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Studies of dynamic ligamentous instability of the knee by electrogoniometric means

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Abstract

Ligamentous injuries to a knee joint increase the risk of post-traumatic degenerative changes. Successful early diagnosis and treatment of such injuries remains a challenging and controversial task.

There are a variety of clinical tests available and some of these are difficult to perform and interpret. These clinical tests are really static in nature and may not reveal the presence of what is essentially a dynamic event. A complete assessment would need to be "dynamic" and by its application during ambulation, incorporate the effects of ground-foot forces, joint motions and muscle activities.

At the Ontario Crippled Children's Centre (OCCC) a triaxial electrogoniometer system (extensively modified CARS-UBC) has been used, together with complementary gait laboratory instrumentation, in order to study the knees of 16 male subjects. Ten subjects had knees without evidence of injury and six had a variety of cruciate and menisceal tears.

The purpose of the study was to investigate if a subject's knee could be classified as "normal" or "unstable" by using just the data provided by the electrogoniometer during walking trials. These data are difficult to interpret in their time series form because they are multidimensional and in all subjects likely to exhibit subtle stride to stride variations. The method described allows the mapping of this data into an abstract two dimensional co-ordinate system, resulting in a set of trajectories which cluster together for data belonging to the "normal" group. Only two subjects, with grossly unstable knees, were judged different from normal using a level walking test protocol. Some potential reasons for this are discussed.

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Introduction

Knee joint function

The knee joint has received much attention over the years in almost all aspects of its function, components, replacement and repair. Discussion here will be restricted to studies pertinent to ligamentous knee injury.

Goodfellow and O'Connor (1978) gave a good functional description of the knee and pointed out that its important overall properties concern its mobility and stability and the interplay between them. Stability is the extent to which mobility is restricted by ligaments, joint surface geometry and active muscles and may be further considered as both a dynamic and a static property. Dynamic stability can only be fully assessed when a person is ambulatory and the forces of gravity and muscle activity are dominant features. Passive, or static, stability is the knee property most often judged by the popular clinical tests such as the "anterior-posterior drawer sign" or the "pivot shift sign". Ligamentous injuries which affect knee stability increase the risk of post-traumatic degenerative changes. The aim of treatment is to restore ligamentous stability and thereby reduce the likelihood of these changes occurring.

Classification of knee injury

A working classification of knee joint instability is mandatory, not only for the diagnosis of a specific injury, but also to apply treatment and to attach a meaningful prognosis.

Fowler (1980) reviewed those classification systems described in the past and pointed out their advantages and shortcomings. It is certain that a useful working classification will combine anatomical and pathological considerations. The type of instability experienced by a patient should ideally be correlated with the specific lesion. This is far from a simple task. There is a close interrelationship of all elements of the joint complex in contributing to the overall stability of the joint. There is not really such an entity as a "pure" lesion of a structure such as a cruciate ligament; some capsular involvement or other injury must invariably be found. A classification system must take into consideration all these factors. Often the extent of involvement of the various structures is the factor determining whether or not a knee can adequately compensate for an injury in the patient's usual range of activity.

Classification by passive assessment

The overall purpose of this type of classification has been to understand and correlate simple clinical stability tests with the various possibilities for internal derangement. The earliest detailed works used subjective observational methods (Brantigan and Voshell, 1941) which were repeated and refined by attempts at objective measurements. Many papers have been published in this area and are well described elsewhere. Recent work includes that by Butler et al, (1980) and Seering et al, (1980).

All of this work has had value in furthering understanding, but does not directly provide us with a classification of how a knee will behave under dynamic or ambulatory conditions. In fact, static clinical testing may be misleading. Butler et al, (1980) illustrated how, under the low forces of clinical testing, a partially torn ligament can deceive the clinician by blocking his attempt to recognise a positive sign.

Classification by dynamic assessment

In contrast to the numerous attempts to describe the role of the structures of the knee in passive testing, dynamic studies have received little attention in the clinical scene.

In general terms, when dynamic force actions are exerted on the limbs during walking they tend to produce dynamic turning effects (or moments) at joints. These turning effects are counterbalanced by the ensemble of reactions provided by muscle activity, ligament tensions and joint surfaces in contact. These internal forces usually cannot be directly measured using non-invasive methods and therefore must be estimated. Those situations where internal forces can be measured directly are few. Rydell (1966) made a direct determination of joint force at the hip using an Austin-Moore prosthesis with attached sensors. Others have implanted similar devices but few results have been reported.

A complete description of the dynamic behaviour of a joint must include information concerning forces, joint motion and muscle activity; all integrated with some concept of the interplay between them.

Attempts have been made to use optimization techniques to infer joint forces by criteria minimizing weighted sums of all lower limb muscle forces and residual unbalanced forces at all joints (Seireg and Arvikar, 1975). Justification for such criteria is still not established.

Generally accepted methods of estimating joint forces made use of anatomical and physiological constraint conditions together with force equilibrium equations. Techniques used by various researchers differ in the way constraint conditions have been applied to the equilibrium equations. One school of thought has used all unknowns in the equilibrium equations and then assumed that certain tendon forces are zero to produce a determinate system. All possible combinations of the unknowns are then tried and illogical solutions rejected to obtain joint forces (Chao et al, 1976).

The method of Paul (1967) for the hip, and Morrison (1967) and Harrington (1974) for the knee, was to identify the prime function of all the major structures and then simplify the equilibrium equations before attempting a solution. Correspondence between the results for Paul's approach and that of Rydell show that estimates obtained by manipulation of external measurements are realistically close.

All of these assessment efforts rely upon multiple signal acquisition of gait data which is combined with a generalized knowledge of functional anatomy to estimate internal states. The process by which this estimation is made is simplistic in comparison with the true situation. Whether or not this will matter depends upon the reasons for a particular investigation.

Whether the aim is clinical diagnosis of an injured knee or the refinement of basic investigative techniques the ability to identify and interpret "abnormal" joint motion would be of value.

Purpose of the study

The aim of this study was to apply a triaxial electrogoniometer to investigate the motion of the knees of subjects with normal and injured knees during level walking and determine whether a knee could be classified as normal or injured on the basis of such data.

Instrumentation

Choice of electrogoniometer

There are many systems intended for the collection of kinematic gait parameter measurements. Each of them has some advantages and disadvantages depending on the application.

The CARS-UBC system was chosen for our application because of:

i) Its availability.
ii) Its relative low cost.
iii) Its ability to detect valgus/varus and tibial rotation angles.
iv) Its ease of interfacing with our existing gait analysis systems.

Of particular importance was the reported ability to detect tibial rotation and valgus-varus angles because of the multifactorial nature of knee motion. These are particularly difficult to measure and attempts to use our existing optical processing methods were frustrating because of necessary increased data handling, operator fatigue and commensurate delays.

The availability of the CARS-UBC system and impressions of its use overrode the use of the systems described by Townsend et al, (1977) or Lamoreux (1971). There are some pitfalls in the use of a triaxial goniometer which have been described in the literature. Chao (1980) has explained some of the experimental limitations of this device.

The CARS-UBC electrogoniometer

The electrogoniometer has been well described by the designers (Hannah and Foort, 1979). Only brief details are given here.

The measurement module consists of a potentiometer/parallelogram cluster. Three potentiometers are arranged to be mutually orthogonal to give an angular measurement of the relative angular motions of the limb segments in three planes. At the knee these would be flexion-extension, internal-external rotation of the tibia with respect to the femur and valgus-varus as an angulation. The parallelogram chain is designed to absorb any translations due to bone movements or potentiometer—joint malalignments but to allow pure angular movements to pass through unchanged (Fig. 1). This makes the potentiometer cluster self-aligning with the anatomical centres of angular movement thus in theory eliminating any forces between the device and the joint which would affect the rotations being measured.

Each limb attachment consists of three parts; the thigh frame, the shank frame and the measuring module. The thigh frame has a lockable telescopic beam that is attached to the measurement module via a ball and socket connector. The manufacturers suggest that the thigh and shank frame be attached to the limb using adjustable plastic straps.

Anticipated problems

In the general area of measurement, no matter how simple the measurement system, several problems can be anticipated which to varying degrees will affect the signals obtained. These problems fall into the area of *quality* related and *application* related.

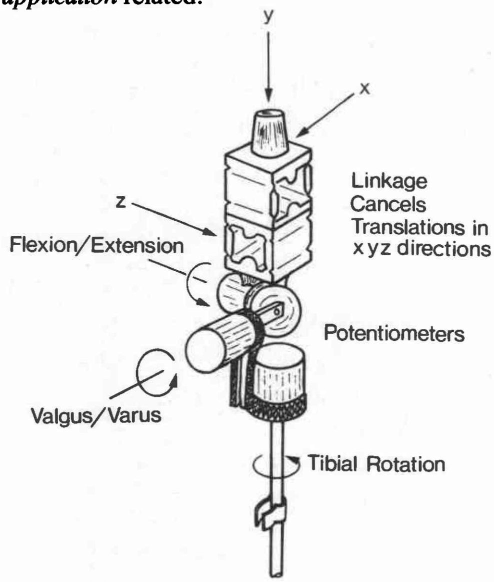

Fig. 1. Electrogoniometer measurement module.

Quality related problems concern all aspects of construction of the device, ie choice of materials, electrical wiring layout, ease of repair etc.

Application related problems are more subtle and fall into three categories. In this application they would be:

a) When the connection of the transducer to the leg affects the operation of the leg.
b) When the mere presence of the transducer changes the value of the measurand, although the operation of the leg is not directly impaired.
c) When the transducer is otherwise not suitable for the application.

In our initial assessment of the CARS-UBC system an attempt was made to identify and where possible, minimize these problems to an acceptable degree.

Results of electrogoniometer assessment

Mechanical changes

An initial evaluation by data collection from the knees of normal subjects gave grossly inconsistent signal patterns. The reasons for this were identified and changes were made to the following goniometer components (Fig. 2).

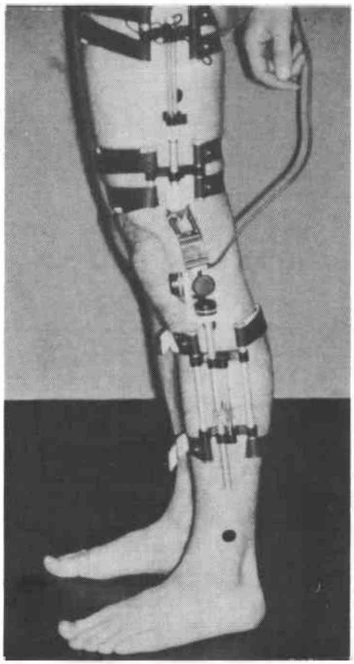

Fig. 2. CARS-UBC (modified) electrogoniometer.

1) The strapping arrangements.
2) The sliding mechanism.
3) The clip transmitting rotation to the tibial rotation shaft from the shank section.

The plastic straps provided had the advantage of easy adaptability to differing limb sizes. For our purposes this was not an important feature. The plastic straps were found to be unsuitable for comfort and attachment security. After short periods of use the heat of a subject's limbs would make the plastic more pliable, thereby loosening the straps. In addition, after several weeks the straps had to be replaced because of their increasing plasticity. These plastic straps were replaced with rubber straps covered with Velcro strips. The thigh unit is now held on by four rubber straps that extend from one side of the attachment to the other, secured by Velcro. The shank unit has two rubber straps attached in the same manner (Fig. 2).

The sliding mechanism and the tibial rotation clip were also changed. The rod extending from the tibial rotation potentiometer was provided in an acrylic material which had an uneven diameter along its length. This meant that in some phases of gait it would be sticking, whilst in others it would be lax; depending upon where the rod was in relation to the shank attachment section. Severe artifacts were introduced into the tibial rotation signals because of this. The rod was replaced with a polished aluminium tube which was light and smooth sliding. The original clip was replaced by a "Lexan" polycarbonate one which gripped the rod more securely than the original Derlin unit. The new clip was machined to eliminate any backlash in the transmission of rotation to the rod.

Effect of misalignment of goniometer parallel linkage

The three signals which are labelled flexion-extension, valgus-varus, and internal-external tibial rotation can only be so labelled because of a fairly arbitrary anatomical reference.

The angles detected by the electrogoniometer sensors are merely the orthogonal projections of the "true" knee angle vector (perceived outside the body). It is because of this that we examined the patterns of the three angle components provided by the goniometer under varying degrees of parallel linkage misalignment. Two protocols were selected.

The goniometer was applied "by eye" in the manner subjectively judged to be best by a group of applicators. The (normal) subject performed a level walk and data was collected. The goniometer was removed completely and then reapplied by the same applicator. Another walking trial was then conducted, data collected and then compared with that collected previously. It was found that each applicator could achieve subjectively consistent results although there were differences between the results of the applicators.

In the second protocol the goniometer was, as before, applied in the best "by eye" manner and data collected. The goniometer parallel linkage was then rotated about the tibial rotation axis by± 30° and the test repeated. Marked differences in the tibial rotation curves were observed with the greatest variability being apparent in the swing phase of gait, demonstrating an interaction between the flexion/extension pattern and internal rotation pattern (Fig. 3).

This concern about the effect of goniometer placement upon the "tibial rotation" motion patterns affected our processing strategies.

To minimize problems caused by goniometer placement inconsistency the following steps were taken:

a) The goniometer was always applied by the same person.
b) Surface landmarks were identified in areas which could be subcutaneously palpated. The exoskeletal system was then applied according to the observations made.
c) The goniometer was placed as close to the limb segment as possible (without contacting the tissue) to minimize cross-effects. The linkage and sliding mechanisms were observed to ensure that no slipping or interference with the body could occur during testing.
d) The distal or tibial attachment was placed as far away from the joint centre as possible.

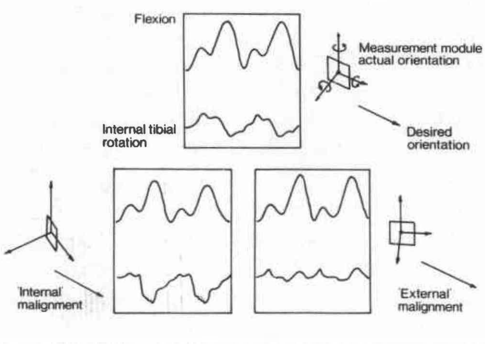

Fig. 3. Signal pattern changes created by measurement module misalignment.

Examination of normal and ligamentous injured knees

Methodology

In order to classify a knee electrogoniometrically as stable or unstable it appeared intuitively reasonable that the following steps be taken.

i) Examine the behaviour of the knees of a significant number of clinically normal individuals using electrogoniometric methods.
ii) Process the data collected in order to statistically represent the normal knee in a compact, non-redundant form.
iii) Examine a number of clinically unstable knees under identical testing circumstances and compare each with the statistical data base of normal knees.

Subject detail and test protocol

Ten volunteer subjects were examined using the electrogoniometer system applied bilaterally. Each of these subjects was judged by the absence of symptoms to be "normal".

The testing protocol of free, level walking in the gait laboratory (12m long) for multiple trials. Transient effects due to the subject speeding up and slowing down at the ends of the laboratory were eliminated by rejecting those strides. Sufficient trials were conducted to establish a record length of at least 40 strides for each subject. Average speed of walking was monitored over a 5m length of the walkway but no attempt was made to control the subjects' speed.

Six subjects with arthroscopically confirmed anterior cruciate injuries were examined using an identical protocol. All subjects had a clinically identified "pivot shift" and complained of episodes in which their knee "gave way" during some activities. None of these subjects had complaints of pain during testing.

Data acquisition

The electrogoniometer system was connected via an overhead cabling link to a DEC

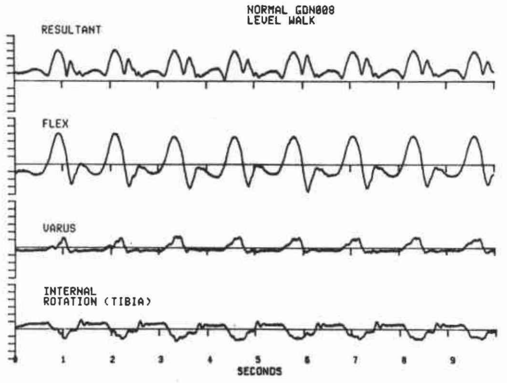

Fig. 4. Graphic display of unprocessed electrogoniometer signals.

PDP–11/34 computer which sampled each signal channel at a rate of 200 samples per second. A fourth order, digital equivalent, Butterworth filter was used to provide low-pass filtering to a cut-off frequency of 20 Hz. The laboratory graphic display terminal allowed immediate post-test display of the signal properties. An example of the signal display is shown in Figure 4.

Previously obtained "bench" calibration of the goniometer was used to scale the signals, to the correct units (10 degrees per vertical division on the axes shown). In addition, the mean values of the signals, calculated over the whole record lengths, were subtracted to form the signals for display.

Processing of data

Introduction

Having performed the level walking protocol with both normal and injured subjects the task of identifying the differences (and the significance of these differences) between these two groups remains. Examination of the unprocessed multiple angle signals "by eye" is difficult to perform objectively because of the volume of data involved. It would be possible to perform fairly straight forward reduction of the data into sets of numbers representing the local peak values of the signals and their times of occurrences. When this is done for all subjects it would be possible to test statistically whether the subjects could be separated into their normal and injured classes, purely on the basis of this data. However, intuitively this approach may sacrifice much of the information retained in the shapes of the signals and lead the investigator to a false conclusion. The methods popularized by Hershler and Milner (1980) which consider shape and magnitude in a so called angle-angle diagram are applicable when the interrelationship between two signals is to be investigated. When it is necessary to examine the interrelation between each of several signals then several angle-angle diagrams are needed. In the statistical literature there exist several methods which attempt to represent the variability in shape and magnitude of multiple signals in a single two dimensional plot. More specifically, the method of processing termed the Principal-Component expansion was thought appropriate and was used. This method consists of representing the multiple signals collected from the electrogoniometer in terms of two functions. These are formed by a transformation process designed to retain a large proportion of the variance, but in a more compact form. The idea behind this approach is that when all the records of all the normal subjects are mapped into a two dimensional display, the region bounded by the set of curves and shape of these curves will define the behaviour of the normal group. When any other individual person is then examined using the same methods and transformation parameters, and his or her data is mapped into the same diagram, it is possible to identify whether that data belongs to the class which represents "normal" (Fig. 5). The detailed method is beyond the scope of this paper but is briefly depicted in Figure 5. (Fukunaga, 1972).

Mapping method

The data collected from our subjects with clinically normal knees and obtained during level walking trials, was subjected to computer editing. All strides from the beginning or end of walking trials were rejected along with those close to turns by the subject. The three signals were adjusted to zero mean value, normalized and placed in an array 'C' (Fig. 5). The covariance matrix of C was determined and an eigenvalue analysis produced three eigenvalues representing the three dimensional property of the signals.

The 3×3 covariance matrix has elements which indicate the relative independence of each signal; with itself and the other two. The matrix is symmetric in form. The eigenvalues and their associated eigenvectors are the essential parameters of a linear system which is created

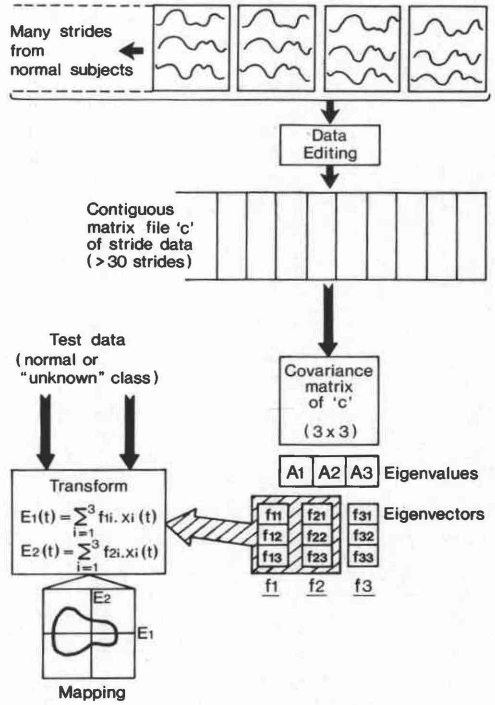

Fig. 5. Method of signal processing, mapping and comparison.

purely for the purpose of the mapping. If this plane is chosen by the linear system in Figure 5, using the eigenvectors corresponding to the two largest eigenvalues A_1 and A_2, then the maximum variance within the normal goniometer data will have been retained. The three goniometer signals are then combined and weighted by the normalized eigenvectors to produce a trajectory in the E_1–E_2 plane.

Computer programs were created to generate the eigenvectors and operate on the test data to produce the curves required on a computer graphics terminal.

Results of electrogoniometric comparison

The method of processing described above allows the representation of the data from the ten normal subjects as a set of trajectories in the E1–E2 plane. The set of curves in Figure 6 represent the data from one of these normal subjects. One individual stride trajectory is shown in Figure 7 and can be seen to represent a closed curve.

The three goniometer signals had a predictably high degree of interdependence. This fact is illustrated by the high percentage of variance retained in the mapping. For the ten normal subjects, computation of eigenvalues and eigenvectors for each revealed a mean variance of the signal retained to be 95·97% with a standard deviation of 3·13% for the ten subjects. The similarity of these data from normal subjects allowed all stride data to be combined and one set of eigenvalues and eigenvectors to be calculated. These eigenvectors were then used to map all the data from normal and injured subjects into the E1–E2 plane using the linear transformation shown in Figure 5.

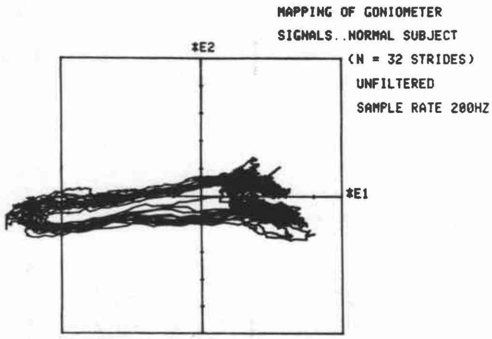

Fig. 6. Mapping of processed data for one subject.

Interpretation

The original data represents the three co-ordinate time history of knee motion for a set of subjects. For this three dimensional case, the process of mapping into the E1–E2 plane can be thought of firstly as transforming the data into a new co-ördinate system oriented such that the plane E1–E2 best illustrates the group variability of the data. The symmetry of the covariance matrix of the data ensures that the eigenvectors

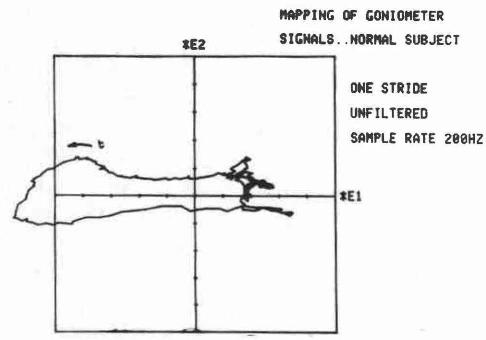

Fig. 7. Mapping of an individual stride.

are orthogonal and therefore that the transformation is orthogonal.

For example, for the whole normal group the raw eigenvalues and vectors were:

$A_1=2{\cdot}591877$ $A_2=0{\cdot}355032$ $A_3=0{\cdot}053092$

VECTOR 1	0·562171	−0·610671	−0·557714
VECTOR 2	0·691935	−0·022063	0·721622
VECTOR 3	0·452979	0·791577	−0·410142

% of variance retained 98·23 percent.

So that $(V_1,V_2), (V_1,V_3),(V_2,V_3)=0$

The result of the mapping is therefore an angle-angle diagram with the viewpoint chosen so that the inherent variability in the data is best visualized. For other applications, where the original data has a higher dimension, the mapping is abstract in form and may have no simple physical interpretation. This is because the map is constructed only for the mathematical convenience of classifying sets of data according to their similarities.

The representation of the zone of normal data in Figure 8 was used to then compare other individual subjects and classify them as normal or not normal. This comparison strongly depends upon the test data being collected under the same test conditions for the normal set of individuals and the individuals being investigated. The possible problems are indicated in Figure 8 which shows the first two strides, collected from a standing start of a normal subject, mapped togther with the "normal" zone. The result of this comparison indicates differences in both stance and swing phase patterns of the goniometer data due to differences in test conditions rather than any knee pathology.

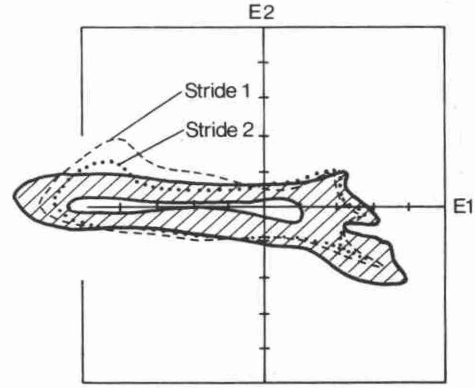

Fig. 8. Characteristics of normal data trajectories and the effect of test protocol changes.

Comparisons and discussion

Comparisons between the normal and injured groups were made from three points of view. The style and rate of trajectory plotting was observed interactively on a computer graphics terminal. The regions of each group of trajectories were defined on the diagram. Finally the methods of Hershler and Milner (1980) were used to compare the perimeter lengths and enclosed areas of trajectories.

As Figure 8 illustrates, radical differences can occur as a result of changing test conditions and this was reflected in the perimeter and area calculations as well as the region occupied by the trajectories. These differences were most clear during the swing phase portions of the data. The stance phase portions of the data appeared to be less sensitive to minor test variations. This is important because instability would manifest itself during stance phase load transmission, with swing phase changes most likely indicating compensatory behaviour by the subject.

Only two subjects could be classified as not exhibiting normal knee motion patterns and their trajectories are given in Figure 9. The first subject, age 36 had prior surgery to his left knee (meniscectomy) five years previously and presented for consultation with a torn anterior cruciate ligament. A positive pivot shift sign was demonstrated (Galway et al, 1972) to be gross on the left. The right knee had a greater than usual anterior-posterior laxity but negative pivot shift. The subject complained that his knee "gave way" on occasion but was mostly pain free. The second subject also had a long standing history of knee injury which had not been diagnosed or treated. Presentation was with a verified anterior

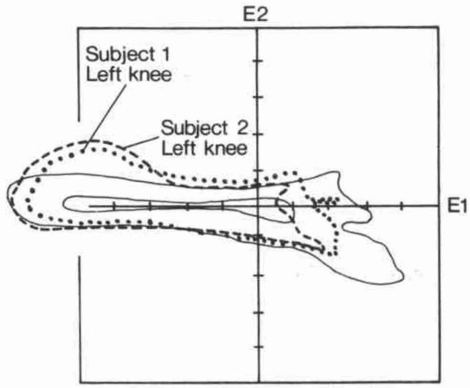

Fig. 9. Mapping of the two subjects judged to exhibit abnormal trajectories.

cruciate insufficiency and a grossly positive pivot shift. Neither subject participated in sport activities.

All the subjects had positive pivot shift signs but only the two above were inactive in sports and had *gross* clinical instability. It is perhaps initially surprising that all the clinically unstable knees could not be identified by motion detection. However, the level walking protocol which was utilized would allow the individual subject to compensate for ligament injury by muscular control (if such control were available). It is clear therefore that individuals who have good neuromuscular control will have stable knees during many activities, even though the commonly used clinical tests grade these knees as unstable. Noyes et al, (1980) have already reasoned that functional stability can be maintained in joints that appear to be unstable using routine clinical tests and this ability will depend upon the individual and his activity level. A need exists to develop dynamic tests for knee instability which consider each individual's capability to compensate under controlled activity conditions.

The triaxial electrogoniometer system does not provide sufficient information to classify knee instability to a clinically useful degree under level walking conditions. Further work will utilize a goniometer which identifies translational as well as angular modes of motion and a more vigorous test protocol which involves "cut" and "crossover" turns by the subject.

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