The Determination of the Mechanical Axis of the Knee on a Short X-Ray: A New Radiographic Technique

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I. ABSTRACT

Most authors recommend drawing the mechanical axis on a three-foot (90 cm) full leg length x-ray for accurate assessment of knee alignment. Three foot x-rays are difficult to perform and reproduce and involve undue radiation to the gonads. The purpose of this project is to propose a new radiographic technique whereby the mechanical axis of the knee can be assessed on a short A/P x-ray of the entire tibia

Methodology:

21 normal adults and 25 patients with malaligned knees were investigated in the following manner - the patient was x-rayed in standing position with the legs positioned exactly parallel to one another and vertical to the floor. Under these circumstances, the ankles were apart by a distance (distance F_1) equal to the distance between the femoral heads (distance F). The mechanical axes were hence parallel to one another and parallel to the long axis of the x-ray cassette and vertical to the floor. Two separate x-rays were taken, a three-foot (90cm) long x-ray and a short x-ray of the entire tibia. The mechanical axis was determined on the 90 cm, three-foot long x-ray.

A vertical line drawn on the short x-ray starting from the centre of the ankle and extended upwards and parallel to the long axis of the x-ray cassette could accurately identify the mechanical axis of the knee using either technique. (Fig. 1)

The technique has been called the "Parallel Mechanical Axes X-ray Technique". It has been validated and it will be demonstrated that such an x-ray technique:

- Standardizes positioning of the lower extremities.
- Is a precise, easily controllable method to assess knee alignment.
- A short x-ray of the entire tibia is sufficient, thus reducing the cost of x-rays by 50%.

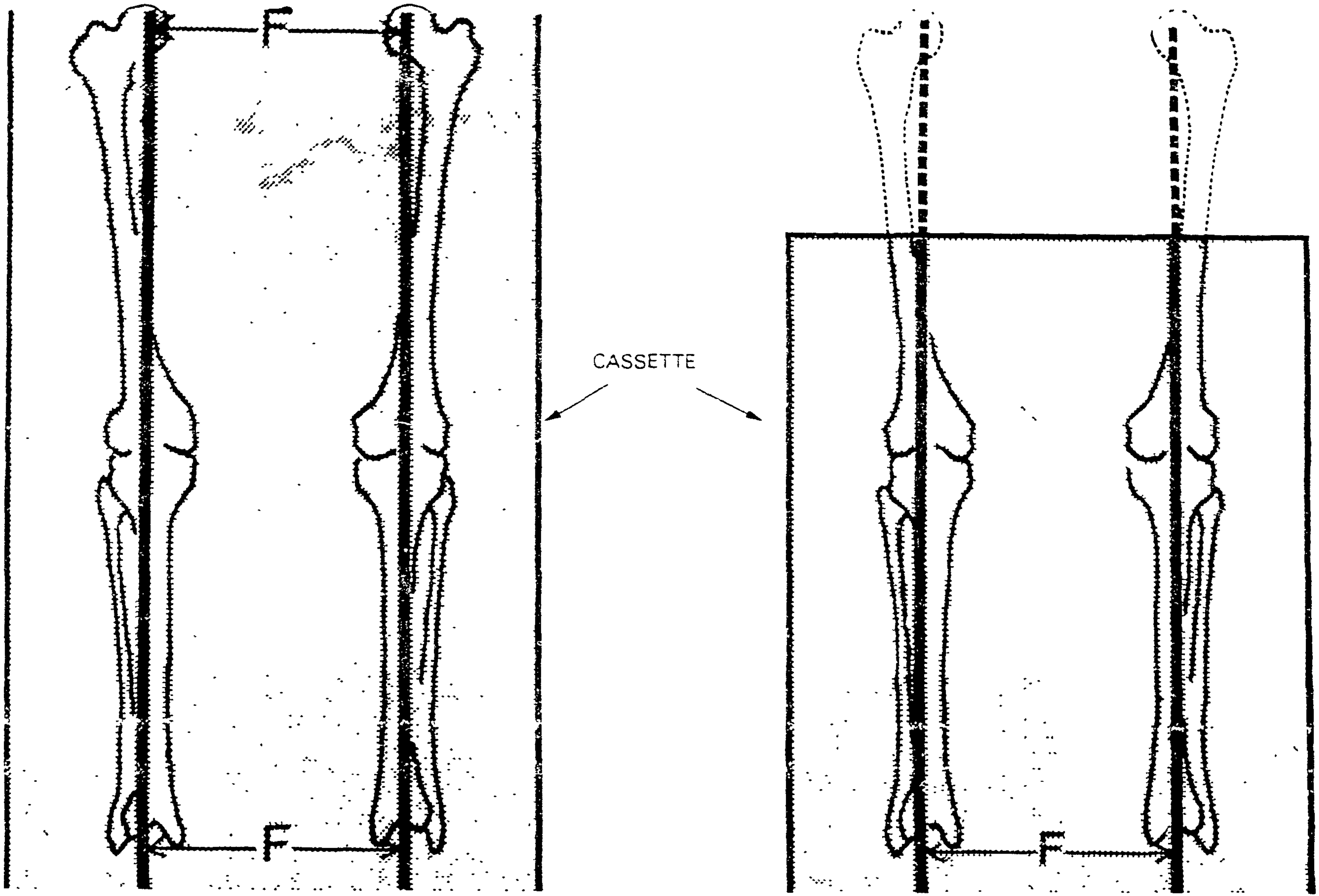


Figure 1
The parallel mechanical axes x-rays

- Obviates the need to visualize the pelvis thus minimizing net radiation exposure.
- May be used in clinics and smaller hospitals, since it requires simple and inexpensive x-ray facilities.

RESUME

La plupart des auteurs recommandent l'utilisation de longues cassettes afin de mesurer avec plus de précision l'axe mécanique des genoux. Cependant ces radiographies sont exigentes pour le personnel, difficilement reproductibles et exposent le patient à des radiations indues. Le but de cette étude était de mettre au point une technique radiologique fiable a l'aide d'une petite cassette de face.

Methodologie

21 adultes normaux ont été comparés à 25 patients avec anomalies d'axe du genou. Les radiographies ont été prises en position debout, alors que les membres inférieurs étaient en position strictement parallèlles à l'axe longitudinal de la cassette (et en même temps verticales au sol). Deux casettes radiographies sont employées prises: une de 3 pied (90cm) de longueur ainsi qu'une courte vue du tibia entier.

L'axe mécanique est déterminé sur la radiographie de 90 cm (longue cassette de 3 pieds).

Une ligne verticale traversant le centre de la cheville et parallèle à l'axe longitudinal de la petite cassette peut reproduira l'axe mécanique du genou aussi précisément sur la courte cassette que su la longue cassette (Fig. 1).

Cette technique a été nommée le "Parallel Mechanical Axes X-rays Technique"; il a éte démontré que cette technique:

- est une méthode précise et facilement controlable pour évaluer l'alignement du genou.
- nécessite seulement une radiographie du tibia.
- minimise l'exposition à la radiation.
- peut être utilisée dans les centres hospitaliers moins favorisés car les petite radiographie sont plus simples a faire et moin chers.

Figure 2
"Bes" – Dwarf-God of Ancient Egypt

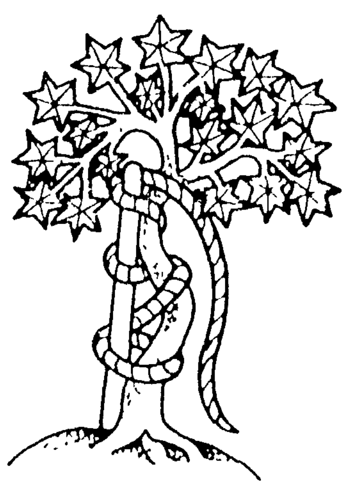


Figure 3
"The Strapped Croocked Tree"

II. HISTORICAL BACKGROUND

Musculoskeletal deformities are as old as mankind. The bones of ancient man provide a rich variety of these disorders that we now recognize as either congenital or acquired; for thousands of years these deformities were a source of superstitions and myths. The ancient Egyptians pictured their evil god *Bes* as a stunted midget with short legs and genu vara (Fig. 2).

In 1741, Nicolas Andry, the father of modern orthopaedics, introduced the term "Orthopaedia", derived from the Greek, to suggest a straight, or undeformed child. The art of preventing and correcting deformities have since adopted the picture of a "strapped crooked tree" to symbolize orthopaedics (Fig. 3). The introduction of diagnostic x-rays by Roentgen in 1895 and of general anaesthesia by Long in 1842, marked the end of the "Strap & Buckle" period and the beginning of "orthopaedic operations". Orthopaedic surgeons, now, correct joint deformities and replace diseased joints. For precise joint deformity correction and/or joint replacement, standardized, precise x-ray techniques are essential to assess and measure these deformities.

The purpose of this investigation was to review the x-ray techniques already in use to assess knee deformities and to propose a new one.

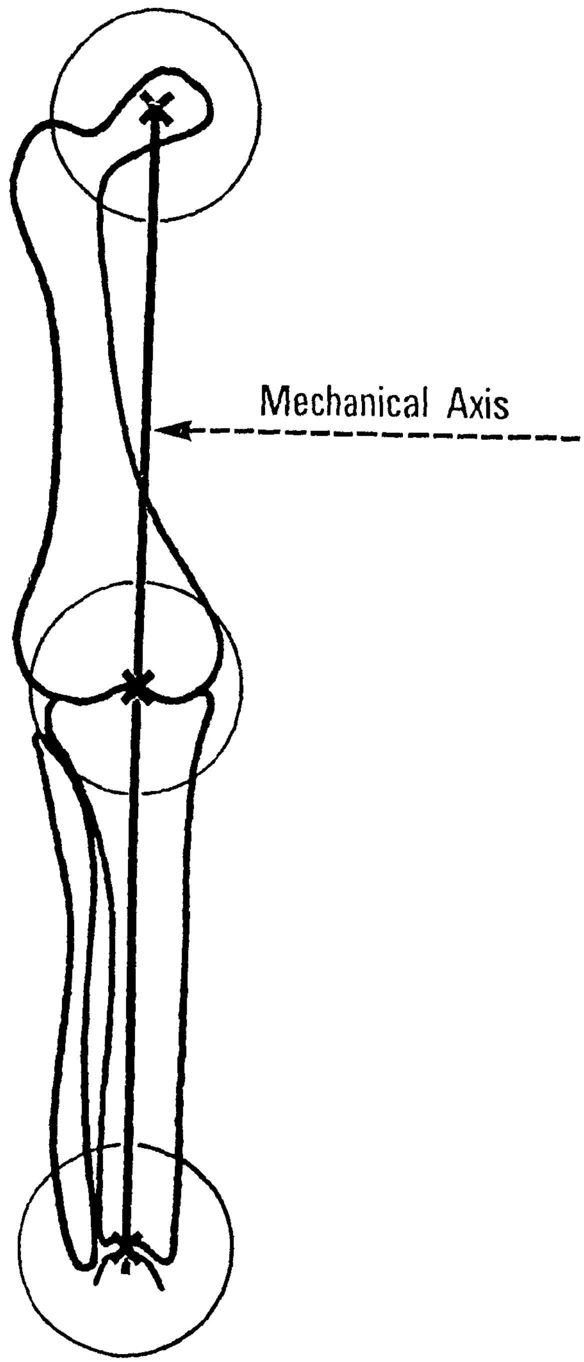
III. INTRODUCTION

The role of malalignment in the pathogenesis and management of osteoarthritis of the knee is now undisputed.

Roger Gariepy of Montreal was the first to describe the High Tibial Osteotomy for treatment of genu varum.[11,12] This was later popularized by Coventry[5] as an established treatment for unicompartmental osteoarthritis of the knee. In 1963, Maquet[34,35] proposed that leg malalignment was the "main" cause of osteoarthritis of the knee.

A new dimension was added to the issue of lower limb alignment with the introduction of total knee arthroplasty operations; correct post-operative alignment is now acknowledged as "probably the most important single factor in total knee replacement" (Apley 1984)[28]. It became obvious that precise pre-operative and post-operative assessment of knee alignment was mandatory for the long-term success of Total Knee Replacement.[3,8,18,31,36,39,43]

Much has been written about alignment of the lower limb and about the methods to measure it.[2,7,9,10,17,20,39,44,46,47,48,49] Clinical assessment of knee alignment was the subject of a thesis at the University of Nottingham, England in 1980[29] This thesis is a parallel effort to investigate the radiological assessment of knee alignment.



Normal Knee alignment

Figure 4

A. Definitions

1. Alignment

As defined by the Oxford English Dictionary, alignment is "An arrangement, in a straight line, of three or more points."

2. Lower Limb Alignment

When applied to the lower limb, the three points used to assess its alignment are; the centres of the hip, the knee and the ankle. When a normal person is viewed from the front, these three anatomical points should form in a straight line (Fig 4).

During this investigation, lower limb alignment is only considered in the frontal plane (i.e. A/P).

3. **Lower limb axes:** (As drawn on radiographs of the lower limb) (Fig. 5)

a. **The Mechanical Axis**

The mechanical axis is a straight line joining the centre of the hip to the centre of the ankle; in normal individuals, that line passes through the centre of the knee*.

Hack and Allen[14] (1981) reviewed 149 normal three-foot x-rays and reported that the mechanical axis normally passes through the medial tibial spine; Denham[28] (1984) considered the middle one third of the tibial plateau as the acceptable range of the normal mechanical axis.

Implications of the mechanical axis of the knee:

The mechanical axis, as drawn on a three-foot, full leg length x-ray is a reliable x-ray technique to measure knee alignment pre-and post-operatively (Denham 1984).[28]

In the bipedal and monopedal stance position, the mechanical axis represents the line of weight bearing through the knee (Maquet[35] 1976, Laskin[28] 1984). In the dynamic gait situation, however, contrary to Maquet's views, the mechanical axis is not the line of weight bearing. Gait analysis using Force-Platform measurements have indicated that load transmission is in fact slightly medial to the centre of the knee. (Johnson & Waugh 1980[25]) In both instances, however, the normal mechanical axis is within the middle third of the tibial plateau.

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* With slight variations, all points are within the middle third of the tibial plateau.[47,28]

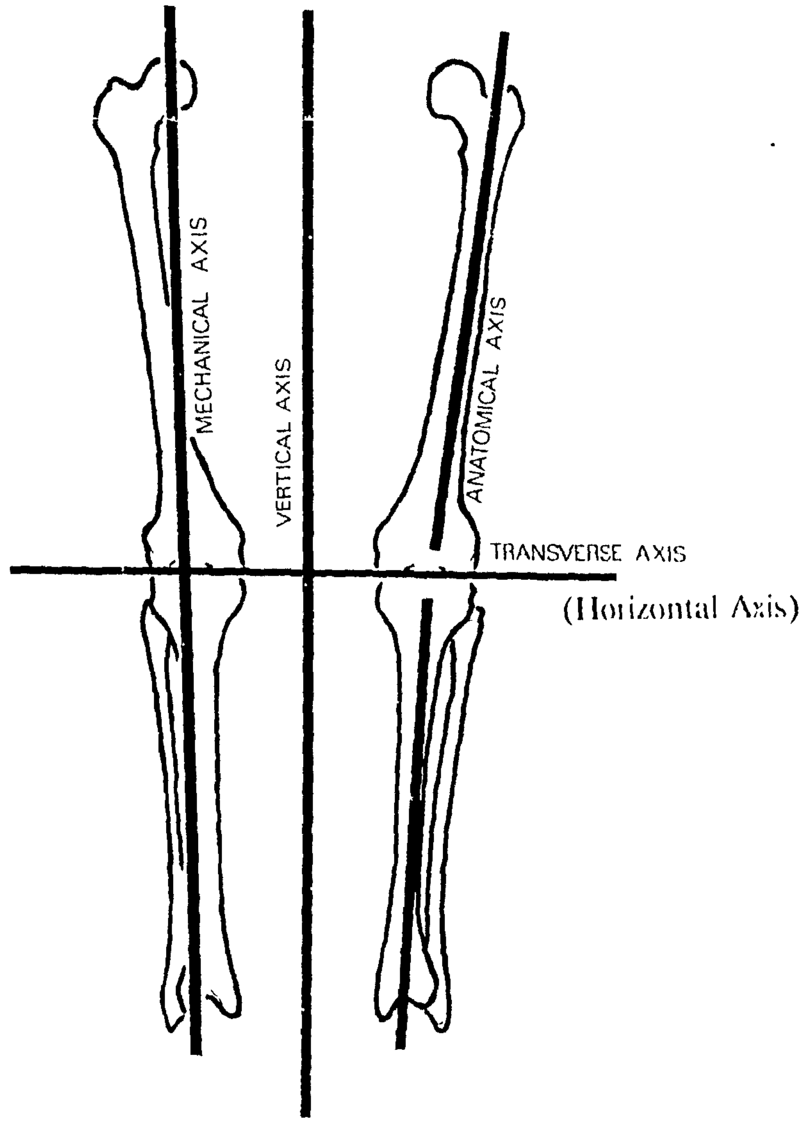

Figure 5 – Lower Limb Axes

b. Anatomical Axis of the Knee (Tibio-Femoral angle)

This axis is determined on an A/P x-ray by drawing two straight lines down the centre of the shafts of the femur and the tibia. The angle formed by the two intersecting lines is called the tibio-femoral angle and corresponds to the anatomical axis of the knee. Controversy persists on what is a normal anatomical axis since a wide range has been reported indeed, it is difficult to measure (clinically or radiologically) the tibio-femoral angle with absolute accuracy (Waugh 1985[47]). Hungerford et al 1982[17] stated that the normal tibio-femoral angle varies (from 7° to 11°, with an average of 9°) with the patient's sex, build and height - the angle being greater in short, stocky patients with wide pelves. Most authors now agree that 7° of valgus is the average "normal" tibio-femoral angle and that the "normal" mechanical axis passes through the centre* of the knee (Waugh 1985[47]).

c. **The Vertical Axis:** (line of body weight)

The vertical axis is the plumb line of body weight (starting from the centre of gravity of the body). The vertical axis always remains vertical to the ground, even when the centre of gravity is shifted sideways, i.e. when walking or in the monopedal stance. (Fig. 6)

In the bipedal stance, the vertical axis is always in the mid-line (Fig.7). Note, however, that the relationship between the mechanical axes changes depending on the distance between the ankles.

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* i.e. within the middle third of the tibial plateau.

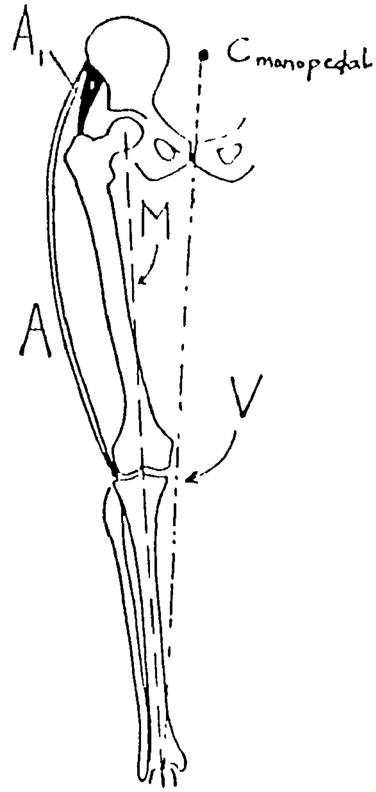


Figure 6 – Monopedal stance

C: center of gravity of the body

V: vertical axis

M: mechanical axis

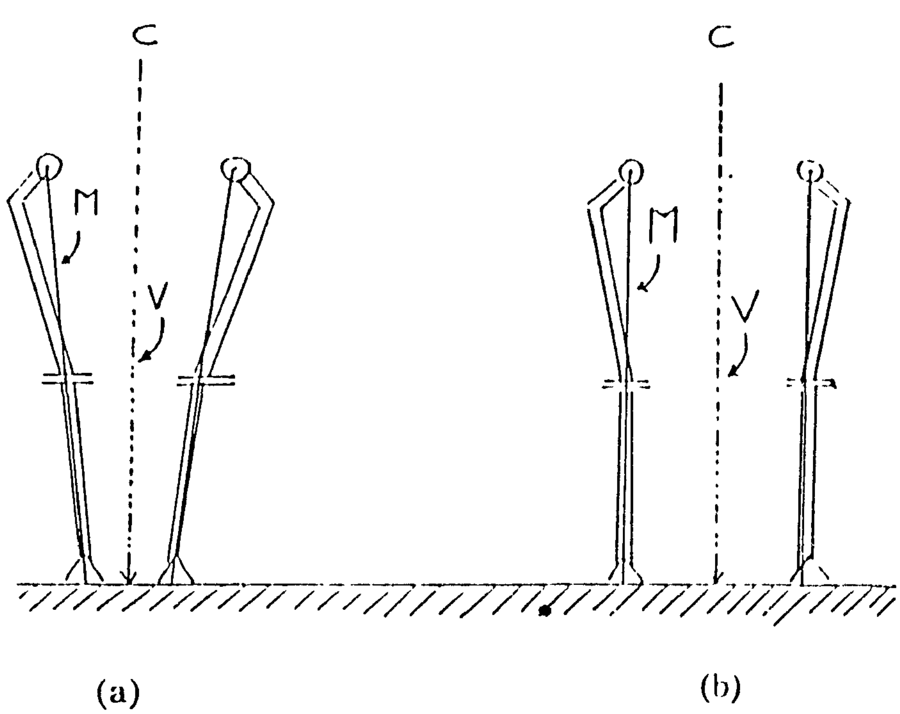
A_1-A: abductor muscular stay

Figure 7 – Bipedal stance
(a) – normal bipedal stance
(b) – bipedal stance with parallel mechanical axes

C: center of gravity of the body

V: vertical axis

M: mechanical axis



d. **The Horizontal or Transverse Axis:** (Knee joint line) (Fig. 5)

This is the axis of knee flexion and extension. Normally, this line is horizontal, i.e. parallel to the ground (Hungerford 1982[17]), hence, the importance of horizontal implantation of the components of a total knee arthroplasty.

B. Malalignment of the knee:

The position of the knee joint in relation to the hip and ankle i.e. its alignment, should be mechanically important. The knee joint is normally subjected to considerable side to side stress because of its unstable bony design as well as its lack of anchorage as exists in the hip to the pelvis or the ankles to the ground.

Knee stability is constantly challenged by body weight as it changes its relationship to the knee during walking or running. The challenge to the knee increases and becomes excessive in the presence of knee malalignment.

1. **Malalignment of the knee in the coronal plane:** (A/P view) (Fig. 8)

a. **Normal alignment:** The knee is aligned with the hip and ankle when the mechanical axis falls through the centre of the knee.

b. **Abnormal alignment:** (1) Valgus knee: The knee then lies "Medial" to the hip and ankle, and the mechanical axis is lateral to the knee centre, i.e. a "Valgus" malalignment. (2) Varus knee: The knee is "lateral" to the hip and ankle and the mechanical axis is medial to the knee centre i.e. varus malalignment.

2. **Malalignment of the knee in the sagittal plane:** (lateral view)

Similarly, when the static knee is in maximal extension and is viewed from the side, there are two possibilities:

a. **Normal alignment:** When the knee is in line with the hip and the ankle, the mechanical axis passes through the centre of all three. (Fig. 9)

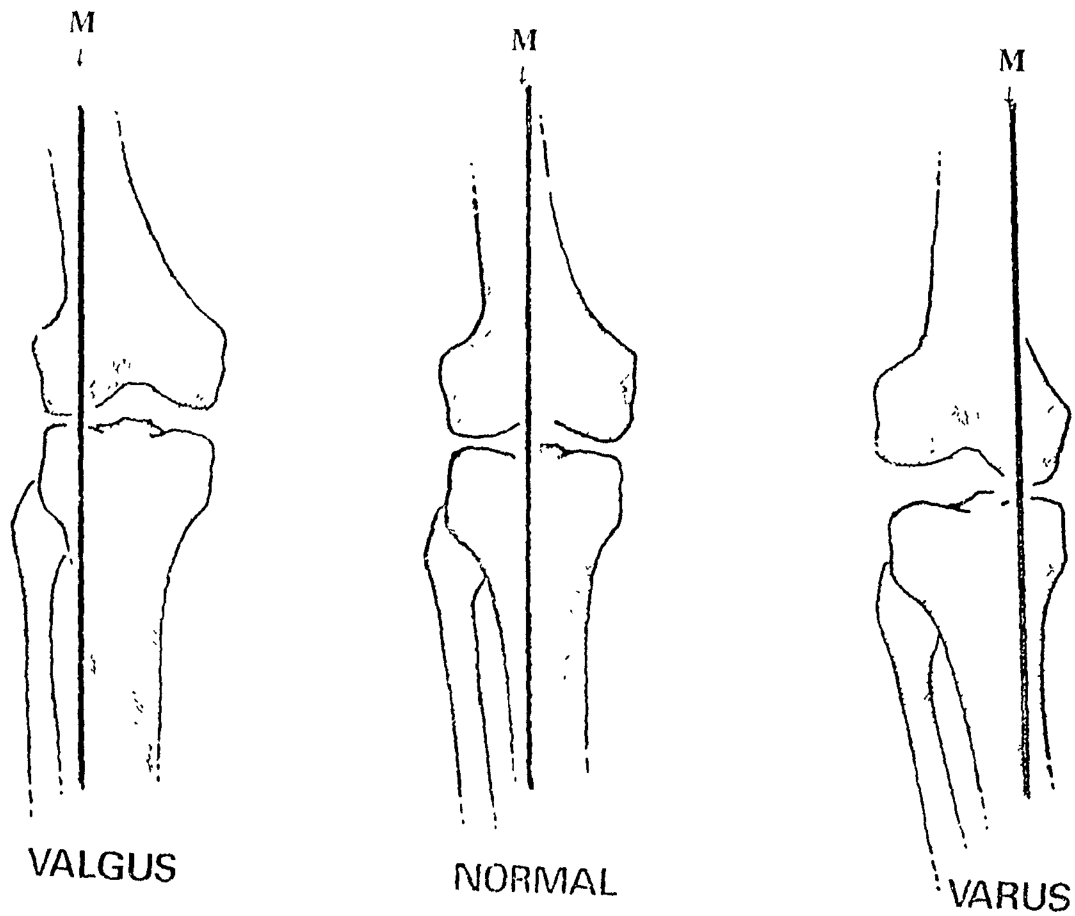


Figure 8
Malalignment of the knee in the coronal plane
M: Mechanical axis

b. **Sagittal malalignment:** (1) Recurvatum: The knee lies posterior to the hip and ankle and the mechanical axis lies in front of the knee, i.e. knee recurvatum. (2) Flexion: The knee lies anterior to the plane of the hip and ankle and the mechanical axis passes behind the knee, i.e. Flexion Contracture. (Fig. 10)

Figure 9

Normal alignment in the sagittal plane

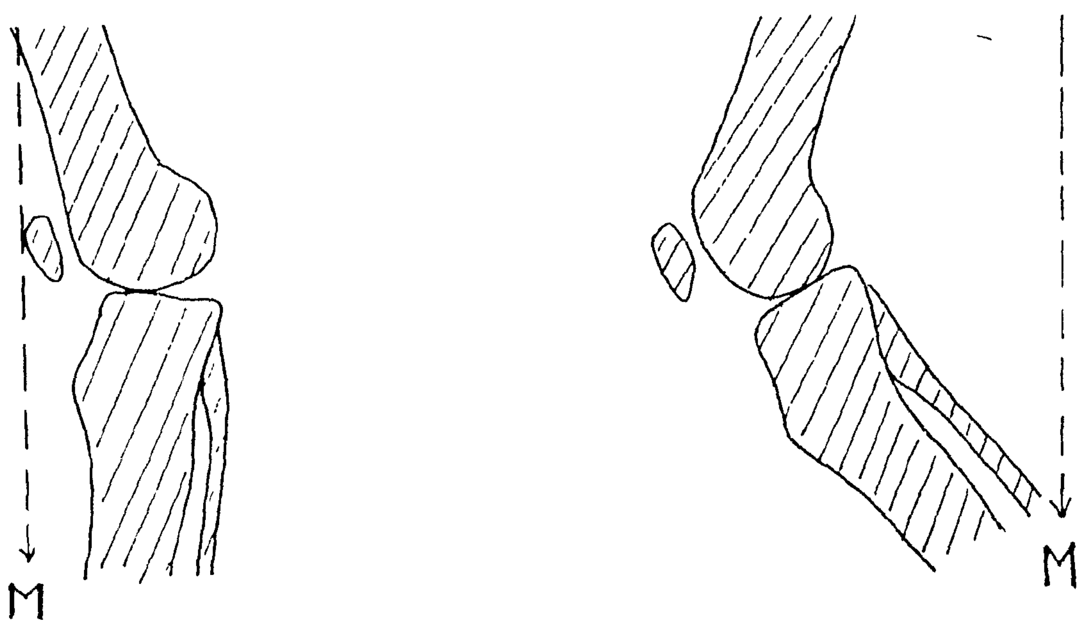


Figure 10

Malalignment of the knee in the sagittal plane
M: Mechanical axis

C. Biomechanics of the knee:

The knees are part of a complex musculoskeletal system which enables man to ambulate with maximal efficiency and minimal energy expenditure. Although a detailed analysis of the biomechanics of the knee is beyond the scope of this work, a brief review of the forces acting about the knee is germane to the topic of radiological assessment of knee alignment.

1. Knee biomechanics in the standing position:

a. Bipedal stance - standing on both feet

During bipedal stance, that part of body weight which is *proximal* to the knees is evenly supported by both knees: each knee supports approximately 43% of total body weight.[35] This mass is concentrated in the body's centre of gravity which lies in the region of the third lumbar vertebra. (Braune & Fischer 1900)[35]

(1) In the coronal plane:

The pelvis acts as a transverse beam and transmits the load equally along the mechanical axis of both legs. (Fig. 11) This load, in turn, is shared equally between the lateral and medial compartments of the knee. (Johnson & Waugh 1980[25])

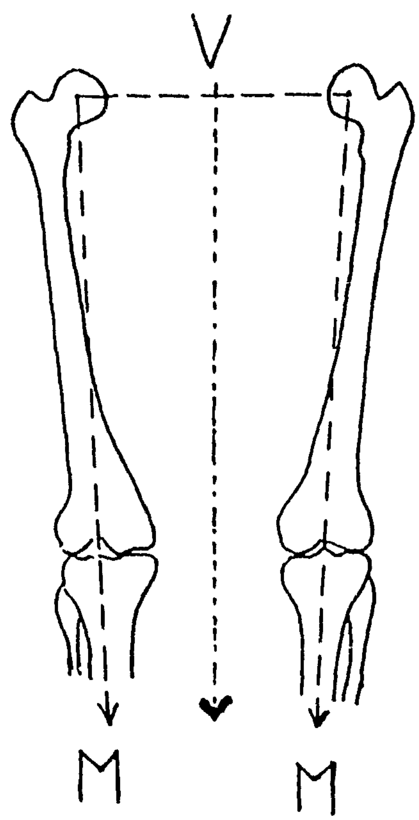


Figure 11
Load distribution in bipedal stance

V: vertical axis
M: mechanical axis

(2) In the sagittal plane:

When the knees are fully extended in the bipedal stance, each leg supports along its mechanical axis, 43% of the total body weight. The other forces, i.e. muscular contractions to maintain the knees in the locked position, are negligible (Maquet P, 1976) [35]

b. **Monopedal stance - standing on one foot**

The load applied on the weight bearing leg equals body weight minus the weight of the loaded leg from the knee downwards: i.e. 93% of body weight. In this position, the centre of gravity of the body mass (Cmonopedal) is slightly lateral to the original centre of gravity (Braune & Fischer 1900).[35]

(1) In the coronal plane: (Fig. 12)

Since the vertical axis (hence, body weight) is medial to the loaded knee, this force (V) is counter-balanced by the hip abductors i.e. the pelvic deltoid (gluteus medius, minimus, assisted by the tensor facia lata and ilio-tibial tract) to act as a stay (A_1-A) that prevent tilting of the pelvis. The resultant load is transmitted to the knee via the mechanical axis of the limb (M) (Duparc & Massare 1967[9], Maquet 1976[35]).

(2) In the sagittal plane:

A slightly flexed limb is usually considered for the schematic analysis in the sagittal plane (Maquet 1976[35]).

According to Maquet, equilibrium in the sagittal plane is the result of several forces acting on the hip, knee and ankle. (Fig 13)

a) Ankle joint: Ankle dorsiflexion created by body weight (V) is

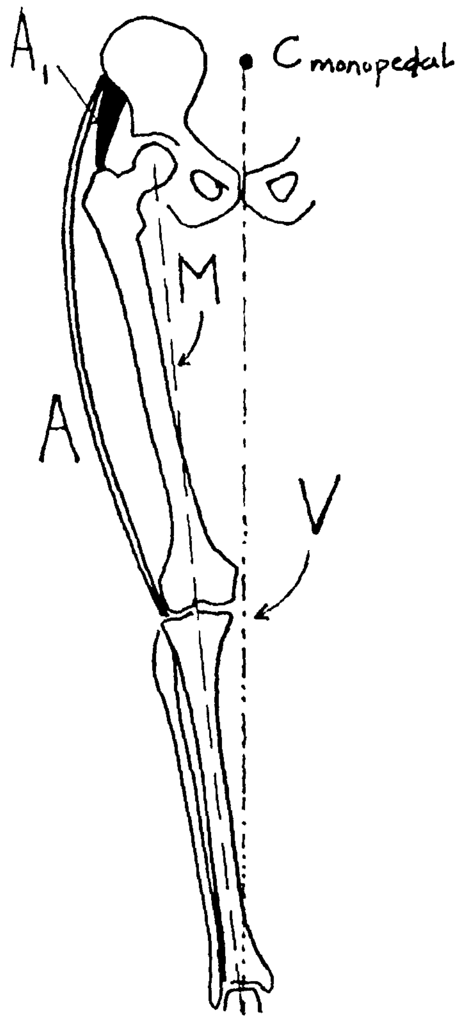


Figure 12
Monopedal stance

C: center of gravity of the body

V: vertical axis

M: mechanical axis

A_1-A: abductor muscular stay

counterbalanced by the calf muscles (Mt), with the resultant force (R1) passing through the centre of the ankle joint. (Fig. 13a)

b) Hip joint: The forward pelvic flexion force created by body weight (V) is counter-balanced by the hamstrings (Mi), with the resultant force (R2) passing downwards through the centre of the hip joint. (Fig 13b)

c) Knee joint: i) The force (R2) from the hip which passes behind the knee, and the action of gastronemii (Mg) will tend to flex the knee joint. (resultant force R3, Fig. 13c)
ii) Knee flexion is counter-balanced by the quadriceps muscle acting through the Patellar tendon (Pa), with a resultant force (R4) leading to compression of the tibio-femoral articulation. (Fig. 13d)
iii) The magnitude of antero-posterior compression of the patella against the femur (R5) depends on quadriceps muscle action (Pa) and the tensile force of the patellar tendon. Force R5 changes with the degree of knee flexion. (Fig. 14)

In the fully extended normal knee, R4 and R5 practically cease to exist. Balance is then maintained by the stretching of the posterior capsule, muscle tone and the screw-home mechanism of the knee as the body weight then falls through the centre of the knee.

c. Bipedal versus monopedal stance in the alignment of the knee

In a normal, stable knee, there is no appreciable change in the position of the mechanical axis or in the tibio-femoral angle, when comparing the monopedal and the bipedal stance. However, when there is joint instability, secondary to bone loss or ligamentous lengthening or both, the position of the abnormal

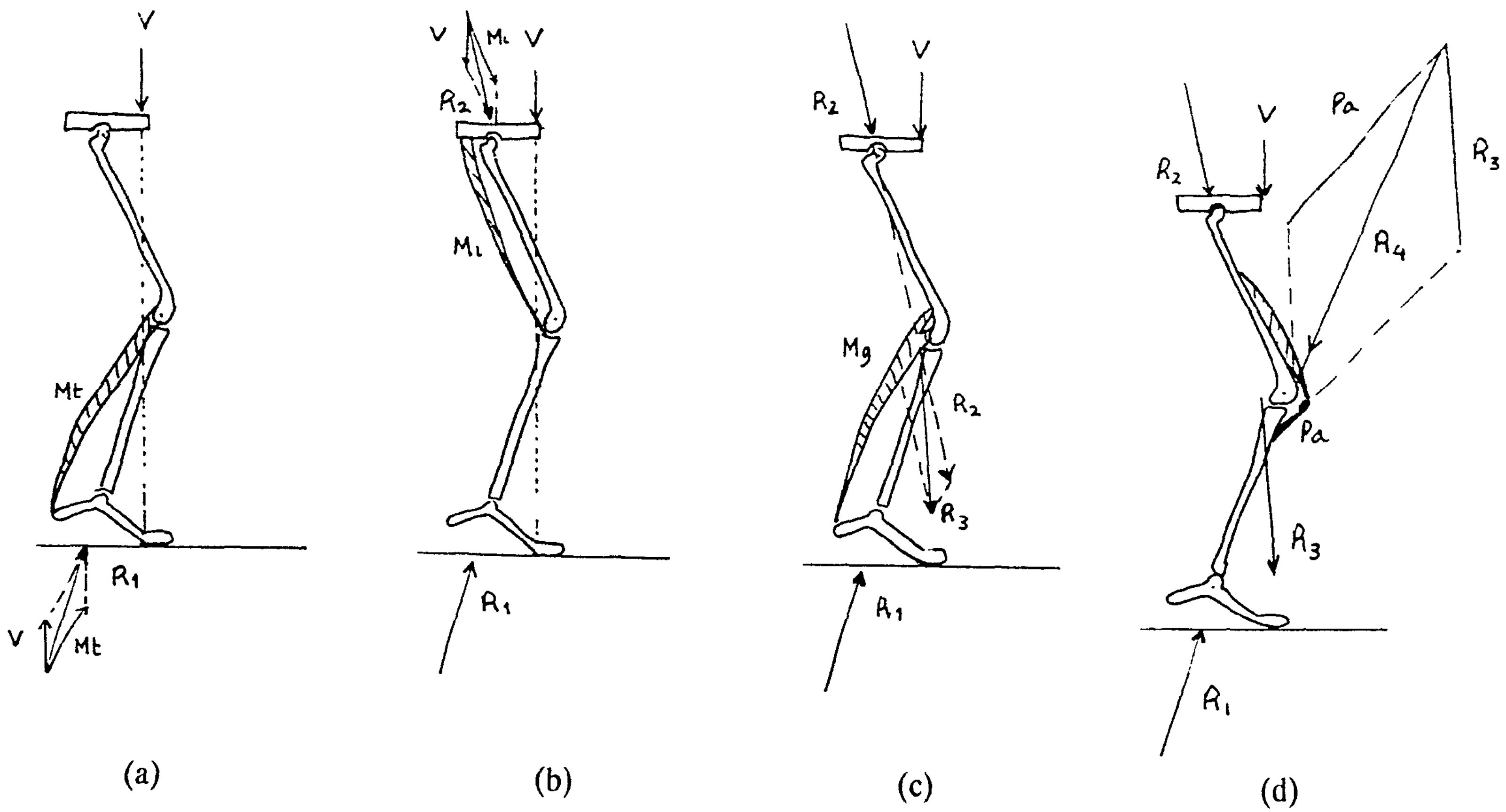


Figure 13

Drawings inspired from Maquet, P.[30]

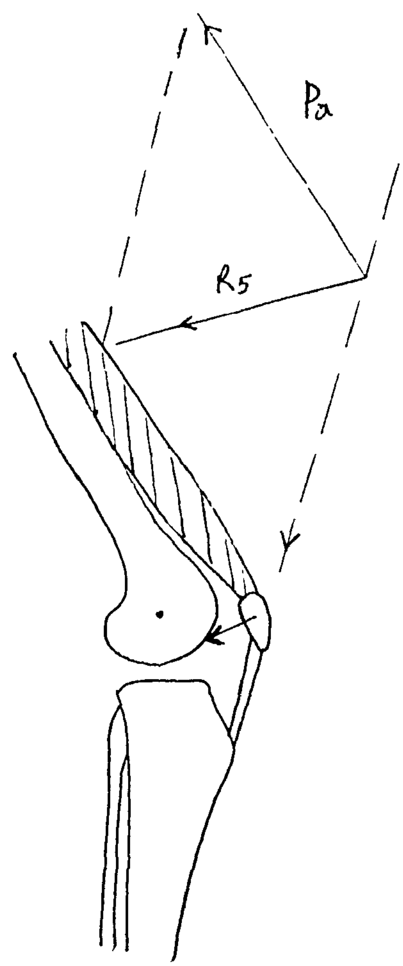


Figure 14
Patello-Femoral Compression (R_5)

mechanical axis is displaced further during monopedal weight bearing. (Fig 15) During the monopedal stance, the load is further increased by the weight of the unloaded limb* and by the body weight lever arm due to the lateral shift of centre of gravity.

For these reasons, monopedal radiologic assessment of knee alignment is more revealing and is often favoured by clinicians,[9,17,35] although it is admittedly more difficult to perform particularly by patients with painful knees. Thus, the main advantage of the monopedal stance is that it mimics the gait situation (Duparc & Massare 1967[9], Insall., Personal Commun., Maquet 1976[35], Hungerford 1982[17])

2. **Knee biomechanics in motion:**

Normal gait is the result of a complex interaction of forces of body weight, muscle contractions and ligamentous tension that act on different regions of the body to produce moments of acceleration or deceleration. This complex operation is masterminded by the brain to produce a smooth, coordinated pattern of ambulation that insures maximum efficiency and optimum energy expenditure. For example, an average adult walks at a cadence of approximately 90-120 steps/minute, with an average energy cost of 100 calories per mile (1.7 km). (S. Hoppenfeld, 1978[16])

Braune W. & Fischer O.[35] in 1900, published the first truly scientific analysis of human gait. They divided the walking cycle into 31 phases and precisely described the three dimensional location of the centre of gravity and the magnitude of the mass of body weight in each phase (Fig 16).

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* 93% of the body weight as opposed to 43% for each knee in the bipedal stance (Braune & Fischer[35]).

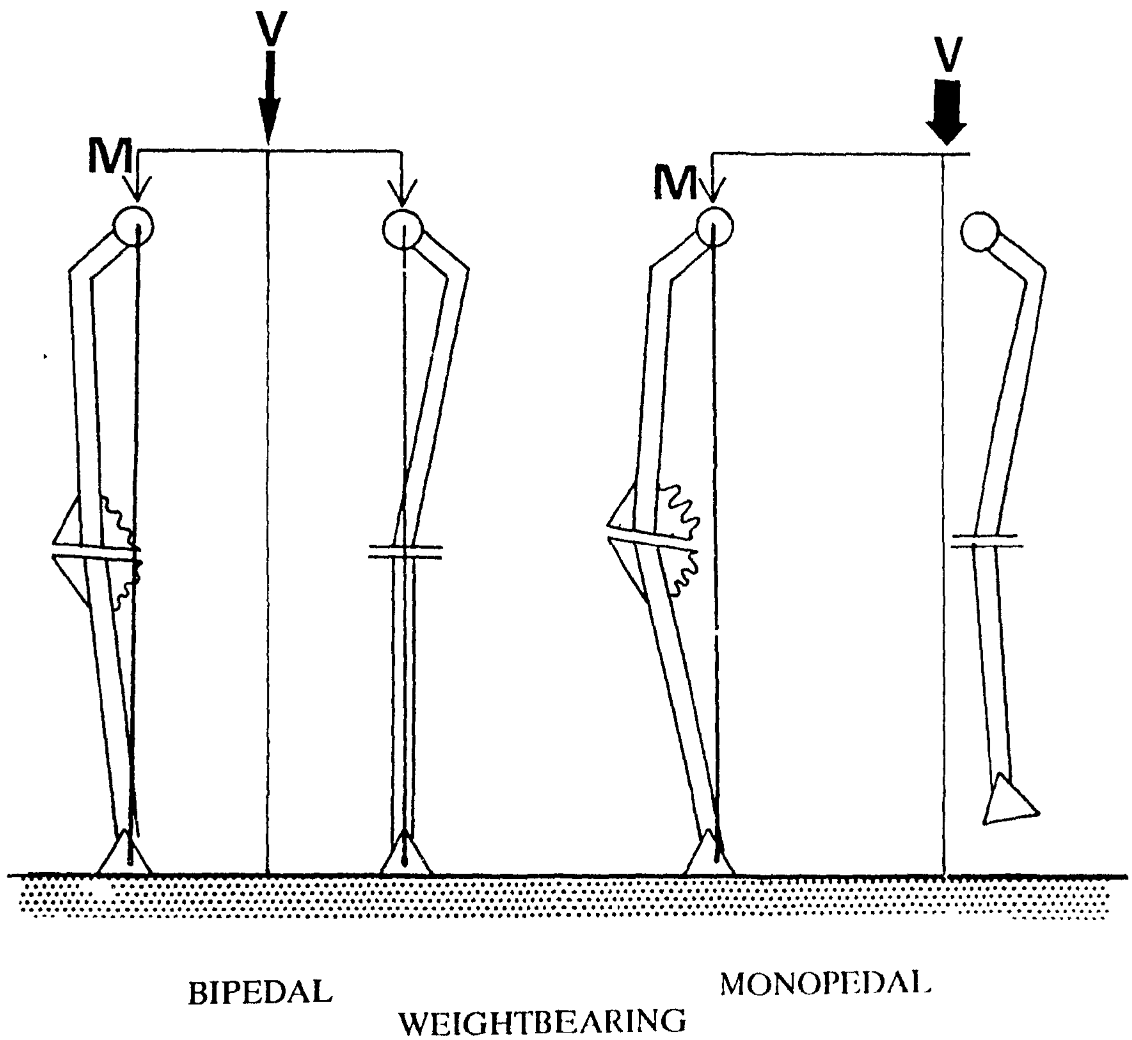


Figure 15

Bipedal vs. Monopedal stance
Note increased stress and changing tibio-femoral angle
with monopedal stance

Phases of gait	x	y	z
1	38.53	−0.86	95.12
2	44.89	−0.89	96.32
3	51.25	−0.84	97.50
4	57.40	−0.77	98.28
5	63.54	−0.71	98.47
6	69.58	−0.65	98.07
7	75.54	−0.56	97.12
8	81.92	−0.43	95.85
9	88.24	−0.25	94.93
10	94.57	+0.08	94.25
11		—	—
12	104.16	−0.17	94.36
13	111.20	+0.21	94.76
14	117.59	+0.47	95.62
15	124.10	+0.59	96.97
16	129.81	+0.59	97.97
17	136.10	+0.54	98.58
18	141.92	+0.42	98.53
19	148.13	+0.34	97.95
20	154.19	+0.20	96.99
21	160.21	+0.04	95.95
22	166.44	−0.27	95.18
23	172.84	−0.71	94.61
24		—	—
25	182.01	−0.56	94.56
26	189.21	−0.82	94.96
27	195.85	−1.03	95.63
28	202.49	1.11	96.68
29	208.40	−1.06	97.60
30	214.34	−0.94	98.28
31	220.02	−0.83	98.32

Figure 16
Three-Dimensional Coordinates of Center of Gravity
derived from Maquet, P.[30]

In 1976, Maquet[35] used their data to calculate the forces acting about the knee in each of these 31 phases.

Based on the three dimensional location of the centre of gravity, Maquet was able to calculate the distance (the lever arm) between the line of body weight "V" (the vertical axis) and a presumed point that lies in the centre of axis of knee flexion (knee centre). Knowing the magnitude of the body weight, he was able to calculate the momentum of the forces of inertia and their direction. He used the monopedal stance as an example for his calculations and was able to demonstrate that the vector of forces act through the normal mechanical axis "M" and that deviation of the mechanical axis to one or the other side of the joint (i.e. valgus or varus deformity) resulted in excessive load bearing on one compartment and the likelihood of eventual osteoarthritis of that knee compartment (i.e. lateral or medial).[35]

In 1980, Johnson & Waugh[25] used a gait analysis laboratory to calculate loads acting about the knee and concluded that Maquet's analysis of forces was only applicable in the static monopedal situation. Their force-platform measurements, done during the stance phase of walking, indicated that the forces' vector was in fact medial to the knee and that in a normal knee, the load was predominantly in the medial compartment. When the knee had a varus deformity the load on the medial plateau rapidly approached 100 percent of the total load on the joint. In the presence of mild valgus deformities, the load remained more medial in 70% of cases; the load was shifted to the lateral compartment in valgus deformities of more than 20° beyond the normal anatomical axis. Similar results were reported in another gait analysis study[46].

D. Pertinence of Knee Malalignment in Osteoarthritis and Arthroplasty of the Knee:

Normal knee alignment ensures efficient ambulation with physiological loading of the knee. The role of malalignment in the pathogenesis of hip osteoarthritis had already been accepted when Malkin proposed proximal femoral osteotomy for osteoarthritis of the hip in 1936[33]. Pauwels[38] pioneer work on the biomechanics of the hip inspired others (Maquet P.[35], Denham & Bishop[8]) to look for similar explanations for the osteoarthritic knee. In the presence of knee malalignment, the increased load on one compartment of the knee, e.g. medial compartment in varus deformity, will result in overuse of that compartment. The net result of these excessive forces is deterioration of articular cartilage and eventually osteoarthritis (Denham & Bishop 1978[8]). The load increase is directly proportional to the severity of the malalignment, hence, the importance of proper realignment following lower limb fractures to avoid knee osteoarthritis and correct alignment of total knee replacements to avoid later deterioration.

The incidence of poor results in early total knee arthroplasties was such that many suspected that total knee replacement was bound to fail if the patient lived long enough (G. Apley[28], Preface to "Replacement of the Knee" 1984). Numerous studies later confirmed that good alignment of the prosthesis was the most important factor in the success of the arthroplasty (Lotke & Ecker 1977[31], Denham & Bishop 1978[8], Coventry 1979[7], Bargren et al 1983[2], Boegard et al 1984[3]). The ideal total knee replacement must be well aligned with a normal tibio-femoral angle of 7° ± 3° of valgus (depending on the body habitus[17]) and a mechanical axis which passes through the middle third of the knee as well as a joint line that is horizontal (i.e. the transverse or horizontal axis of the knee prosthesis is parallel to the ground when weight bearing).

E. Methods of Assessment of Knee Alignment:

Knee alignment is usually assessed clinically and radiologically. Most x-ray techniques were designed to measure the tibio-femoral angle in the coronal plane. More recently, measurement of the mechanical axis has proven to be of greater value, since as long as the mechanical axis is normal, the exact degree of the tibio-femoral angle is less important.

1. Clinical assessment:

Goniometers were used to assess the tibio-femoral angle of patients in the supine position. This method of assessment was unsatisfactory since the measured angle inevitably varied to the nearest 5° (Waugh W. 1985[47]) and the arms of the goniometer were usually too short to be accurate. For that reason, Lawrence in 1980[29], suggested the use of special, long goniometers with extendable arms; the proximal end was placed over the anterior superior iliac spine, its centre over the knee centre and the distal end was over the centre of the ankle. This method was reproducible and accurate to the nearest 1°.

When performing total knee arthroplasty, intra-operative measurement of tibio-femoral angle and of mechanical axis using jigs and alignment rods is now routine[17,50].

2. Radiologic assessment:

The radiologic techniques to assess knee alignment have changed and evolved considerably over the years.

a. Supine, short knee x-rays (only showing the knee):

Such x-rays are inadequate to assess knee alignment since they only show the ends of tibia and femur making the identification of the anatomical axis of the tibia and femur impossible. Furthermore, non weight bearing provides little information regarding stability. (Leach 1970[30])

Patients who are unable to stand because of severe knee pain should be assessed by supine valgus and varus stress x-rays. (Gibson, Goodfellow 1986[13])

b. Standing (weight bearing), short knee x-rays:

The value of weight bearing x-rays was first reported by European authors (Maquet 1963[34], Alhback 1968[44]). Maquet in 1963[34] stated that "only a radiologic examination of the loaded knee shows a picture close to the conditions of gait, when the stress is maximum". Furthermore, weight bearing x-rays demonstrate narrowing of the affected compartment (in addition to a varus or valgus deformity) which may not be obvious on non weight-bearing x-rays (Leach 1970[30]).

In conclusion, short x-rays showing only the knees render measurement of tibio-femoral angulation inaccurate, and are inadequate for pre-operative planning as well as for post-operative assessment of osteotomies and total knee arthroplasties (Hungerford 1982[17], Denham 1984[8]).

c. **Standing (weight bearing), long x-rays:** (Hip-Knee-Ankle x-rays)

Long x-rays or anterio-posterior x-rays of the whole leg (hip-knee-ankle) have been preferred to demonstrate the mechanical axis of the lower limb and to measure the tibio-femoral angle following total knee replacement (Coventry 1979[7], Insall et al 1981[20], Hungerford et al 1982[17], Denham 1978[8], 1984[28]).

Numerous techniques have been described:

(1) J. Duparc & C. Massare 1967[9]: "Panonography"

To our knowledge, these authors were the first to describe in detail a technique to x-ray the entire leg. Three 36 x 43 cm cassettes were mounted one on top of the other in the apparatus - "The Panonographe" - then, 3 exposures of hip, knee and ankle were taken respectively at a tube-to-cassette distance of 3 meters. Positioning of the cassettes was accurate and a single x-ray of the entire lower extremity in the standing position was thus obtained.

(2) W. Waugh et al 1980[25]:

A scanogram of the patient in the bipedal stance was taken with instructions to put as much weight as possible on the affected leg: the cassette was 35 x 90 cm and the tube-to-film distance was 80 cm.

(3) Ranawat et al 1982[42]:

The authors used a single 35 x 90 cm cassette at a 180 cm tube-to-film distance, to obtain a long "hip-knee-ankle" view. No further description of the technique was mentioned.

(4) Denham R.A.:

Denham R.A. is an advocate of long x-rays or what he calls a "Leg Alignment" x-ray. He has described two different techniques:

a) Denham R.A. 1980[10]: Radiologic examination of the knee, in the book *Arthritis of the Knee:*

- Cassette and frame: a 30 x 112 cm film put in a long cassette with screens of graded intensity. The cassette is mounted in a vertical frame behind the patient.
- Tube-to-film distance: 3 meters
- Positioning: the patient stood up with equal weight on each leg. The knees should present a true A/P view and should not press against each other. A handrail at chest level may be used for stability. X-ray

tube was centered at knee level.

b) Denham R.A. 1984[28]: in the book *Replacement of the Knee* described a similar technique with the following differences.

- Cassette: four carnex films loaded exactly with their edges touching into a 35 x 109 cm cassette.
- Tube-to-film distance: 180 cm

(5) Boegard et al 1984[3]:

To assess their results following 74 "Attenborough" total knee arthroplasties, whole limb radiograph were taken at a tube-to-film distance of two meters with the patient standing on the examined leg (monopedal stance); no further technical details were given.

(6) Laskin R.S. 1984[28]:

An A/P view of the weight bearing lower limb taken at 180 cm tube-to-film distance with an average exposure of 60MAS-76KV.

(7) Cook et al 1986[4]:

The authors have introduced an x-ray frame, fitted with radio-opaque markers for the lower extremity, in order to standardize their x-rays. The data were processed in a desk-top computer.

3. Difficulties with long leg x-rays:

Long, full length x-rays are difficult to obtain, interpret and store. "In spite of the numerous techniques that were described to obtain a hip-knee-ankle radiograph, considerable logistical and technical problems preclude their routine use" (Insall J. 1981[20]).

a. Difficulties in performing the x-rays:

(1) Short of using a computerized x-ray frame[34] and with the exception of Duparc & Massare 1967, no other author, to our knowledge, gave sufficient technical details to reproduce their technique reliably. As a result, patient positioning and x-ray technique vary considerably and the variable x-ray images preclude valid comparisons between successive x-rays.

(2) The lower extremities of tall patients are usually longer than the available three-foot (90 cm) cassette and the use of two separate films adds further inaccuracy to the assessment.

(3) The procedure is time consuming, implies needless and sometimes multiple x-ray exposure of the pelvis that harbours 36% of the body's total red bone marrow.[41] This is of major concern especially in young patient with added risk of tumour induction or genetic mutation.[37]

(4) If there is a flexion contracture of the knee, any degree of rotation of the limb will change the x-ray image of the tibio-femoral angle.

b. Difficulties with equipments and cost:

(1) Three-foot (90 cm) films require a special long x-ray cassette, long x-ray film and viewing box. The cost may be prohibitive for smaller hospitals and private clinics in developed countries and expecially for the third world.

(2) Storage and filing of three foot (90cm) films can be problematic (serrated, bending x-rays are now available).

c. Difficulties in interpretation:

Unless the physician is in attendance while the x-ray is taken, he is never certain that proper weight bearing x-rays in a true A/P position have been taken. Furthermore, the hip, knees and ankles are rarely equally in focus and the x-ray image is unsatisfactory.

4. Objective of the new technique:

The reasons for undertaking this investigation were related to the many difficulties related to long x-rays. We therefore standardized the radiologic assessment of the knee alignment using a short x-ray film instead of a three-foot (90 cm) long x-ray.

The key to this technique is that the patient stands with the centres of his/her ankles apart by a distance (F_1) that is equal to the distance between the centres of his/her hips, i.e. distance F. Under these circumstances, the mechanical axes are parallel to the long axis of the cassette and vertical to the ground. X-rays taken in this position have been called The "Parallel Mechanical Axes X-rays". (Fig. 17)

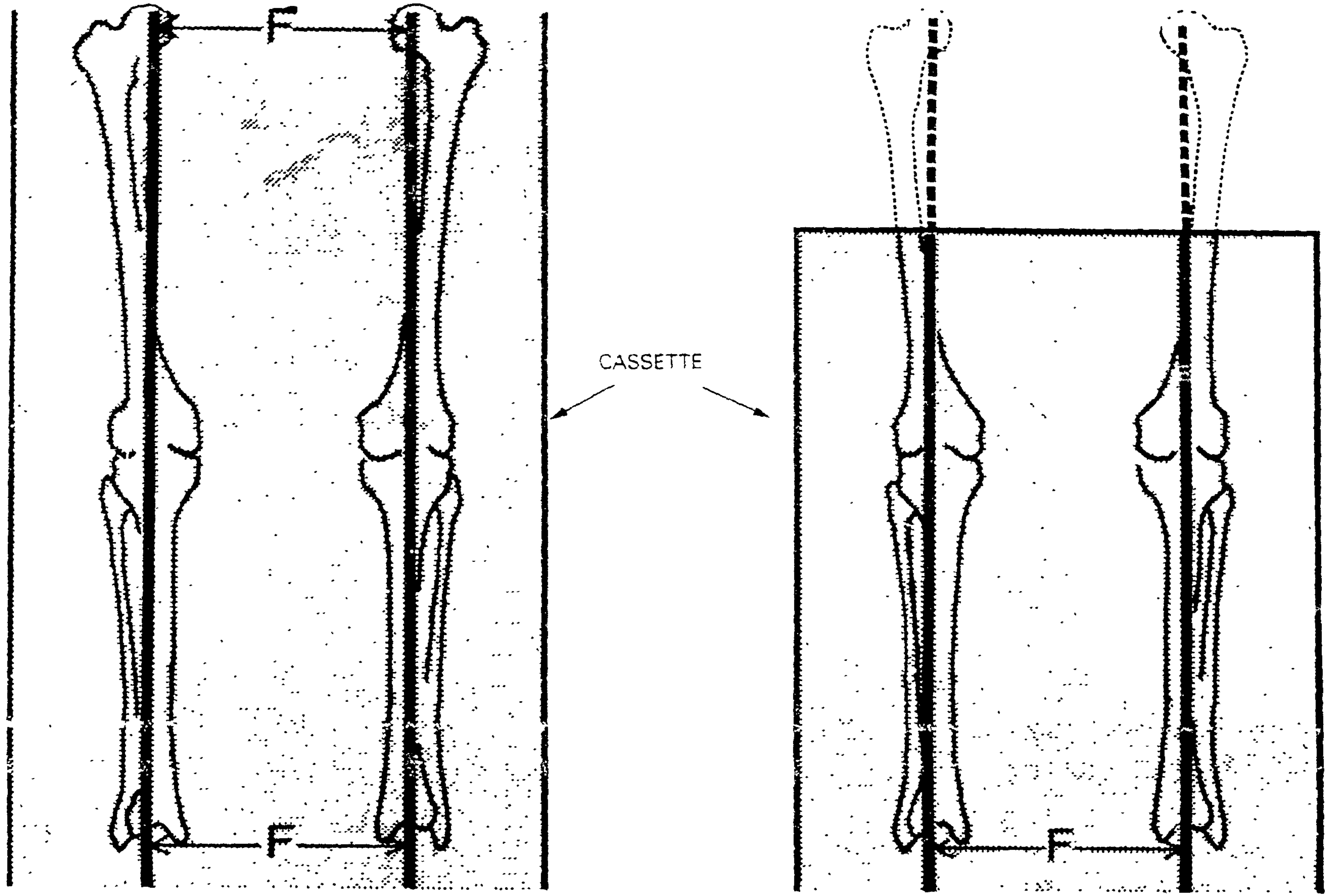


Figure 17
The parallel mechanical axes x-rays

The merit of this technique is that it minimizes the technical variables and permits reliable determination of the mechanical axis on a standard x-ray of the entire tibia. The A/P View of the tibial plateau is subdivided into three zones; when the mechanical axis passes through the middle third of the tibial plateau, it is considered as normal and the knee is thus well aligned (Waugh 1985[47]). (Fig. 18)

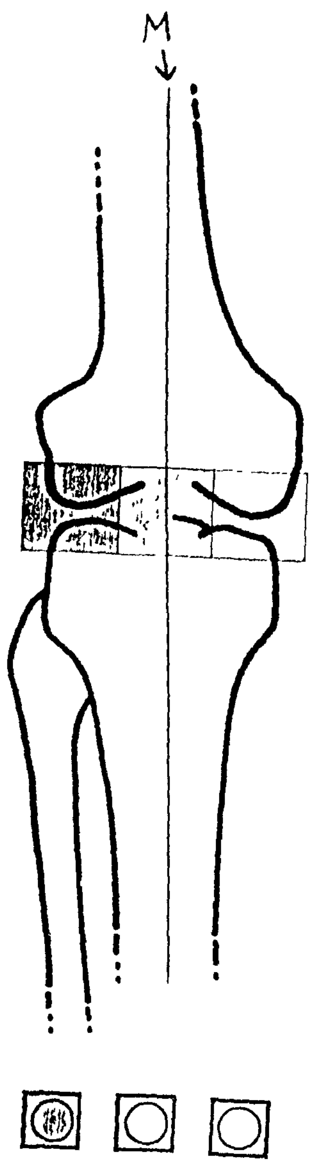


Figure 18

Normal Alignment:
the mechanical axis passes through the middle third of the tibial plateal

IV. MATERIAL AND METHODS

Twenty-one normal individuals and twenty-five patients with malaligned knees fulfilled the following criteria.

(1) All patients measured less than 175 cm. in height. Taller people usually have lower extremities that are longer than the three-foot (90 cm) x-ray cassette.

(2) Patients with hip or ankle pathology were excluded.

- The control group was made up of 8 females and 13 males; their ages ranged from 18 to 68 years with a mean age of 35 years.
- The patient group had the following knee pathology: 18 patients with osteoarthritis, 6 patients with Rheumatoid Arthritis, and one patient with psoriatic arthritis.

Malalignment of the knee was clinically assessed with a goniometer and ranged from 10° of varus to 30° of valgus.

There were 15 females and 10 males, their ages ranged from 34 to 80 years with a mean age of 52 years.

A. Methodology:

I. Instruments:

a) Cassette & Films:

(1) One 35 x 90 cm (14" x 36") cassette is fitted with Dupont gradient screen (High speed for pelvis - low speed distally) - Film: 35 x 90 cm Kodak XRP - and perforated to fold up to 35 x 30 cm size.

(2) Two 35 x 43 cm (14" x 17") cassettes with 35 x 43 cm Agfa scepix RPI films.

b) Frame: (Fig. 19)

An adjustable wall bucky is fixed to the wall so that the transverse edge of the cassette is consistently horizontal and parallel to the ground, while the long edge is vertical and perpendicular to the ground.

c) Radio-opaque plumb line: (Fig. 19)

A 180 cm aluminum rod is vertically mounted in the middle of the cassette.

d) A Metal Caliber (by Melco) (Fig. 20)

e) A 45 cm plexiglass ruler inlaid with radio-opaque measurements (by Picker)

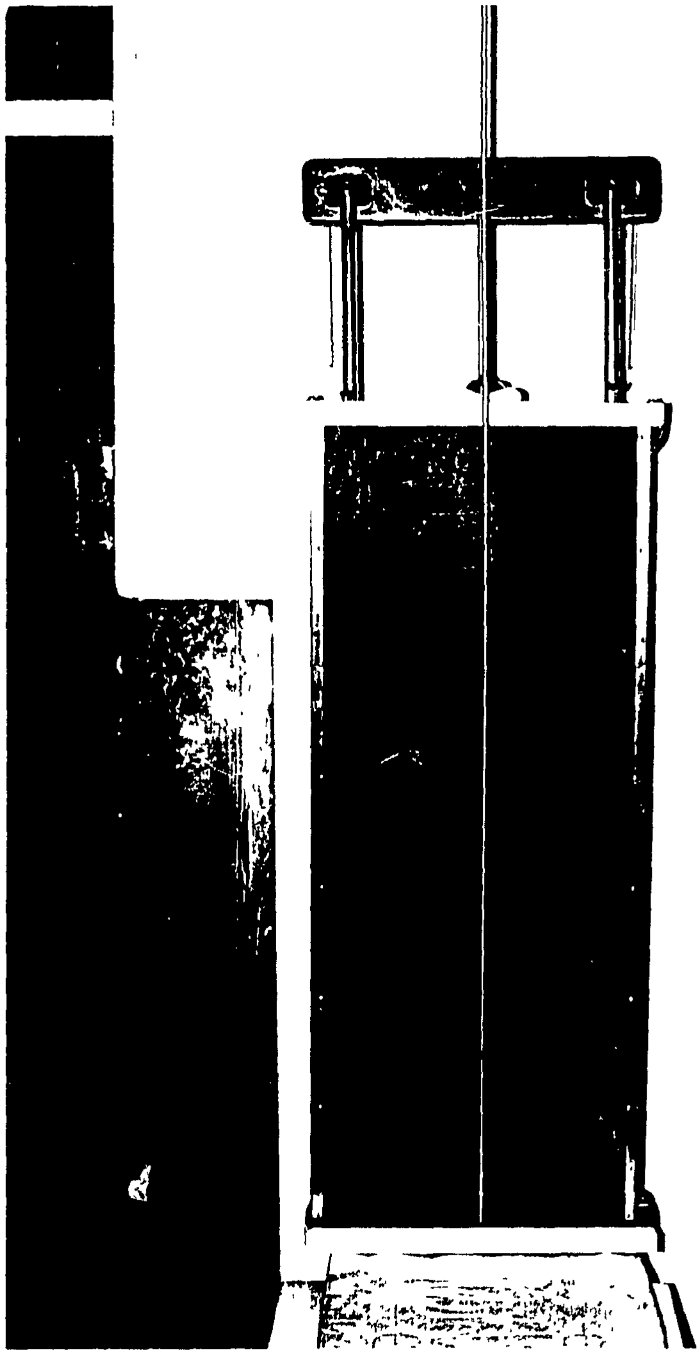


Figure 19

3 foot long cassette in x-ray frame
Note radio opaque plumb line in the midline

2. **Technique:**

a) The patient was positioned so that the distance between the centres of the ankles (Ac) equals the distance between the centres of the hips i.e. the centres of the femoral heads (Hc); patient positioning three steps:

Step 1: Radiographic measurement of the distance between the centres of the hip joints (Hc). (i.e. distance F)

Distance F was measured on an A/P x-ray of the pelvis taken at a tube to cassette distance of 180 cm (72") to minimize magnification - a plexiglass ruler was taped transversely on the cassette. (Fig. 21 22)

Step 2: The patient was positioned so that the distance between the centres of the ankles (Ac) (i.e. distance F_1) was equal to the distance between the centres of the hips (Hc) (i.e. distance F).

Rationale: The centre of the Ankle (Ac) is midway between the lateral and medial malleoli. (Ma = distance between medial and lateral malleoli of the same ankle). In order to position the centres of the ankles at the desired distance F_1, the outer surfaces of both lateral malleoli should be placed apart by a distance F + Ma (see math formula in Fig. 23).

Technique: The patient stood facing the x-ray tube.

Figure 20

Adjustable metal caliper

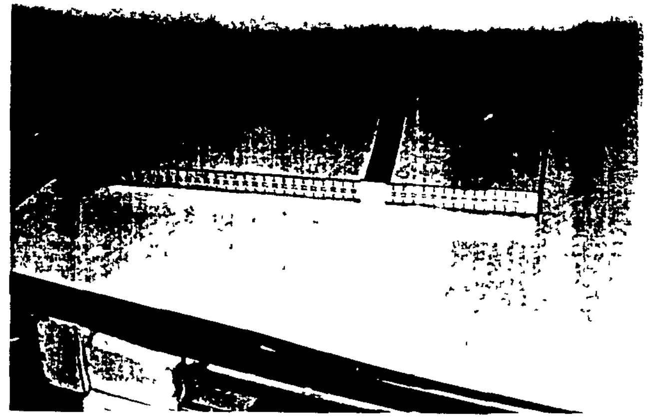


Figure 21

X-ray cassette with radiopaque ruler

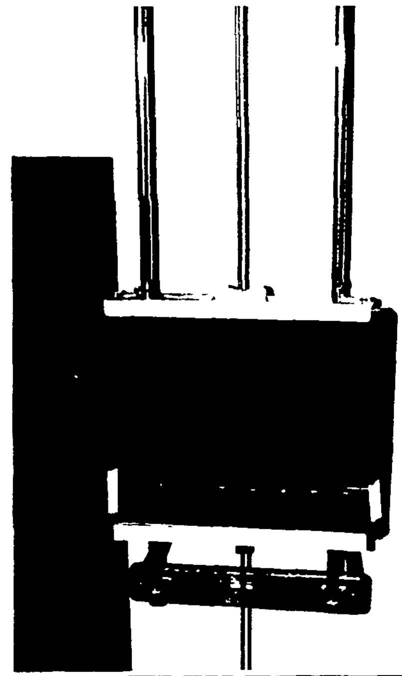


Figure 22

Radiographic measurement of distance F.

(1) The distance between the outer surfaces of medial and lateral malleoli, i.e. distance Ma (in fact, it corresponds to the vidth of the ankle) was measured first using a calliper. (Fig. 24a)

(2) The calliper arms were then opened to a distance of F + Ma (distance F known from step 1). The ankles were positioned with the outer surfaces of both lateral malleoli in contact with the calliper arms. (thus $F_1 = F$) (Fig. 24b)

<u>Step 3:</u> The patient stood with the hips in neutral rotation and with both knees fully extended to ensure a true A/P view of the knees as verified by the position of the patellae. Body weight is equally applied to both legs and the metallic plumb line should be exactly in the patient's midline. (Fig. 25) Any lurching to one side can thus be controlled. (Fig. 26)

b) **Projection Guide:** X-rays were taken at a tube to cassette distance of 180 cm (72") for a minimum magnification. The x-ray beam was centred at the knee joint line level; a 35 x 90 cm (17" x 36") grid was used for obese patients (85 lines per inch, 8:1 ratio).

The projection technique for a triple phase, twelve pulse generator was:

<u>A/P Pelvis:</u> Average patient (70 kg): 32 MAS, 75 KVP + Grid.

Metal caliper used to measure the width of the ankle = M_a

Figure24/a

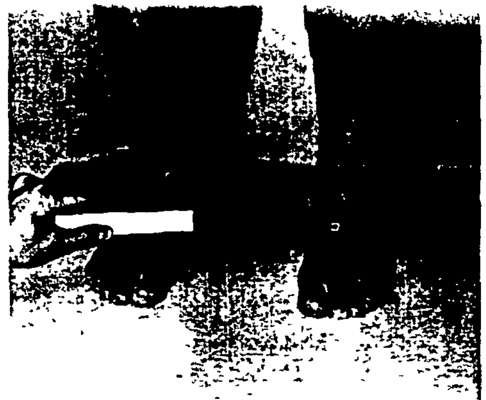
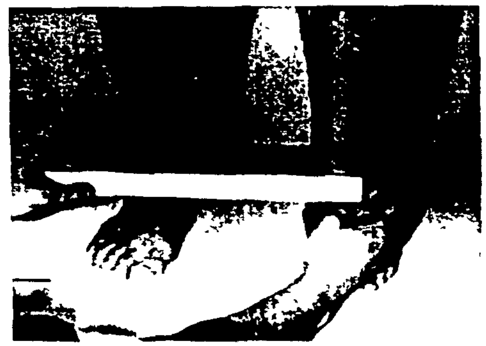


Figure 24

Metal caliper used to place ankles at distance = $F + M_a$

Figure24/b



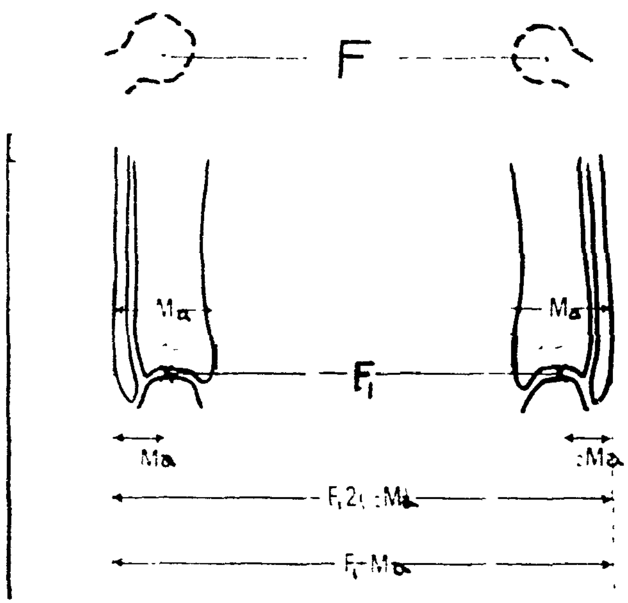


Figure 23

Rationale behind ankle positioning

Figure 25
Patient in true bipedal position

Figure 26
patient lurching to one side

A/P X-rays of lower limbs: Average patient 32 MAS, 75 KVP + Grid or 32 MAS, 65 KVP no Grid.

c) **X-rays:** For the sake of consistency, two radiology technicians (F.M./J.G.) were specifically trained and assigned to the project. The following x-rays were taken:

(1) A long 35 x 90 cm (3 foot) A/P x-ray of the hip-knee-ankle (Fig 27). The patient was then asked to step down and was again repositioned for the second short x-ray.

(2) A short 35 x 43 cm A/P x-ray of the entire tibia including the knee and ankle was then taken.

Since the mechanical axis of the lower extremity is now vertical to the ground and parallel to the long axis of the cassette and of the x-ray film, a vertical line drawn on the short x-ray starting from the centre of the ankle (Ac) and running parallel to the long axis of the film, will automatically go through the centre of the hip (Hc) (which therefore need not be visualized). (Fig. 28)

d) To test the validity of this technique, the mechanical axis was drawn on both the long x-rays and the short x-rays. (Fig. 28)

Figure 27

Mechanical axes drawn on a 3-foot long whole leg length x-ray.

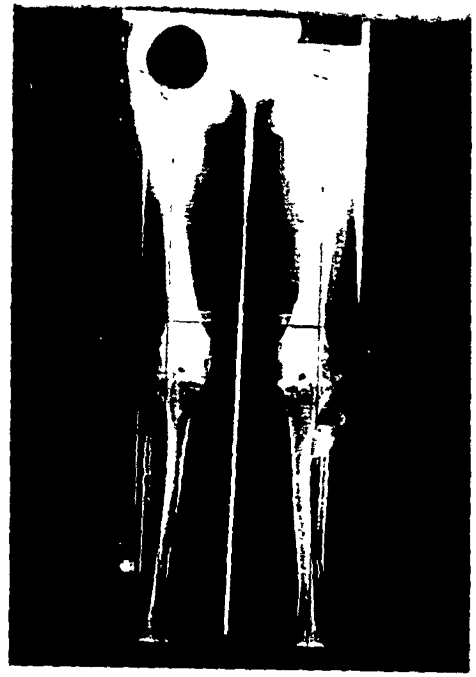


Figure 28

Mechanical axes drawn on a short x-ray of the entire tibia

The following parameters were measured:

(1) the distance (F_1) between the centres of the ankles (Ac) as compared with the distance (F) between the centres of the hips (Hc) (this is done to test for accuracy of ankle positioning).

(2) the position of the mechanical axes on the x-ray film as compared to the vertical metallic plumb line (this is done to test for accuracy of the technique in achieving vertical and parallel mechanical axes).

(3) the mechanical axis of the knee of the same patient measured on a three foot film was compared with the mechanical axis as drawn on the short x-ray.

The tibial plateau was divided into three zones (lateral, middle and medial) and the zone crossed by the mechanical axis as drawn on long and short x-rays was noted and compared (Fig. 29). (This is done to test the accuracy of the technique in reproducing the position of the mechanical axis on the short x-ray)

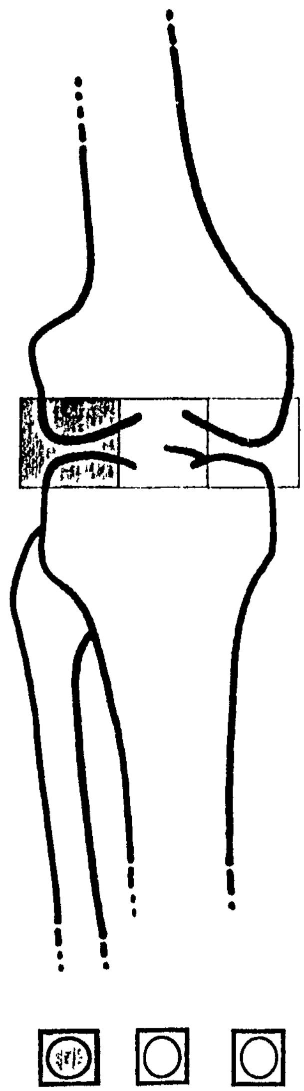


Figure 29

Tibial plateau divided into 3 zones

TABLE I

CONTROL GROUP

No.	NAME	SEX	AGE	ALIGN / DIAGNOSIS	Distance between centers of hips (cm)	Distance between centers of ankles (cm)	Deviation M.A. off vertical (°) *	Deviation at knee level long vs short xray(cm) *
1	D.M.	F	26	(N)	17.8	18.5	----	0.3 cm
2	G.B.	M	32	(N)	19.6	21	1 - 2°	0.7 cm
3	R.B.	MF	30	(N)	18	20	2°	1 cm
4	H.P.	M	51	(N)	18.2	18.7	----	0.5 cm
5	R.B.	F	51	(N)	19.5	20.5	1°	0.5 cm
6	A.C.	M	25	(N)	20.2	21.2	1°	0.5 cm
7	L.D.	M	21	(N)	20	20.3	----	----
8	P.G.	M.	27	(N)	19.5	19	----	0.2 cm
9	D.W.	F	24	(N) (R) PATELLECTOMY	20	20.3	----	----
10	J.E.	F	27	(N)	20	19	1°	0.5 cm
11	C.D.	F	19	(N)	18	17.5	----	0.5 cm
12	R.C.	M	39	(N)	18	18	----	----
13	JG B.	M	36	(N) osteoid os. / (R) tibia	21	20.5	----	0.2 cm
14	I K.	F	68	(N)	20	20.3	----	----
15	Y G	M	30	(N)	18.2	19	1°	0.2 cm
16	G F	M	50	(N)	19.2	19.2	----	----
17	B I	M	21	(N)	20.2	20	----	0.5 cm
18	A.C.	M	52	(N)	19	18.8	----	----
19	G.M.	M	28	(N)	18.5	20	1 - 2°	
20	T P	F	18	(N) (L) ACL reconst	18.1	18.8	1°	0.7 cm
21	J D	F	62	(N), (L) ankle OA	18.5	19	----	0.4 cm

* *Spaces marked as (----) = No deviation*

TABLE II

MALALIGNMENT PATIENTS

No	NAME	SEX	AGE	ALIGNMENT/DX	Distance between centers of hips (cm)	Distance between centers of ankles (cm)	Deviation M.A. off vertical (°)*	Deviation at knee level long vs short xray (cm)*
1	M.D.	F	72	(L) valgus knee / Bil. TKA	17.6	17.6	----	----
2	T.C.	F	61	(L) genu valgum 3 cm LLD	18.3	19.3	1°	4 cm Diff zone
3	R.G.	F	61	(R) varus knee	18.5	20.3	2°	0.9 cm
4	A.V.	F	79	Bil. genu vara	18.2	18.4	----	1.2 cm
5	F.B.	F	63	(L) HTO	19.5	20.5	1°	0.5 cm
6	A.H.	F	43	Bil. genu valga/RA	20	20.7	1°	0.3 cm
7	P.N.	M	24	Post (L) # femur	20.5	21.5	1°	0.2 cm
8	F.W.	F.	34	Bil. genu valga	18	19.8	2°	0.9 cm
9	J.K.	M	20	(L) genu valgum	19	20	1°	0.6 cm
10	E.G.	M	77	(L genu varum	20.5	20	----	0.2 cm
11	L.C.	F	58	(L) TKA 20° flexion contrature	19.5	19.8	----	0.5 cm
12	H.G.	F	62	Psoriasis/(L) TKA	20.5	20.5	----	----
13	S.D.	F	61	Bil. genu valga	18.8	21.2	3°	0.5 cm
14	E.T.	M	25	Bil. varus	18.2	18.5	----	0.5 cm
15	M.S.	M	27	Bil. genu vara	19.5	20.5	1°	0.2 cm
16	J.A.	F	59	(L) varus knee / Bil. TKA	18.5	18.7	----	0.6 cm
17	W.B.	M	43	Bil. genu vara/(R) HTO	18.5	19	----	0.3 cm
18	M.D.	F	33	Bil. lig. instability	18.0	19	1°	0.4 cm
19	G.S.	F	80	(R) valgus knee / (R) TKA	18.5	18.5	----	----
20	A.T.	F	68	Bil genu valga	17.8	17.6	----	----
21	G.M.	M	77	(R) varus knee/(L) TKA	18.5	21	2°	1.5 cm
22	B.M.	M	78	(R) valgus/(L) TKA	18	17.2	1°	0.4 cm
23	F.G.	F	59	(L) valgus knee/(R) TKA	19.5	21	2°	0.7 cm
24	J.B.	F	77	(L) varus knee / (L) TKA	18	17.7	----	0.2 cm
25	J.B.	M	59	Bil genu vara	18.5	20	2°	0.8 cm

** Spaces marked as (----) = No deviation*

V. RESULTS

(See tables I & II)

1. The average difference found between distance F_1 and distance F - i.e distance between centres of the ankles (Ac) as opposed to distance between the centres of the hips (Hc) - was 0.6 cm in normal control subjects and 0.8 cm in malaligned subjects.

   The maximal difference between the two measurements was 2 cm in the control group and 2.4 cm in the patient group, both seen during the early stages of the study.

2. Using our positioning technique, a vertical mechanical axis (within 2°) i.e. perpendicular to the floor, was obtained in all control subjects and in 96% (24/25) of patients with malaligned knees, the only failure (3° deviation in patient #13) being in a patient with severe bilateral genu valgum (see discussion).

3. The point and the zone of intersection of the mechanical axis on the tibial plateau in the long and short x-rays were identical (within 1 cm) in all control subjects and in 88% (22/25) of patients with malaligned knees.

   The mechanical axis was noted to be in a different zone (on long x-ray as compared to short x-ray) in one patient (#2) of the malalignment group (see discussion).

At the end of the study, we could consistently position our subjects (controls and patients) so that the ankles and hips were vertically aligned, resulting in mechanical axes that were vertical to the floor and parallel to one another. It was then possible to determine the mechanical axis of a limb on a short x-ray of the entire tibia (i.e. parallel mechanical axes x-rays). (Figure 30)

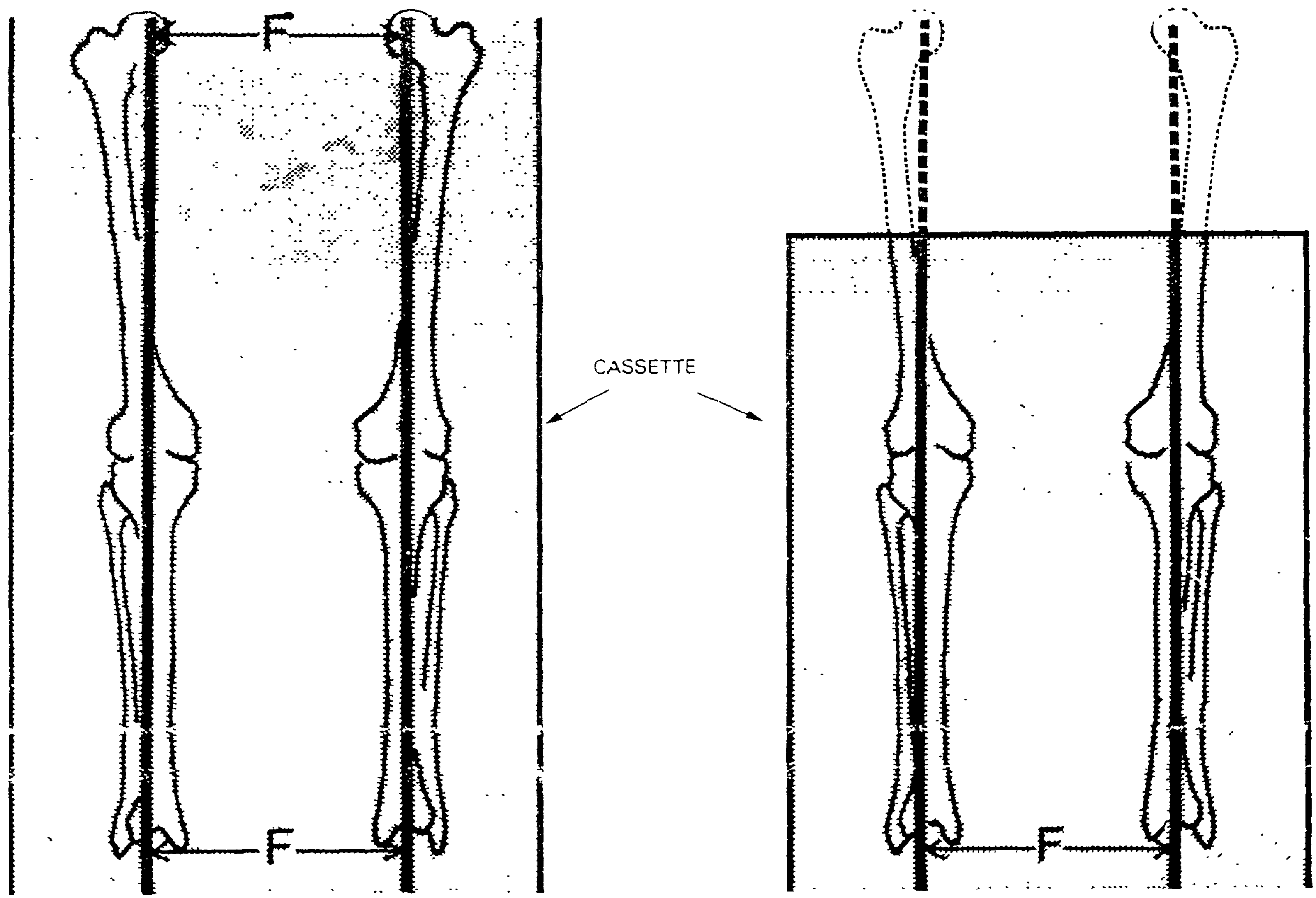


Figure 30
The parallel mechanical axes x-rays

VI. DISCUSSION

The outcome of knee reconstructive surgery depends on accurate realignment of the lower limb (Lotke & Ecker 1977[31], Insall et al 1981[20], Bargren et al 1983[2], Johsson B. 1988[24]) The two main methods of assessing normal limb alignment are the tibio-femoral angle (normally measuring 7° ± 3° valgus) and the mechanical axis (normally passing through the middle third of the tibial plateau).

Three-foot, full leg length weight bearing radiographs are still considered the gold standard for the radiological assessment of knee alignment (Peterson, Engh 1988[39]). In an attempt to perfect long A/P x-rays of the lower limbs, Cook et al[4] Queen's University Clinical Mechanics Group (CMG) have introduced the "Standardized Radiograph Technique" which entails the use of a standardized radiographic frame with multiple radio-opaque markers to identify anatomical landmarks as well as reference points built into the frame. Long full leg length x-rays are then taken and all available data are digitized and automatically processed in a desk-top computer. A hard copy with a detailed 18 point analysis of malalignment is provided. The procedure is regrettably complex, expensive and requires trained personnel.

Furthermore, three-foot (90 cm) long x-rays are difficult to standardize, store and entail irradiation of the pelvis.

The authors propose a standardized and reproducible technique whereby the ankles and the upper body are precisely positioned and controlled. Under these circumstances, the mechanical axis can be drawn on an x-ray of the entire tibia only. This technique is now called the "Parallel Mechanical Axes X-ray".

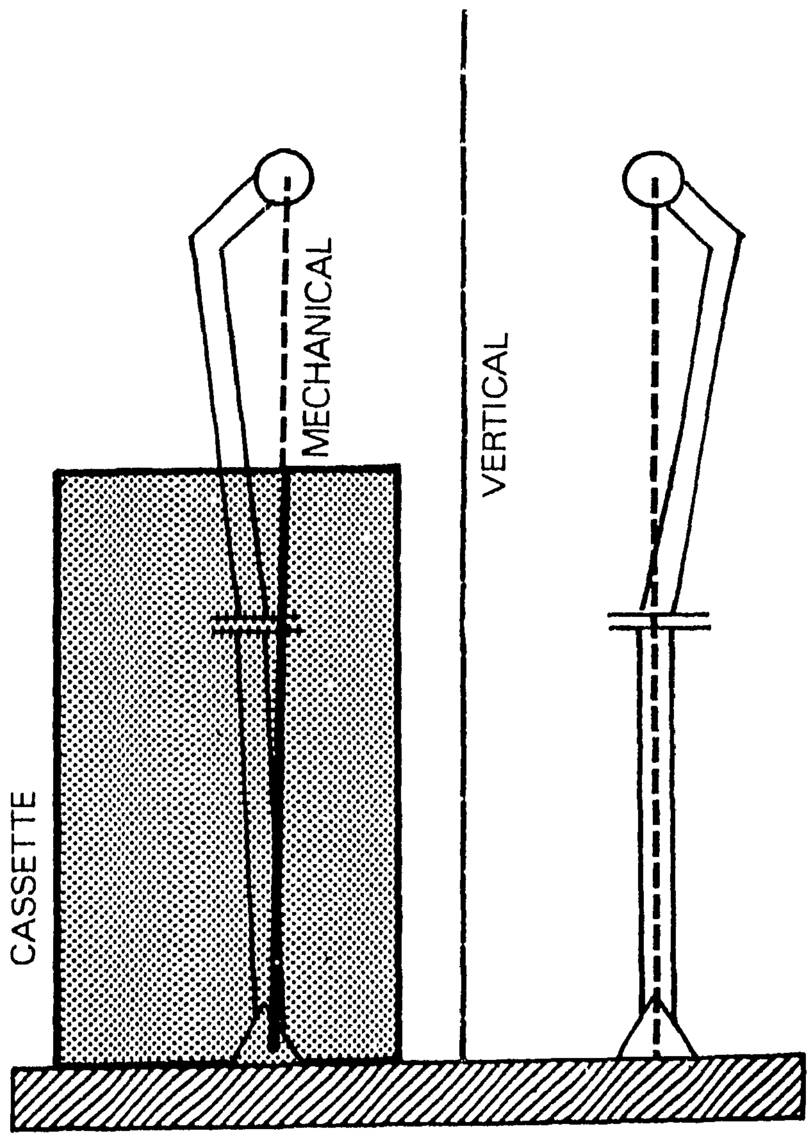
Technical difficulties during the early stages of the study were mainly related to inexperience. Accuracy in positioning patients improved with time. This learning curve accounts for poor results in three patients (#2,3,13 table II) and in one control subject (#3 table I).

Specific clinical situations merit discussion:

1. For very tall patients, the 35 x 43 cm short cassette may not be long enough to visualize the entire tibia. A three-foot (90 cm) film is then used but the proximal femur and the pelvis are not visualized nor irradiated. (Fig. 31)

2. Pelvic obliquity, be it due to a fixed lumbar curve or leg length discrepancy does not, by itself, modify the relationship between the hip, knee and ankle (i.e. knee alignment) although it likely alters the biomechanics of weight bearing, particularly in the presence of associated knee malalignment. Pelvic obliquity, however, will modify, ever so slightly, the horizontal distance between the hips;

Figure 31



the pelvis should therefore be horizontalized by blocks for correct assessment of distance F and hence, of distance F_1 when using the parallel mechanical axes x-ray technique.

Since correction of leg length discrepancy with blocks is not necessary when leg alignment is radiologically assessed using the three-foot x-ray technique, the latter may be preferred in instances of marked pelvic obliquity.

3. Bilateral knee deformities: Mild to moderate degrees of bilateral varus or valgus deformities could be radiologically assessed using the parallel mechanical axes x-ray technique (Case #4,6,8,13,15,17,20,25, Table II)

   - **Severe bilateral genu varum:**

   With the ankles placed apart by a distance F_1 = F, the distance between the varus knees may exceed the width of the x-ray cassette i.e. 35 cm or 17" and a wider cassette is then necessary; alternately, the x-ray cassette may be moved to either side in order to visualize the knee.

   - **Severe bilateral genu valgum:**

   When these patients separate their ankles by distance F_1, their knees may touch one another. If the knees are touching, they support each other medially and true weight bearing knee alignment can not be assessed (Coventry 1987).[6] This restriction obviously applies to short and long x-rays.

- **Valgus-varus deformity combinations (windswept knee deformity)**

This should not interfere with proper ankle positioning as long as the knees are not touching one another. The x-ray cassette may have to be moved to one side to visualize both knees, on the same cassette.

4. Patients with internal or external tibial torsion deformity:

Severe torsional deformities of the tibiae may render simultaneous frontal (A/P) visualization of the knees and ankles impossible. In such instances, the knee is positioned in the correct A/P plane i.e. patellae facing forward. As for ankle positioning, it is not necessary to visualize the ankles in true A/P plane as long as they are positioned apart by a distance of $F_1 = F$.

Rotating the foot and ankle to obtain a true A/P view of the knee joint does not affect the vertical position of the mechanical axis as long as the deformities are purely rotational without any angular diaphyseal or metaphyseal component.

5. Patients with angular deformities of the tibia or femur e.g. Post-traumatic:

Angular deformities of the tibial or femoral shafts will exaggerate knee malalignment and further displace the mechanical axis. The knee malalignment will be increased or decreased by malrotation and x-rays should be taken in a position of neutral rotation. These precautions however, also apply to positioning for three-foot full leg length x-rays and are not contra-indications to the use of the "parallel mechanical axes x-ray".

Considerable attention to detail is necessary to achieve accurate and reproducible parallel mechanical axes x-rays in patients whose knee malalignment is due to multidirectional deformities. For example, a patient with a malaligned knee secondary to malunion of a tibial shaft fracture with a marked varus angulation, internal rotation of the distal tibia and 3 cm of shortening must be carefully assessed both clinically and radiologically to ensure that each component of the malalignment is considered. Although limb shortening and pure torsional diaphyseal deformities may not modify knee alignment, angular deformities of the tibia and/or the femur, on the other hand, will alter the alignment of the knee and its x-ray assessment will be greatly altered by any malpositioning of the limb when the x-ray is taken. For instances of complex and multidirectional knee deformities, alignment is probably best assessed radiologically using carefully executed three-foot x-ray films

Two issues would seem to favour the "parallel mechanical axes x-ray technique", namely radiation exposure and cost. Diagnostic radiology accounts for a major part of radiation dosage received by patients.[37] Although radiation exposure has been shown to increase the incidence of breast cancer[1], the **REAL** risk of various diagnostic radiographic procedures remains unknown.[37] This has prompted the introduction of the ALARA principle[45] in diagnostic radiology (as low as reasonably achievable). On the other hand, the relative sensitivities of different organ tissues to radiation have shown the gonads to be the most sensitive, followed by breast tissue and red bone marrow.[21] (36% of the body's red bone marrow is in the pelvis)

Also, irradiation of the gonads, the bone marrow and active epiphyseal plates of young patients, may increase the risk of genetic mutation and tumour induction.

It would, therefore, seem prudent that pelvic irradiation should be kept to a minimum and the advantages of an x-ray exposure limited to the entire tibia only would seem obvious.

There are also economical advantages. A comparison of price listings obtained from Kodak, Canada 1990, showed that long x-ray cassettes and films cost double that of short x-rays as follows:

	Long (35 x 90) cm x-rays	Short (35 x 43) cm x-rays
X-rays cassette & screen	$ 1125.80 Can.	$ 484.00 Can.
X-ray film	$ 5.00 Can.	$ 2.28 Can

Thus the "parallel mechanical axes x-ray technique" would appear to be a cost-effect've method to assess knee alignment.

The "parallel mechanical axes x-ray technique" also has the following added potential advantages:

First, the technique is easier to standardize and the x-ray images are reproducible.

Second, although determination of distance F (the distance between the centres of the hip joint Hc) requires an x-ray of the pelvis, that measurement can be recorded on film and used later for follow-up x-rays with less resultant net irradiation to the gonads than repeat long (90 cm) three-foot x-rays.

Third, the vertical radiopaque plumb line, as seen in the middle of the x-ray, ensures equal weight bearing on both limbs, lurching to one side is easily noted and should be corrected.

Finally, while a long (90 cm) three-foot x-ray may be preferred for pre-operative planning of a total knee replacement, short parallel mechanical axes x-rays are perfectly adequate for follow-up assessment of knee alignment. They require no special viewing box and present no storage problem.

VII. CONCLUSION

A new radiographic technique, called the "parallel mechanical axes x-ray technique" is described for the assessment of knee alignment using a short x-ray of the entire tibia. The technique is reliable, reproducible and spares the patient unnecessary irradiation and is a viable alternative to and less costly than three foot long x-rays.

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