometric evaluation consisted of motion of the hip in the frontal and saggital planes and of knee flexion-extension during slow walking.

Rozin et al found that continuous knee flexion occurred on the braced leg as well as persistent contraction of the quadriceps muscle.

The mechanics of the brace used was below the knee and did not involve the knee joint. They suggested that these changes in the pattern of gait may explain early fatigue and the possible development of secondary degenerative changes of the knee joint.

Biomechanical evaluation of knee function was carried out by Lehman et al (1970), who analyzed the forces affecting knee stability in normal subjects using short-leg, below-knee braces. Transducers were mounted just below the calf band or shell of the brace to monitor the force produced, in pounds, between the leg and the brace during the various phases of normal gait. Their study showed that many designs of below-knee braces can be used to prevent hyperextension of the knee in conditions of genu recurvatum and that knee stability can be inhanced by the use of toe levers from the flat foot to the toe-off stage of stance.

Bracing the Unstable Knee

Roser et al (1971) have produced data concerning the effect of taping and bracing on medio-lateral and antero-posterior stability of the knee. Medial and lateral instability were measured in four male college athletes with clinically unstable knees by applying varus and valgus stress to the knee while maintaining it flexed to twenty degrees. A twenty pound force was applied to the ankle via a felt sling keeping the knee stable. The knee was then flexed to ninety degrees and anterior and posterior stress exerted by applying a twenty pound force on the proximal tibia.

Roentgenogram evaluation was carried out under these stressed conditions and displacement of the articulating surfaces calculated for taped and untaped and braced and unbraced situations using one and one half inch athletic trainer's tape and a Palmer Knee Brace. The study showed that the only significant improvement in stability occurred in antero-posterior movement with the combined use of tape and a Palmer Knee Brace.

Kennedy et al (1974) have made use of a clinical stress machine to apply forces to the knee joint. Medial, lateral and anterior laxity were measured by stress roentgenogram analysis and values obtained for patients with chronic knee instability. The effect of the application of the Lennox-Hill De-rotation Knee Brace on knee joint laxity was determined. Kennedy et al showed that nine out of 32 patients who had chronic instability and who wore the Lennox-Hill Brace showed marked reduction in anterior displacement of the medial and lateral tibial condyles. Case studies were cited in which displacement of the tibial condyles was reduced from ten millimeters to 0.5 millimeters medially and from 15.4 millimeters medially to one millimeter laterally after application of the Lennox-Hill Brace in two subjects.

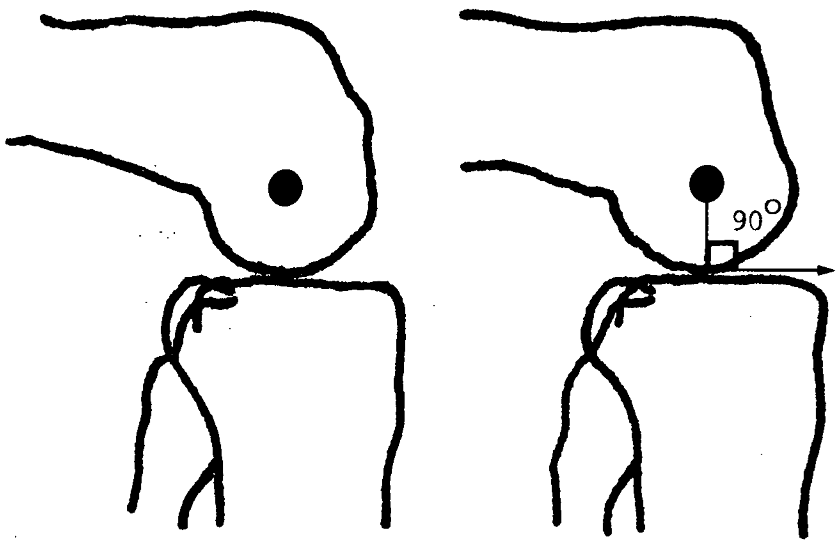
Instant Center of Rotation Theory

From Rouleaux's Theory of Machines (1876) we find that "relative motions of plane figures in a common plane (con-plane figures) may be considered to be a rolling motion and the motion of any points in them can be determined as soon as the centroids (or instantaneous centers of rotation) of the figures are known." This concept can be applied to a cylinder rolling on a plane or to two circles rolling on each other.

If we consider the femur and tibia (a combination of cylinder and plane) to be rigid bodies undergoing angular motion in one, common plane (flexion-extension), then the points along that rigid body move, except one, that point being the instant center of rotation or centroid for the instant being considered. In considering the movement of the femur and tibia, we assume that all other axial rotations of internal-external rotation and varus-valgus do not exist. During articulation between these two links, movement may be considered to be sliding or rolling. If the femur moves on a fixed tibia, sliding occurrs when the femoral axis remains at a constant angle with the axis of the tibia; or rolling occurs as the femoral axis undergoes angular motion relative to the axis of the tibia. Usual knee motion in the saggital plane is considered to be a combination of both. By locating the instant center, it is possible to identify the type of motion at the articulating surface since an instant center on the surface indicates that there is a rolling motion, while an instant center not on the surface indicates that there is sliding (Frankel and Burstein, 1971).

Figure 8-A shows a particular instant center with the relative position of the tibia and femur. The direction of the velocity of the instant center can be obtained by drawing a line perpendicular to a line joining the instant center to a point on the condylar surface. If the

velocity line at the point of contact between the joint surfaces is tangential to the surfaces, they will be sliding on each other with a relatively free and normal action as the knee moves (Figure 8-B).



8-A 8-B

Figure 8. Instant center location with relative positions of the tibia and femur (8-A), and joint velocity line tangential to the joint surfaces (8-B).

Velocity lines non-tangential to the joint surface indicate abnormal friction and wear at the point of contact as a result of some pathomechanical change in the articulating surfaces. This means that the motion will tend to separate or compress the joint surfaces, producing a cam-like action. Sliding will not be taking place but the frictional and compressive forces at the surface will be increased.

The least amount of friction occurs when the direction of the joint surface velocity line is tangent to the contact surface. When the line joining the instant center to a point on the articular surfaces at their point of contact is perpendicular (ninety degrees) to the articular surfaces, then this condition takes place. Helfet (1959, 1963) had related worn areas in the tibio-femoral joint to areas of joint surface in contact with displaced menisci, fibrotic fat pads and to abnormal patterns as the result of displaced or damaged ligaments.

The technique determines whether the surface direction of the femoral and tibial articulating surfaces produces efficient sliding or not. Examination of the instant center of rotation pathway and the instant center joint velocity angles may indicate abnormal patterns and abnormality of articulation as a result of some pathomechanical change in the joint.

Summary

A review of the available literature reveals that a comprehensive study evaluating the dynamic efficiency and function of an athletic knee brace has not been found. Initial studies of braces involved the electrogoniometric evaluation of non-athletic, below-knee braces designed for the correction of foot deformity associated with clinical conditions.

Results from electromyographical and stress analysis studies showed results from normal subjects only. Evaluation of athletic knee braces has been confined to the application of external forces for the calculation of joint laxity. Recent advances in the electrogoniometric recording of joint motion in three axial rotation parameters appear sufficient to conduct an analysis of knee motion of the internally deranged knee and of the effect of bracing on that pattern.

CHAPTER III

METHODS AND PROCEDURES

Subjects

Three male athletes, ages twenty-four, twenty-five and twenty-nine years served as test subjects for the study. One of the subjects (A) had normal (stable) knees with no previous history of knee injury. Both of the other subjects (B and C) had suffered lesions of the medial collateral ligament and the medial meniscus of one leg as the result of athletic competition. In addition, one of the two subjects showed marked antero-posterior laxity with internal tibial rotation under examination with the anterior drawer test. The abduction stress test produced an abnormal amount of medial joint line opening.

The second test subject showed degenerative changes in the articular surface of the femur on roentgenogram examination. A diagnosis of osteochondritis dessecans was made. Both subjects related a history of chronic pain, swelling and lack of function of the injured knee joint with active use (See Case Histories, Appendix B).

Apparatus and Instrumentation

Dynamic evaluation of knee joint motion requires instrumentation precise enough to detect and register movement in degrees. Roentgenogram analysis of instant centers of rotation of the knee joint and stress analysis require the use of sophisticated techniques and equipment. The following apparatus and instrumentation was available for this study:

(a) two 2 x 2 collapsible parallelogram chain electrogoniometers* (Appendix C) capable of measuring movement in three planes.

(b) a signal attenuator box to apply a voltage to the potentiometers and to reduce the signal from the electrogoniometer to a voltage recordable by the strip chart recorder.

(c) an S.E. Laboratories ultra-violet strip chart recorder model 3006 for recording the knee joint movements in graphical form. Flexion-extension, internal-external rotation and varus-valgus of both knees were simultaneously recorded using six separate channels. A deflection of one millimeter on the graphical print-out was calibrated to register five degrees of motion.

(d) a Phillips Telestater remote control x-ray unit with x-omatic film and fluorscopic pre-positioning facility. This device was used for roentgenogram measurement of the knee joint in braced and unbraced conditions for instant center of rotation analysis.

(e) a Picker model 6800 S x-ray unit with single phase full wave rectification and Kodak x-omatic regular intensifying screens. This device was used for roentgenogram measurement during stress analysis.

(f) a General Electric x-ray viewer model 11 FV1 for use in x-ray interpretation and evaluation.

(g) a stress application apparatus for applying forces to the knee joint consisting of a hand rachet and supporting stand.

(h) a Pacific Scientific cable tensiometer model 401-1C-2 with one-sixteenth inch steel cable to monitor the force generated during stress application.

---

* permission for use of the 2 x 2 collapsible parallelogram chain electrogoniometers has been kindly given by Mr. Steven Cousins of the Canadian Arthritis and Rheumatism Society, Vancouver, British Columbia, Canada.

(i) a nylon sling for comfortable attachment of the steel cable to the leg for stress analysis.

(j) three prototypes of the lateral iron, rotational, convex, poly-axial, mechanical knee brace (Taylor Brace).+

Experimental Procedure

The Taylor Brace was evaluated under the following test conditions:

(a) subjective evaluation

(b) electrogoniometric measurement

(c) instant center of rotation measurement

(d) stress analysis

Subjective Evaluation

(i) Brace application

The Taylor Brace was comfortably applied by the subject in the following manner: the foot was inserted through the thigh and calf cuffs and the brace positioned on the leg. The proximal extension arm of the brace was positioned parallel to and approximating the femur and the distal extension arm of the brace was positioned parallel

---

\+ permission for use of the lateral iron, rotational, convex, poly-axial, mechanical knee brace prototypes has been kindly given by Mr. George Taylor, G.F. Strong Rehabilitation Center, Department of Orthotics, Vancouver, British Columbia, Canada.

to and approximating the tibia (See Figure 5, page 8). The center of the mechanical joint was located in a position six centimeters above the head of the fibula in a position at the center of the patella with the knee in full extension (See Figure 4, page 7).

The medial support strap was applied from its attachment on the lateral leg iron, over the patella, and secured to "D" hooks on the thigh and calf cuffs. The elastic tibial strap was then tightened and secured to the tibial cuff. The femoral cuff was aligned by lining up a fastener on the medial aspect of the thigh. The elastic thigh strap was then tightened and secured to a "D" ring on the femoral cuff.

(ii) Test Criteria

With the Taylor Brace applied, the subject engaged in a selected physical activity of his own choosing. After completion of the activity, the subject was asked to verbally evaluate the brace on the following points:

(a) comfort and fit

irritation points, pinching, constriction and numbness, brace movement on leg, slippage.

(b) joint function

ease of articulation, range of articulation, restrictions to movement.

(c) weight, size, ease of application and removal, cosmetics.

At the completion of the study, the subject was asked for a written assessement as an overall evaluation of the Taylor Brace.

Electrogoniometric Measurement

Electrogoniometer application

(i) unbraced

The proximal attachment of the electrogoniometer consisted of a thigh cuff frame constructed of 0.40 centimeter steel wire. The frame was fixed to the thigh by means of a velcro strap which extended behind the leg and was fastened. Two brass brackets fastened the proximal arm of the electrogoniometer rigidly to the frame and allowed no movement. (Figure 9).

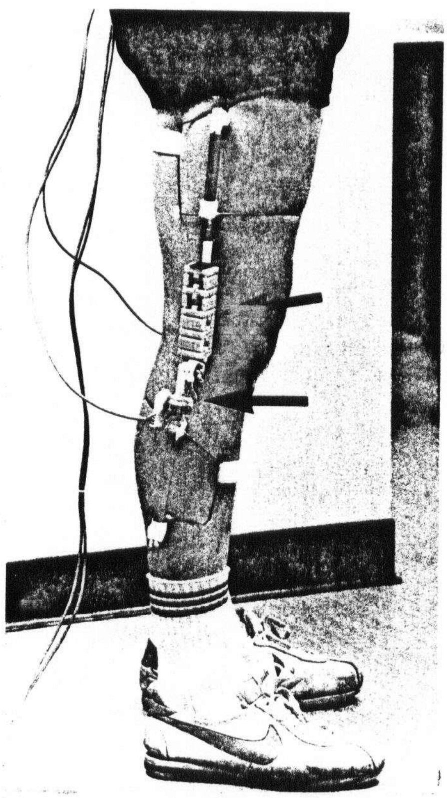


Figure 9. Electrogoniometer application showing the collapsible parallelogram chain and potentiometer cluster (arrows). Note the thigh and calf wire frames with the velcro attachments.

Attachment of the distal arm of the electrogoniometer to the calf was accomplished in the same manner. A metal wire frame was applied to the calf muscles and secured by a velcro strap at the front of the leg. The distal arm of the electrogoniometer was allowed to telescope freely inside a hollow brass tube which was rigidly attached to the frame.

The potentiometer cluster was positioned at a level beside the patella with the knee in full extension. Proper alignment of the collapsible parallelogram chain of the electrogoniometer from its full extended position was achieved by rotating it outward from the knee to an angle of forty-five degrees (Figure 10).

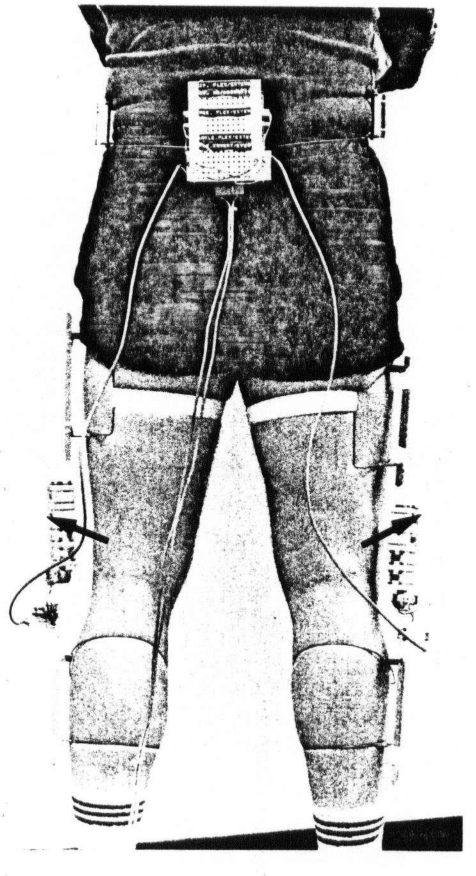


Figure 10. Proper parallelogram chain position (arrows) at 45^{o} external rotation. Note the waist pack, umbilical cord and potentiometer leads.

Power for the potentiometers was supplied by a standard 110 volt, 60 cycle wall outlet via independent leads to each electrogoniometer. Voltage output from the potentiometers travelled to the recorder via an umbilical cord attached to a waist pack.

(ii) braced

The Taylor Brace was applied to the knee as previously described. The electrogoniometer was attached to the brace by "U"-beam struts of aluminum bolted to the brace extension arms. The proximal attachment of the elgon consisted of a hollow brass tube attached to a plastic "I"-beam and rigidly fixed to the aluminum strut (Figure 11).

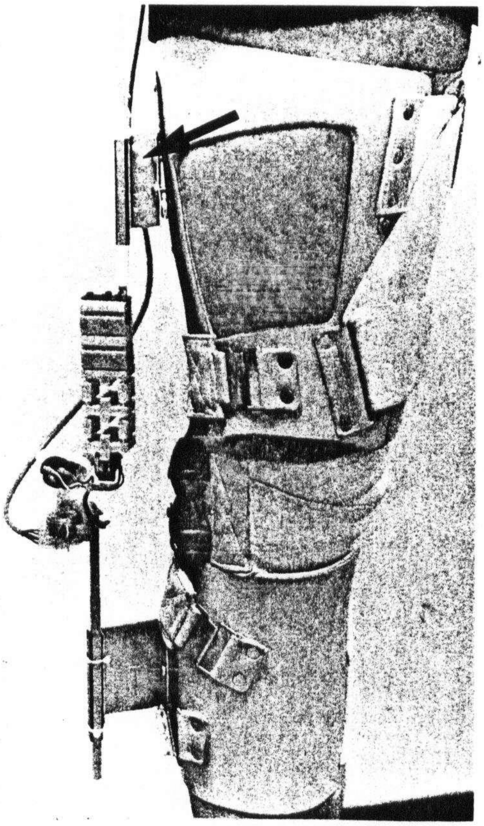


Figure 11. Electrogoniometer application to the braced knee. Arrow points to rigid "U"-beam aluminum strut. Note the position of the potentiometer cluster relative to the brace joint.

The distal attachment of the elgon was constructed in the same manner. The elgon arms were inserted inside the hollow brass tubes. The proximal arm of the elgon was rigidly fixed to the brass tube by adhesive tape, while the distal arm was allowed to telescope freely inside the tube. Potentiometer and parallelogram chain alignment were the same as previously described for unbraced attachment.

Test Procedure

Following application of the electrogoniometer, the subject walked about the laboratory to become accustomed to the apparatus. He then stood in his natural standing position (neutral stance) and the recording light beam channels of the strip chart recorder were adjusted to the zero position. It should be noted that the zero position represents the standing position of the subject. Records of knee joint motion were then recorded as motion from the neutral stance position. All tests were conducted in the laboratory setting in a segment of hallway forty meters long (Figure 12).

The subject was instructed to stand at one end of the hallway and the recorder beams were adjusted to zero again. The subject then walked until ten steps were recorded, exclusive of the first and last steps of the walk. He then repeated the walk. Recordings were obtained under test conditions of slow, level walking and slow, level running. After a ten minute rest, the subject was asked to apply the Taylor Brace.

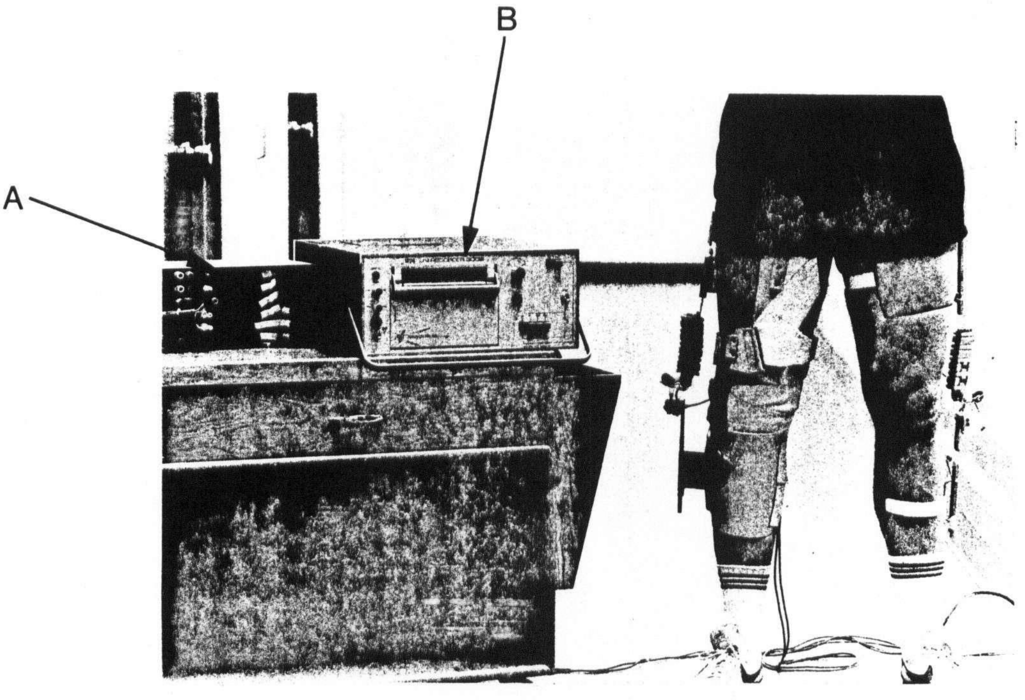


Figure 12. Experimental set-up showing segment of hallway used, (a) signal attenuator box and (b) ultra-violet light strip chart recorder. The subject is in neutral stance with the brace and electrogoniometer applied.

The elgon was then mounted and the procedure repeated. The pattern of knee motion as represented by the ultra-violet light strip chart recordings was determined from the beam deflection. Six channels were used to record, simultaneously, movements of flexion-extension, internal-external rotation and varus-valgus for both knees under unbraced and braced test conditions. A beam deflection of one millimeter on the pront-out represented five degrees of motion. The chart speed was set at five millimeters per second. An electrogoniometric testing data sheet was kept on the statistics of each test (See Appendix D).

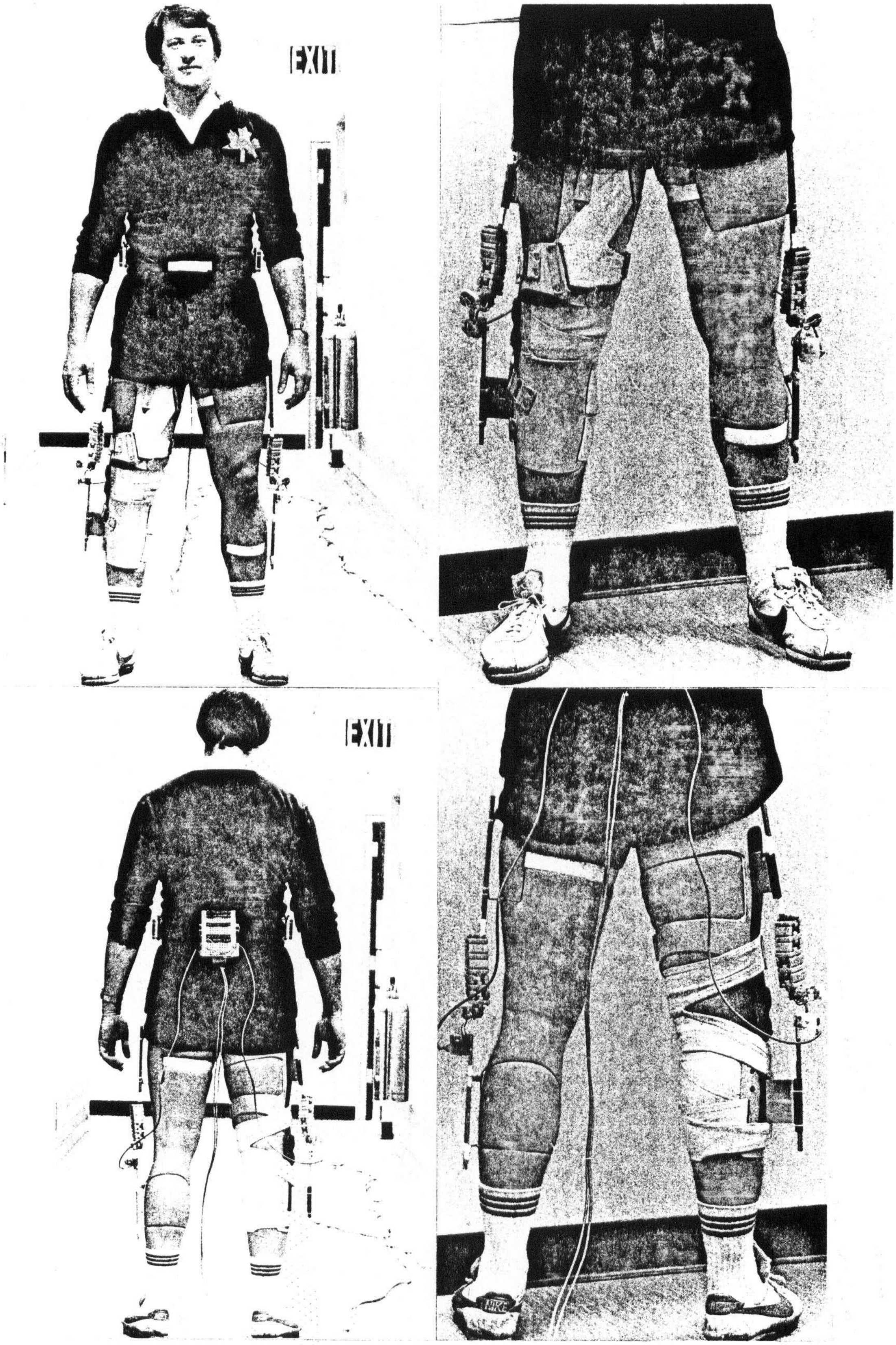


Figure 13. Experimental set-up for braced testing.

Instant Center of Rotation Measurement

Instant center of rotation measurement was made possible by the use of the Phillips Telestater remote control x-ray unit. The subject assumed a position lying on the side with the selected leg underneath. The thigh was fixed to the x-ray table by means of a canvas cuff attached to the table edge. Tension in the cuff was controlled by a rachet tightening device mounted to the x-ray table by a sliding bracket (Figure 14).

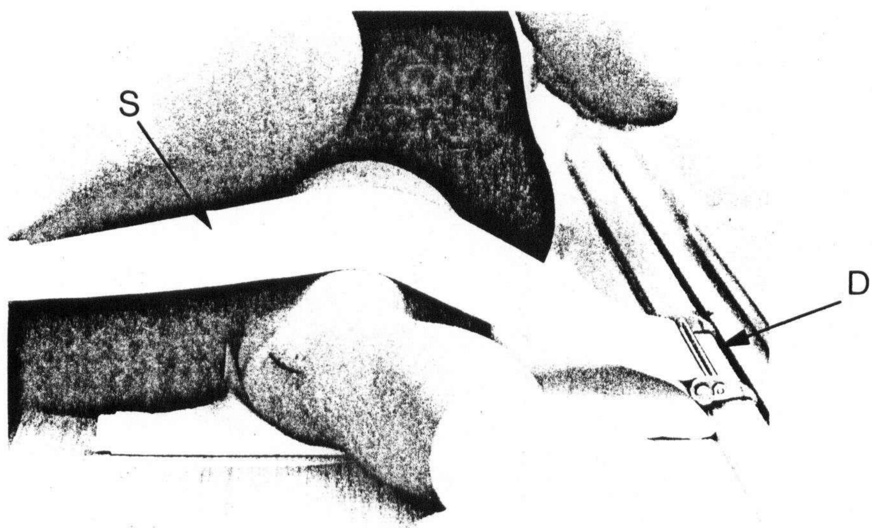


Figure 14. Subject position for instant center of rotation x-ray analysis. Note the canvas cuff (s) and the sliding bracket (d) for cuff application to the table.

Superimposition of the medial and lateral condyles of the femur was obtained by fluoroscopy. A sample x-ray was taken to ensure proper exposure and position. The exposures were taken using a one hundred centimeter focus film distance. The exposure factors were kept constant at one hundred MA, one-tenth of a second at eighty Kvp. Kodak

G film was used with x-omatic screens. The focal spot was 0.6 millimeters.

With the femur fixed to the x-ray table, the tibia was manually moved by the experimenters from ninety degrees of flexion to full extension in increments of fifteen to twenty degrees. At each interval, a medial roentgenogram was taken of the knee joint. Care was taken to maintain the femur in a constant position. The position of the medial and lateral femoral condyles was monitored at each exposure to ensure superimposition. A total of seven medial roentgenograms were taken of the unbraced knee.

The patient was told to sit up and relax. The Taylor Brace was then applied in the previously described manner, and the process of x-ray exposures repeated. Seven medial x-rays were obtained of the knee joint with the Taylor Brace applied. The roentgenograms were then examined and the instant center of rotation calculated for the series of braced and unbraced exposures.

Instant Center of Rotation Calculation

From the study of Kinematics, or the relative motion between rigid bodies called links, we can derive the following statements for the evaluation of a joint:

(a) the bones may be considered to be rigid bodies and to constitute kinematic links (Frankel and Burstein, 1971).

(b) as one of the links rotates about the other, at any instant in time there is a point which has zero velocity and constitutes the instantaneous center of rotation, or centrode.

The centrode is located by identifying the displacements of two points on a limb segment as the segment moves from one position to another. The successive positions of each of these points are identified as the segment moves and lines are drawn connecting them. These lines represent the serial translation of each selected point. If perpendicular bisectors are drawn through the line midpoint for each pair of displacements, the intersection of these bisectors represents the centrode or instantaneous center of rotation for that particular segmental translation (Figure 15).

In considering the knee, the guiding action of ligaments and muscles on motion in the saggital plane causes a translation of the instantaneous center for successive positions of the links. A pathway can therefore be constructed along which the instant center

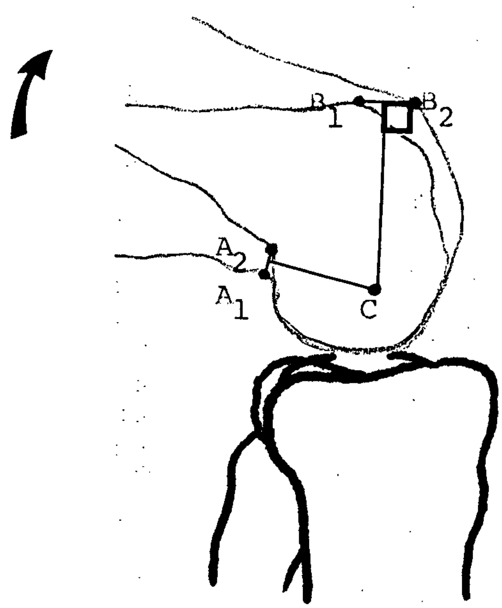
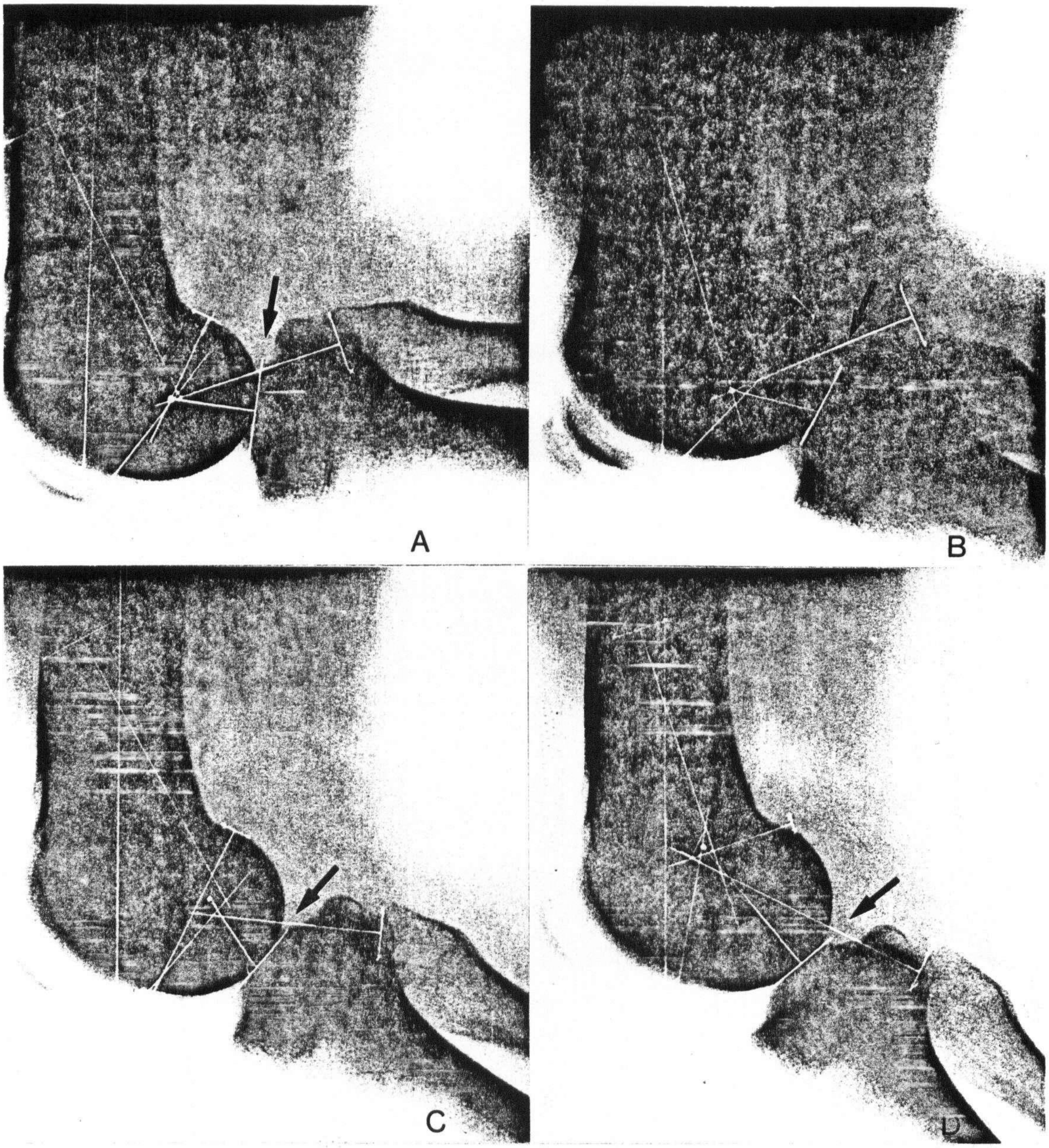


Figure 15. Centrode location from the movement of two points A_1 to A_2 and B_1 to B_2. Note the centrode location (C) from the perpendicular bisectors.

moves as the joint goes from flexion to extension (figure 16). From the method of Rouleaux (1876) and later expanded by Frankel, Burstein and Brooks (1971), the instant center of rotation or centrode may be determined (Appendix E).



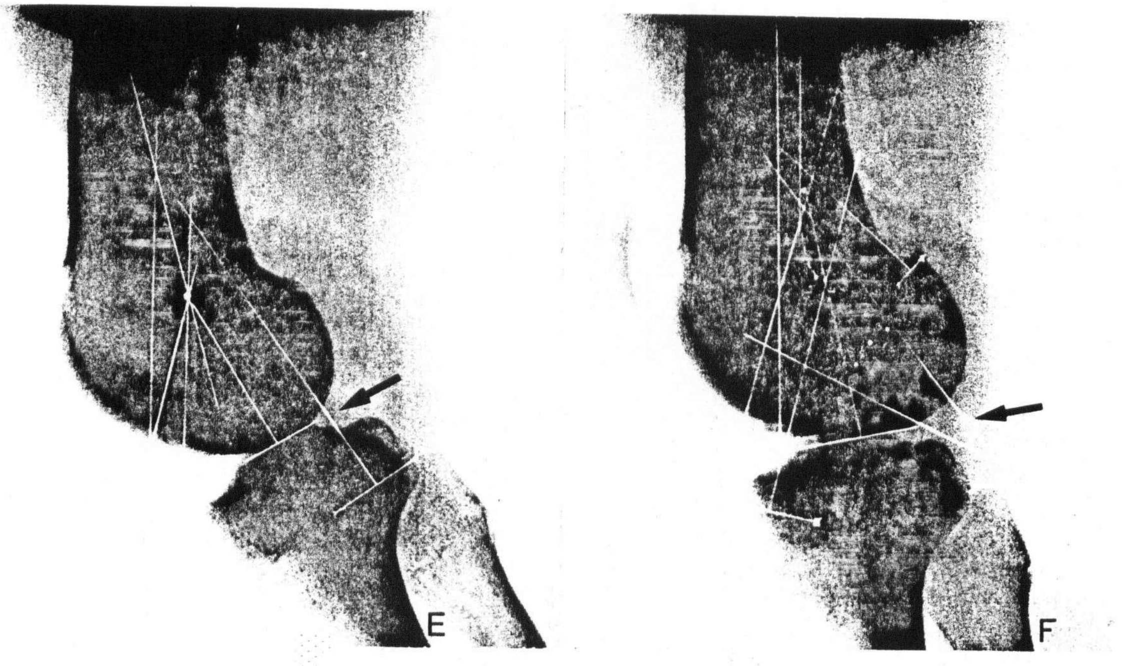


Figure 16. Instant center of rotation translation from (A) 90° of flexion to (F) 10° of flexion. Note the instant center of rotation pathway (F) for the six successive knee positions. The arrows indicate the joint surface velocity angles at the point of contact between the articulating surfaces.

Stress Analysis

Regulated forces were applied to the knee joint using a mechanical stress apparatus. Radiographic changes in the laxity of the knee joint were recorded for unbraced and braced conditions to give an indication of knee stability. Anterior and medial laxity measurements were made for each subject with abnormal (unstable) knees.

Anterior Laxity

The subject was asked to assume a sitting position on the stool facing the direction of force. The thigh of the selected leg was secured firmly to the stool. The knee was flexed to ninety degrees and the ankle secured to the base of the stool by a strap. A medial exposure of the resting joint was made.

A nylon sling was then applied to the proximal tibia and connected to a one-sixteenth inch steel cable. The cable was connected to the hand-cranked winch. The cable tensiometer was applied to the cable (Figure 17).

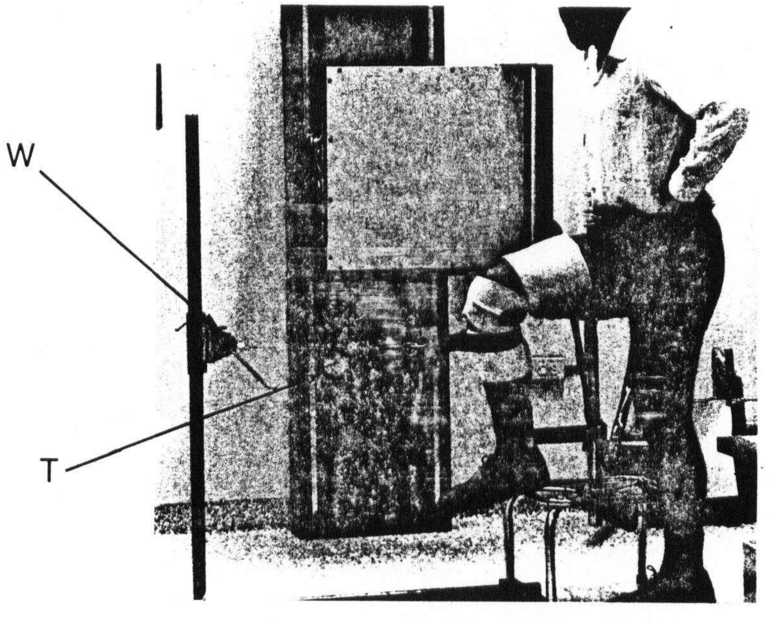


Figure 17. Mechanical stress apparatus positioned for anterior laxity measurement, joint unstressed. Note the flexed knee position, the ankle secured to the base of the stool, the cable tensiometer (T) and the hand-cranked winch (W).

The subject was instructed to relax the muscles of the leg and a gentle pull was exerted on the proximal tibia. The force was gradually increased until a twenty pound equivalent reading was obtained on the cable tension indicator. The hand-cranked winch was then locked and a medial exposure taken of the stressed knee joint. The force was reduced and the subject told to relax. The Taylor Brace was then applied to the knee joint and the knee stressed again to twenty pounds. A third medial exposure was taken and the tension released.

The three medial exposures were taken using the Picker Model 6800 S x-ray unit. Radiation consisted of 400 MA for one-sixth of a second at eighty Kvp with a bucky screen cassette.

Medial Laxity

The subject was asked to assume a supine position on the x-ray table with the knees flexed to twenty degrees. This position was maintained by sponge padding. The knees were padded and secured together by a webbed, nylon belt. The thigh of the selected leg was positioned in an aluminum thigh cuff and securely fastened to prevent movement (Figure 18). An antero-posterior exposure was then made of the knee in this resting position.

With the thigh of the selected leg gripped firmly in the aluminum cuff, a nylon sling was applied to the ankle of the leg and connected to a one-sixteenth inch steel cable. The cable was attached to the hand-cranked winch and the cable tensiometer positioned on the cable.

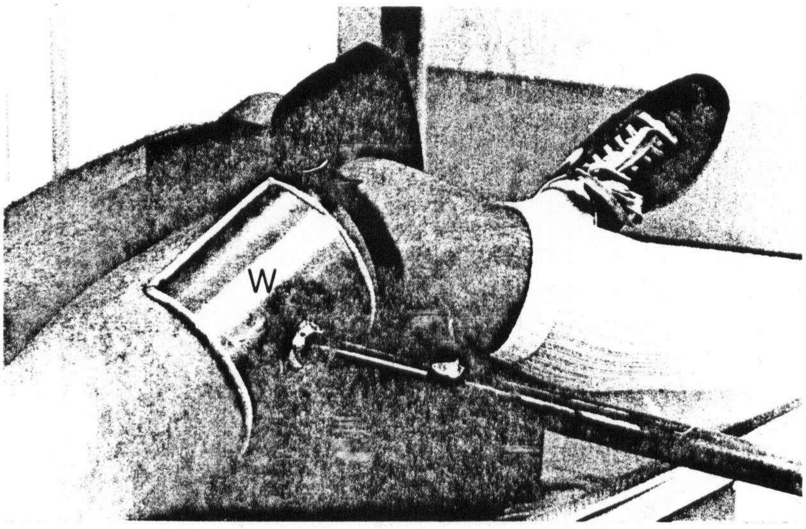


Figure 18. Knee position for medial laxity measurement. Note the sponge padding between the knees and under the knees for support and protection. The aluminum thigh cuff (W) is securely fastened to prevent movement.

A gradual valgus tension was then applied to the ankle. The subject was reminded to relax the muscles of the leg. The tension was increased until a twenty pound equivalent reading was obtained on the cable tension indicator. The winch was then locked and an antero-posterior exposure of the stressed knee joint was made (Figure 19). The tension was released and the subject told to relax. The Taylor Brace was then applied to the knee joint and the knee stressed again to twenty pounds. A third antero-posterior exposure was made and the tension released.

The three antero-posterior exposures were taken using the Picker Model 6800 S x-ray unit. Radiation consisted of one hundred MA for one-sixth of a second at seventy-eight Kvp. Kodak x-omatic regular intensifying screens were used. All x-rays were developed using an R.P. X-omatic processor with the "rapid processing" technique. All x-rays were taken using Kodak G film.

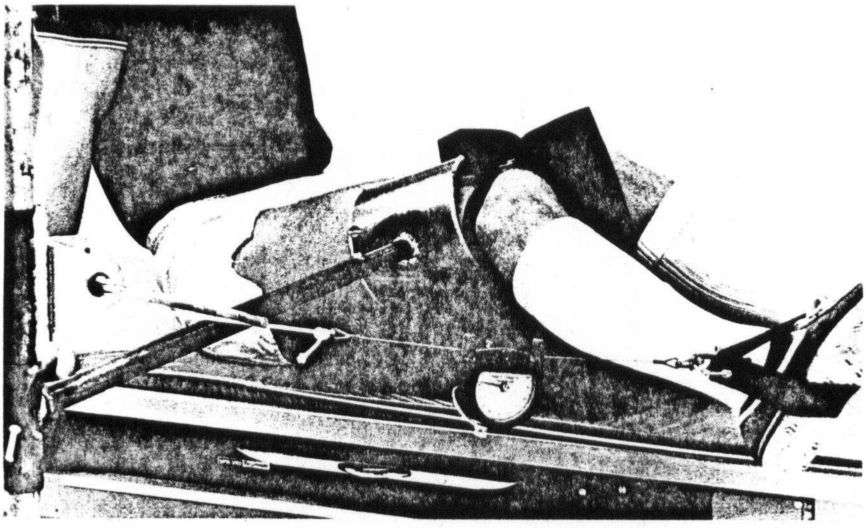


Figure 19. Experimental set-up for medial laxity measurement.

Laxity Measurement Technique

Anterior Laxity

Anterior laxity was measured by placing exposure A (for the unbraced, unstressed knee) with a vertical line tangential to the posterior condylar surface of the femur and another vertical line tangential to the anterior surface of the tibial plateau. The same procedure was carried out for the unbraced, stressed knee (exposure B) and for the braced, stressed knee (exposure C). The distance FmTm was measured and the excursion of the anterior surface of the tibia recorded in relation to the posterior condylar surface of the femur for the three exposures (Figure 20). All measurements were made with Vernier calipers and recorded to within the nearest 0.10 millimeter as an indication of anterior laxity.

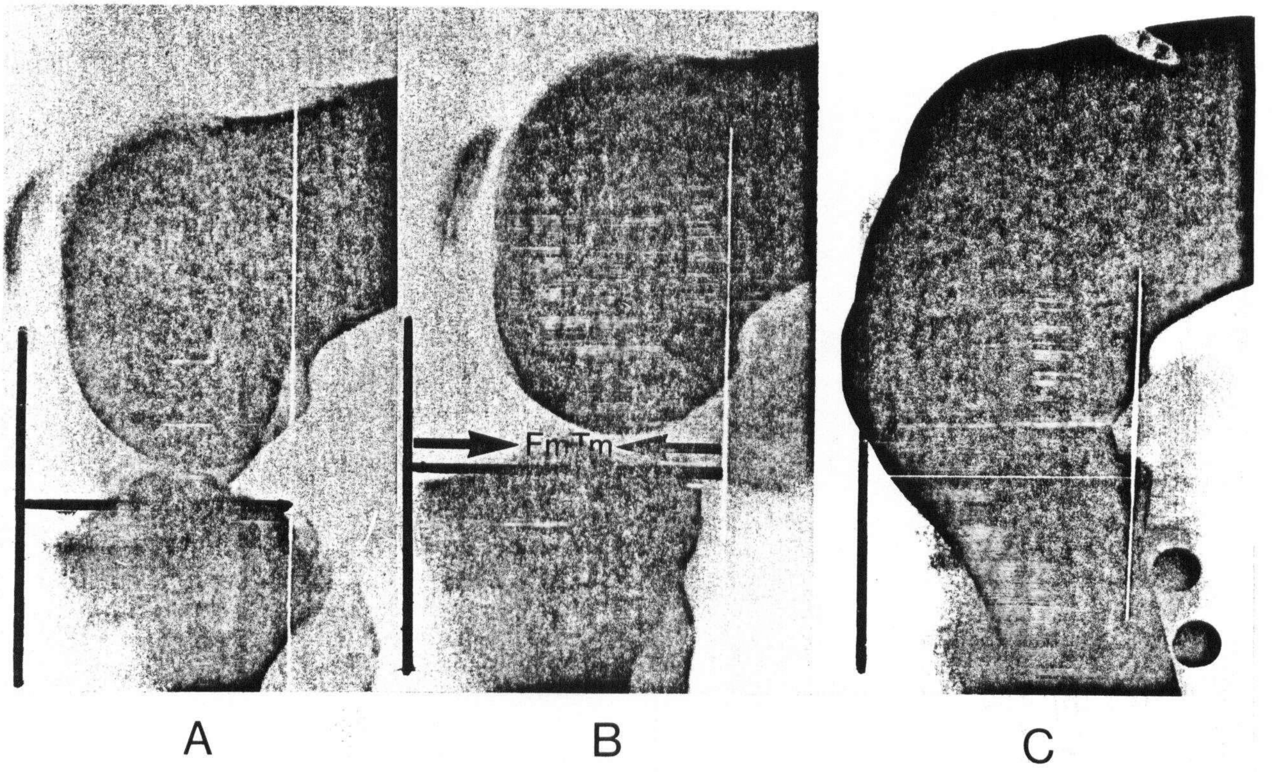


Figure 20. Anterior laxity measuring technique showing (A) exposure A, unbraced, unstressed; (B) exposure B, unbraced, stressed; and (C) exposure C, braced, stressed. The distance FmTm was taken as the amount of anterior laxity for the stressed knee.

Medial Laxity

Medial laxity was measured by placing exposure A for the unbraced, unstressed knee with a horizontal line tangential to the most distal portions of the sub-chondral bone of both femoral condyles. Another horizontal line was then drawn tangential to the most distally placed portions of the sub-chondral bone of both tibial condyles. The same procedure was carried out for the unbraced, stressed knee (exposure B) and for the braced, stressed knee (exposure C). The distance FoTo or intra-articular gap for the three exposures was recorded for the medial side of the joint (Figure 21). This distance was taken as the amount of medial laxity as measured with the Vernier calipers to the nearest 0.10 millimeter.

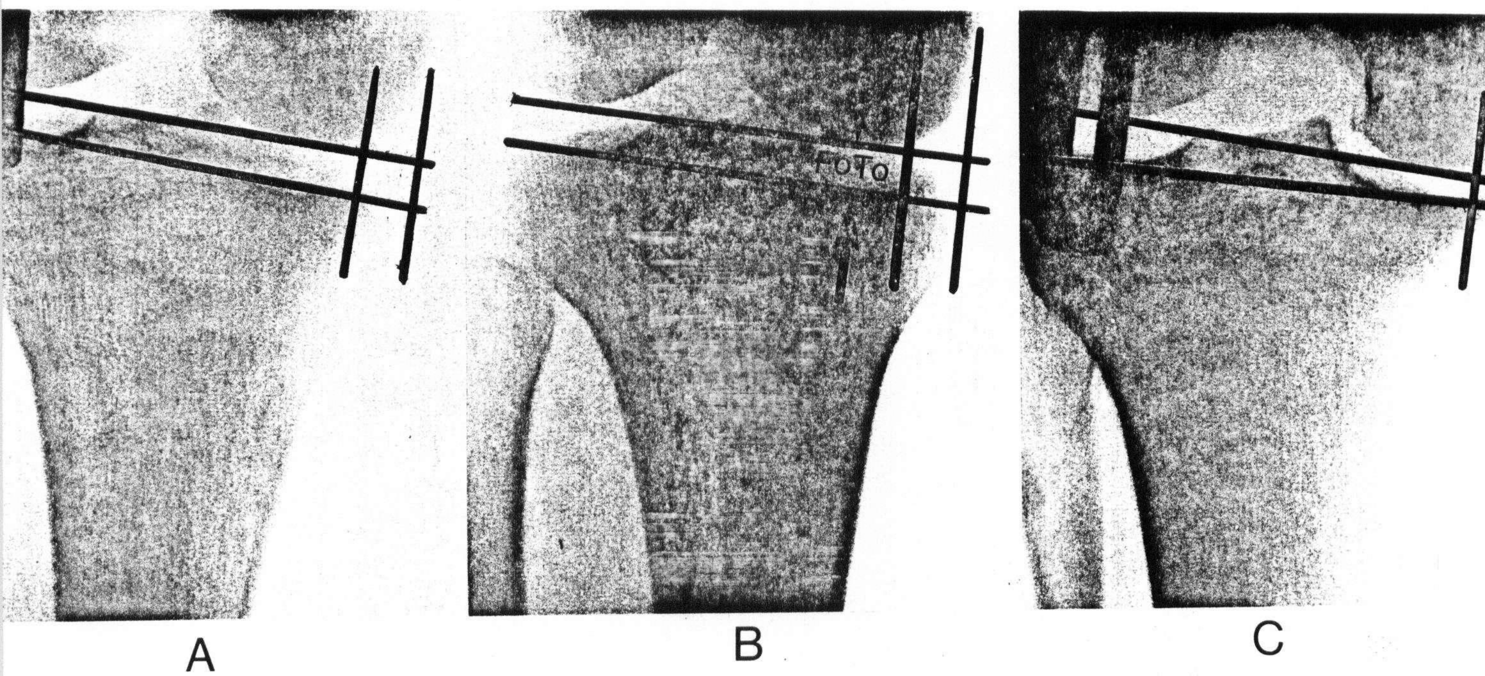


Figure 21. Medial laxity measuring technique showing (A) unbraced, unstressed; (B) unbraced, stressed; and (C) braced and stressed knee. The distance FoTo was taken as the amount of medial laxity for the stressed knee.

CHAPTER IV

RESULTS AND DISCUSSION

Electrogoniometer

Data was collected for each subject during slow, level walking and slow, level running under unbraced and braced conditions. Electrogoniometric values were calculated for knee flexion-extension, internal-external rotation and varus-valgus. Values were determined for each subject from the average of five steps.

The summary of results for Subject A with normal (stable) knees is presented for slow, level walking (Table 1, Figures 22-A and 22-B) and for slow, level running (Table 2, Figures 23-A and 23-B). Values for the braced knee were recorded using the Taylor Brace.

The results from two subjects (B and C) with abnormal (unstable) knees are presented for slow, level walking (Tables 3 and 5, Figures 24-A, 24-B, 26-A, 26-B) and for slow, level running (Tables 4 and 6, Figures 25-A, 25-B, 27-A, 27-B). All braced results were recorded with the Taylor Brace applied.

Comparison values from Subject D with an abnormal (unstable) knee are provided for slow, level walking and slow, level running (Table 7, Figures 28-A, 28-B and Table 8, Figures 29-A and 29-B). All braced results were recorded with the use of the Lennox-Hill De-rotational Brace.

TABLE I

Average values of knee motion
(degrees) during slow level walking
for Subject A with normal (stable) knees

	UNBRACED		BRACED	
	left knee	right knee	left knee	right knee*
Flexion-extension	74°	75°	75°	64°
Internal-external rotation	10°	8°	11°	6°
Varus-valgus	15°	12°	15°	7°

* indicates knee braced with Taylor Brace

TABLE II

Average values of knee motion
(degrees) during slow level running
for Subject A with normal (stable) knees

	UNBRACED		BRACED	
	left knee	right knee	left knee	right knee*
Flexion-extension	75°	105°	75°	82°
Internal-external rotation	15°	20°	15°	18°
Varus-valgus	15°	20°	16°	17°

* indicates knee braced with Taylor Brace

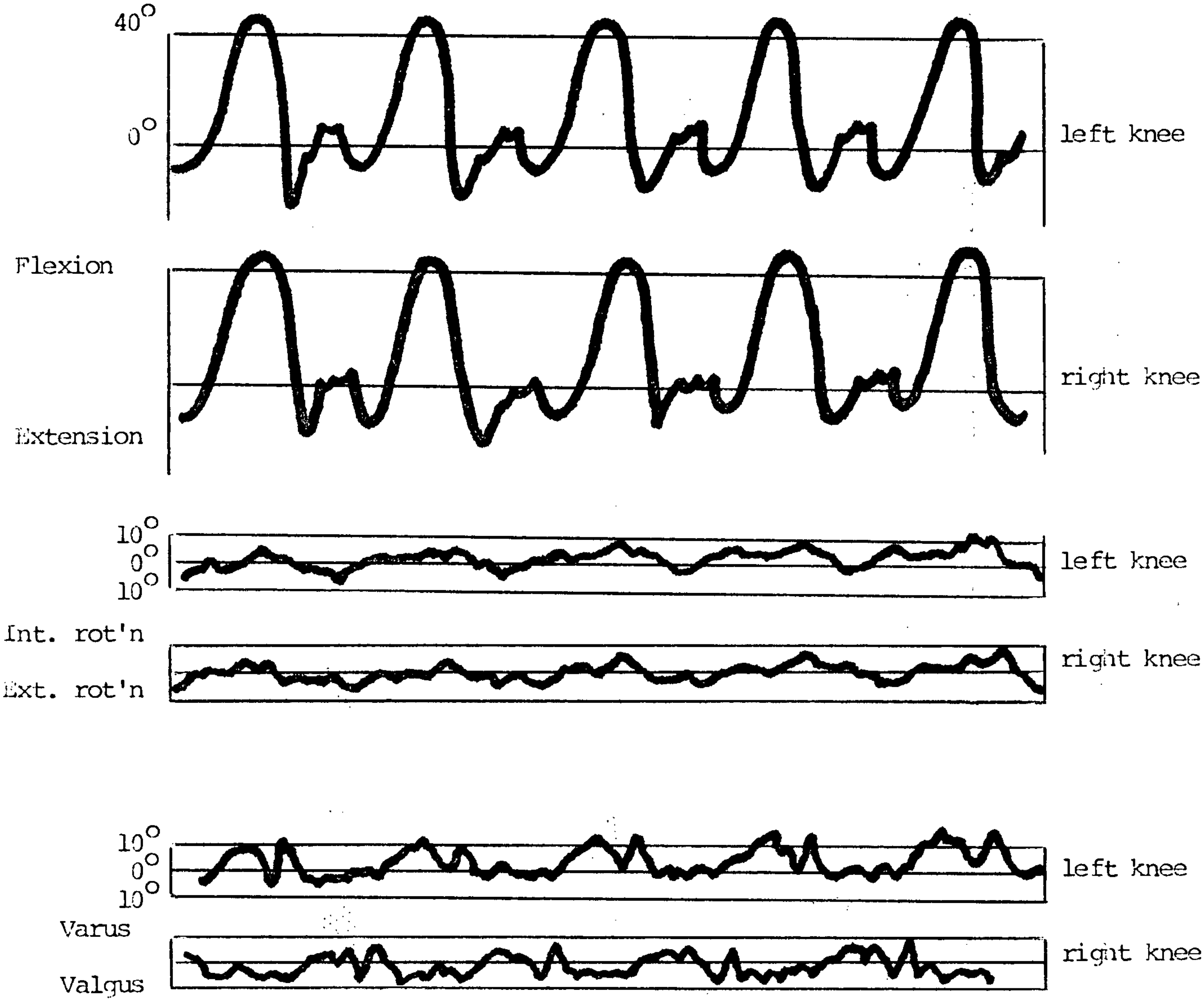


Figure 22-A. Electrogoniometric tracings* of Subject A with normal (stable) knees during unbraced, slow, level walking. Zero line represents the position of the knee at neutral stance.

* due to a lack of clarity in the original, freehand tracings have been used in some cases.

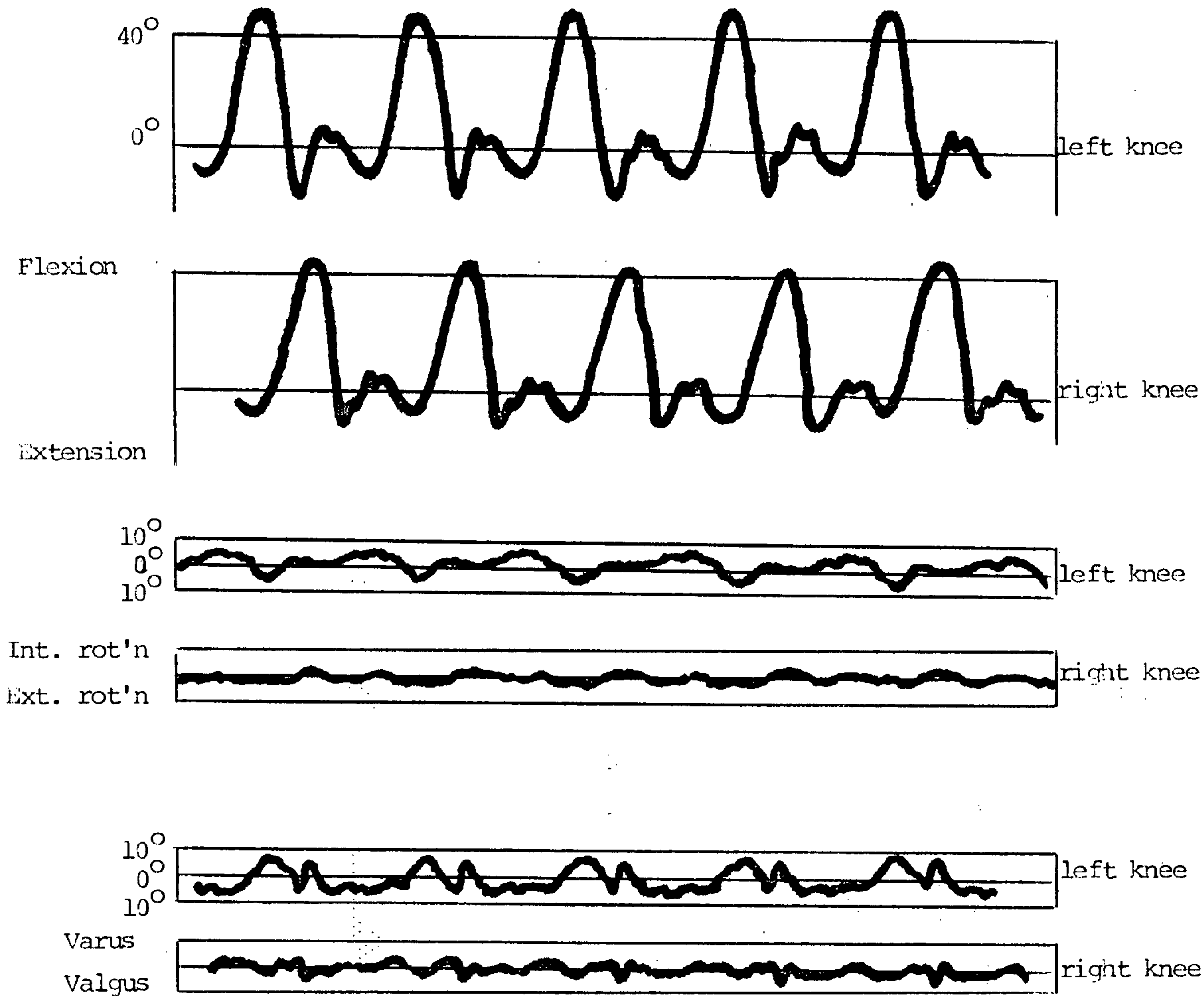


Figure 22-B Electrogoniometric tracings of Subject A with normal (stable) knees during slow, level walking with the Taylor Brace on the right knee.

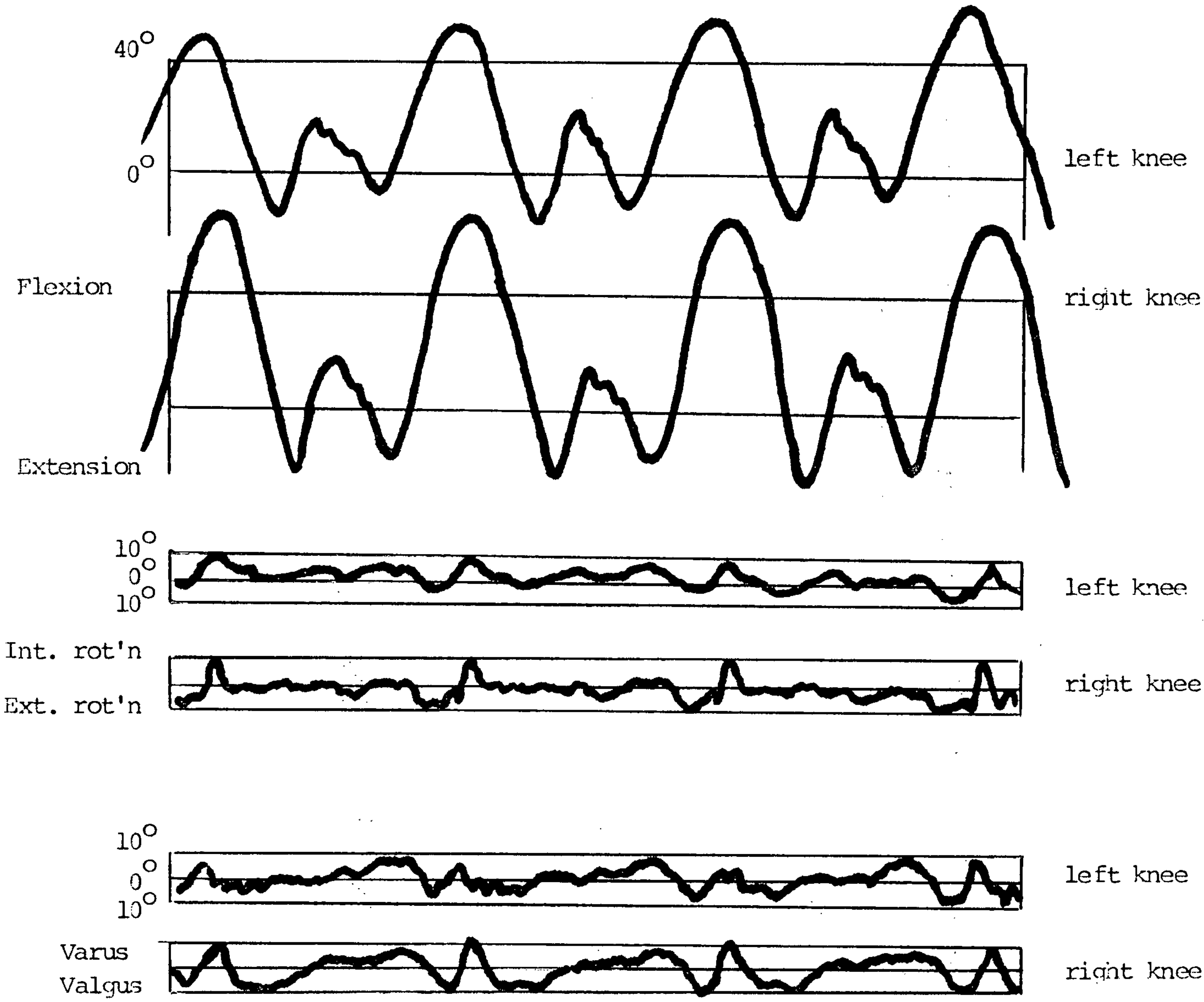


Figure 23-A. Electrogoniometric tracings of Subject A with normal (stable) knees during unbraced, slow, level running.

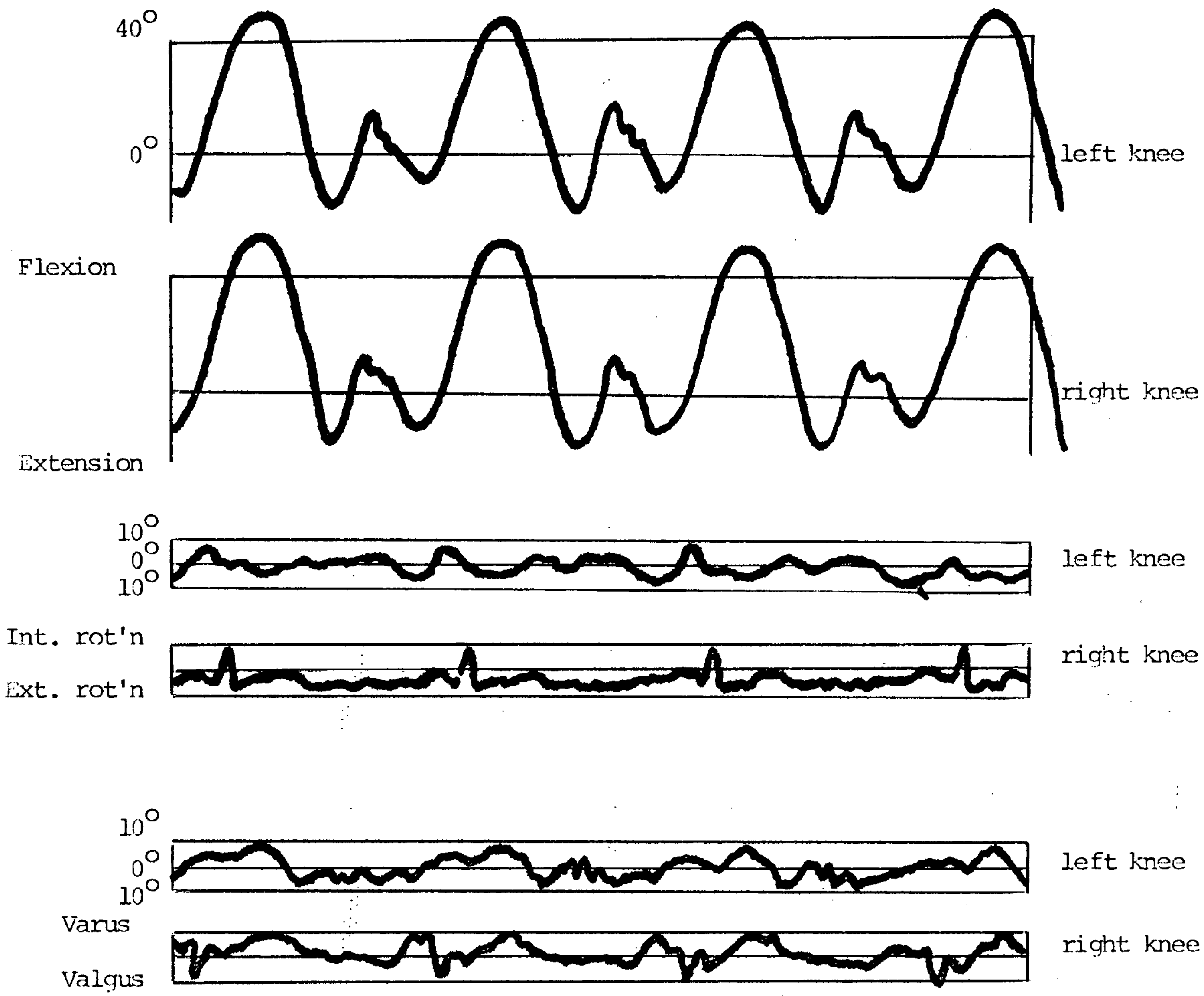


Figure 23-B. Electrogoniometric tracings of Subject A with normal (stable) knees during slow, level running with Taylor Brace on right knee.

Results

Table 1 (walking subject with normal (stable) knees, in a comparison of the unbraced and braced columns, shows a reduction in the range of movement values for the right knee of 11° for flexion-extension (75° to 64°); of 2° for internal-external rotation (8° to 6°) and of 5° for varus-valgus (12° to 7°) following application of the Taylor Brace. The left, unbraced knee range shows a slight increase of 1° in flexion-extension (74° to 75°); an increase of 1° in internal-external rotation (10° to 11°) and remained the same at 15° of varus-valgus movement.

Table 2 (running subject with normal (stable) knees), in a comparison of the unbraced and braced columns, shows a reduction in the range of movement values for the right knee of 23° for flexion-extension (105° to 82°); of 2° for internal-external rotation (20° to 18°) and of 3° for varus-valgus (20° to 17°). The left, unbraced knee range remained consistent for flexion-extension at 75°, for internal-external rotation at 15° and increased 1° (15° to 16°) of varus-valgus movement.

The increased speed of ambulation produced a net decrease in the range of flexion-extension for the right, braced knee of 11° (for a slow, level walk), to 23° (for a slow, level run). The net decrease in the range of internal-external rotation and varus-valgus for the right, braced knee remained the same following an increase in the speed of ambulation (2° vs 2° and 5° vs 3°). The magnitude of the recorded values, however, increased from 6° to 18° for internal-external rotation and from 7° to 17° for varus-valgus.

The range of movement for the left, unbraced knee after application of the Taylor Brace to the right knee remained consistent (See Table 1). Similarly, when the speed of ambulation increased, there was very little change in the range of movement values (Table 2).

TABLE III

Average values of knee motion
(degrees) during slow level walking
for Subject B with abnormal (unstable) knee

	UNBRACED		BRACED	
	left knee	right knee	left knee*	right knee
Flexion-extension	80°	79°	66°	80°
Internal-external rotation	23°	16°	12°	16°
Varus-valgus	13°	19°	5°	19°

* indicates knee braced with Taylor Brace

TABLE IV

Average values of knee motion
(degrees) during slow level running
for Subject B with abnormal (unstable) knee

	UNBRACED		BRACED	
	left knee	right knee	left knee*	right knee
Flexion-extension	93°	100°	97°	105°
Internal-external rotation	25°	25°	16°	31°
Varus-valgus	16°	25°	7°	20°

* indicates knee braced with Taylor Brace

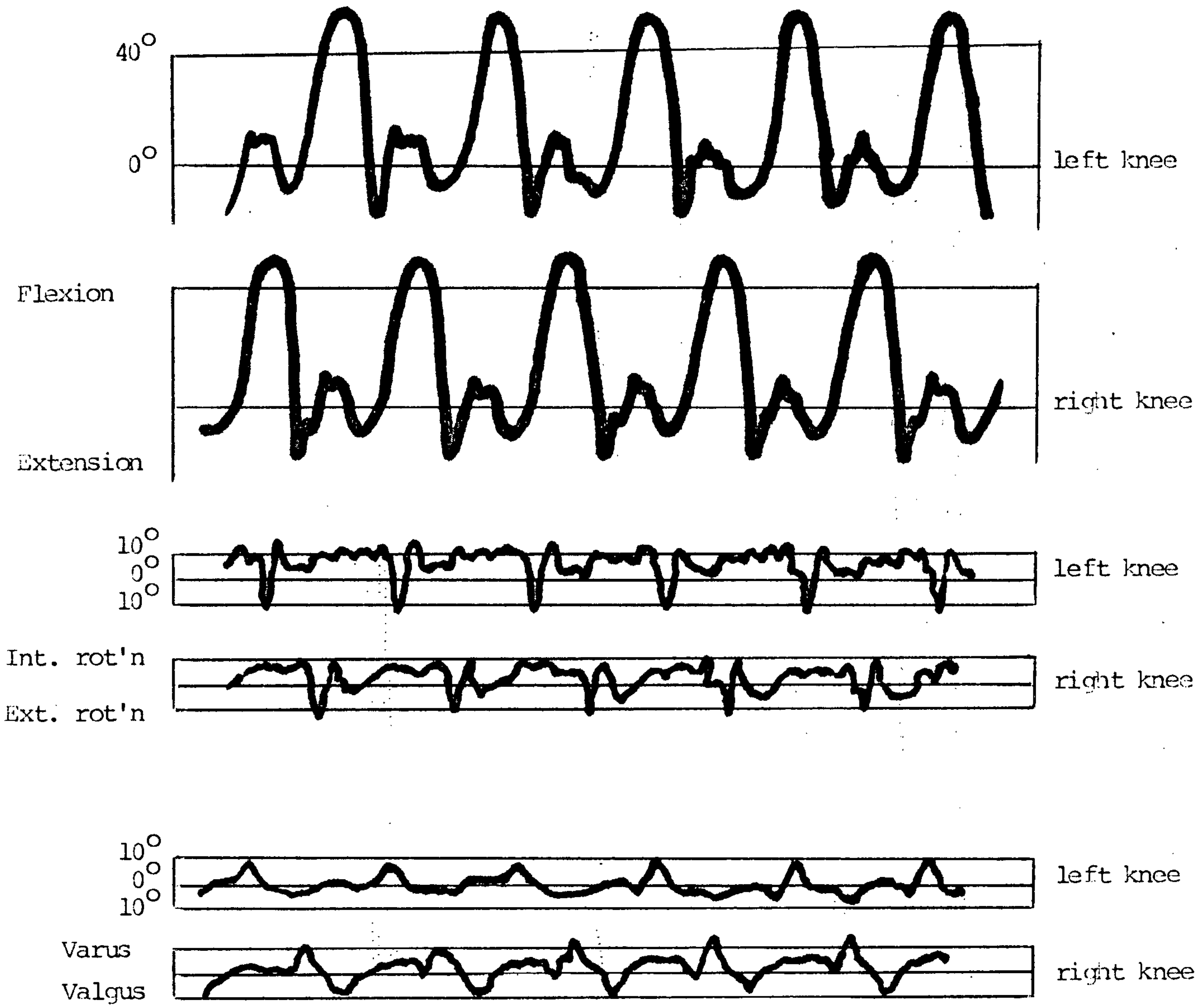


Figure 24-A. Electrogoniometric tracings of Subject B with abnormal (unstable) knee during unbraced, slow, level walking. Zero line represents the position of the knee at neutral stance.

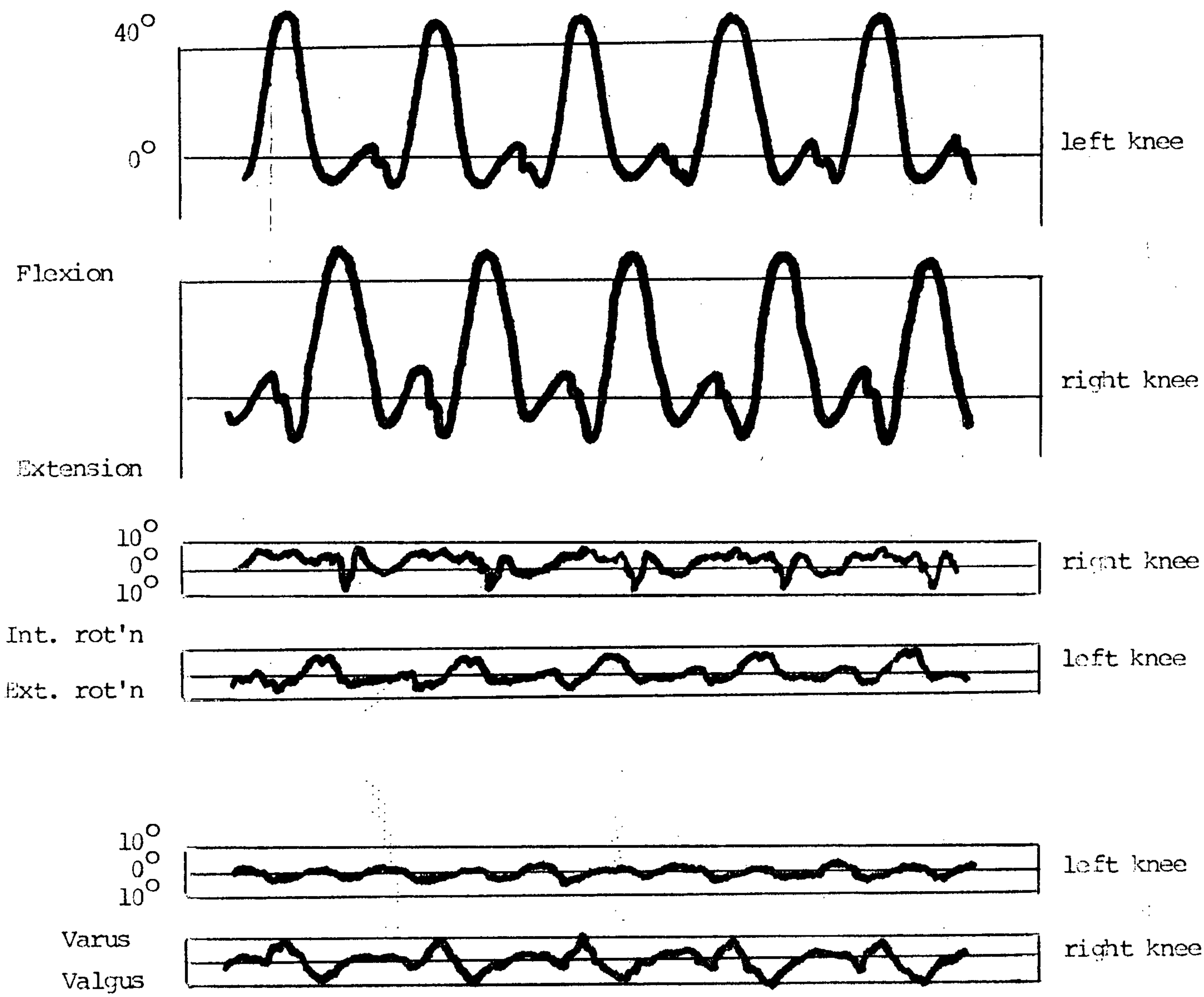


Figure 24-B. Electrogoniometric tracings of Subject B with abnormal (unstable) knee during slow, level walking with the Taylor Brace on the left knee.

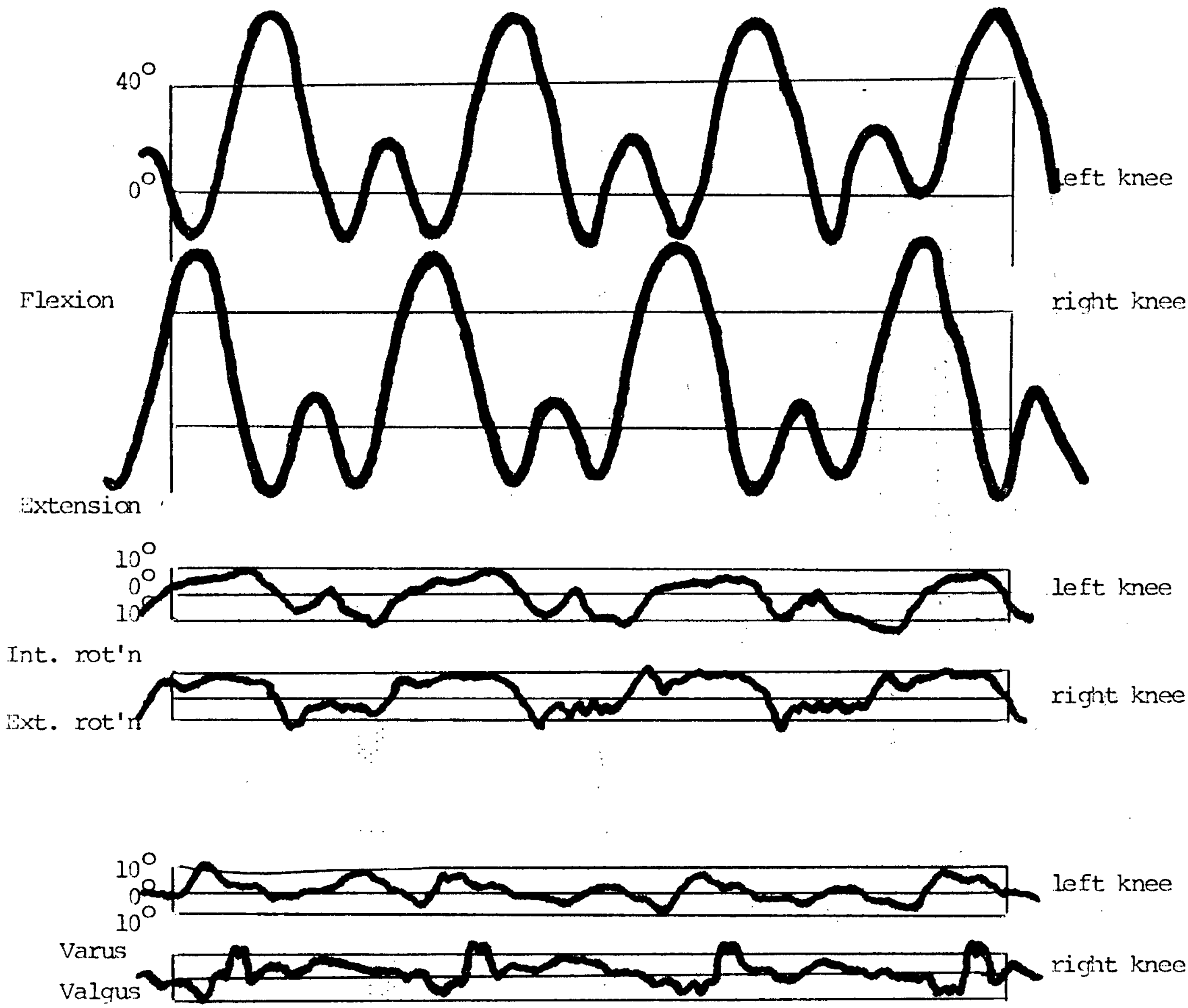


Figure 25-A. Electrogoniometric tracings of Subject B with abnormal (unstable) knee during unbraced, slow, level running.

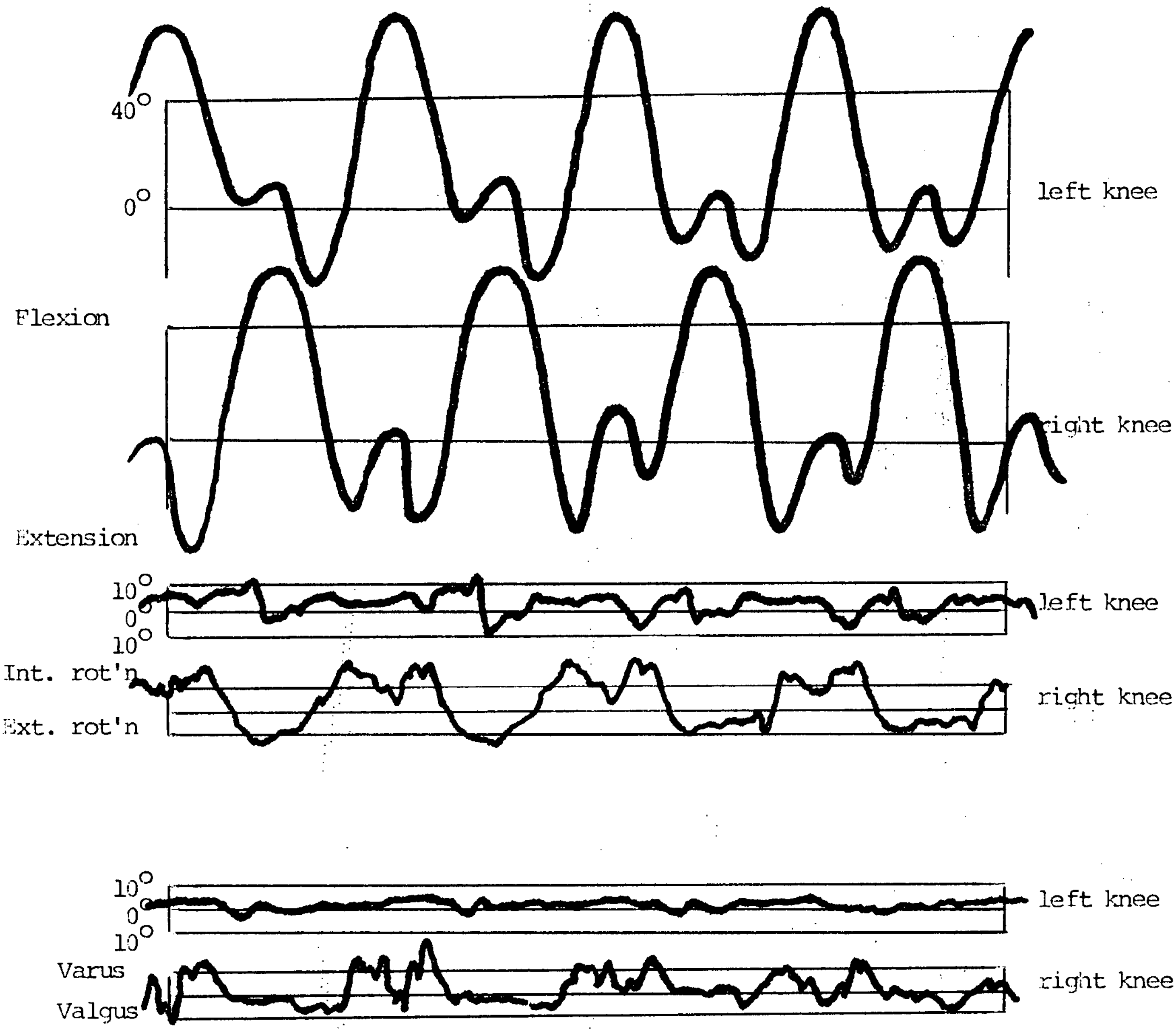


Figure 25-B. Electrogoniometric tracings of Subject B with abnormal (unstable) knee during slow, level running with the Taylor Brace on the left knee.

Results

Table 3 (walking subject with abnormal (unstable) knee), in a comparison of the unbraced and braced columns, shows a reduction in the range of movement values for the left knee of 14° for flexion-extension (80° to 66°); of 11° for internal-external rotation (23° to 12°) and of 8° for varus-valgus (13° to 5°) following application of the Taylor Brace. The right, unbraced knee range shows a slight increase of 1° in flexion-extension (79° to 80°); and maintained the same values for internal-external rotation (16°) and varus-valgus (19°).

Table 4 (running subject with abnormal (unstable) knee), in a comparison of the unbraced and braced columns, shows an increase in the range of movement values for the left knee of 4° for flexion-extension (93° to 97°); a decrease in the range of internal-external rotation values of 9° (25° to 16°) and a decrease in the varus-valgus range of 9° (16° to 7°). The right, unbraced knee range showed an increase of 5° for flexion-extension (100° to 105°); an increase of 6° for internal-external rotation (25° to 31°) and a decrease of 5° for varus-valgus (25° to 20°).

The range of flexion-extension of the left, braced knee was reduced 14° in a subject walking slowly on the level. These results are consistent with the results of the normal (stable) knee for slow, level walking where a reduction of 11° was recorded. Increasing the speed of ambulation from a slow, level walk to a slow, level run produced an increase in the flexion-extension range of 4° for the left, braced knee. These results are not consistent with the results from the normal (stable) knee where a decrease of 23° in the flexion-extension range was recorded.

There was a consistent net decrease in the range of internal-external rotation for the left, braced knee of 11° for a slow-walking subject and of 9° for a slow-running subject. There was also a consistent net decrease in the range of varus-valgus for the left, braced knee of 8° in a walking subject and of 9° in a running subject.

The range of movement of the right, unbraced knee remained the same following application of the Taylor Brace to the left knee of the walking subject. An increase in the speed of ambulation, however, to a slow, level run resulted in increases in the range of flexion-extension of 5° (100° to 105°); and in the range of internal-external rotation of 6° (25° to 31°). The range of varus-valgus decreased 5° (25° to 20°) for the right, unbraced knee following application of the Taylor Brace to the left knee of the slow-running subject.

TABLE V

Average values of knee motion (degrees) during slow level walking for Subject C with abnormal (unstable) knee

	UNBRACED		BRACED	
	left knee	right knee	left knee	right knee*
Flexion-extension	90°	80°	85°	56°
Internal-external rotation	20°	18°	25°	9°
Varus-valgus	10°	11°	8°	10°

* indicates knee braced with Taylor Brace

TABLE VI

Average values of knee motion (degrees) during slow level running for Subject C with abnormal (unstable) knee

	UNBRACED		BRACED	
	left knee	right knee	left knee	right knee*
Flexion-extension	90°	86°	86°	59°
Internal-external rotation	23°	21°	30°	11°
Varus-valgus	10°	11°	7°	11°

* indicates knee braced with Taylor Brace

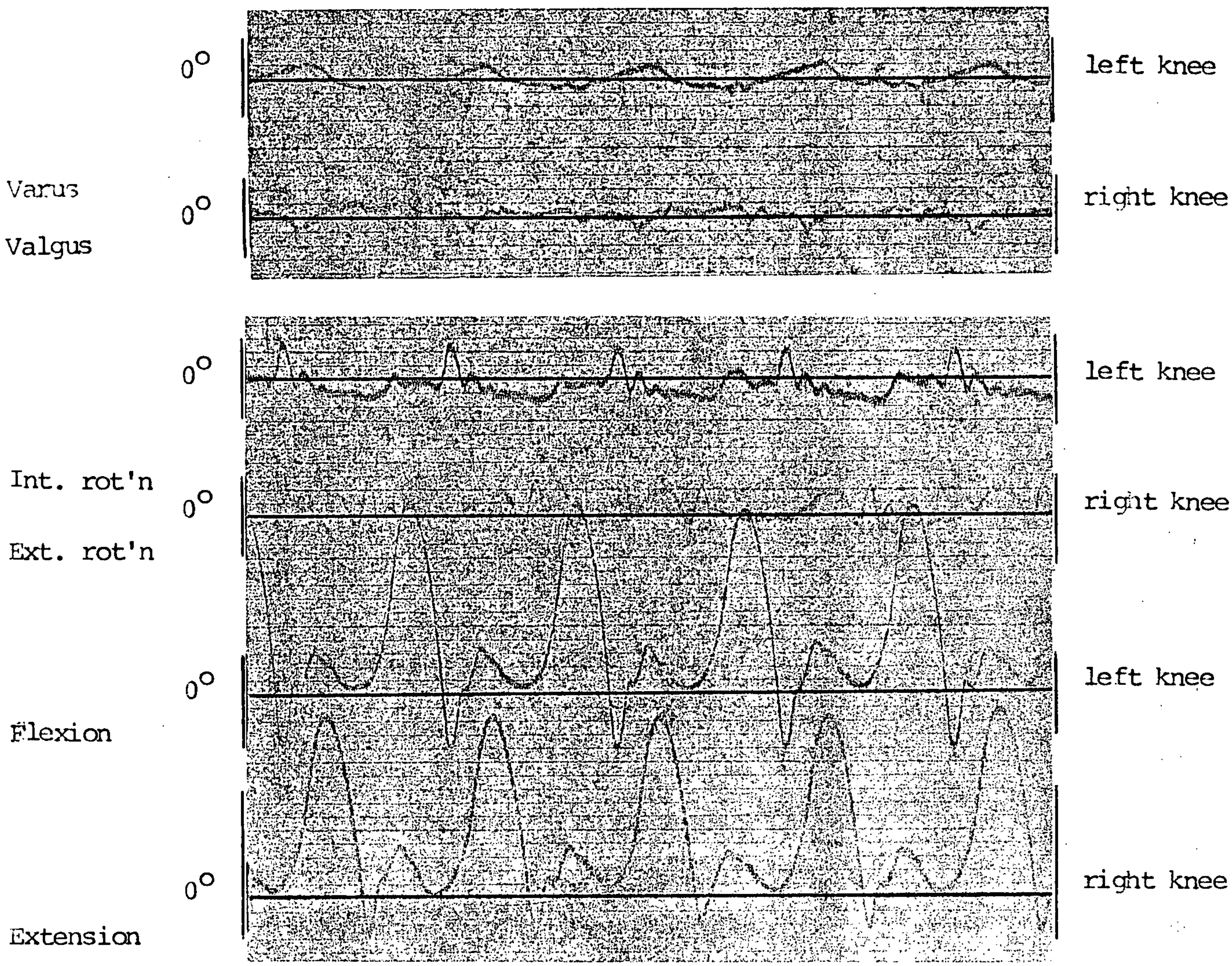


Figure 26-A. Electrogoniometric tracings* of Subject C with abnormal (unstable) knee during unbraced, slow, level walking. Zero line represents the position of the knee at neutral stance. Each line represents five degrees of movement.

* original

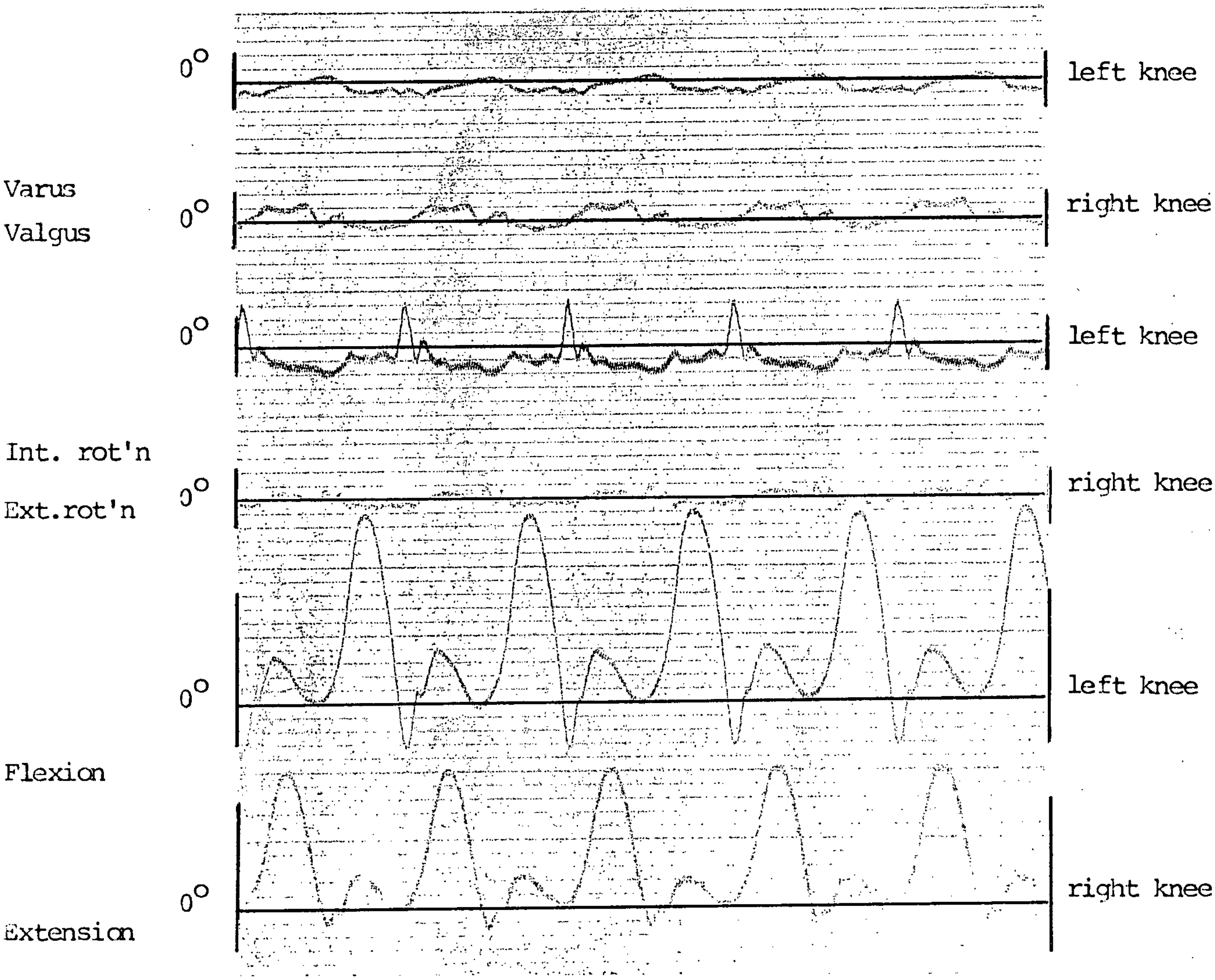


Figure 26-B. Electrogoniometric tracings of Subject C with abnormal (unstable) knee during slow, level walking with the Taylor Brace on the right knee.

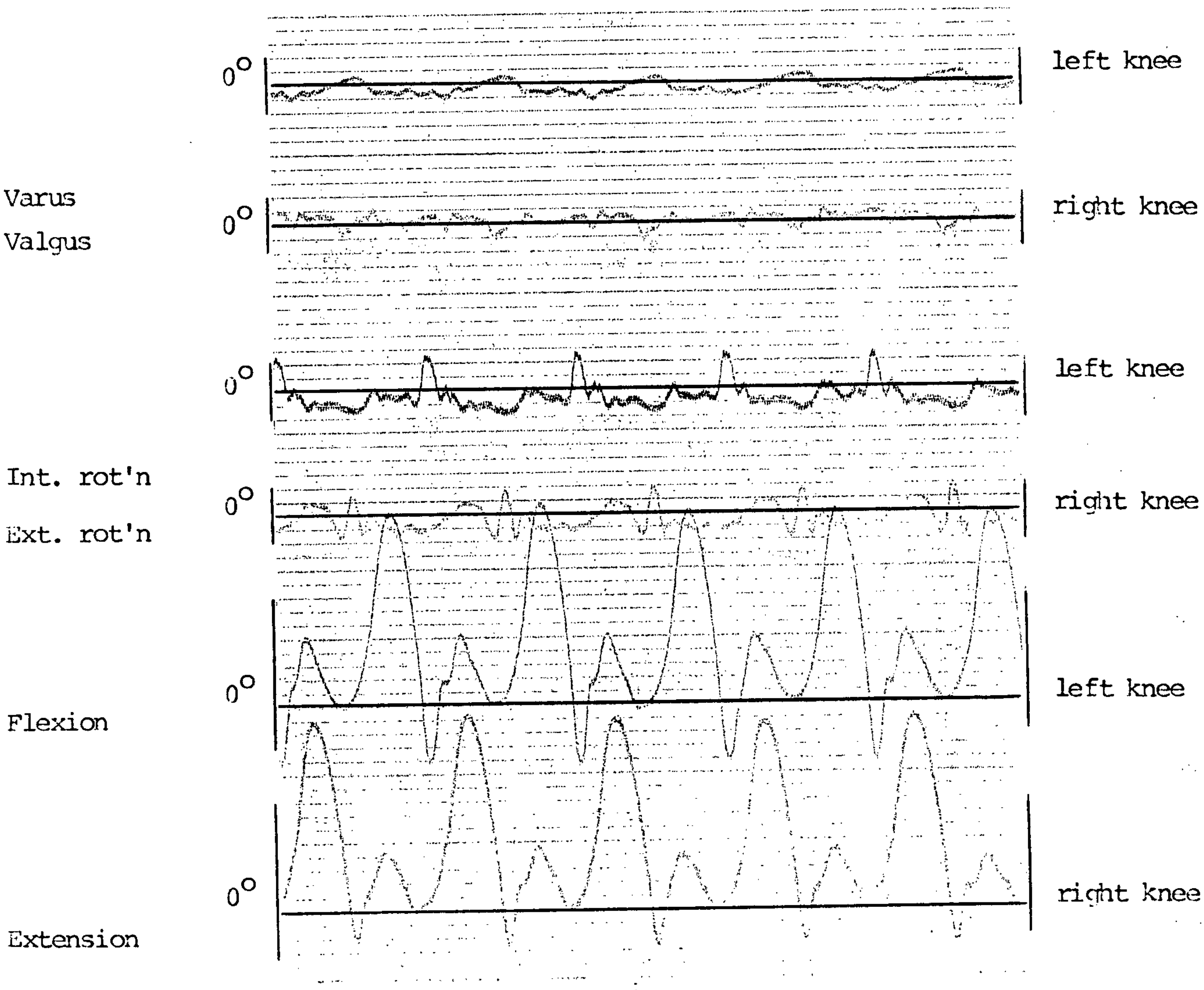


Figure 27-A. Electrogoniometric tracings of Subject C with abnormal (unstable) knee during unbraced, slow, level running.

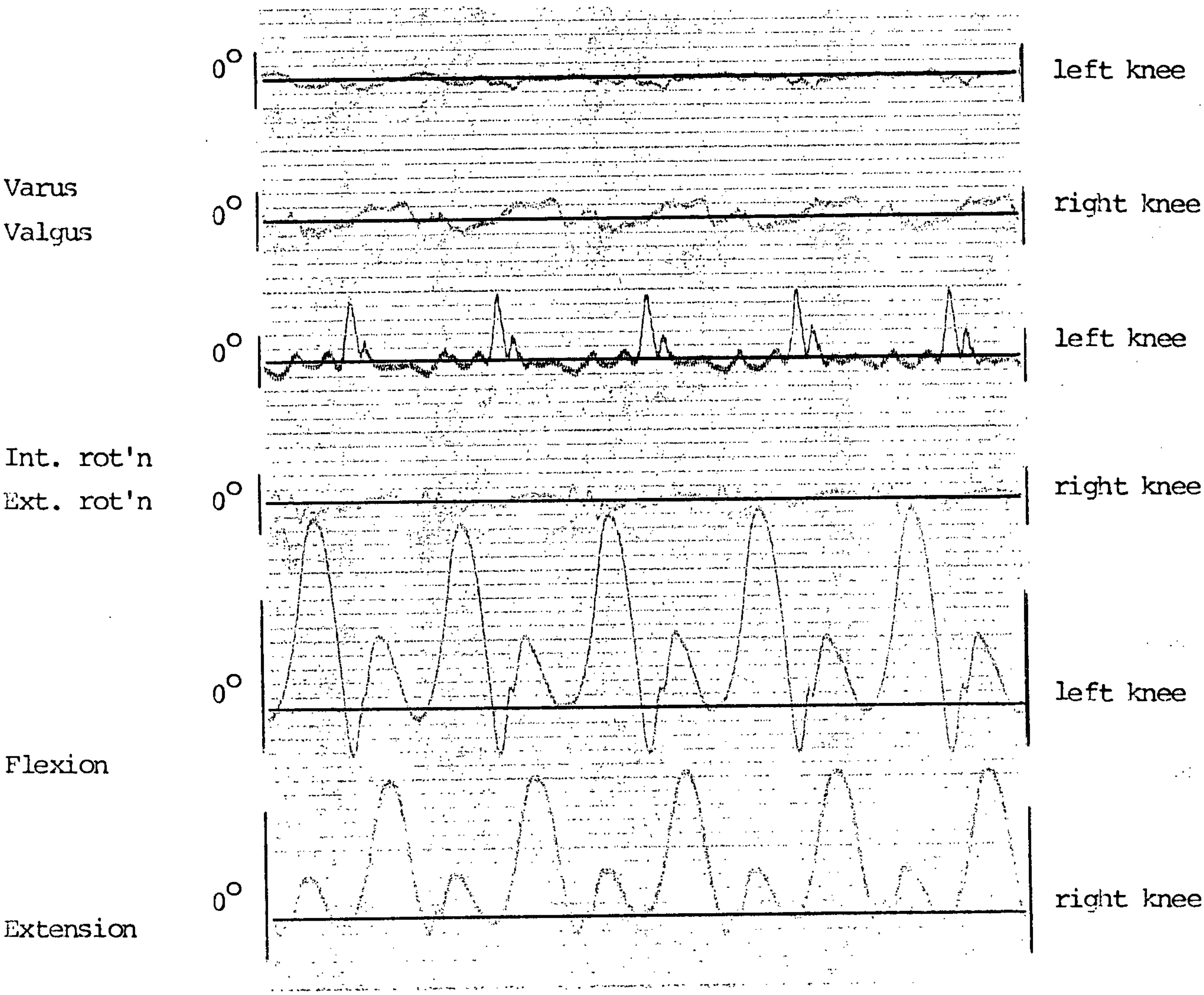


Figure 27-B. Electrogoniometric tracings of Subject C with abnormal (unstable) knee during slow, level running with the Taylor Brace on the right knee.

Results

Table 5 (walking subject with abnormal (unstable) knee), in a comparison of the unbraced and braced columns, shows a reduction in the range of movement values for the right knee of 24° for flexion-extension (80° to 56°); of 9° for internal-external rotation (18° to 9°) and of 1° for varus-valgus (11° to 10°) following application of the Taylor Brace. The left, unbraced knee range shows a slight decrease of 5° in flexion-extension, a slight increase of 5° in internal-external rotation and a decrease in varus-valgus of 2° (10° to 8°).

Table 6 (running subject with abnormal (unstable) knee), in a comparison of the unbraced and braced columns, shows a decrease in the range of movement values for the right knee of 27° for flexion-extension (86° to 59°); of 10° for internal-external rotation (21° to 11°) and of zero in the varus-valgus value of 11°. The left, unbraced knee fluctuated slightly following application of the Taylor Brace decreasing 4° in flexion-extension (90° to 86°); increasing 7° in internal-external rotation (23° to 30°) and decreasing 3° in varus-valgus (10° to 7°).

The range of flexion-extension of the right, braced knee consistently decreased from the unbraced range dropping 24° in the walking subject and 27° in the running subject. There was a consistent decrease in the internal-external rotation range of the right, braced knee of 9° (fifty percent) for the walking subject and of 10° (forty-seven percent) for the running subject, from the unbraced values. There was very little fluctuation in the magnitude of the internal-external rotation range, however, keeping constant values despite the increase in the speed of ambulation. These results were consistent with the results of Subject B who showed decreases of forty-seven percent and thirty-six percent respectively in internal-external rotation values for the braced knee. The varus-valgus values of the right knee fluctuated very little after bracing, reducing only 1° during slow, level walking and remaining the same during slow, level running.

TABLE VII

Average values of knee motion
(degrees) during slow level walking
for Subject D with abnormal (unstable) knee

	UNBRACED		BRACED	
	left knee	right knee	left knee	right knee*
Flexion-extension	85°	79°	85°	60°
Internal-external rotation	15°	27°	13°	5°
Varus-valgus	13°	8°	15°	7°

* indicates knee braced with Lennox-Hill De-rotational Brace

TABLE VIII

Average values of knee motion
(degrees) during slow level running
for Subject D with abnormal (unstable) knee

	UNBRACED		BRACED	
	left knee	right knee	left knee	right knee*
Flexion-extension	95°	96°	85°	69°
Internal-external rotation	20°	28°	18°	10°
Varus-valgus	14°	11°	16°	7°

* indicates knee braced with Lennox-Hill De-rotational Brace

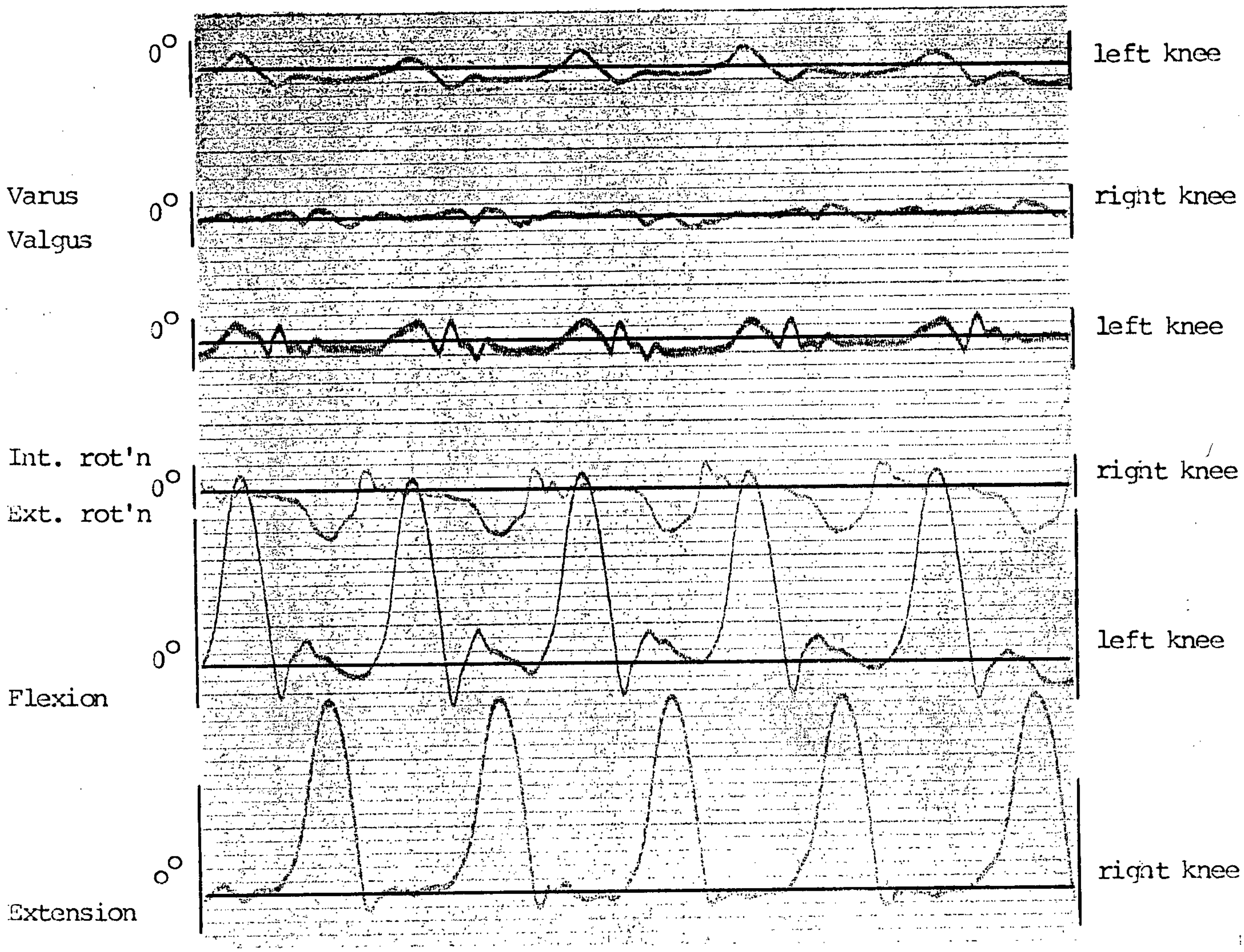


Figure 28-A. Electrogoniometric tracings of Subject D with abnormal (unstable) knee during unbraced, slow, level walking. Zero line represents the position of the knee at neutral stance. Each line represents five degrees of movement.

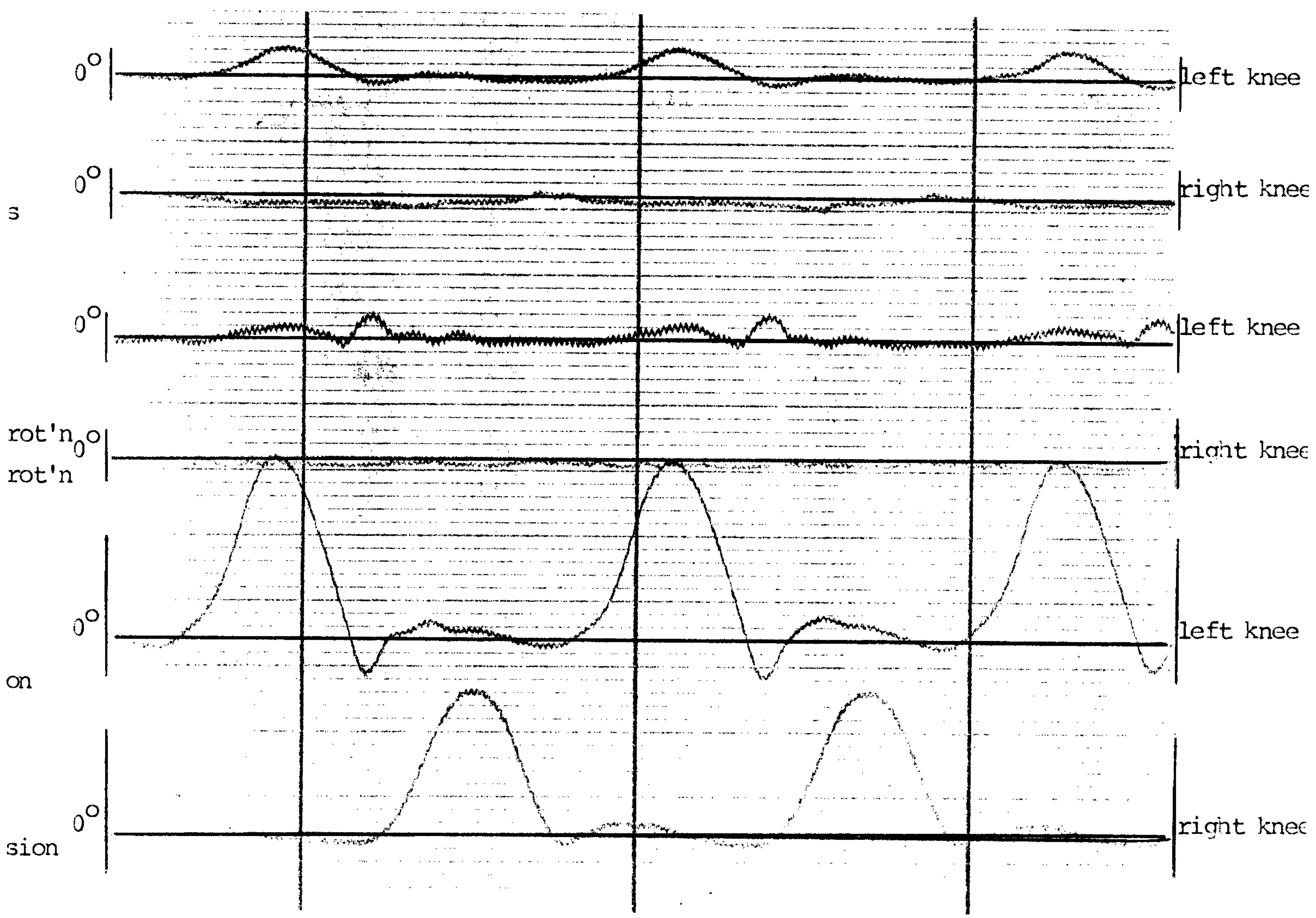


Figure 28-B. Electrogoniometric tracings of Subject D with abnormal (unstable) knee during slow, level walking with the Lennox-Hill De-rotational Brace on the right knee.

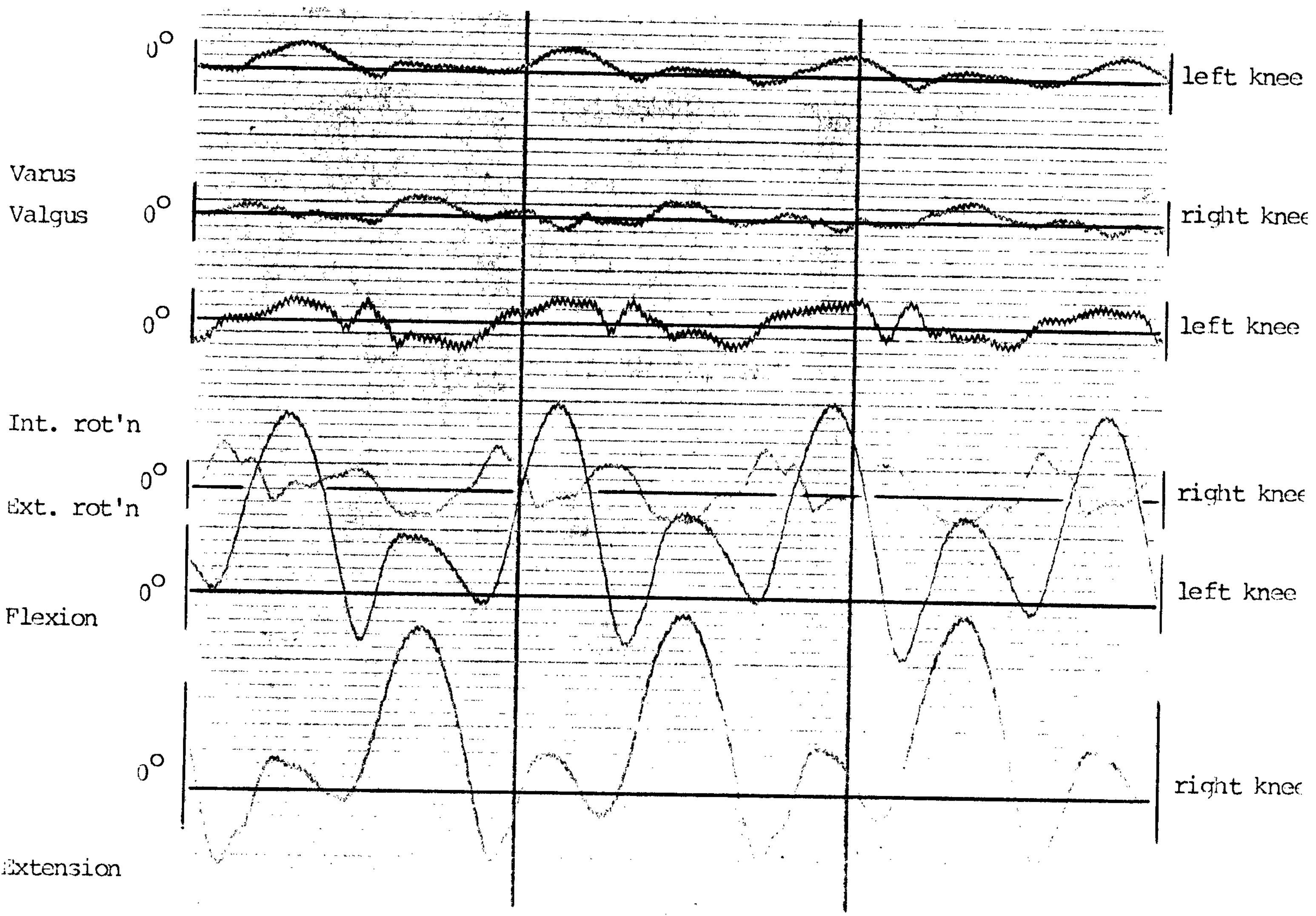


Figure 29-A. Electrogoniometric tracings of Subject D with abnormal (unstable) knee during unbraced, slow, level running.

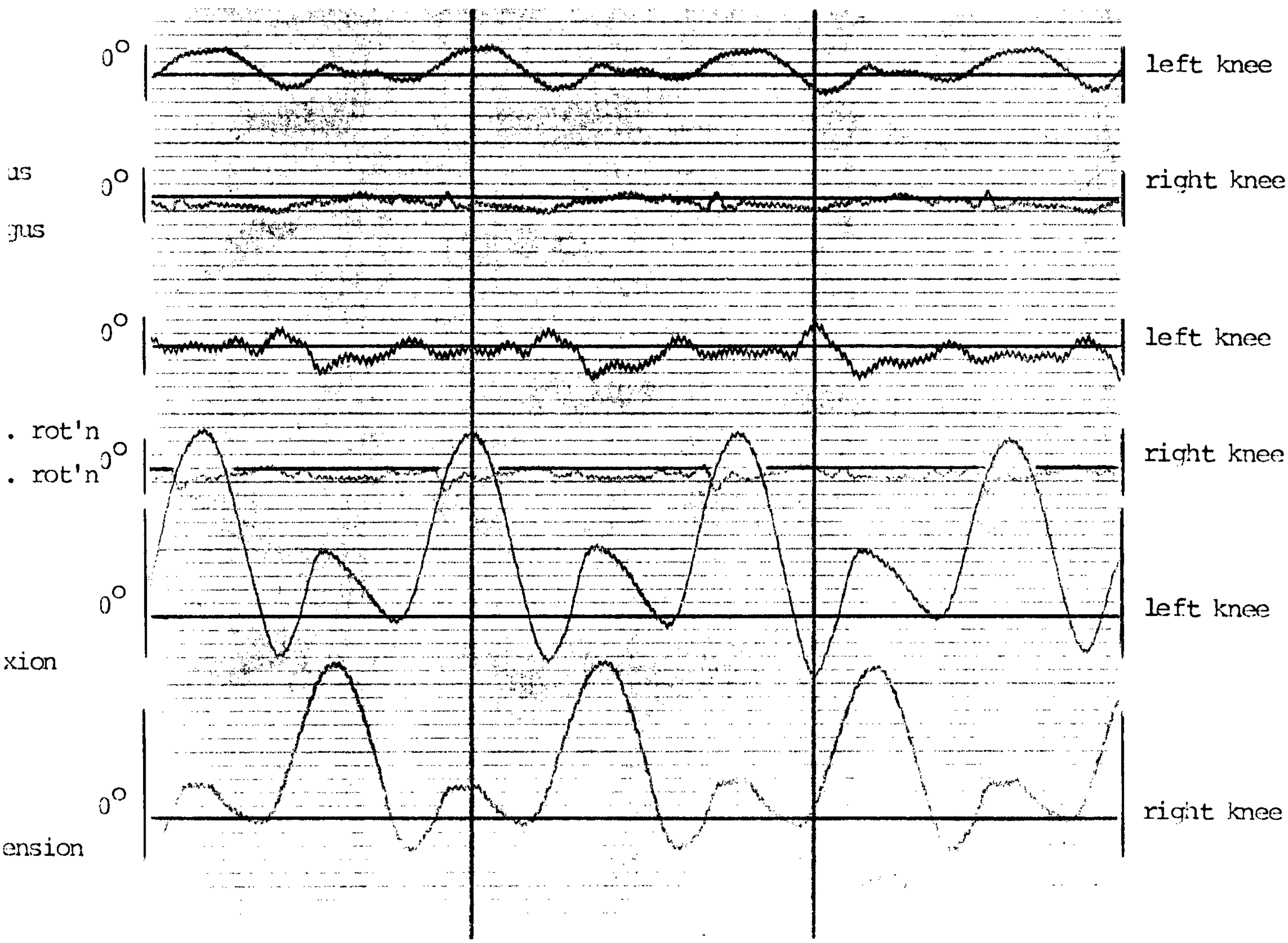


Figure 29-B. Electrogoniometric tracings of Subject D with abnormal (unstable) knee during slow, level running with the Lennox-Hill De-rotational Brace on the right knee.

Results

Table 7 (walking subject with abnormal (unstable) knee), in a comparison of the unbraced and braced columns, shows a reduction in the range of movement values for the right knee of 19° for flexion-extension (79° to 60°); of 22° for internal-external rotation (27° to 5°) and of 1° for varus-valgus (8° to 7°) following application of the Lennox-Hill De-rotation Brace. The left, unbraced knee range values remained constant for flexion-extension at 85°; decreased 2° for internal-external rotation (15° to 13°) and increased 2° for varus-valgus (13° to 15°).

Table 8 (running subject with abnormal (unstable) knee), in a comparison of the unbraced and braced columns, shows a decrease in the range of movement values for the right knee of 27° for flexion-extension (96° to 69°); a decrease of 18° for internal-external rotation (28° to 10°) and a decrease of 4° for varus-valgus (11° to 7°). The left, unbraced knee values fluctuated following application of the Lennox-Hill De-rotation Brace, decreasing 10° in flexion-extension (95° to 85°); decreasing 2° in internal-external rotation (20° to 18°) and increasing 2° (14° to 16°) in varus-valgus movement.

The range of flexion-extension of the right, braced knee consistently decreased from the unbraced range dropping 19° in the walking subject and 27° in the running subject. The reduction in the recorded values for internal-external rotation were the greatest for the walking subject at 22° (eighty-one percent) and were reduced to 18° (sixty-four percent) in the running subject. Varus-valgus values fluctuated very little increasing 1^{o} during walking and 4^{o} during running.

Walking with the Lennox-Hill De-rotational Brace on the right knee of Subject D did not greatly alter the range of the contra-lateral knee. Running, however, decreased flexion-extension by 10^{o}, decreased internal-external rotation by 2^{o} and increased varus-valgus by 2^{o}.

Discussion

All subjects tested with the Taylor Brace under conditions of slow, level walking showed an overall reduction in the range of flexion-extension of the braced knee (Subject A, 11^{o}; Subject B, 14^{o}; Subject C, 24^{o}). Increasing the speed of ambulation to a slow, level run produced a further decrease in the flexion-extension range of the braced knee (Subject A, 23^{o}; Subject C, 27^{o}), with the exception of Subject B who recorded an increase of 4^{o}. Results from Subject D (Lennox-Hill De-rotational Brace) showed similar findings with decreases of 19^{o} for slow, level walking and 27^{o} for slow, level running.

With the exception of Subject B (for slow, level running), it appears that the Taylor Brace is having a restraining effect on the dynamic flexion-extension range of the braced knee that increases in magnitude as the speed of ambulation increases. This effect is similar in magnitude to the reduction produced by the Lennox-Hill

De-rotational Brace.

All subjects tested with the Taylor Brace under conditions of slow, level walking showed an overall reduction in the range of internal-external rotation of the braced knee (Subject A, 2^{O}; Subject B, 11^{O}; Subject C, 9^{O}). Increasing the speed of ambulation to a slow, level run produced minor fluctuations in the internal-external rotation range of the braced knee (Subject B, 9^{O}; Subject C, 10^{O}) with the exception of Subject A who remained the same at 2^{O}. Results from Subject D (Lennox-Hill De-rotational Brace) showed similar findings with decreases for internal-external rotation of 22^{O} for slow, level walking and 18^{O} for slow, level running.

With the exception of Subject A (normal, stable knee) it appears that the Taylor Brace is having a restraining effect on the dynamic internal-external rotation range of the braced knee. This restraining effect is constant (with minor fluctuations) despite increases in the magnitude of the rotation measurements as a result of increases in the speed of ambulation. Application of the Taylor Brace to the abnormal (unstable) knees of Subjects B and C reduced the high rotatory values for slow, level walking to within the range recorded from the normal (stable), unbraced knee (Subject A) for slow, level walking. This effect is similar in magnitude to the reduction produced by the Lennox-Hill De-rotational Brace on internal-external rotation.

All subjects tested with the Taylor Brace under conditions of slow, level walking showed an overall reduction in the range of varus-valgus of the braced knee (Subject A, 5^{O}; Subject B, 8^{O}; Subject C, 1^{O}). Increasing the speed of ambulation to a slow, level run produced similar decreases in the varus-valgus range of the braced knee (Subject A, 3^{O}; Subject B, 9^{O}), with the exception of Subject C who recorded no change. Results from Subject D (Lennox-Hill De-rotational Brace) showed similar findings with decreases of 1^{O} for slow, level walking and 4^{O} for slow, level running.

With the exception of Subject C, it appears that the Taylor Brace is having a restraining effect on the dynamic varus-valgus range of the braced knee. In one subject (B), this restraining effect increased in magnitude with the speed of ambulation. The results from Subject B are similar to the reduction produced by the Lennox-Hill De-rotational Brace on varus-valgus.

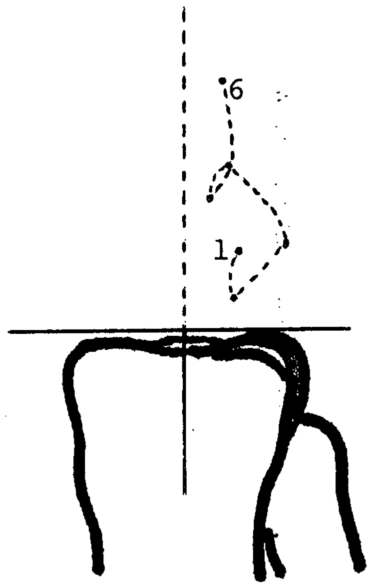
Application of the Taylor Brace under conditions of slow, level walking produced minor fluctuations in the range of the contra-lateral (unbraced) knee (Subject A, 1^{O} flexion-extension, 1^{O} internal-external rotation; Subject B, 1^{O} flexion-extension) with the exception of Subject C who recorded major fluctuations in the range of all three movement parameters. Increasing the speed of ambulation to a slow, level run produced major fluctuations in the range of the contra-lateral (unbraced) knee (Subject B, Subject C) with the exception of Subject A who recorded minor fluctuations of 1^{O} in the varus-valgus range. Results from Subject D (Lennox-Hill De-rotational Brace) showed similar findings with minor fluctuations for slow, level walking and major fluctuations for slow, level running.

With the exception of Subject C, it appears that the Taylor Brace os having very little effect on the dynamic range of the contra-lateral (unbraced) knee for slow, level walking. Increasing the speed of ambulation to a slow, level run appears to produce major fluctuations in the range of the contra-lateral knee for both subjects with unstable knees (Subjects B and C). This effect is similar to the fluctuations produced by the Lennox-Hill De-rotational Brace.

Instant Center of Rotation

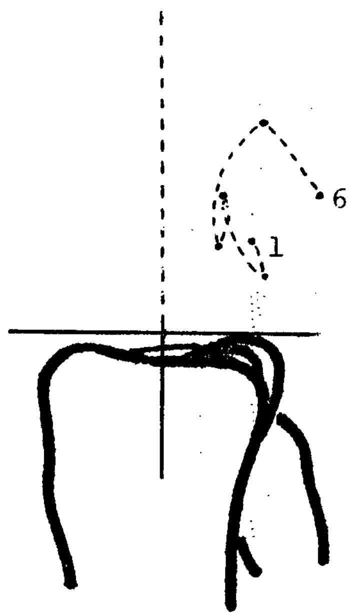
Data was collected for each subject from the unstable knee under unbraced and braced conditions. A total of six roentgenograms were taken and the instant center calculated for the series from ninety degrees of flexion to zero degrees of flexion. Each subject assumed a position lying on the side with the selected knee non-weight-bearing.

The summary of results is presented for the instant center of rotation pathways (Figures 30 and 31). Joint surface velocity angles are shown for the six calculated instant centers for each subject from zero degrees of flexion (number six) to ninety degrees of flexion (number one) Tables 9-A, 9-B, 10-A and 10-B).



unbraced

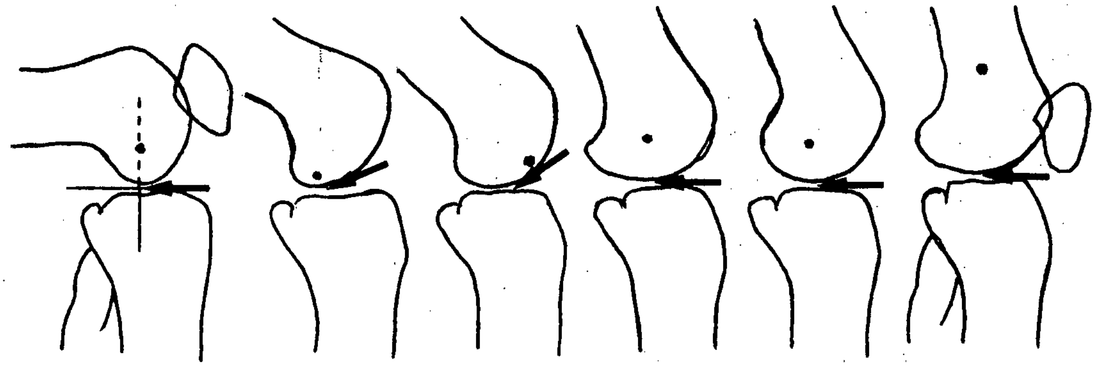
circle diameter 4.6 centimeters



braced

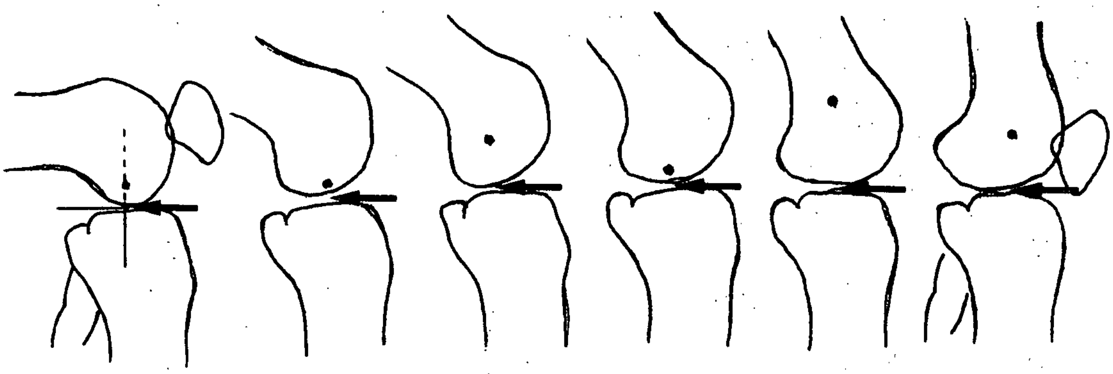
circle diameter 3.5 centimeters

Figure 30. Pathway of instant center of rotation with respect to the tibia and femur for Subject B, left knee, unstable. Scale is approximately one third.



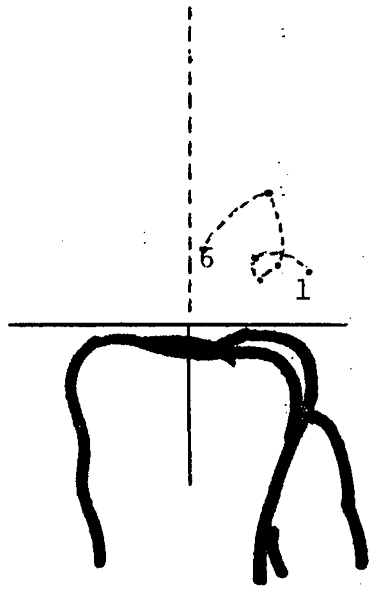
Angle of Joint	90°	75°	60°	40°	20°	10°
VelocityAngle (unbraced)	90°	76°	107°	90°	88°	90°

Table 9-A. Joint surface velocity angles, Subject B, unstable knee, unbraced.



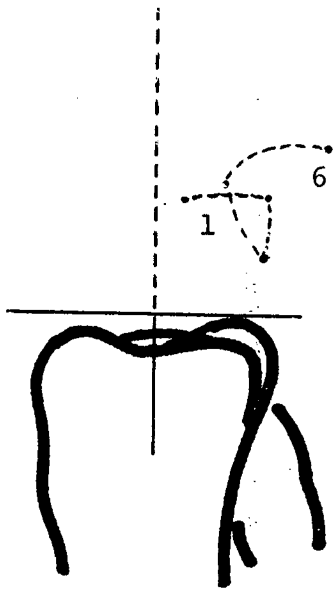
Angle of Joint	90°	75°	60°	40°	20°	10°
Velocity Angle (braced)	88°	90°	96°	90°	94°	90°

Table 9-B. Joint surface velocity angles, Subject B, unstable knee, braced.



unbraced

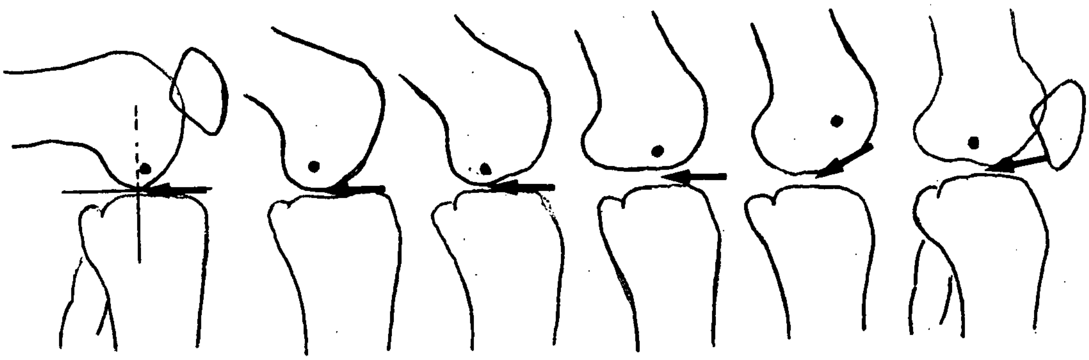
circle diameter 1.65 centimeters



braced

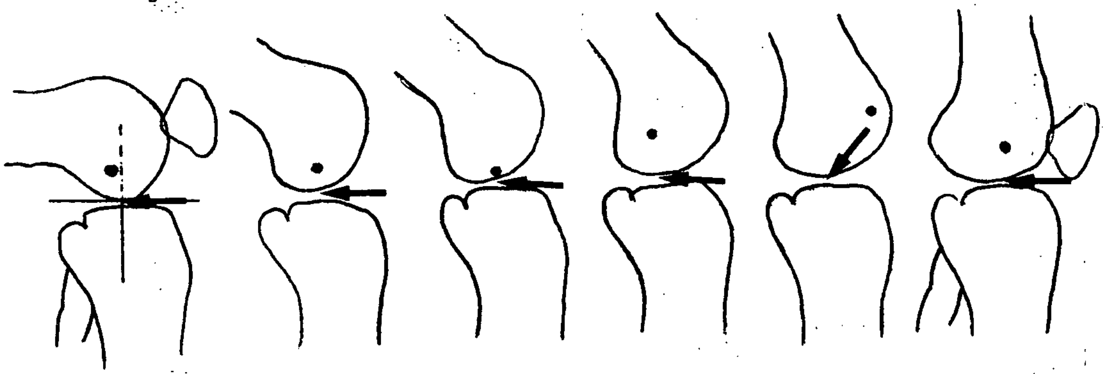
circle diameter 2.20 centimeters

Figure 31. Pathway of instant center of rotation with respect to the tibia and femur for Subject C, right knee, unstable. Scale is approximately one third.



Angle of Joint	90°	75°	60°	40°	20°	10°
Velocity Angle (unbraced)	92°	90°	90°	90°	107°	96°

Table 10-A. Joint surface velocity angles, Subject C, unstable knee, unbraced.



Angle of Joint	90°	75°	60°	40°	20°	10°
Velocity Angle (braced)	90°	90°	90°	91°	116°	90°

Table 10-B. Joint surface velocity angles, Subject C, unstable knee, braced.

Results

Results from both subjects (Figures 30 and 31) show that the instant centers for the six different knee angles are located in the posterior portion of the medial femoral condyle. The results also show that there is no standard pattern to the instant center pathway for the abnormal, unbraced knee. The instant center movement in the posterior portion of the medial femoral condyle is quite random. There was a tendency for the instant center pathway to move posteriorly and superiorly following application of the Taylor Brace that was consistent for both subjects.

For Subject B, the location of the instant center for the six different knee angles fell within a circle with a diameter of 4.60 centimeters. Following application of the Taylor Brace, the circle diameter was reduced to 3.50 centimeters. These findings were not consistent with Subject C who showed an increase in circle diameter from 1.65 centimeters to 2.20 centimeters following application of the Taylor Brace.

The joint surface velocity angles were judged to be abnormal in both of the subjects tested. Subject B showed abnormal velocity angle values with impingement to flexion between sixty and seventy-five degrees inclusive (Table 9-A). Application of the Taylor Brace to Subject B resulted in values indicative of relatively free gliding at the articular surfaces with no restriction to flexion (Table 9-B). Subject C showed relatively free knee motion throughout the entire unbraced range except for the last few degrees of extension where abnormal values were noted (Table 10-A). Application of the Taylor Brace increased the abnormal values in this range.

Discussion

Both subjects tested with the Taylor Brace located the instant center of rotation pathway in the posterior portion of the medial femoral condyle. These results are consistent with the findings of related researchers (Frankel and Burstein, 1971; Smidt, 1972; Meek, Martens and Temets, 1975). There appears to be no set pattern to this pathway for the abnormal (unstable) knee but, rather, random movement on the condylar surface. Meek et al (1975) and Walker (1973) have reported similar results for abnormal knee pathways. For both of the subjects tested, the instant center pathway moved posteriorly and superiorly following application of the Taylor Brace.

Both of the subjects tested showed an alteration in the pattern and circle diameter of the instant center of rotation pathway after application of the Taylor Brace. There was not, however, any consistency in the patterns of any subject nor in the change of circle diameter. Subject B recorded a decrease in circle diameter while Subject C recorded an increase following bracing.

It appears that application of the Taylor Brace to the unstable knee produces changes in the pattern and dispersion of the instant center of rotation pathway that has no definite trend. There does appear, however, to be a definite shifting of the instant center pathway posteriorly and superiorly following bracing.

Both subjects tested showed abnormal joint surface velocity angles (Tables 9-A and 10-A). Application of the Taylor Brace to Subject B showed changes in the abnormal joint surface velocity angle values to values indicative of smooth, normal movement at the articular surfaces (Table 9-B). Application of the Taylor Brace to Subject C resulted in an increase in already abnormal values for the last few degrees of extension (Table 10-B). This increase may be explained by rotation of the tibia as a result of the screw-home mechanism of the knee. During the last few degrees of extension, tibial rotation projects points on a different plane, not representing a true lateral roentgenogram. The rotation of the tibia at this point was significant enough to produce incorrect projection of the instant center from points not on the midline. The use of points on the midline of the tibial shaft rather than on the margins for the projection of the instant center would produce a more accurate calculation. Except for this impingement in the last few degrees of extension, Subject C demonstrates free gliding at the articular surfaces.

It appears that application of the Taylor Brace to the unstable knee produces changes in abnormal joint surface velocity angles to within the normal range. With the exception of Subject C in the last few degrees of extension, these changes are indicative of relatively free gliding at the articular surfaces, throughout the monitored range. Increases in abnormal values for Subject C can be explained by the presence of tibial rotation and the use of points away from the midline causing miscalculation of the instant center for that particular segment.

Stress Analysis

Mechanical stresses were applied to the knee joint by means of a stress machine. Data was collected for each subject from the unstable knee. Roentgenograms were taken and the amount of medial and anterior laxity determined for unbraced and braced conditions.

The summary of results is presented below for medial laxity (Table 11) and anterior laxity (Table 12). All values for the braced knee were recorded using the Taylor Brace.

TABLE 11

Medial Laxity*

Subject	Unbraced Unstressed	Unbraced Stressed	Braced Stressed
B	0.70 cms.	0.90 cms.	0.80 cms.
C	0.45 cms.	0.90 cms.	0.90 cms.

* all measurements of medial laxity were made in millimeters of distance between the sub-chondral bone of the medial femoral condyle and the sub-chondral bone of the medial tibial condyle at a distance one centimeter from the medial margin of the proximal tibia.

TABLE 12

Anterior Laxity

Subject	Unbraced Unstressed	Unbraced Stressed	Braced Stressed
B	6.40 cms.	7.80 cms.	6.90 cms.
C	7.35 cms.	8.95 cms.	7.50 cms.

The overall effect of the Taylor Brace on anterior laxity can be seen in Table 13.

TABLE 13

Anterior Laxity Reduction Values

Subject	unbraced	braced	reduction	percentage
B	1.40 cms.	0.50 cms.	0.90 cms.	64
C	1.60 cms.	0.15 cms.	1.45 cms.	90

Results

Table 11 (medial laxity), in a comparison of the unbraced, unstressed and unbraced, stressed columns shows a range of medial laxity for the two subjects of 0.20 centimeters to 0.45 centimeters. Application of the Taylor Brace to the unstable knee of Subject B produced a reduction in the medial laxity measurement of 0.10 centimeters (fifty percent) while Subject C remained the same.

Table 12 (anterior laxity), in a comparison of the unbraced, unstressed and unbraced, stressed columns shows a range of anterior laxity for the two subjects of 1.40 centimeters to 1.60 centimeters. Application of the Taylor Brace to the unstable knee produced a reduction in the anterior laxity measurements of both subjects; of Subject B by 0.50 centimeters (sixty-four percent) and of Subject C by 1.45 centimeters (ninety percent) (Table 13).

Discussion

The range of medial laxity for this sample was 0.20 centimeters to 0.45 centimeters. Subject B with a medial laxity measurement of 0.20 centimeters is below the values reported by Kennedy and Fowler (1971) and Roser et al (1971) for unstable knees. Subject C with a medial laxity measurement of 0.45 centimeters was within their reported range.

Both subjects tested with the Taylor Brace under conditions of medial stress showed minor or negligible changes in the medial laxity range. These results are consistent with the stress analysis findings of Roser et al (1971) who reported reductions of 0.30 centimeters and increases of 0.10 centimeters in medial instability following application of the Palmer Knee Brace to the unstable knee. With the exception of Subject B who showed a decrease of 0.10 centimeters, it appears that the Taylor Brace is having little or no effect on the medial laxity of the unstable knee.

The range of anterior laxity for this sample was 1.40 centimeters to 1.60 centimeters. These values are within the range reported by Kennedy and Fowler (1971) for abnormal knees. Both subjects tested with the Taylor Brace under conditions of anterior stress displayed major decreases in the anterior laxity range (Table 13). The values demonstrated here are within those found by Roser et al (1971) who reported reductions of 0.30 centimeters to 0.50 centimeters in anterior laxity following application of the Taylor Brace. From the results of both subjects, it appears that the Taylor Brace is producing a substantial decrease in the anterior laxity of the stressed knee.

Subjective Evaluation

Subjective evaluation of the Taylor Brace consisted of a verbal discussion with the subject following each session of physical activity, as well as an overall written assessement. Both the discussion and assessement were based on pre-determined criteria.

Subject A wore the Taylor Brace while participating in the following activities; rugby, cycling, volleyball, distance running, sprinting and weight lifting. These are his comments:

"The most impressive thing about this brace is the joint. It fits closely to the leg and can do anything the normal knee does. Even deep knee bends are easily done. The brace was easily applied and fit snugly. It gave the immediate impression of stability. There was some initial irritation along the front of the tibia and behind the knee on the tendon of biceps, from rubbing on the cuffs. The thigh and calf cuffs fit well but soon began to get slippery because of sweat building up inside. With prolongued use the medial knee strap and cuffs began to slip down the leg. During this slippage the joint still articulated well but the cuffs dug into the thigh and shin making movement difficult. There was never any constriction or numbness in the leg to hamper movement despite prolongued use of over three hours on occasion. The brace was so light that after a while one forgot that there was anything at all on the knee."

Subject B wore the Taylor Brace while participating in the following activities; squash, handball, volleyball, cycling, alpine skiing, interval running and tree planting. These are his comments:

"The articulation of the joint was excellent. The range of motion was in no way hampered in either flexion or extension. The fiberglass thigh and calf cuffs had a tendency to jab into the thigh at some points and pinch behind the knee and along the tibial spine. The stiff fiberglass (of the thigh cuff) would not conform to the changing upper leg muscles and tended to slip down the leg. The medial support strap had a tendency to slip down with active use. Because of the design, the popliteal region behind the knee was never seriously occluded. The weight of the brace (.75 kilograms) was not noticeable and did not hamper movement. Application of the brace was quick and simple.

Subject C wore the Taylor Brace while participating in the following activities; squash, rugby training sessions, slow jogging. These are his comments:

"When I first began to use the brace it was a bit uncomfortable, especially at the back of the knee (long head of biceps) and on the shin. After a while this all went away. The joint moved well. There was never any restriction to movement at all. There was a definite movement of the brace down the leg with active use and frequent adjustements were necessary. The fit was snug, the device light and it never felt restricting or uncomfortable, after the initial wearing in. You could even wear it under the pants without it being noticeable.

Discussion

All subjects subjectively evaluated following active use of the Taylor Brace reported the following major points:

(a) excellent joint articulation range even after displacement of the joint from the knee area.

(b) irritation from the fiberglass cuffs on the skin, especially in the region of the long head of biceps and along the anterior surface of the tibial shaft.

(c) lack of conformity of the rigid fiberglass thigh cuff to the changing quadriceps muscle mass.

(d) definite slippage of the thigh and calf cuffs and medial support strap down the leg with active use.

(e) ease of application.

(f) light weight, not bulky.

(g) comfort of fit with no pinching or binding after the initial wearing-in period.

(h) no constriction or numbness of the leg resulting in restrictions to movement.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

The purpose of this study was to determine the effect of the Taylor Brace on the stability and dynamic range of motion of the knee joint. The study was divided into an analysis of the Taylor Brace under the following experimental conditions; (a) electrogoniometric testing, (b) instant center of rotation calculation, (c) stress analysis and (d) subjective evaluation.

Electrogoniometric testing consisted of recordings of knee movement in three mutually perpendicular movement parameters of flexion-extension, internal-external rotation and varus-valgus for the unstable knee. Testing was conducted in a level segment of hallway forty meters long. Experimental runs consisted of ten steps, exclusive of the first and last steps of the run, for unbraced and braced conditions.

Instant center of rotation calculation was carried out through roentgenogram measurement of the unstable knee. With the femur firmly fixed to the x-ray table, the tibia was manually moved. Seven medial roentgenograms were taken of the knee from ninety degrees of flexion to zero degrees of flexion in increments of fifteen to twenty degrees.

The instant center of rotation was calculated for each x-ray for unbraced and braced conditions.

Stress analysis was carried out on the unstable knee using a mechanical stress apparatus. Regulated forces were applied to the knee and radiographic changes in the laxity of the knee joint recorded for unbraced and braced conditions. Medial and anterior laxity measurements were made for unbraced, unstressed; unbraced, stressed; and braced and stressed conditions.

Subjective evaluation consisted of verbal evaluation of the brace function after periods of physical activity as well as an overall written assessement at the conclusion of the study. Both parts of the subjective evaluation were based on pre-determined criteria.

Electrogoniometric results indicated a general reduction in the dynamic flexion-extension, internal-external rotation and varus-valgus range of the braced knee following application of the Taylor Brace to the walking subject. The restraint on the dynamic flexion-extension range was considered undesirable but not significant in altering the total gait pattern. Reduction of internal-external rotation and varus-valgus values, however, were considered to be important factors in the brace's ability to restrain undesirable motions. The movement parameters of the unbraced knee showed some fluctuations in the magnitude of the range following application of the Taylor Brace to the contra-lateral knee. These fluctuations were minor in the walking subject with a tendency to increase in magnitude as the speed of ambulation increased.

Instant center of rotation calculation located the instant center of rotation pathway in the region of the medial femoral condyle. There was no set pattern to the pathway. Application of the Taylor Brace produced changes in the pathway pattern and distribution (diameter) but no trends were evident.

Abnormal joint surface velocity angles showed definite alterations to normal values, indicative of free gliding at the articular surfaces, following application of the Taylor Brace to the unstable knee.

There were very little changes in the medial laxity measurements of the unstable knees following application of the Taylor Brace to the stressed knee. It was felt that this was due in part to both subjects having relatively stable medial structures. Anterior laxity values showed marked decreases by as much as ninety percent in one subject following bracing with the Taylor Brace.

Subjective evaluation showed excellent range and articulation of the Taylor Brace joint with very little restriction to movement. Subjects found the brace lightweight, easy to apply, non-restricting and comfortable to wear. Observations were made that the cuffs and medial strap did tend to slip down the leg with active use and that there were some initial pressure areas along the anterior surface of the tibial shaft and the tendon of the long head of biceps. The rigid structure of the thigh cuff was not accommodating enough to the changing quadriceps muscle mass during active use.

Conclusions

1. The Taylor Brace has a restraining effect on the dynamic flexion-extension range of the braced knee that increases with the speed of ambulation. This restraining effect is considered undesirable but not significant in altering the total gait pattern.
2. The Taylor Brace has a restraining effect on the dynamic internal-external rotation and varus-valgus range of the braced knee that remains constant with increases in the speed of ambulation. The brace's ability to restrain these undesirable motions is considered an important factor.
3. Application of the Taylor Brace to the knee produces changes in the movement patterns of the contra-lateral, unbraced knee.
4. Changes in the pattern and dispersion of the instant center of rotation pathway occurrs following bracing with the Taylor Brace but no definite trends are evident.
5. There is no recordable reduction in medial laxity measurements following application of the Taylor Brace to the unstable knee. It was felt that this was due in most part to both subjects having sound medial structures. Anterior laxity, however, was greatly reduced in the unstable knee following bracing.
6. Joint articulation range of the Taylor Brace is considered to be excellent with comfortable fit. Slippage of the brace is considered to be a significant problem as well as the rigid nature of the fiberglass thigh cuff construction.

CHAPTER VI

RECENT DEVELOPMENTS AND SUGGESTIONS FOR FURTHER RESEARCH

New Prototypes

Since the development of the first prototype (Prototype I), continuing research has been carried out on the Taylor Brace. From subjective evaluation and continuing subject use, several refinements have been made in the brace design to enhance comfort and fit.

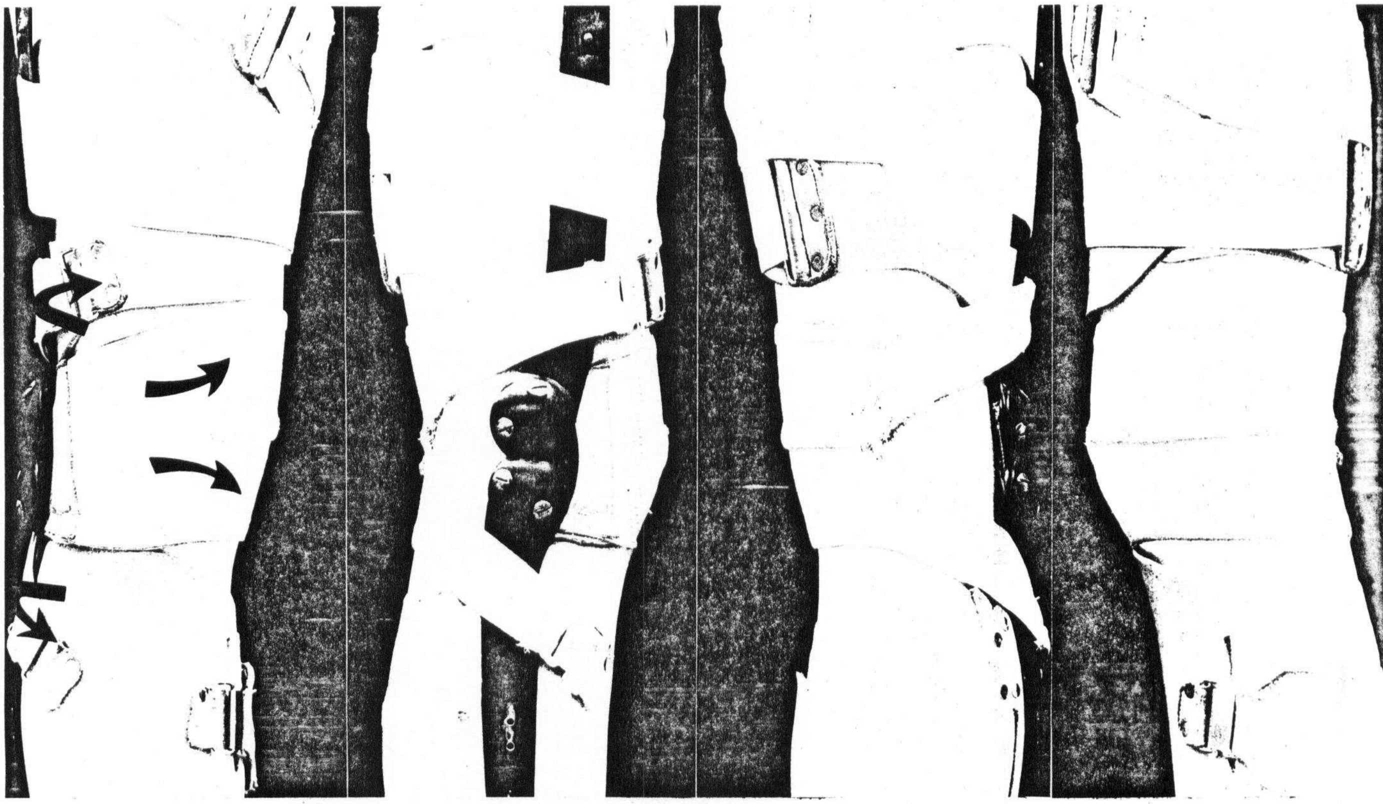
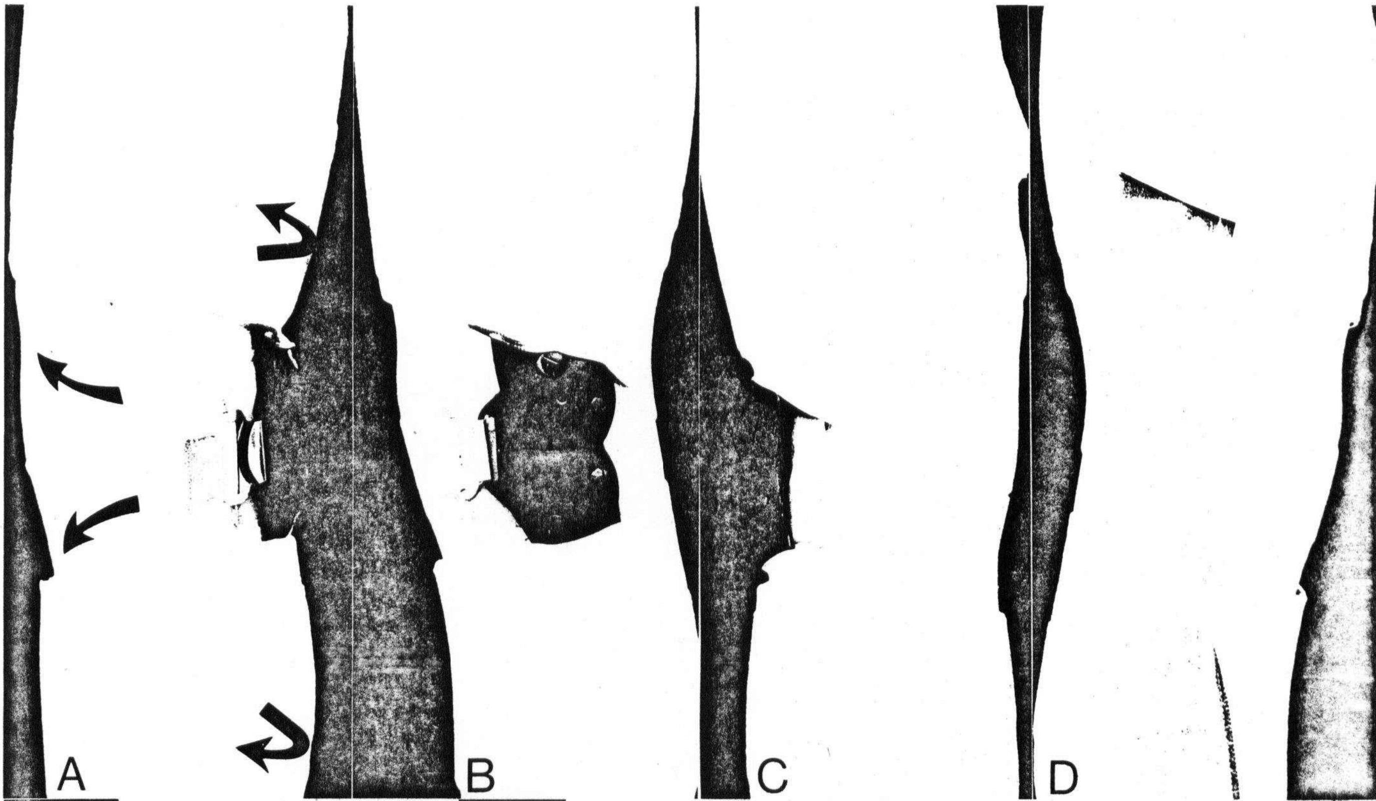


Figure 32. Prototype I, Taylor Brace. Arrows indicate split medial strap and direction of application. Note the polyester resin thigh and calf cuffs.



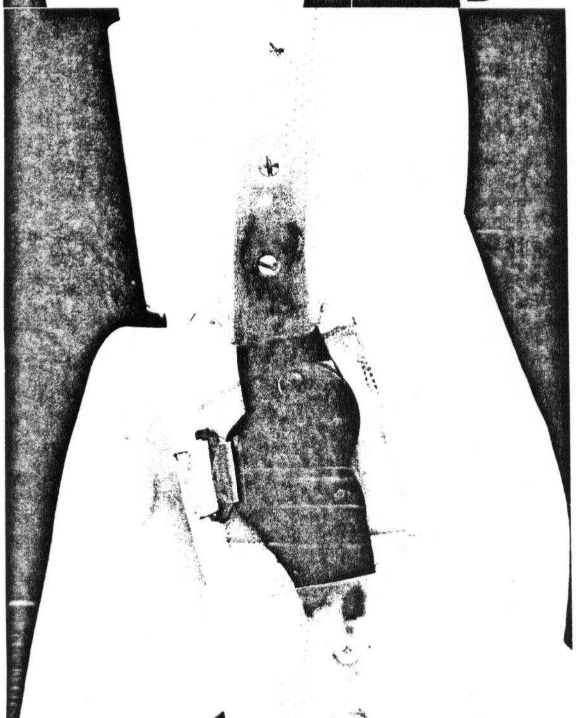


Figure 33. Taylor Brace, Prototype II, (A to E). Arrows indicate split medial strap and direction of application (A). Note the replacement of "D" hooks by velcro straps (D) and the incorporation of spiral webbing to fasten the brace to the leg. Print E shows the brace cuffs with the webbing removed. Note that the size of the thigh cuff has been reduced to half the previous size and the polypropylene material used in cuff construction.

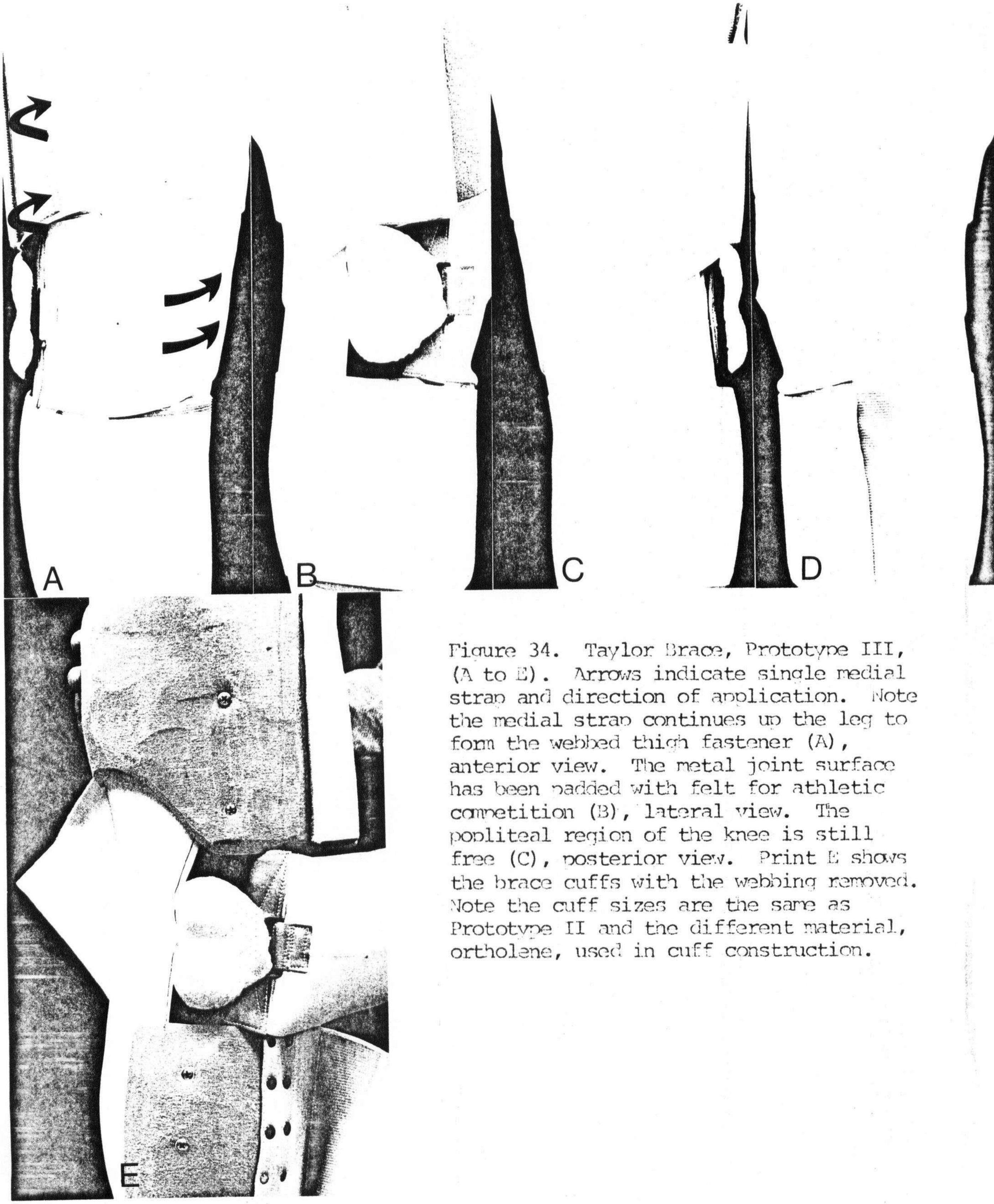


Figure 34. Taylor Brace, Prototype III, (A to E). Arrows indicate single medial strap and direction of application. Note the medial strap continues up the leg to form the webbed thigh fastener (A), anterior view. The metal joint surface has been padded with felt for athletic competition (B), lateral view. The popliteal region of the knee is still free (C), posterior view. Print E shows the brace cuffs with the webbing removed. Note the cuff sizes are the same as Prototype II and the different material, ortholene, used in cuff construction.

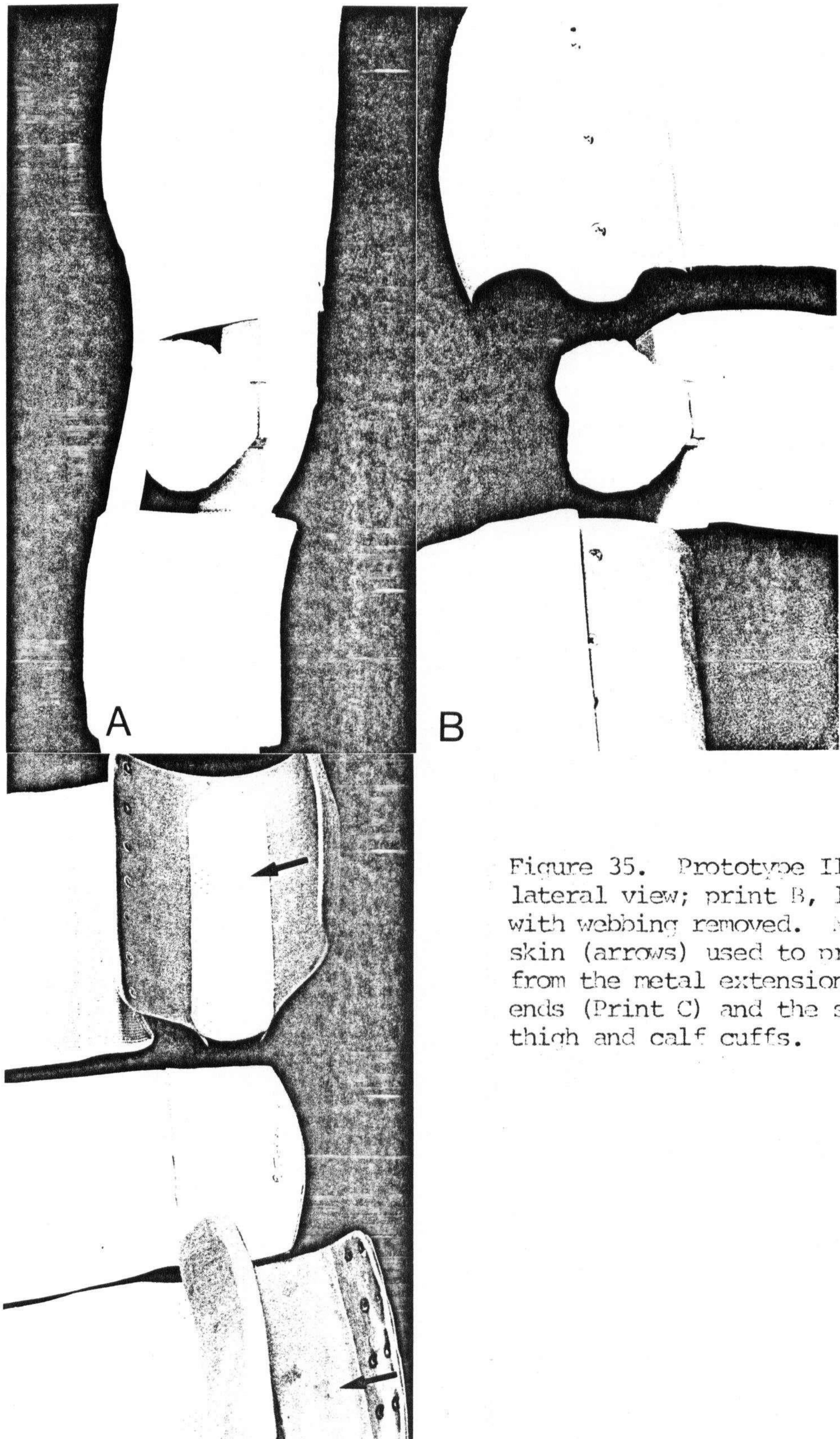


Figure 35. Prototype III. Print A, lateral view; print B, lateral view with webbing removed. Note the mole skin (arrows) used to prevent chaffing from the metal extension arms and screw ends (Print C) and the shapes of the thigh and calf cuffs.

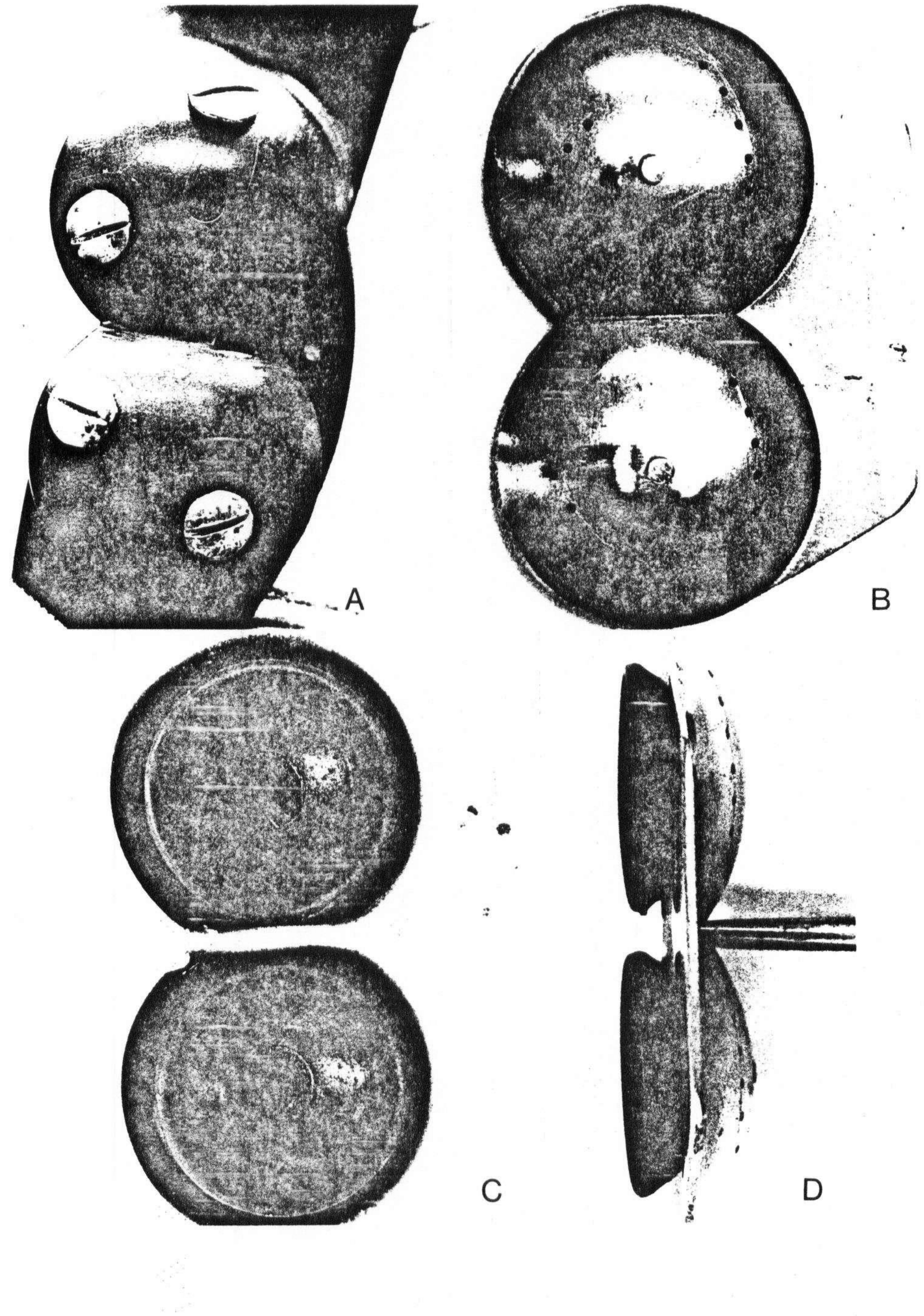


Figure 36. Joint Fixation. (A) mechanical brace joint positioned; (B) assembly base with uncut geometry, top view; (C) assembly base, bottom view, showing suction cups; (D) assembly base, side view. To ensure proper position of the mechanical brace joint near the anatomical knee joint and prevent slippage with active use, suction cups have been applied with skin cement to the skin at the knee.

Suggestions for Further Research

The following topics are suggested as continuing areas of research:

1. Standardization and classification of typical stable and unstable knee patterns for varying rates of ambulation.
2. Association of specific structural lesions of the knee with specific characteristics of gait.
3. The use of cinematography in conjunction with electrogoniometry in the analysis of knee function under various conditions.
4. Correlation of electromyography with electrogoniometry of leg function.
5. Electrogoniometric evaluation of specific sport activities, both indoor and outdoor, with relation to joint function.
6. Investigation of the use of the Taylor Brace joint design in the cast-brace treatment of tibial fractures.

BIBLIOGRAPHY

Cousins, S.J., A Parallelogram Chain Designed to Measure Human Joint Motion, Unpublished Masters Thesis, Department of Mechanical Engineering, University of British Columbia, Canada, 1975.

Eriksson, E., Sports Injuries of the Knee Ligaments: Their Diagnosis, Treatment, Rehabilitation, and Prevention, Medicine and Science in Sports, Vol. 8, No. 3: 133-144, 1976.

Frankel, V.H., Burstein, A.H. and Brooks, D.B., Biomechanics of Internal Derangement of the Knee, Journal of Bone and Joint Surgery, Vol. 53-A, No. 5: 915-962, 1971.

Gollnick, P.D. and Karpovich, P.V., Electrogoniometric Study of Locomotion and of Some Athletic Movements, The Research Quarterly, Vol. 35, No. 3: 357-369, 1962.

Hallen, L.G., The "Screw-Home" Movement in the Knee Joint, Acta Orthop. Scandia, 37: 97-106, 1966.

Helfet, A.J., Disorders of the Knee, J.B. Lippincott Company, Philadelphia, U.S.A., 1974.

Helfet, A.J., Mechanism of Derangements of the Medial Semilunar Cartilage and their Management, Journal of Bone and Joint Surgery, 41-B: 319-336, May, 1959.

Hughston, J.C., Andrews, J.R., Cross, M.J. and Moschi, A., Classification of Knee Ligament Instabilities Part I. The Medial Compartment and Cruciate Ligaments, Journal of Bone and Joint Surgery, 58-A, No. 2: 159-172, March, 1976.

Hughston, J.C., Andrews, J.R., Cross, M.J. and Moschi, A., Classification of Knee Ligament Instabilities Part II. The Lateral Compartment, Journal of Bone and Joint Surgery, 58-A, No. 2: 173-179, March, 1976.

Jesswein, P.O., Lower Extremity Orthotics III, VAPC Research, Bulletin of Prosthetics Research, pp. 261-262, Fall, 1966.

Johnston, R.C., Measurement of Hip Joint Motion During Walking: An Evaluation of Electrogoniometric Method, Journal of Bone and Joint Surgery, 51: 1083, 1969.

Karpovich, P.V., Electrogoniometric Study of Joints, U.S. Armed Forces Medical Journal, 11: 424, 1960.

Kennedy, J.C. and Fowler, P.J., Medial and Anterior Instibility of the Knee, Journal of Bone and Joint Surgery, Vol. 53-A, No. 7: 1257-1270, 1971.

Kennedy, J.C., Weinberg, H.W. and Wilson, A.S., The Anatomy and Function of the Anterior Cruciate Ligament, Journal of Bone and Joint Surgery, Vol. 56-A, No. 2: 223-235, 1974.

Kettlekamp, D.B., Johnson, R.J., Smidt, G.L., Chao, E.Y.S. and Walker, M., An Electrogoniometric Study of Knee Motion in Normal Gait, Journal of Bone and Joint Surgery, 52: 775-790, 1970.

Lamoreux, L.W., Kinematic Measurements in the Study of Human Walking, Bulletin of Prosthetics Research, pp. 3-81, Spring, 1971.

Laubenthal, K.N., Smidt, G.L. and Kettlekamp, D.B., A Quantitative Analysis of Knee Motion During Activities of Daily Living, Physical Therapy Journal, Vol. 52, No. 1: 34-42, January, 1972.

Lehmann, J.F., Warren, C.G. and DeLateur, B.J., A Biomechanical Evaluation of Knee Stability in Below-Knee Braces, Archives of Physical Medicine and Rehabilitation, pp. 688-695, December, 1970.

Meek, R.N., Martens, M. and Temets, D., Correlation of Instant Center Displacement and Internal Derangement of the Knee, Research Paper, unpublished, Vancouver General Hospital, Department of Orthopaedics, Vancouver, Canada.

Noonan, R.C., and Cooke, C., A Pictoral and Descriptive Taping Manual For Athletic Injury Management, going to press, 1977.

O'Donoghue, D.H., Surgical Treatment of Fresh Injuries to the Major Ligaments of the Knee, Journal of Bone and Joint Surgery, Vol. 32-A, No. 2: 721-738, 1950.

O'Donoghue, D.H., Reconstruction for Medial Instability of the Knee, Journal of Bone and Joint Surgery, Vol. 55-A: 941-55, 1973.

Roser, L.A., Miller, S.J and Clawson, D.K., Effects of Taping and Bracing on the Unstable Knee, Northwest Medicine: pp. 544-546, August, 1971.

Rozin, R., Robin, G.C., Magora, A., Gonen, B. and Saltiel, J., Investigation of Gait: III Analysis of Lower

Extremities Braced with a Standard Below-Knee Appliance, Electromyography and Clinical Neurophysiology, Vol. 12, 433-440, 1972.

Rouleaux, F., The Kinematics of Machinery; Outlines of A Theory of Machines, Translated and Edited by A.B. Kennedy, Macmillan and Company, London, England, 1876.

Slocum, D.B., Larson, R.L. and James, S.L., Pes Anserinus Transplant: Impressions After a Decade of Experience, Journal of Sports Medicine, 2: 123-136, 1974.

Slocum, D.B., Larson, R.L. and James, S.L., Late Reconstruction of Ligamentous Injuries of the Medial Compartment of the Knee, Clinical Orthopaedics, 48: 23-55, 1975.

Smidt, G.L., Biomechanical Analysis of Knee Flexion and Extension, Journal of Biomechanics, Vol. 6, pp. 79-92, 1973.

Tipton, C.M. and Karpovich, P.V., Clinical Electrogoniometry, Journal of the Association for Physical and Mental Retardation, Vol. 18, No. 4, pp.90-109, July-August, 1964.

Tipton, C.M. and Karpovich, P.V., Electrogoniometric Records of Knee and Ankle Movements in Pathologic Gaits, Archives of Physical Medicine and Rehabilitation: 267-272, March, 1965.

Wang, C.J., Rotatory Laxity of the Human Knee Joint, Journal of Bone and Joint Surgery, 56: 161-70, January, 1974.

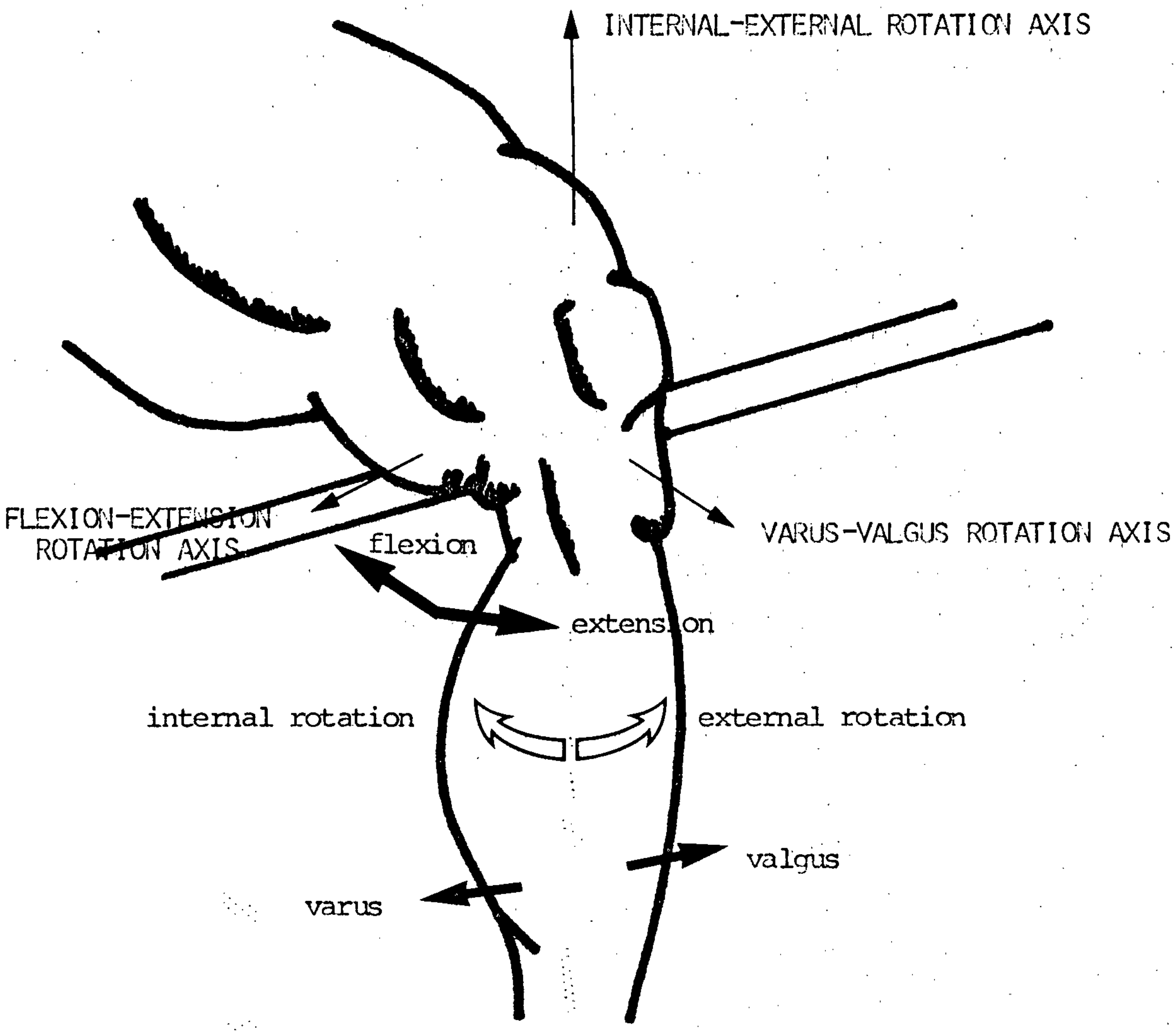
Wolf, B., The Effects of Flexion and Rotation on the Length Patterns of the Ligaments of the Knee, Biomechanics, Vol. 6: 587-596, 1973.

APPENDIX A

KNEE AXES OF ROTATION

APPENDIX A

Knee Axes of Rotation



APPENDIX B

SUBJECT CASE HISTORIES

APPENDIX B

SUBJECT CASE HISTORIES

Subject B

Weight: 70.4 Kg.

Age: 24 years Occupation: Student Height: 140.8 cms.

This young man received a twisting injury to the medial aspect of the left knee during the winter of 1970. During a slalom ski race, the tip of his left ski caught a pole and forcefully externally rotated. The left leg became abducted and pressure of the fall was directed on the medial aspect of the left knee. He remembers a pain on the medial aspect but got up and continued the race. Tenderness and swelling persisted and he consulted an orthopaedic surgeon.

Clinical examination reveals a relatively lean and muscular young man of stated age with good quadriceps bulk and tone. There is demonstrable medial laxity in both left and right knees on application of valgus stress. There is marked antero-posterior laxity with internal tibial rotation on examination with the anterior drawer test.

Since the time of the initial injury, the subject has maintained an active life. He continues to ski, run, play handball and squash. He suffers repeated bouts of "knee collapse", pain and swelling if he attemps to internally rotate with the hip on a flexed and weight-bearing knee. He appears to suffer from the "pivot-shift" phenomenon. The subject has never been a candidate for surgery.

Subject C

Weight 104.5 Kg.

Age: 29 years Occupation: Businessman Height: 162.8 cms.

This man has had a history of knee injury from the age of 10 years. He reports collapsing on the knee of the right leg repeatedly while playing as a youngster. As he grew older, he developed the quadriceps musculature and was able, with few problems, to actively engage in competitive rugby. For several years he continued, reaching national caliber and then retiring. After a year's absence, he returned to the rugby scene suffering a "knee collapse" during a practice. Swelling resulted and he consulted an orthopaedic surgeon.

Clinical examination revealed a loose body in the medial aspect of the knee which was confirmed by x-ray. Surgery was performed on the right knee in 1973 and the bone chip removed. He resumed his activity after rehabilitation playing rugby, handball and squash. After another lay-off of a year, he resumed competitive rugby.

Another injury to the right knee resulted in swelling and pain on the medial aspect of the knee. The excess fluid was drained and the diagnosis of a strain of the medial collateral ligament was made. Another collapse of the knee resulted in arthroscopy in 1976 where incisions were made on the medial and lateral aspects of the right knee. No involvement of the menisci was found but the diagnosis of osteochondritis dessecans was made. The subject continues to be active, has lost some weight (10 kilos) and still suffers from knee collapse, pain and swelling. There is no demonstrable anterior or medial laxity on clinical examination.

APPENDIX C

2 x 2 COLLAPBIBLE PARALLELOGRAM CHAIN ELECTROGONIOMETER

APPENDIX C

2 x 2 COLLAPSIBLE PARALLELOGRAM CHAIN ELECTROGONIOMETER

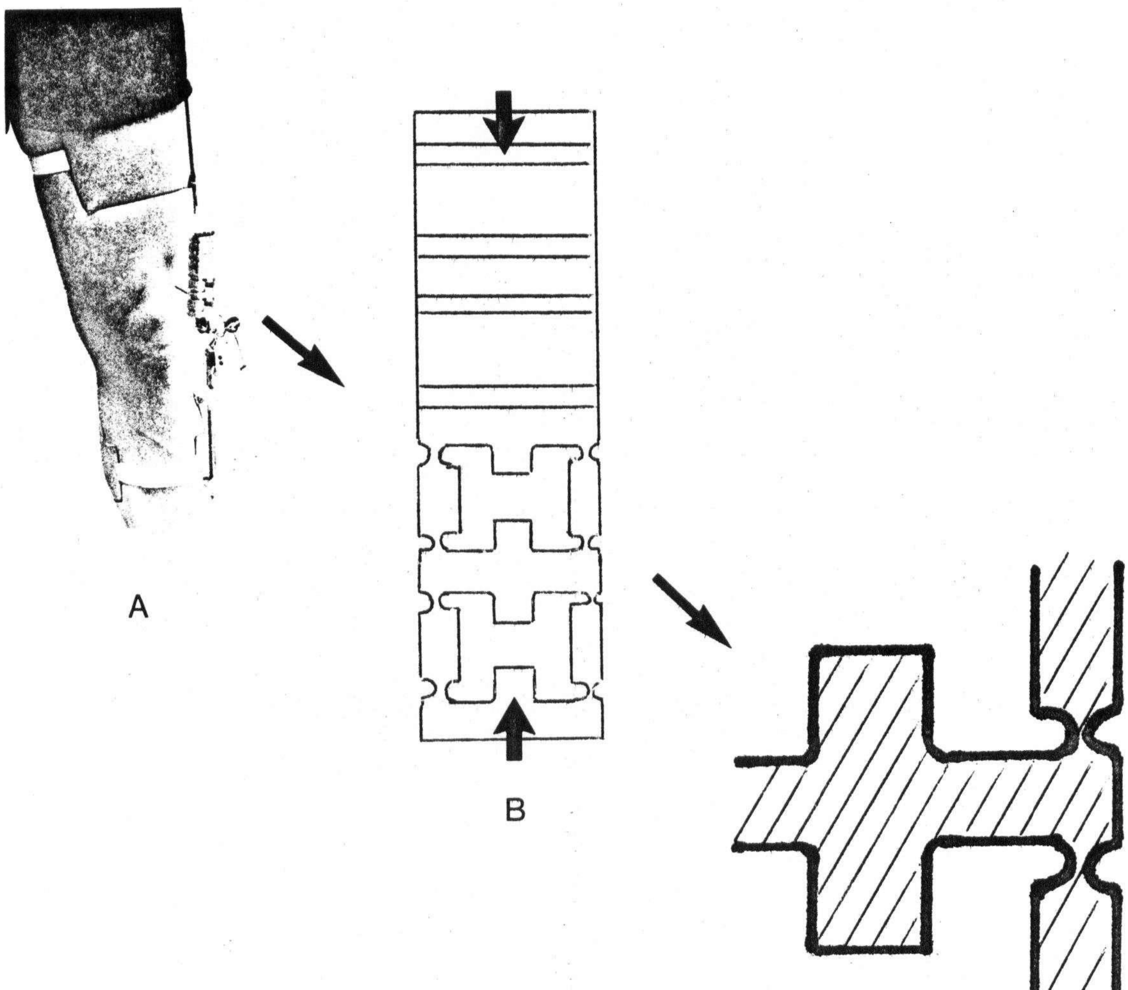


Figure 37. Parallelogram chain linkages showing (A) application on leg with brass brackets, metal wire thigh and calf frames and potentiometer cluster, (B) enlarged view of 2 x 2 parallelogram chain; arrows indicate longitudinal direction of chain scissoring allowing perpendicular rotations to pass through the chain unchanged while absorbing unwanted translations, and (C) enlarged section of parallelogram chain showing hinge design. Parallelogram chain is constructed of polyurethane and is cast vacu-moulded.

APPENDIX D

ELECTROGONIOMETRIC TESTING DATA SHEET

APPENDIX D

Electrogoniometric Testing Data Sheet*

Patient: ____________________ Test Date: ____________________

Test Sequence Time Lines:

	start									end
A. Motions measured										
B. Activities										
C. Aids used										
D. Chart speed										

* *

A. Code Boxes for Motions: (shade in boxes)

	HIP		KNEE		ANKLE			
1.	L	R	L	R	L	R	DIR'N	
V/V							VAL	
I/E							EX/ROT	
F/E							FLEX	
							STANDING ZEROS	+

	HIP		KNEE		ANKLE			
2.	L	R	L	R	L	R	DIR'N	
V/V							VAL	
I/E							EX/ROT	
F/E							FLEX	
							STANDING ZEROS	+

	HIP		KNEE		ANKLE			
3.	L	R	L	R	L	R	DIR'N	
V/V							VAL	
I/E							EX/ROT	
F/E							FLEX	
							STANDING ZEROS	+

	HIP		KNEE		ANKLE			
4.	L	R	L	R	L	R	DIR'N	
V/V							VAL	
I/E							EX/ROT	
F/E							FLEX	
							STANDING ZEROS	+

+ values are for F/E, I/E Rotation, V/V left to right on page

* revised from an original version by Steven Cousins, Canadian Arthritis and Rheumatism Society, Vancouver, British Columbia.

B. Code for Activities:

1. Slow level walk
2. Comfortable level walk
3. Fast level walk
4. Slow level run
5. Comfortable level run

C. Code for Aids:

1. None

Braces - Knee	Left		Right		Bilateral		
	L.Varus	L.Valgus	R.Varus	R.Valgus	Varus	Valgus	
Taylor Brace (lateral iron)	2	3	4	5	6	7	
Other Experimental Brace(s)	8	9	10	11	12	13	

	Left Knee		Right Knee	
	Int.Rot'n stop	Ext.Rot'n stop	Int.Rot'n stop	Ext.Rot'n stop
Lennox-Hill Brace	14	15	16	17

D. Code for Chart Speeds

	mm/min	mm/sec
50	1	5
125	2	6
500	3	7
1250	4	8

Test Results

Patient: ____________________ Test Date: ____________________

Code Boxes**								
Knee	F/E	Dynamic Range of Motion	R					
			L					
	I/E/R	Dynamic Range of Motion	R					
			L					
	V/V	Dynamic Range of Motion	R					
			L					

** Use codes for Activities and Aids from Page 1, eg.,

1/1	= slow, level walk, no aids.
1/5	= slow, level walk, Taylor Brace, right knee, right valgus.

APPENDIX E

INSTANT CENTER OF ROTATION CALCULATION

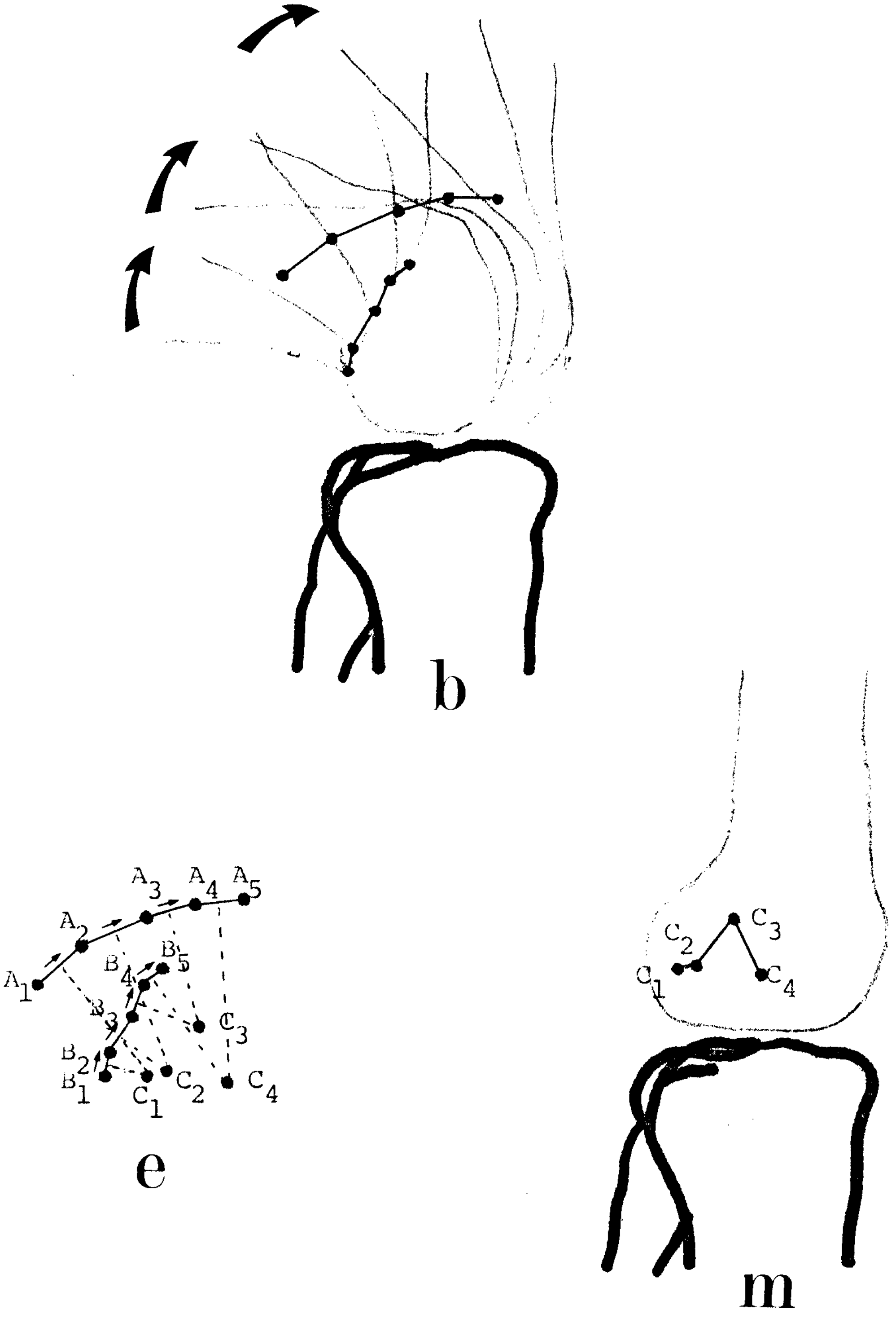


Figure 38. Instant center of rotation calculation showing (B) successive positions of points for plotting center for knee motion from flexion to extension; (E) calculation of instant center from perpendicular bisectors of points, and (M) instant center of rotation pathway on medial condyle of femur.