FORM AND FUNCTION OF THE RHEUMATOID FOOT

by

Leon Lourens du Toit

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ABSTRACT

Rheumatoid arthritis (RA) is a debilitating systemic disease affecting connective tissue structures throughout the body. With reference to the foot, this can have serious implications for its form and function. The purpose of this study was to analyse the form and function of the feet and lower extremities of a selected group of rheumatoid patients in order to discover how and why they differed in these aspects from a control group of normal subjects. I am confident that this study is sufficiently relevant and that it goes some way toward fulfilling the need for research on RA from a biomechanical perspective. I shall briefly discuss the two main reasons upon which I base my confidence. First, foot involvement is extremely common among RA patients, affecting between 70% and 90% of all people suffering from RA. Second, a very small proportion of the already limited research effort expended on the rheumatoid foot, has been devoted to investigation which takes cognisance of the biomechanical factors involved.

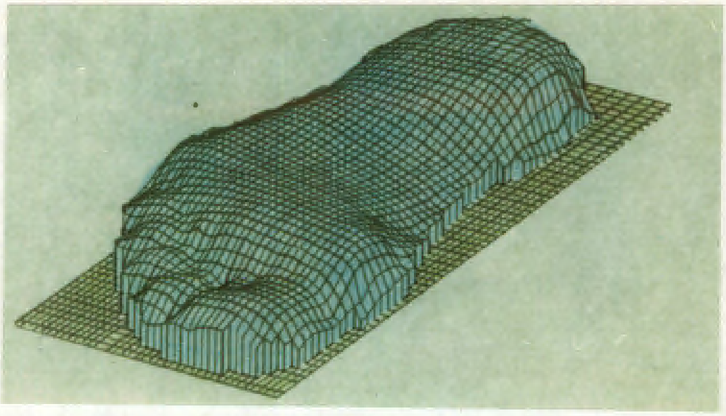
The evaluation of the form of the rheumatoid foot consisted of measuring and comparing the external shape of its plantar surface, using plaster of Paris footcasts and iodine footprints, and assessing the internal bony architecture by means of X-rays. Contour diagrams were constructed of the footcasts, distances measured on the footprints and angles determined on the X-rays. Indices were derived from the contour diagrams and iodine footprints to evaluate the degree of flatfootedness in rheumatoid patients. According to these indices rheumatoid feet were

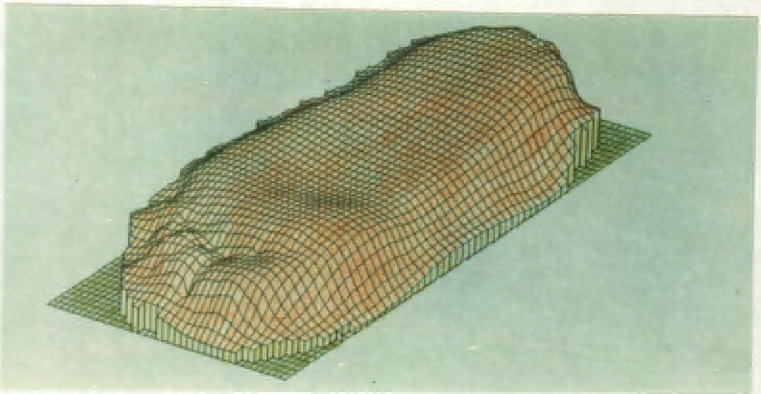
significantly flatter than normal feet. Visual comparisons between the X-ray, iodine footprint and contour diagram for the same foot revealed a definite correlation between the external shape and the internal structure of rheumatoid and normal feet.

The functional status of the rheumatoid foot during gait was evaluated by concentrating on the movements of the lower extremity (kinematics) and the ground reaction forces experienced by the foot (kinetics). A digital camera was used to evaluate parameters pertaining to the kinematic function of the lower extremity during walking, while the force plate at the Princess Alice Orthopaedic Hospital enabled me to assess kinetic parameters of foot function during the stance phase. It was clear that the rheumatoids had a significantly reduced stridelength compared to normal controls, which meant that they walked significantly slower because the cadences of both groups were essentially the same. Eliminating the effects of walking speed revealed the fact that the rheumatoids experienced ground reaction forces which were equal in magnitude to that experienced by normals during the earlier and middle stages of the stance phase. However, during the latter stages of stance, rheumatoids experienced significantly reduced ground reaction forces. This indicated that rheumatoids definitely delayed the loading of their forefeet, which were painful as a result of a very common problem in RA, i.e. metatarsalgia. It is clear that physical and psychological factors can cause rheumatoid patients to adopt an apropulsive antalgic gait pattern which is significantly different from that of normal, non-rheumatoid subjects.

Futhermore, it seems that forefoot pathology has a much larger role to play than hindfoot pathology in changing rheumatoid gait.

In conclusion, it is evident that the combination of footcasts, footprints and X-rays can provide the clinician with a better understanding of the form of the rheumatoid foot than X-rays alone. Similarly, combining force plate and digital camera data will provide the clinician with improved insight into the biomechanical function of the rheumatoid foot and lower extremity when used in conjunction with visual inspection of the patient's gait pattern.





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Summary

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LIST OF ABBREVIATIONS

RA	Rheumatoid arthritis
PAOH	Princess Alice Orthopaedic Hospital
FFR	Flatfootedness ratio
ROM	Range of motion
2D	Two-dimensional
3D	Three-dimensional
BW	Bodyweight
Hz	Hertz
P	Perimeter of an angle-angle diagram
A	Area of an angle-angle diagram
P_A	Ratio $P/\sqrt{A}$

CHAPTER 1

THE PROBLEM AND ITS SETTING

Statement of the Problem

Rheumatoid arthritis (RA) is a debilitating disease. Throughout the body, structures containing connective tissue such as joint capsules, tendons, ligaments, muscles, bones, and articular cartilage are affected by this disease. The synovium of joint capsules become inflamed and the capsules may stretch, tendons and ligaments are weakened and may rupture, muscles atrophy, and bones and cartilage are eroded. In the case of the foot this can have some serious implications for its form and function as well as for that of the lower extremity as a whole.

The purpose of this study was to analyse the form and function of the feet and lower extremities of a selected group of rheumatoid patients in order to discover how and why they differed in these aspects from a control group of normal subjects.

The Need for this Study

The foot is a very important part of the locomotor system because its functional status affects the proper functioning of the whole of the lower extremity, the lack of which, in turn, might place some serious limitations on a person's mobility. According to the literature (Vainio, 1956; Helfet and Gruebel Lee, 1980), between 70 and 90 per cent of the people who suffer from RA, have got some kind of foot involvement. In some cases only minimal discomfort exists with no visible damage to the foot while in others there is serious disfigurement, constant pain, and a total inability to walk. In-depth studies, which look specifically at the biomechanical factors influencing the form and function of the rheumatoid foot, are therefore very necessary. However, of the research on RA in general, and the rheumatoid foot in particular, very little effort has been devoted to investigation which takes cognisance of the biomechanical factors involved. This is especially true of the present research situation in South Africa as far as RA is concerned. These are the reasons why, in this study, I have endeavoured to look at the rheumatoid foot from a biomechanical perspective and to determine the relationships which exist between quantifiable and clinical parameters. By so doing, I hoped to proceed to the point where this study might form the basis for a more scientific and objective assessment of the foot and lower extremity in RA. Up to now clinicians have mainly used subjective methods to assess these aspects. Combining our increased knowledge of the biomechanics of the rheumatoid foot with the available clinical knowledge could afford the clinician the chance of understanding this perplexing disease more clearly. As a result of this new insight, clinicians might then be able to offer more effective treatment to their rheumatoid patients.

The Definitions

Form. The form is the shape of the foot; both the internal arrangement of the bones and the external shape of the plantar surface of the foot.

Function. The function of the foot is described by the forces that the foot experiences while on the ground during walking. The function of the lower extremity is described by the two-dimensional (2D) positions, in the sagittal plane, of the hip, knee, and ankle joints.

Lower extremity. The lower extremity is the leg from the hip down.

Rheumatoid patients. Rheumatoid patients were patients with definitive RA at the Princess Alice Orthopaedic Hospital (PAOH) in Retreat, Cape Town who had never had any surgery done to their feet.

Normal control subjects. These were persons in good health who were not suffering from RA or any affliction of their feet.

The Subproblems

The main problem -- stated as the purpose of this study -- was divided up into the following researchable subproblems:

- What is the form of the rheumatoid foot?
- What is the form of a normal, non-rheumatoid foot?
- What is the functional status of the rheumatoid foot and lower extremity?
- What is the functional status of a normal, non-rheumatoid foot and lower extremity?
- What will an analysis of the form and function of the

feet and lower extremities of a group of rheumatoid patients indicate when contrasted with the results of a control group of normal subjects?

The Hypotheses

The following hypotheses were posed to assist in guiding the direction of the investigation:

- The form of the rheumatoid foot is significantly different from that of a normal foot.
- From a biomechanical point of view the rheumatoid lower extremity, including the foot, functions significantly differently from that of a normal person.

The Assumptions

This study was conducted under the following assumptions:

- The group of rheumatoid patients selected at the Princess Alice Orthopaedic Hospital is reasonably representative of people suffering from RA.
- The control group of normal subjects is reasonably representative of normal people not suffering from RA and any affliction of the foot.
- Most of the relevant and important information on the external three-dimensional (3D) shape of the foot could be obtained by measuring the plantar surface of the foot.
- The joint centres at the hip, knee and ankle could be

located with the necessary accuracy.

- The influence of skin movement on the marker positions was neglible.
- The information contained in the 2D positions of hip, knee, and ankle markers moving in the sagittal plane, together with the pressures under the foot during stance adequately described the biomechanical function of the lower extremity.

The Delimitations

All the rheumatoid subjects were patients at the Princess Alice Orthopaedic Hospital.

The study did not take into account the effect that previous surgery to rheumatoid patients' hips and knees might have had on their gait pattern.

No serial monitoring was done i.e. all subjects were seen only once for each procedure.

The study did not look at muscle function of the lower extremity and the recording of electromyographic activity was therefore not included.

Organisation of this Study

In Chapter 2 I present a review of related literature on evaluation of the form and function of normal and rheumatoid feet.

In Chapter 3 I describe the sample, the experimental design and procedure, and the method of collection and analysis of data.

In Chapter 4 I present the processed results, comparisons between rheumatoid and normal people and interpretation of the results.

In Chapter 5 I bring together all the significant aspects in proper perspective by means of a summary. On the basis of this summary I state the conclusions I reached with respect to the problem . I also state whether the hypotheses have been supported or not and make some recommendations for further study.

CHAPTER 2

THE REVIEW OF RELATED LITERATURE

I shall discuss the literature, related to the topic of this thesis, by considering first the form of the rheumatoid foot. Second, I shall discuss the functional status of the rheumatoid foot and lower extremity.

The Form of the Rheumatoid Foot

The problem of studying the rheumatoid foot can be done in two parts (i) measuring the external shape of the foot, and (ii) assessing the internal structure of the foot. Going further, one might reflect on the relationship between the internal derangement of soft and hard tissues and the visible, external deformity of the rheumatoid foot.

First, I shall discuss literature related to measurement of the external shape of the foot.

According to Vidigal (1975) more than 50 per cent of patients with definite RA had pain or deformities in their feet. Sixty per cent of the patients required modified shoes. Realizing the severity of the deforming power of RA, Craxford et al (1981) noted that there was a continuing need for a simple yet quantitative method to evaluate the progress of RA in the foot by measuring its external shape. The results of surgery could also be compared with the pre-operative picture. They used expanded polyethylene foam (Plastazote) to record the imprints of

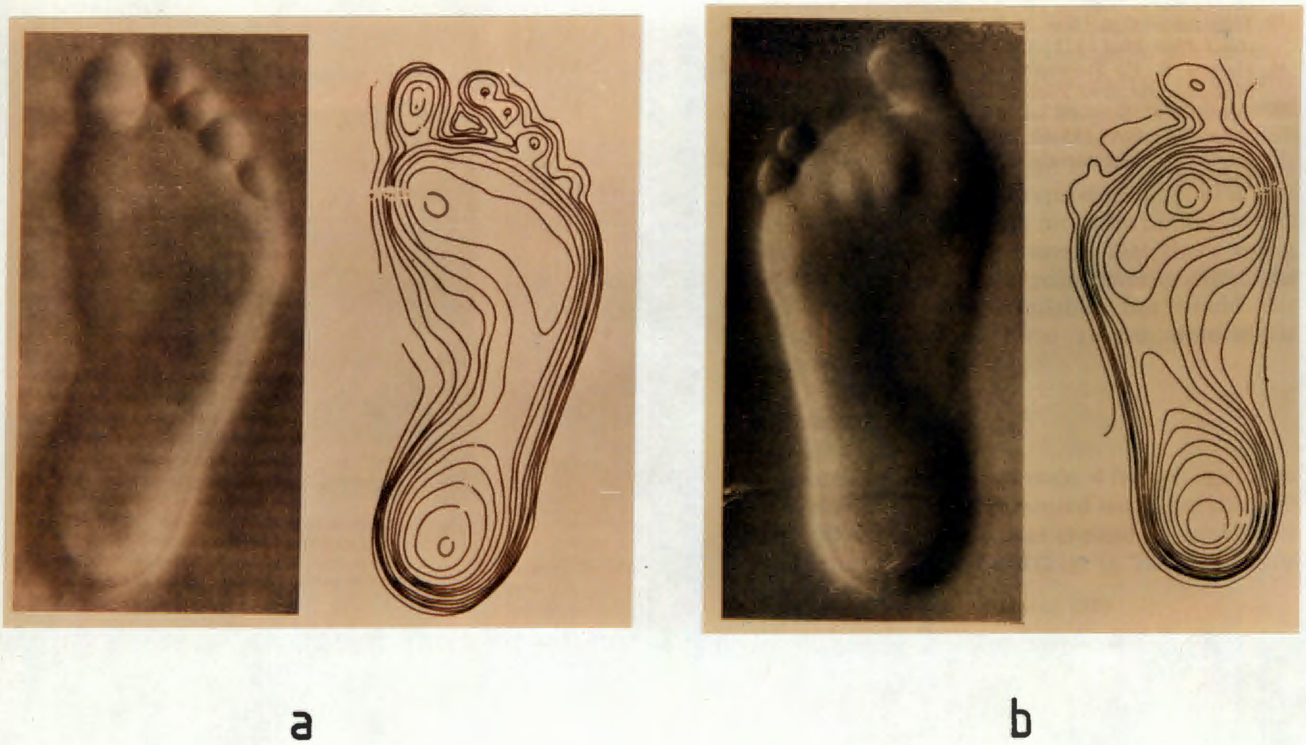


Fig. 1. Relief photograph and stereophotogrammetric plot of (a) a normal foot and (b) a rheumatoid foot with prolapsed metatarsal heads (Craxford et al, 1981).

subjects' feet. Relief photographs were then taken of the imprints and by means of stereophotogrammetry 3D plots and contour diagrams could be constructed of the feet (see Fig. 1). Stereophotogrammetry is the science of 3D analysis of photographs using stereoscopic methods and equipment. The combination of relief photography and stereophotogrammetry thus provided them with graphic and quantitative representations of the static foot in load. The authors felt that the ability to look at the sole of the weightbearing foot, in more than one way, was invaluable in the clinical management of foot deformities. Results of surgery could be reviewed and the natural history of the deforming foot illuminated by repeated examinations over a period of time.

Ghosh (1983) was in agreement with this line of thinking because he felt that the photogrammetric technique, with assistance from computer technology, was unmatched in solving many intricate measurement problems. According to him the technique offered distinct advantages in the medical field because of the non-contacting method of acquiring the data.

Whereas these two techniques relied on the taking of stereoscopic photographs and then measuring them, the Reflex Metrograph enabled Scott (1981) to take 3D measurements directly from small objects. The operation of the Reflex Metrograph was based on a principle which relied on the operator's depth perception The instrument and its operation will be discussed in detail in Chapter 3. This instrument is eminently capable of taking over from photogrammetry for a small but important group of measuring tasks. These tasks concern small objects which can be kept stationary for the period of measurement. This method of 3D measurement, using the Reflex Metrograph, was much quicker, more flexible and simpler to perform than conventional photogrammetry. Scott remarked :

> "The instrument is so 'transparent' in its principle and simplicity that it is possible to teach a novice to use it in no more than five minutes."

Although the use of the pedobarograph (Minns, 1982) to measure plantar pressures under the feet of a standing subject was really concerned with the functional status of the feet, Minns compared the results of the pedobarograph with those of two other systems, which were used to record the external shape of

Fig. 2. (a) Shutrak recording of a rheumatoid patient and (b) pedobarogram from the same patient (Minns, 1982). There is a clear similarity between high pressure areas on the Shutrak recording (dark areas) and the pedobarogram (white areas).

the feet. The Shutrak system (DHA Inc., 799 Bloomfield Ave., Verona, New Jersey 07044, USA) made use of carbon-paper to record standing foot prints. The other system required sheets of polyethylene foam (Plastazote) of 17 mm thickness to be heated up. Subjects then stepped onto the sheets and, while bearing full weight, created an imprint of each of their feet (cf. Craxford et al, 1982). From these impressions stereophotograms were constructed, which showed contours at 1 mm intervals (see Fig. 1). The pedobarogram and the Shutrak recording for the same foot were compared and showed a close similarity - in recording the shape of the foot as well as the pressures under the foot (see Fig. 2). The Plastazote impressions correlated well, both in shape and position, with the pedobarogram of that foot. It should be remembered that with the pedobarogram the foot was supported by a flat, unyielding surface, while with the Plastazote the surface was soft and yielding. Thus the deformation of the plantar surface and substructures occurred under different circumstances in each case. It was the opinion of Minns that these three devices could be used, either individually or combined, as crude diagnostic tools for investigating foot disorders.

I shall now discuss literature which is related mainly to the internal bony architecture of the foot. In this regard Larsen et al (1977) stated :

> "Radiography is of primary importance in the evaluation of chronic inflammatory conditions with joint manifestations, such as rheumatoid arthritis."

They developed a series of six radiographs for the joints in the body most commonly affected by RA. It started at grade 0 which was normal and ran through to grade V which represented mutilating abnormality with gross bone deformation (see Fig. 3). Larsen's group recognised that the system was a purely radiographical evaluation method for RA and that it could not be considered as a general measure of the severity of the disease. Clinical and functional evaluation were of equal importance for the total assessment of the joints. Many systems have been presented over the years for grading the severity of arthritis. Indeed, according to Sharp (1983) the variety of methods for

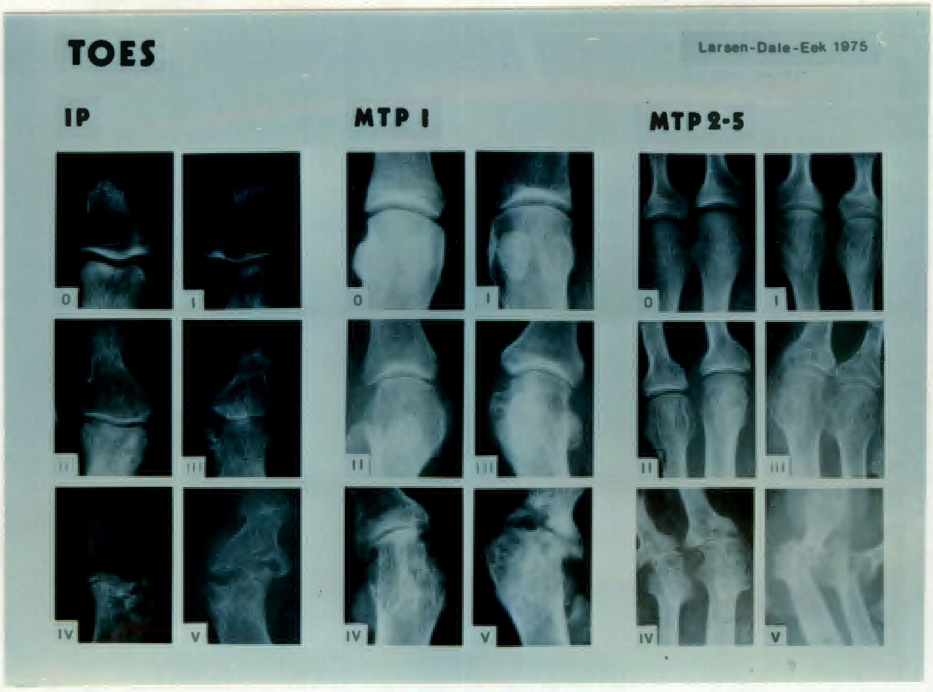


Fig. 3. Standard X-rays of articular deterioration in the foot (Larsen et al, 1977).

assessing outcome, emphasized the lack of agreement on what constituted an appropriate measurement. Researchers did not disagree on what constituted significant abnormalities but rather on how these abnormal changes should be quantified. However, Sharp felt that a case could be made for relating the extent of erosive lesions in the joints of the wrist and hand to the overall severity of the disease.

Apart from a clinical evaluation of joint space narrowing, erosions, osteoporosis and soft tissue swelling, X-rays can also be used to study the spatial relationships of bones, especially those in the foot.

Lequesne et al (1984) gave a number of angles which could be measured in the foot. According to the authors the magnitude of the lateral talometatarsal angle was normally 180° and therefore a straight line -- the so-called Meary-Tomeno line (see Fig. 4). The talometatarsal angle was the angle between the axis of the talus and the axis of the first metatarsal. An antero-posterior (AP) view of the foot revealed the varus angulation of the first metatarsal (normally 10°) and the angle between the first metatarsal and the proximal phalanx (also 10°). The angle between the proximal and distal phalanges of the big toe was normally 5° giving a total phalangeal valgus deflection of 15° (see Fig. 5).

Kirkup et al (1979) set the following limits which, if exceeded, indicated pathology in the forefoot :

- Angle between first and second metatarsals; more than 10° indicated metatarsus primus varus.
- Angle between first metatarsal and its proximal phalanx; more than 20° indicated significant hallux valgus.
- Angle between proximal and distal phalanges of the big toe; more than 5° indicated distal valgus.

Kirkup et al proposed that deformities of the forefoot could be determined by pathology in the joints of the hind- and midfoot. However, according to the authors it was still debatable whether metatarsal deviation initiated hallux valgus or followed it as a compensatory sequel to the subluxation of the proximal phalanx.

With regard to the question of the pathomechanics of deformities in the rheumatoid foot, Tillmann (1979) remarked :

> "... it can be said that the pathomorphology of the rheumatic foot is a combination of or rather an interchange between mechanical, congenital and

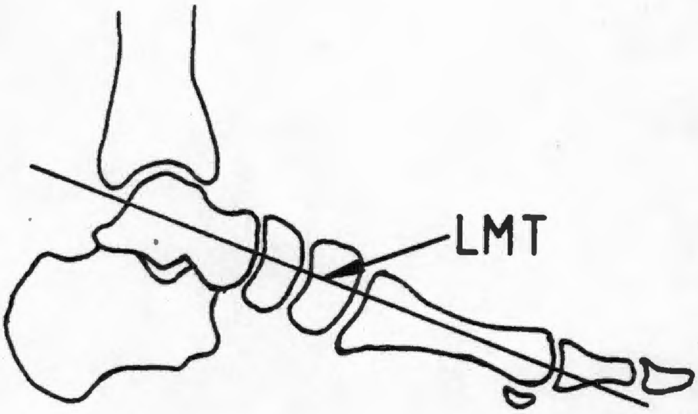


Fig. 4. Lateral X-ray of the weightbearing foot. LMT denotes the Meary-Tomeno line (after Lequesne et al, 1984).

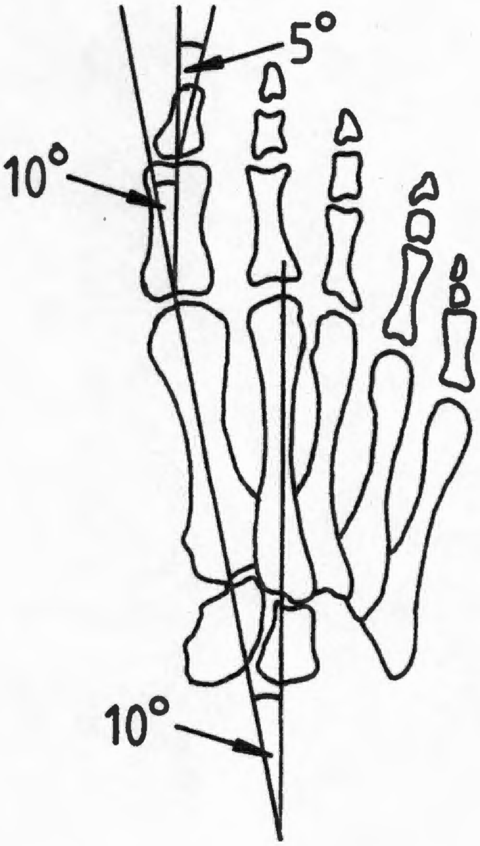


Fig. 5. Antero-posterior X-ray of the weightbearing foot with relevant angles (after Lequesne et al, 1984).

> interchange between mechanical, congenital and inflammatory factors. The first mentioned factor has importance in the direction of the deformity, the second on intermediate function, and the third a dominating importance regarding the degree of the deformities."

With specific reference to hindfoot deformities in RA, Tillmann (1979) stated that inflammatory changes in the tarsal joints were mainly responsible for the development of most common hindfoot deformities. Tillmann maintained that, although enigmatic, there was a definite causal relationship between the existence of tenosynovitis of the ankle joint and the occurrence of hindfoot deformities in RA. According to Tillmann it had not yet been proved satisfactorily that deformity of the hindfoot was solely the result of mechanical factors and not also of a disturbance to the innervation of the foot muscles. With regard to forefoot deformities, Tillmann stated quite categorically that they were dependent on deformity of the hindfoot, and that the most frequent deformity of the rheumatoid forefoot was hallux valgus. He suggested that a combination of inflammatory and mechanical factors were responsible for this deformity.

Vainio (1956) identified the elevation of the first metatarsal (a result of inflammatory changes) and its supination and medial deviation (a result of the flattening of the longitudinal arch) as instrumental in the development of hallux valgus. These three factors, together with inflammatory hindfoot changes, inflicted upon the rheumatoid foot a multitude of deforming forces. These forces had their origin in one or more of the following :

* the displacement of tendons causing bowstringing,

- the laxity of ligaments,
- destruction and rupture of tendons,
- displacement and subsequent abnormal dominance of certain muscles in the foot.

This view was supported by Pastershank (1981) who believed that midfoot dissociation, causing flat feet in RA, was due to lax or ruptured ligaments. According to him, the end result, as seen on X-ray, was usually a subluxed hindfoot.

With regard to the relationship between hindfoot and forefoot deformities, Dimonte and Light (1982) proposed that depression of the medial longitudinal arch and outward rotation of the calcaneus caused a valgus deformity of the heel during weightbearing. In agreement with Tillmann (1979) they felt that this instability in the hindfoot could subsequently lead to deformity in the forefoot, specifically to hallux valgus and depression of the metatarsal heads.

In addition, D'amico (1976) stated that severe hallux valgus in RA is directly due to the inflammatory disease process itself and only secondarily influenced by any pre-existing structural or positional deformities.

Having discussed the measurement of the external shape and of the internal structure of the rheumatoid foot, I want to reflect for a moment on the relationship between these two aspects of form. I shall mention the work of Reynolds et al (1982) even though they were not specifically interested in studying the foot. They used stereoradiography to record the 3D positions of internal skeletal landmarks. They then investigated the geometric relationships existing between these skeletal landmarks and external surface landmarks which were used in traditional anthropometry. Their aim was to construct a model eventually which would accurately describe the 3D kinematics of the lumbar/pelvic/femur linkage system.

The Functional Status of the Rheumatoid Foot

The review of literature related to the functional status of the rheumatoid foot will be divided into two sections. First, views on the kinematics of the foot and lower extremity -- rheumatoid and normal -- will be presented. For this thesis, kinematics involved the study of the movements of the feet and legs that were the results of forces acting on the feet. Second, literature relating to the kinetics of the foot will be reviewed. For this thesis, kinetics was defined as the branch of mechanics which was concerned with studying the forces that were acting on the feet and therefore generating motion.

Evaluation of the kinematics of normal and rheumatoid feet.

Kinematics for this study was divided into two areas of investigation i.e. calculating values for temporal and distance parameters of gait and determining the changing angles at the hip and knee joints. I shall therefore concentrate the discussion of related literature on these two broad areas. The techniques for collecting and processing the data as well as the clinical relevance of the processed information will be discussed.

McMahon (1984) maintained that there was no unique way to describe the motions of the legs during walking, but he felt that the description of gait given by Saunders et al (1953) was quite

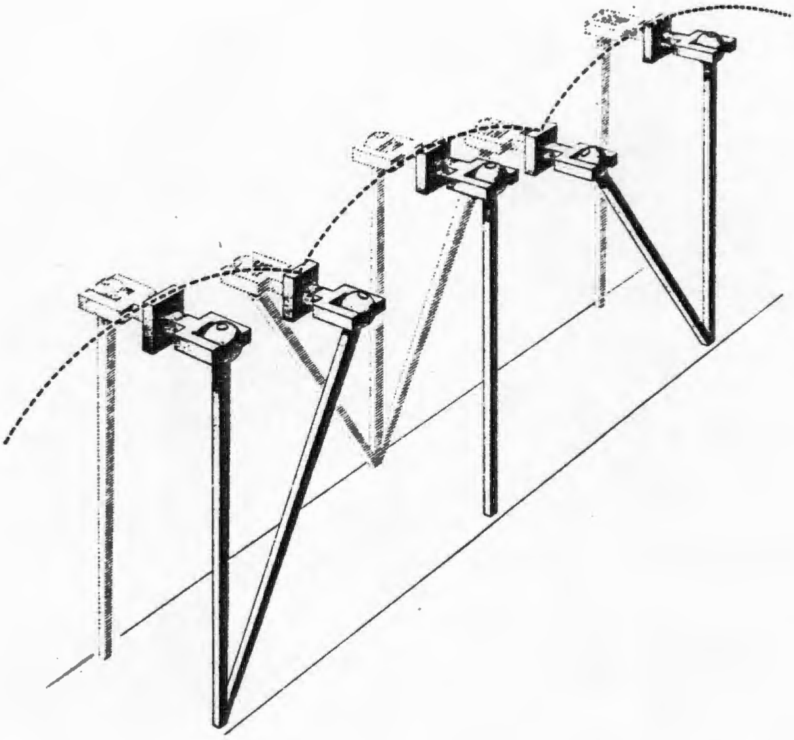


Fig. 6. Hypothetical "compass" gait (Saunders et al, 1953).

useful because of its simplicity and its completeness. In this description six determinants of normal gait were distinguished. Each of these determinants contributed towards the fundamental concept that locomotion is the translation of the body's centre of gravity through space along a pathway requiring the least expenditure of energy.

In a hypothetical "compass" gait, the legs were fixed in extension and articulated only at the hips. The pathway of the centre of gravity in forward translation would then be a series of intersecting arcs (see Fig. 6).

<u>First determinant</u> : Pelvic rotation

In normal level walking the pelvis rotated about a vertical axis. This had the effect of flattening the arc through which the

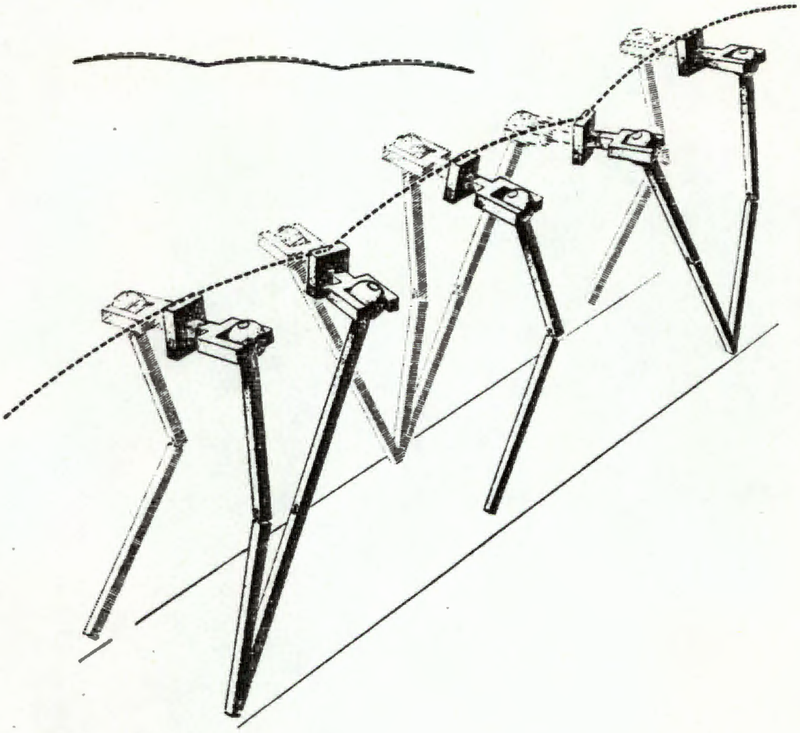


Fig. 7. Knee flexion coupled with pelvic rotation and pelvic tilt achieve minimal vertical displacement of the centre of gravity (Saunders et al, 1953).

centre of gravity passed in "compass" gait, thereby reducing the energy cost in locomotion (see Fig. 7).

Second determinant : Pelvic tilt

As the body rolled over the leg in stance the pelvis dropped on the opposite side, lowering the centre of gravity and flattening out the arc of its passage, and saving energy. To permit pelvic tilt, flexion at the knee joint of the swinging leg had to occur in order to allow ground clearance (see Fig. 7).

Third determinant : Knee flexion during stance

Knee flexion of the stance leg had the effect of flattening out the arc of the centre of gravity even more; thus saving energy because of the reduction in its vertical displacement (see Fig.7).

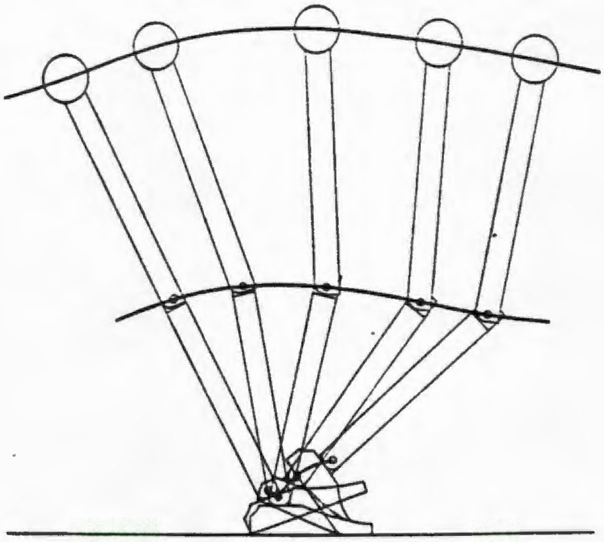


Fig. 8. Interaction of ankle and knee rotation smooth out the abrupt inflexions at the intersections of the arcs of the centre of gravity (Saunders et al, 1953).

<u>Fourth and fifth determinants</u> : Foot and knee mechanisms

The intimate relationship between the angular motions at the foot, ankle, and knee served to smooth out the pathway of the centre of gravity at the point of intersection of its arcs (see Fig. 8).

<u>Sixth determinant</u> : Lateral displacement of the pelvis

The centre of gravity was displaced laterally towards the weightbearing leg. Excessive lateral displacement was prevented by the influence of the tibiofemoral angle and adduction of the hip.

Saunders et al found that in pathological gait, the loss of one determinant could reasonably be compensated for by exaggeration of some of the unaffected determinants. However, loss of two or more deteminants made effective compensation impossible and the cost of locomotion in terms of energy increased three-fold when compared to normal walking.

Shifting our attention from the gait itself to the technique for acquiring data on gait, Van Best et al (1984) contended that during clinical gait analysis the motion of as many body segments as possible on both sides should be evaluated, because local dysfunction always influences the total pattern of gait. In addition, the person should be free to walk at his own cadence. Van Best et al found a distinct correlation between the clinical description of the gait and the measured parameters. They concluded that it was therefore possible to detect compensatory mechanisms -- mentioned by Saunders et al, (1953) -- in patients with local muscle insufficiency.

Grieve (1969) pointed out that gait should be analysed not only for aiding the diagnostic process where possible, but also to assess whether a person had a reduced ability to walk, and if so, whether a course of treatment produced a real restoration of function. Objective evaluation of gait would also permit the degree of restoration of function to be assessed.

With regard to the role of temporal and distance parameters in clinical gait analysis, Mann (1981) stated that speed of walking and steplength were the two most sensitive indicators of lower extremity pathology.

Hannah (1980) suggested that, next to speed of walking, asymmetry in the motion of the lower extremities could also be an important indicator of pathology.

Yack (1984) reminded clinicians that temporal and spatial variables e.g. speed, cadence, stride length were the end products of the movement pattern. These variables could not be used to make specific inferences relative to the movement pattern, as there existed no direct cause-and-effect relationship.

Andriacchi et al (1977) raised a very important issue when they showed the general dependence of kinematic and kinetic parameters on walking speed. This should be borne in mind by anyone attempting to classify gait abnormalities. One particular feature that was observed among all patients with diseased joints, was a slower than normal walking speed. The authors therefore cautioned :

> "... when quantitating gait abnormalities one should distinguish which variations from normal walking patterns are due to differences in walking speed and which are due to gait abnormalities."

For normal gait patterns both time of swing and time of support were observed to be inversely proportional to walking speed, while cadence and step length were observed to vary linearly with walking speed. Temporal parameters, especially time of swing, were found to be quite sensitive indicators of gait abnormalities in subjects with knee disabilities.

The influence of walking speed on gait parameters was confirmed by Simkin (1981). He found that all stride parameters such as speed, stride length, cadence, and support time were significantly different when comparing rheumatoid with normal subjects. However, he maintained that the gait patterns of the RA patients were not distorted and the changes were such as could be expected from normal persons walking at a reduced speed.

Not only are data on temporal and distance parameters collected during the kinematic part of gait analysis, but also

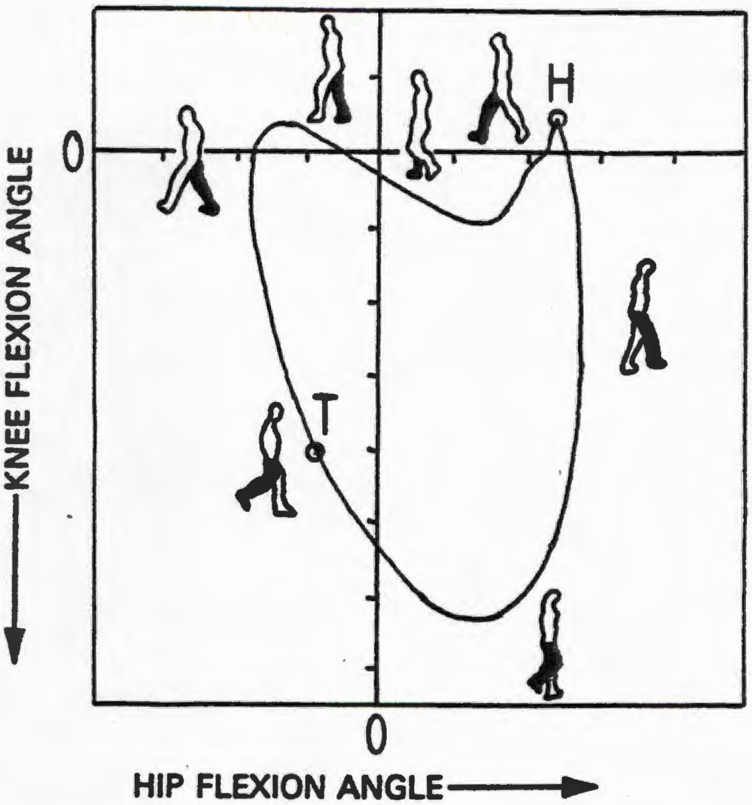


Fig. 9. Hip-knee angle-angle diagram for a normal subject walking at a moderate speed (Kolstad et al, 1982). The diagram reads anticlockwise from heelstrike H to toe-off T. Both axes are marked at 10° intervals.

data on angular displacement at the lower extremity joints.

Grieve (1968) proposed the presentation of angular data collected at two joints as a hip-knee angle-angle diagram. The angle of the thigh relative to the vertical was plotted on the X-axis and the knee angle of flexion on the Y-axis. This resulted in a repeatable loop diagram which was quite characteristic of all normal gait patterns (see Fig. 9). Grieve drew attention to the validity of his angle-angle diagram technique by noting :

> "... walking is a cyclic process and the continuity is emphasized by plotting the result as a cycle."

He also felt that angle-angle diagrams emphasized the

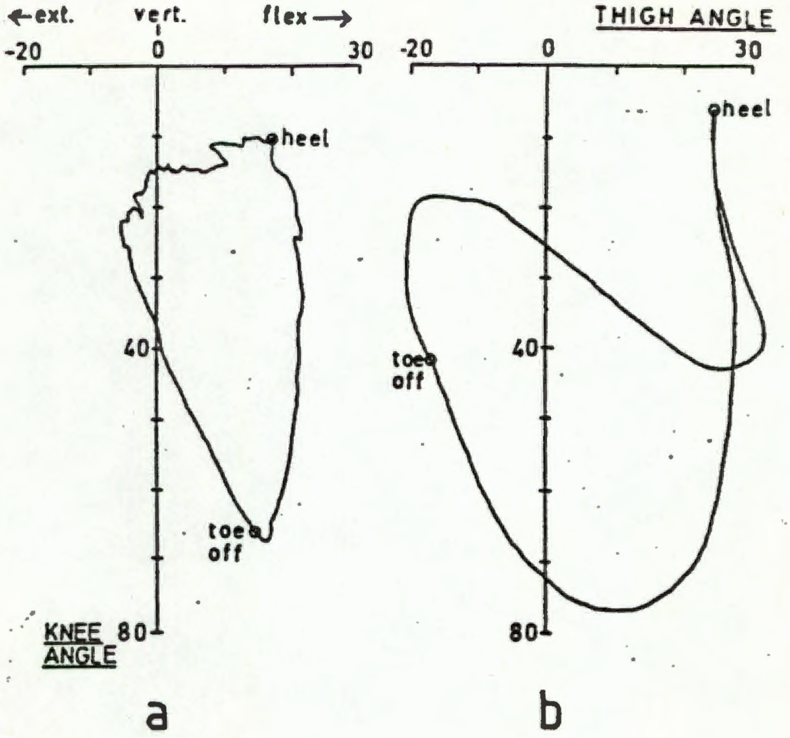


Fig. 10. Thigh-knee angle-angle diagrams for a person walking at (a) a slow and (b) a fast speed (Grieve, 1968). Read anticlockwise from heel to toe off.

relationships between angles at different joints more clearly than the conventional angle-time plots. In order to investigate the possible influence of walking speed on the appearance of angle-angle diagrams, Grieve constructed diagrams for normal subjects walking at speeds ranging from slow to fast. At slow speed, and with a short stride, the support phase was unstable because the knee had to bear weight while still slightly flexed (see Fig. 10a). At this speed, the knee motion contributed more to the stride than the hip motion. At fast speed the knee was fully extended when the heel struck the ground but flexed considerably just after heel strike to cushion the impact of the foot striking the ground (see Fig. 10b). In fast walking, the motion at the thigh contributed much more to the stride than was the case at slow speed. This showed that normal gait did not exist as a fixed pattern of movements. In fact, a normal person would exhibit a pattern under given circumstances which was only one of a whole series of possibilities within that person's range. Grieve maintained that angle-angle diagrams went some way toward presenting gait data in a clinically acceptable form. The technique also lent itself to standardisation so that normal and abnormal patterns could be recognised easily. Although Milner et al (1973) assessed the effects of surgery to patients with degenerative disease of their hips and knees, they felt that the method of representing angular data by means of pre- and post-operative angle-angle diagrams was clinically useful. According to them, a considerable amount of information was conveyed in a very simple way.

Following on the observations of Grieve (1968) in connection with walking speed, Charteris (1982) maintained that usually the gait of a patient was usually compared pre- and post-operatively, or after a period of rehabilitation, against a single loop made by a normal person walking at a typically unspecified, though usually slow to moderate, speed. In his paper, Charteris calculated the average angle-angle diagrams for three groups of young adults walking at controlled speeds representative of the range of normal human gait. To show the speed-dependence of these diagrams, one of each of the three groups had to walk at a slow (0.5 R.Sp.), medium (0.9 R.Sp.), and fast (1.3 R.Sp.) pace (see Fig. 11). Relative speed (R.Sp.) was calculated according to the equation R.Sp. = Velocity (m/s) / Stature (m). Thus a

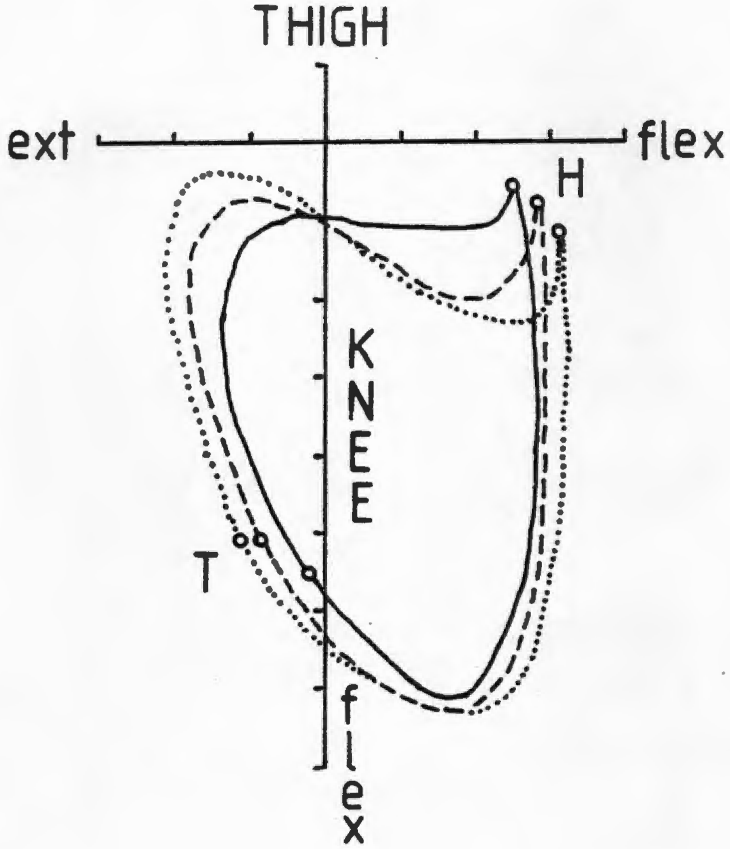


Fig. 11. Overlay of slow (——), medium (---), and fast (...) speed thigh-knee angle-angle diagrams (after Charteris, 1982). Both axes are marked at 10° intervals. Read diagram anticlockwise from heelstrike H to toe-off T.

person walking at 0.5 R.Sp. was covering 50 per cent of his stature in overground distance per second. It will be noted that the terms "hip" and "thigh" were used interchangeably by different researchers when referring to the angle measured at the hip joint; it being the angle of the thigh with respect to the vertical. Overlaying the slow, medium, and fast speed diagrams showed that the knee was influenced more by changes in speed than the hip, and that these changes occurred mainly during the support phase of gait. This was confirmation of Grieve's (1968) observations. Charteris stated that in some cases the thigh-knee angle-angle diagram seemed to provide a rather vague and inaccurate description of the pathomechanics of the walking foot. He suggested that other combinations such as ankle-knee and thigh-foot diagrams were perhaps more sensitive indicators of foot pathology. As was the case with the thigh-knee diagram, the latter two diagrams, where applicable, enhanced understanding of their respective link-segment interactions.

Hershler and Milner (1980) discussed the limitations of visual inspection of angle-angle diagrams. In addition, they proposed a number of key parameters which could be of value for interpreting the diagrams and making the data amenable to statistical analyses.

With regard to the visual inspection of angle-angle diagrams, Hershler and Milner noted the following :

- various gaits had easily recognisable loops;
- overall range of motion at the hip and knee could be appreciated readily;
- sequential loops rendered a visual impression of the repeatability of the gait.

Having discussed aspects of visual inspection of angle-angle diagrams, let us turn now to the key factors, which Hershler and Milner claimed to be representative of the overall properties of the angle-angle diagram. These were :

1. Area A, of a closed loop.
2. Perimeter P, of the boundary of a closed loop.
3. Dimensionless ratio $P_A = P/\sqrt{A}$; a description of the shape of the loop.

According to Hershler and Milner the area of an angle-angle diagram is representative of the total conjoint range of angular motion experienced at the hip and knee joints during one stride. By conjoint range was meant the mapping of all possible angle-angle points during one gait cycle. To contribute area to the angle-angle diagram, simultaneous rotations had to occur at the hip and knee joints. Changes in the angle at either joint also resulted in changing the perimeter of the diagram. If the angular variation at either joint was uncoordinated and therefore jerky, the perimeter would increase even if the area (conjoint range) stayed constant. The perimeter thus appeared to reflect the coordination or lack thereof between the movements of two joints during gait. The ratio P_A was suggested as a quantifier of the shape of the angle-angle diagram. A few well-known geometric shapes were examined and P_A plotted against the ratio of length/breadth (rectangle, parallelogram, rhombus and square) or major axis/minor axis (ellipse and circle) (see Fig. 12). From this it was clear that the absolute value of P_A did not always uniquely specify a particular geometric shape. However, it was clear that for any given ratio length/breadth a given value of P_A could be associated with a particular geometric shape. Hershler and Milner concluded that the ratio P_A had potential value in reflecting relative changes in shape, because each shape had a particular P_A value. The results in Hershler and Milner's paper showed that the shapes of angle-angle diagrams appeared to reflect control mechanisms inherent in the observed gaits and P_A was thus potentially a quantifier of the neuro-musculo-skeletal control of the lower extremity. If the ranges of motion at the

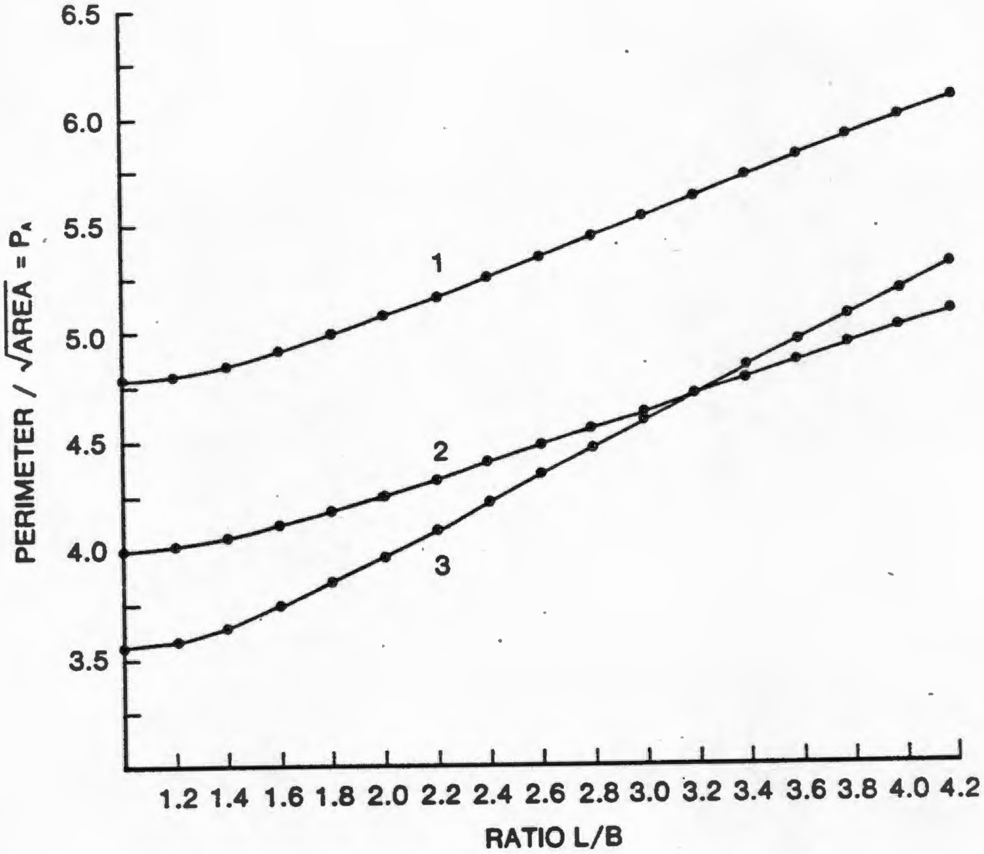


Fig. 12. Plot of P_A versus length/breadth (L/B) for (1) parallelograms (2) rectangles, and (3) ellipses (Hershler and Milner, 1980).

hip and knee stayed constant but the lower extremity movements were uncoordinated and jerky, P_A would tend to increase. If, on the other hand, the gait was robot-like with only one joint angle varying at a time, P_A would tend to decrease (see Fig. 13). It would appear that, in general, both area A and perimeter P had a remarkably close linear relationship to walking speed while the ratio P_A was essentially constant with walking speed. I fully agree with Hershler and Milner when they remarked that this type of quantitative analysis coupled with a visual inspection of the angle-angle diagram would assist in providing a more complete assessment of locomotor function.

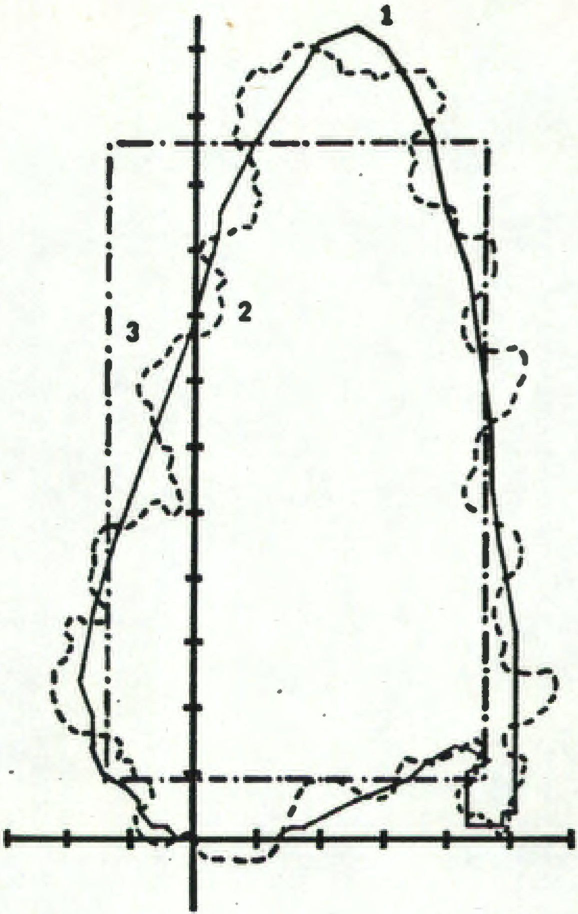


Fig. 13. Three superimposed angle-angle diagrams. (1) Normal (——), $P_A = 4.46$. (2) Jerky, uncoordinated motion (---) $P_A = 6.04$. (3) Hypothetical rectangle resulting from robot-like motion (-.-.), $P_A = 4.11$. In all instances area $A = 1452$ degrees^2 with only perimeter P varying (Hershler and Milner, 1980).

Although the case for techniques concerned with angular data, such as the angle-angle diagram, had been argued convincingly, Chao et al (1983) found that the most significant variables were obtained from temporal, spatial, and force plate data with angular displacement data low down on the list. From this they concluded that joint displacement data -- at least in normal subjects -- might be redundant.

Yack (1984) contended that two questions, which needed to be answered for general gait evaluation, were :

- Did joint displacement data relate better to the clinical and functional level of the patient than the more easily obtainable, temporal and spatial variables?
- What additional information was contained in joint displacement data obtained during functional activity?

In contrast to these two authors, Saleh and Murdoch (1985) stated that, at the very least, step length and step time as well as angular movements at the pelvis, hip, knee, and ankle should be observed during the gait cycle. This procedure would comply with the major determinants of gait as identified by Saunders et al (1953). Saleh and Murdoch recognized the ability of time and distance parameters to quantify pathological gait, and with it the value of being able to confirm a diagnosis. Analogous to Hershler and Milner (1980), but on a lower level of complexity, they concluded that visual observation alone was inadequate for the accurate assessment of gait. Quantitative measurement systems were absolutely necessary, especially where force measurements were required. Serial investigations, over a prolonged period of time, benefitted greatly from the objectivity that a quantitative system imparted. They therefore recommended that, for the very reasons of objectivity and reliability during gait evaluation, visual observation at least be combined with simple time-distance measurement and biomechanical analysis.

Turning for a moment to the rheumatoid foot in particular we shall first consider the views of Marshall et al (1980). They looked at the gait of rheumatoid patients with ankle and subtalar joint involvement. Here they identified two primary gait abnormalities i.e. a lack of plantar flexion as the heel struck the ground and a late heel rise during terminal stance. Movement at the hip, knee, and ankle was altered to compensate for the changes away from the normal (cf. Saunders et al, 1953). According to the authors their study showed that subtalar involvement in RA caused the kinematics of the gait of such rheumatoid patients to be substantially different from that of normal people.

Wright (1983), in a discussion of objective assessment in rheumatology, stressed the fact that the range of motion at the ankle and subtalar joints was quite limited, even for normal subjects. Just a small reduction, as a result of RA, in the range of motion at these joints could therefore have a substantial influence on the gait pattern as a whole.

Locke et al (1984) also documented the ankle and subtalar motion during gait in healthy and rheumatoid subjects. Plantar flexion during early and late stance was significantly decreased in the rheumatoids compared to the normals. The collapse into dorsi-flexion at heel strike and the weak push-off before the foot was lifted off the ground were attributed to weakened calf muscles. The patients also demonstrated lower gait velocities, which were thought to be correlated with the reduced plantar flexion. Metatarsal head pain would certainly have been a factor contributing to decreased plantar flexion, but the authors attempted to exclude patients with moderate to severe metatarsalgia. The authors regarded painful ankles and hindfeet together with instability of the subtalar joint, as the factors responsible for the reduced velocity and single limb support time in RA gait. The use of an extended ankle-foot orthosis to improve gait velocity and single limb support time demonstrated the quasi-diagnostic capabilities of dynamic range of motion data. This becomes clear when one considers that by using the orthosis the stability of the subtalar joint was improved and both the painful motion in the hindfoot and the tibial collapse, secondary to calf weakness, were prevented.

Gerber and Hunt (1985) discussed the importance of evaluation in the management of the rheumatoid foot. In addition to a clinical and a static examination they recommended that a dynamic gait evaluation should also be performed routinely. This should include a study of what is happening at the hip and knee joints and a dynamic evaluation of the foot. Parameters which could be measured are stridelength, cadence (stride frequency) speed of walking, time spent for each foot in swing and stance and time spent for double and single limb support. The authors suggested that a subject be viewed from the front, back and sides in order to identify frontal, transverse, and sagittal plane movements. They listed a number of characteristic abnormalities seen in the gait pattern of patients with RA : gait velocities were usually decreased with shorter stride lengths; shorter periods of single limb stance -- either due to instability caused by muscular weakness or to a painful foot -- and longer periods of double limb support. Prolonged heel contact which either resulted from metatarsal head pain, weakness or inappropriate electrical activity of the plantar flexors was commonly observed. Regardless of cause, the RA patient demonstrated a gait pattern that minimized transfer of weight to the forefoot, resulting in an apropulsive gait.

The theory that the rheumatoid foot should not be studied in isolation was confirmed by Kettelkamp et al (1972). They showed that in RA the overall range of motion at the knee was significantly reduced when compared to that of a normal person. However, they also found that people, suffering from foot involvement as well, typically had even less flexion-extension during stance and swing. This finding suggested to them that treating the rheumatoid foot might improve knee motion, which demonstrated the inter-relationship between the segments of the lower extremity.

Evaluation of the kinetics of rheumatoid and normal feet.

The dominant external force acting on the body during gait is the ground reaction force experienced by the foot during foot-ground contact. The conventional method whereby this force is measured utilizes some kind of force platform. This force platform usually consists of an independently supported plate utilising force transducers of some description; the whole system being incorporated in a walkway.

Helfet and Gruebel Lee (1980) noted that the effects of RA on the joints of the foot had been described in isolation . They felt that whereas in some cases it might be adequate to consider the foot alone, in the case of patients suffering from severe large joint polyarthritis, the complex patterns of deformity could be difficult to understand if these joints were viewed in isolation. The authors proposed that not only did erosion of cartilage, capsular fibrosis, and muscular atrophy play a role in the development of deformity but so did the habitual load and posture applied to the joints of that limb. In the foot of an ambulatory patient, in particular, the standing posture regulated the development pattern of deformity.

Cracchiolo (1983) stressed the importance of quantitating the biomechanics of gait i.e. for normal and pathological feet. He hoped that with a reliable assessment of gait, information could be obtained that would assist in clarifying the complicated foot pathology for which there is still no known aetiology and thus no causal treatment.

According to Yack (1984) it should be borne in mind that the ground reaction force at any moment in time is the algebraic summation of the mass-acceleration products of all fifteen recognizable body segments. Force plate data have been shown to be less sensitive to changes in the clinical status of the patient's locomotor system than temporal and spatial variables (cf. Andriacchi et al, 1977). Yack also felt that force plate data alone had limited value in the assessment of human movement. A complete kinematic analysis was also necessary in order to perform an accurate kinetic analysis in which the time histories of joint reaction forces and moments were determined. Moment analysis involved the determination of net forces, which caused a movement, and defining these forces in terms of the moments acting at each joint. Using a link-segment model, a time history of the moments at each joint could be constructed. Not only could deviations in the movement pattern at a pathological joint be described through such an analysis but also compensatory changes at other joints (cf. Saunders et al, 1953). The information in moment analysis was related to the causes of the movement disorder i.e. the malfunctioning of specific muscle groups. Yack believed that such information could be invaluable in diagnosing the movement disorder and in formulating a treatment approach.

Rose (1983) agreed that the force plate alone had only a modest value in the clinical field, because in spite of considerable variations in gait, the compensatory capacity of the body might cause very similar results to be produced. To be clinically useful, force plate data should be combined with kinematic, electromyographic or X-ray data (cf. Saleh and Murdoch, 1985). However, Rose maintained that force plate data was useful for objective monitoring of gait performance, creating an improved understanding of the requirements of treatment and the evaluation thereof. A further benefit was that patients, having had gait analysis and having seen the results, were reassured about the proposed treatment.

Three different force plates, each measuring the vertical component of the ground reaction force, will now be discussed. In each case an example will also be given of the research which has been done on the clinical application of the force data. No attempt will be made to compare the force plates with regard to performance, accuracy, or any other technical parameter.

Arcan and Brull (1976) developed a force plate by which local forces were measured simultaneously across the entire contact area and the shape of the contact area was determined immediately. The force plate had the great advantage of giving quantitative data on the pressure distribution. According to them the centre of gravity location was not a good indicator of stance or gait characteristics. Instead, they defined some parameters which were more sensitive to changes in load distribution. These were the ratios of the load on the forefoot midfoot, and heel to the total load that the foot experienced. Arcan and Brull felt that in order to evaluate quantitatively, for example the degree of "flatfootedness", it was not enough to know only the geometry of the contact surface, as in podography. What was also needed was the pressure distribution on the midfoot and the ratio of midfoot load to total load.

Simkin (1981) measured the dynamic vertical force distribution during gait under rheumatoid and normal feet, using the "Footprint" instrument developed by Arcan and Brull (1976). The graphical display consisted of a frame of each subject's feet. On to this was superimposed either the force distribution (see Fig. 14) or the pathway of the centre of pressure (see Fig. 15). A force-time curve for the total load on the foot could be calculated and drawn (see Fig. 16). The patients all had definite RA, but no marked limitation or pain at their knee or hip joints which could dominate their foot problems. The subjects walked barefoot at their normal walking speed. The impulse impulse imposed on the heel was significantly increased in RA patients with painful feet, indicating an attempt to delay loading of the painful forefoot. During single limb support the load on the forefoot could be reduced by accelerating the

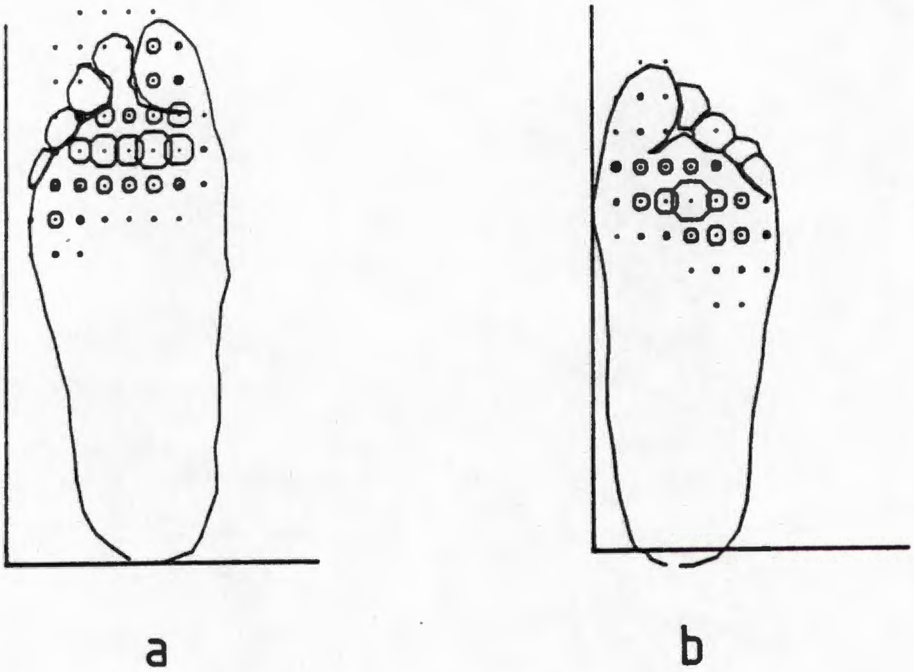


Fig. 14. Force distribution at heelrise under (a) a normal foot and (b) a rheumatoid foot. The diameter of a circle indicates the relative force at that point (Simkin, 1981).

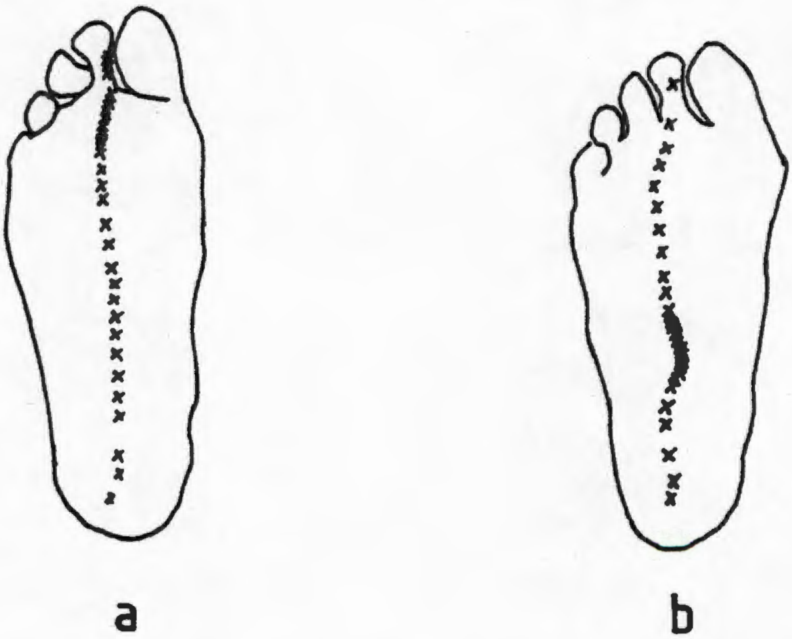


Fig. 15. Traces of the centre of pressure under (a) a normal foot and (b) a rheumatoid foot. Each cross represents 1 frame of cine film at 48 frames/s. Note the clustering under the midfoot in the case of the rheumatoid patient (Simkin, 1981).

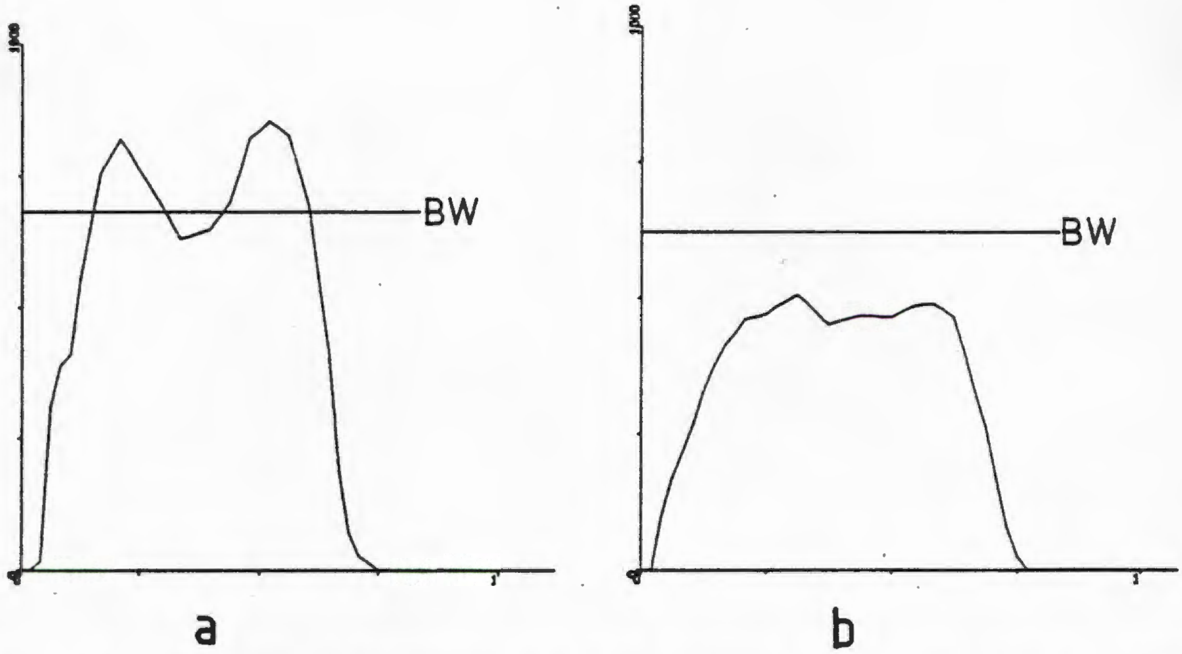


Fig. 16. Curves representing the ground reaction force during stance as a function of time under (a) a normal foot and (b) a rheumatoid foot. Horizontal axis : seconds. Vertical axis : newtons. BW : bodyweight (Simkin, 1981).

swinging foot to its heel strike or by prolonging the midstance phase. RA patients chose the latter solution as is borne out by the shape of the locus of the centre of pressure (see Fig. 15). According to Simkin there was a much larger reduction for all RA patients in the force and impulse under the toes than could be explained by the reduction in walking speed. He felt that this, which was evidently caused by the elevation of the clawed toes, was an early sign of RA in the foot, appearing when clawing was hardly noticeable. Simkin argued that the force concentration factor (peak load / average load) seemed to be a better indicator of the local stresses under the metatarsal heads than the local forces and impulses. High force concentrations were also related to pain. Thus pain could be a trigger to some of the changes seen in the rheumatoid foot because, unlike diabetic or leprotic patients, rheumatoids did not usually suffer sensory neuropathy and their pain threshold remained virtually normal.

Dhanendran et al (1979) built a force platform system with high frequency response and good spatial resolution. It utilized 128 load cells -- each having its own amplifier -- which were arranged in a matrix of 16 x 8. The whole force platform measured 25 cm x 12.5 cm. My comment on the size of the platform is that it would need quite a bit of effort on the part of the patient and analyst to get a decent, representative recording as the platform is scarcely larger than the average adult foot (see Fig. 17). The platform also enabled the operator to obtain the total force waveform, distribution of load under the foot, and the pathway of the centre of pressure during stance. The foot was divided into 8 areas of interest (see Fig. 18). Each of these areas in pathological feet could be compared with the corresponding area of a normal foot, using the force-time plot for that particular area (see Fig. 19). Patient-time required for the procedure was about 15 minutes and another 15 minutes for processing and displaying the results. The authors felt that the system measured the force distribution under the foot quickly and accurately.

Sharma et al (1979), in using the force plate described by Dhanendran et al (1979) , had rheumatoid and normal subjects walking at their normal speed. The peak forces -- as a percentage of body weight -- under the hallux and the lesser toes was reduced significantly in rheumatoid patients. There were no

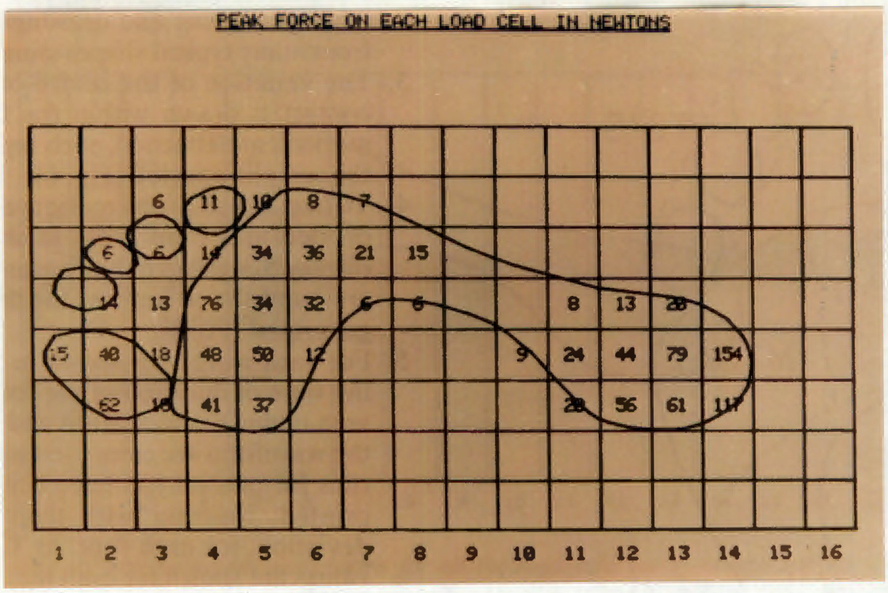


Fig. 17. The outline of the load cells and a normal foot drawn to scale as well as the peak forces experienced by each load cell (Dhanendran et al, 1979).

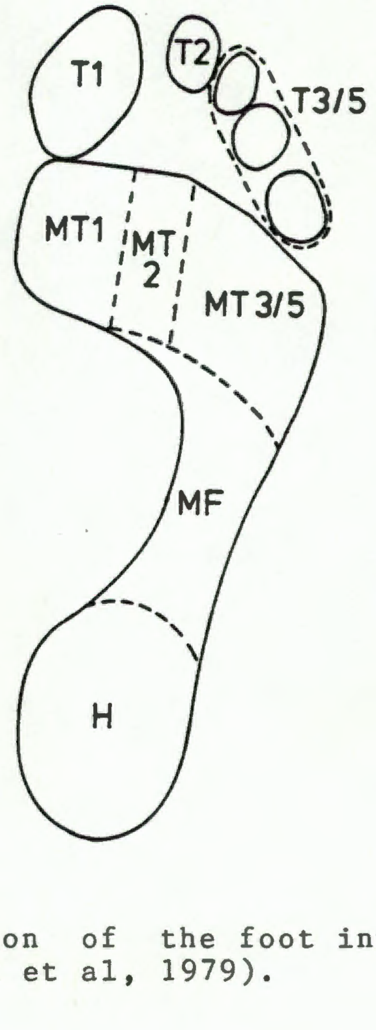


Fig. 18. The division of the foot into 8 areas of interest (Dhanendran et al, 1979).

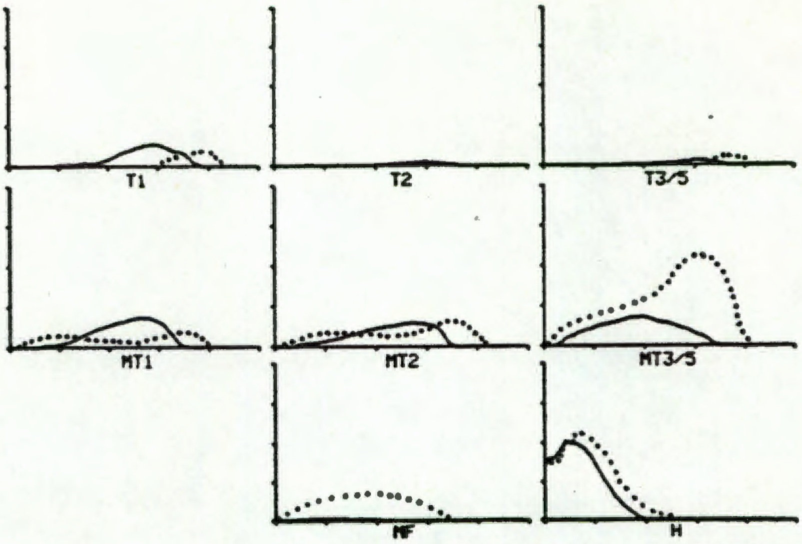


Fig. 19. Force-time waveforms for the 8 areas under a normal foot (——) and a patient with hallux valgus (....) (Dhanendran et al, 1979). Scale intervals: vertical - 200 N, horizontal - 0.15 s.

significant differences between rheumatoid and normals in the loading of the metatarsal heads, the mid- or hindfoot. There was a lateral shift in loading at the metatarsal heads. However, the authors felt that this could not be described satisfactorily by the presence of pain alone. The authors could not offer a definite explanation for the increased load on the lateral metatarsal heads. However, they did suggest that an attempt to redirect the loading back on to the structurally stronger medial forefoot, might be of benefit to the patient. To some extent this had been done with rigid insoles. Sharma et al expressed the need for more research on whether insoles really modified the pattern of loading in the foot, and whether insoles which were designed to alter the gait pattern to one nearer normal, were actually beneficial to the patient's comfort and gait.

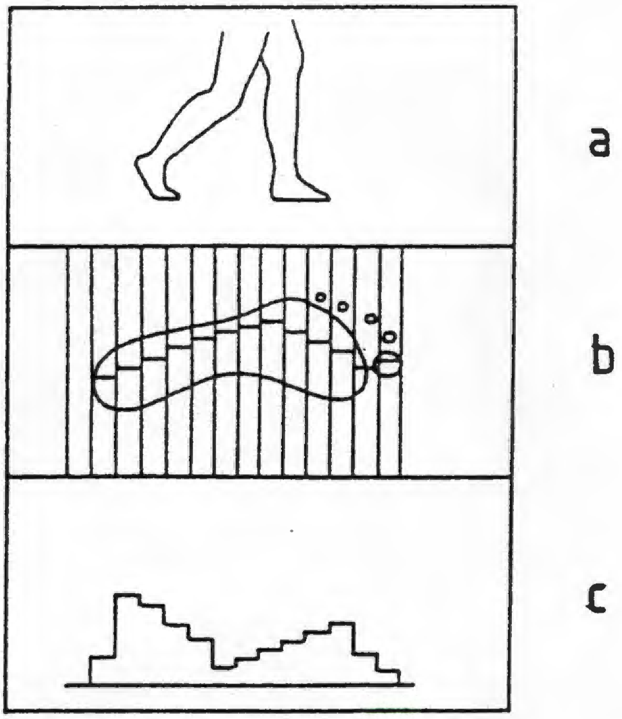


Fig. 20. Schematic representation of a single video picture during stance consisting of (a) a lateral view, (b) a plantar image of the foot, and (c) a bar chart of forces (Manley and Solomon, 1979).

Manley and Solomon, 1979 constructed a force plate which combined visually recorded data with the instantaneous forces that the foot experienced during stance. It was eminently suitable for studying the biomechanics of the foot as it was able to record the small and subtle movements of the foot during stance. A central controller and processor generated a composite three-tiered video picture based on simultaneous data coming from two video cameras and the force plate itself. The picture showed (i) a lateral view of the legs of the subject, (ii) a plantar image of the weightbearing foot with the centre of pressure line of each beam superimposed, and (iii) a dynamic bar chart display of the load carried by each beam at that moment (see Fig. 20). It was therefore possible to see at a glance not only the magnitude of the load carried by different sections of the foot, but also the pattern of loading applied to the plantar surface. Manley and Solomon believed that their technique of displaying the foot and its applied loads would facilitate a fuller understanding of this hitherto ignored component of the locomotor system.

Dall (1984), in using the system developed by Manley and Solomon (1979) commented favourably on the ease with which the results of dynamic pressure assessment could be interpreted clinically. He attributed this to the fact that the flow pattern of the stance phase could be readily visualized. The fact also that subtle variations in the relative smoothness of this flow pattern could be identified, was of inestimable value in the analysis of total foot function. This allowed useful clinical application of the method such as monitoring the effects of adjusting orthotic devices and assessing the results of operative procedures.

It is also possible to analyse the output from a force plate by employing mathematical techniques. Using one such a technique -- Fourier analysis -- Schneider and Chao (1983) showed that there were significant differences between the gait of patients with knee joint pathology and that of normal healthy people. However, Vaughan et al (1985) found similar differences between the gaits of normal people walking at specified speeds i.e. slow, moderate, and fast. They concluded that the differences in Schneider and Chao's study could have been due to knee joint pathology or walking speed or both. Thereby they confirmed the notion that walking speed is indeed an important parameter that should not be overlooked when studying normal and pathological gait.

CHAPTER 3

METHODOLOGY

Subjects

Fifteen RA patients (13 women and 2 men) and 6 healthy control subjects (5 women and 1 man) participated in the study. The patients were people with definitive RA who had never had surgery to their feet before. The control subjects were people who had never before suffered from RA and/or any foot trouble. The ages of the RA patients ranged from 26 to 75 years with a mean of 58.2 +- 13.3, while the ages of the control subjects ranged from 46 to 58 years with a mean of 52.5 +- 4.1. The average mass and height of the RA patients were 64.4 +- 10.9 kg and 1.60 +- 0.06 m respectively and that of the control subjects 72.0 +- 9.2 kg and 1.60 +- 0.05 m.

Instrumentation and Procedures

The evaluation of the form of rheumatoid and normal feet consisted of measuring the external shape of the plantar surface of the foot using plaster of Paris footcasts and iodine footprints and assessing the internal bony architecture by means of X-rays.

Evaluation of form : footcasts. A special type of casting sand -- Petrobond -- which is used in foundries, was employed to take the imprints of subjects' feet. The sand was contained in a

Fig. 21. Subject standing in sand-filled casting frame.

rectangular aluminium frame 30 cm x 15 cm that was big enough to accept one foot at a time (see Fig. 21). There were two of these frames so that, when standing in the casting sand, each foot bore the normal amount of weight. The height of the frames were 5 cm and both were normally filled to the brim, ensuring some measure of standardisation. The sand was sifted beforehand to prevent the formation of lumps which could have a detrimental effect on the imprint of a subject's foot. Talcum powder was added to the sand to ensure an even more uniform consistency after sifting. Plaster of Paris powder was used to make up a liquid solution, which was then poured into the imprints and left to harden. When the casts were firm enough to be handled safely, they were removed from the sand. A grid of lines was drawn on the plantar surface (see Fig. 22). This grid facilitated the process considerably when digitising the plantar surface of the foot,

Fig. 22. Plaster of Paris casts of a normal and a rheumatoid foot with grid lines drawn on the plantar surface to facilitate digitising.

using an instrument, which is housed at the University of Cape Town's Department of Surveying, called the Reflex Metrograph (see Fig. 23). The Metrograph is very useful for taking 3D measurements directly off small objects (less than 30 cm x 15 cm). The instrument makes use of a special bi-layered half-silvered mirror to create an image of the object on the other side of the mirror (see Fig. 24). A fine pinpoint of light is connected to 3 potentiometers which record the 3D coordinates of any point in space. The pinpoint of light can be placed on the surface of the perceived image of the object and, by moving the light around, the whole surface can be measured without interference from the real object. For this study the grid of lines, previously drawn, ensured that the whole surface was covered uniformly during the digitising process. A BASIC program

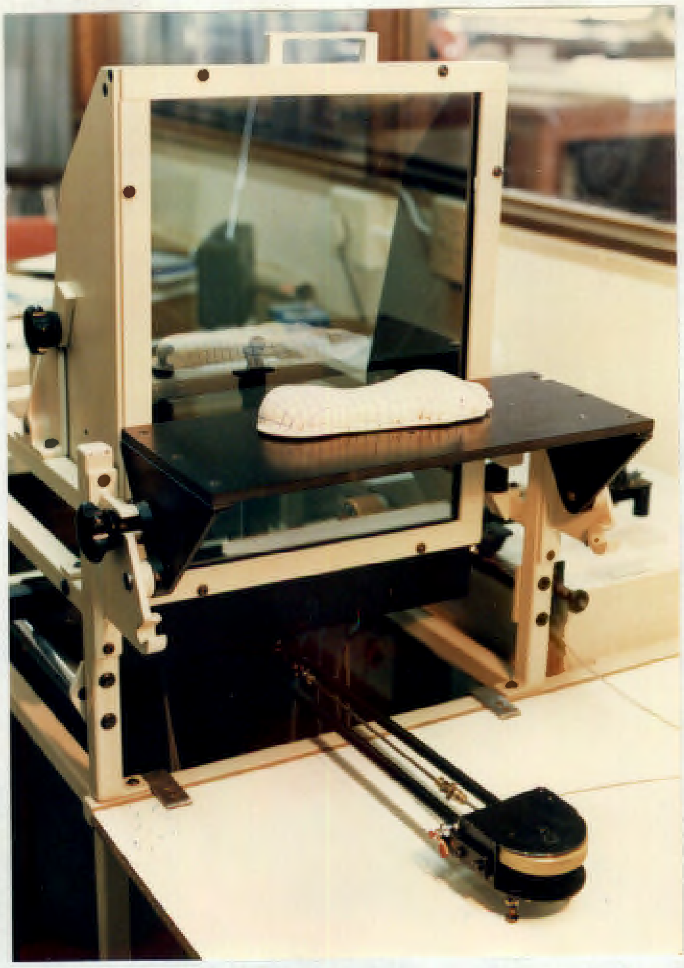


Fig. 23. The Reflex Metrograph.

Fig. 24. A footcast on the digitising table of the Reflex Metrograph. Note the mirror image that will be used to actually digitise the cast.

(see Appendix C) permitted the acquisition of the data using a Tektronix 4051 intelligent terminal. A print-out of the raw values of the 3D coordinates was obtained before sending the data to the mainframe computer of the University of Cape Town. Once there, the data was processed in order to produce 3D plots and contour diagrams of the individual footcasts (for mainframe runstream see Appendix C). The contour diagrams consisted of contour lines drawn at 1 mm intervals. A straight line was constructed from the high point on the heel to the high point on the head of the first metatarsal (see Fig. 25a). The vertical distances shown on the profile drawing of section XX' (see Fig. 25b) are representative of the following points on the contour diagram :

H -- the highest point at the heel,

T -- the highest point at the site of the first metatarsal head,

A -- the lowest contour crossed by the section along XX'.

A simple formula was devised to express the degree of flatfootedness by means of an index, using these heights. This index was representative of the height of the arch of the foot with respect to average height of the heel and the first metatarsal head.

$$\text{Contour index} = [(H-A)+(T-A)]/2$$
$$= (H+T)/2 - A$$

Consequently, a high value would indicate a normal or even cavus foot whereas a low value would be indicative of some degree of flatfootedness.

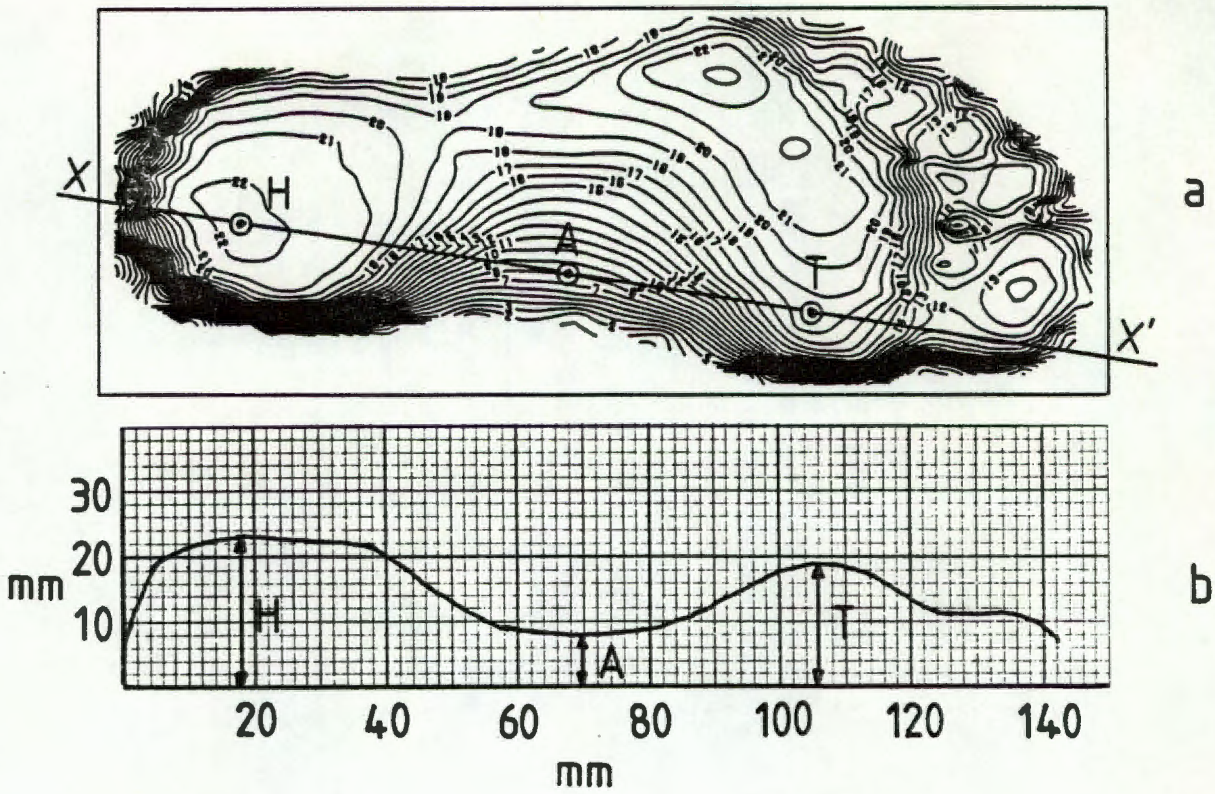


Fig. 25. (a) Contour diagram of a footcast with a section along XX' and (b) the profile drawing of the section along XX'. H - height of heel, A - height of arch, and T - height of first metatarsal head.

<u>Evaluation of form : footprints.</u> Prints of the underside of subjects' feet were made by wetting the plantar surface with Povidone iodine and having the subjects stand on clean sheets of paper. Certain measurements were taken off these prints (see Fig. 26). These were :

- the distance, length-wise, from the edge of the heelpad to the edge of the metatarsal pad -- called the heelpad distance (HP);
- the distance across the middle of the foot where the waist was at its narrowest -- called the narrowest

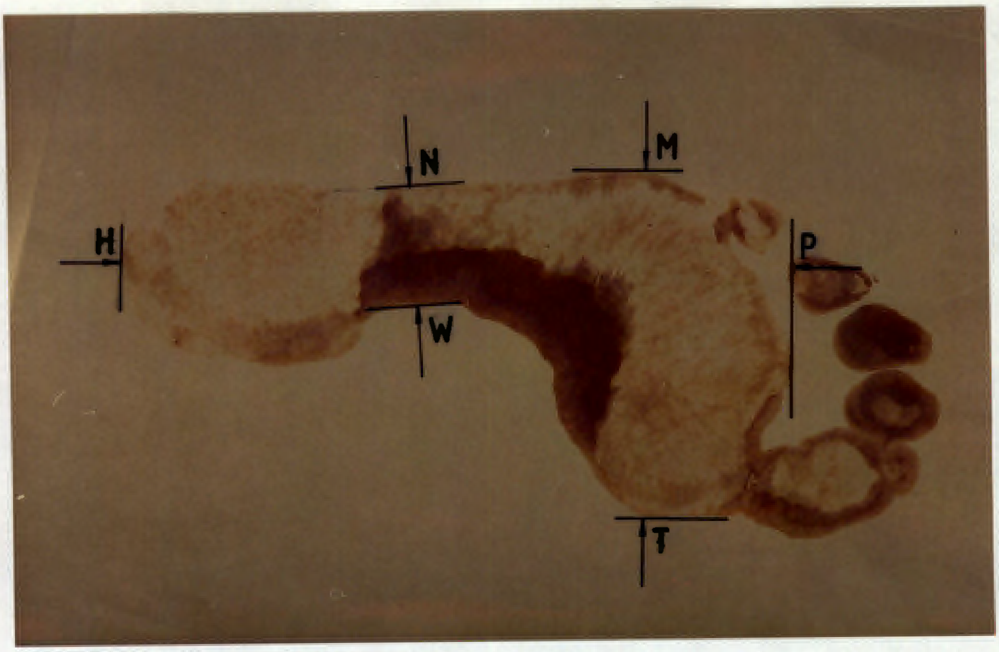


Fig. 26. Iodine footprint. HP - heelpad distance, MT - metatarsal width, and NW - narrowest waist distance.

waist distance (NW) (this applied to normal and cavus feet; in case of some severe flatfeet the waist could actually be broader than the hindfoot, the distance was then measured halfway between the heel and the metatarsal pad);

* the width of the metatarsal heads pad -- called the metatarsal width (MT) (Lequesne et al, 1984).

The ratio of the narrowest waist distance to heelpad distance (NW/HP) was defined as an index of flatfootedness and called the flatfootedness ratio (FFR). If, according to this index, a foot had a higher than normal FFR, that would be indicative of some degree of flatfootedness.

Lequesne et al (1984) formulated yet another index for quantifying the degree of flatfootedness i.e. the ratio of narrowest waist distance to metatarsal width (NW/MT). They proposed a value of approximately 0.33 for a typical normal foot. Thus a foot having a higher Lequesne index than this normal value would be classified as possessing some degree of flatfootedness.

Evaluation of form : X-rays. Subjects' feet were X-rayed from a number of perspective angles. This was done to consider the disease process in the foot from a clinical as well as a biomechanical point of view. Both weightbearing and non-weightbearing X-rays were taken. For the non-weightbearing pictures the joints of the foot were manipulated passively to establish their range of motion (ROM). However, from a functional point of view the weightbearing pictures were more relevant to this study, especially the lateral and antero-posterior views of the foot. On the lateral view the angle of interest was that between a line through the body of the talus and a line along the superior margin of the first metatarsal -- called the talometatarsal angle (see Fig. 27). The antero-posterior view presented me with two angles of interest. First, the angle between the first and second metatarsals -- called the metatarsal 1,2 angle -- and second, the angle of valgus deflection between the first metatarsal and its proximal phalanx -- the so-called hallux valgus angle (see Fig. 28). On the the lateral view it was also possible to assess the amount of damage done by the disease to the subtalar and talonavicular joints. The antero-posterior view also provided information on the damage done by the disease to the metatarsophalangeal and interphalangeal joints.

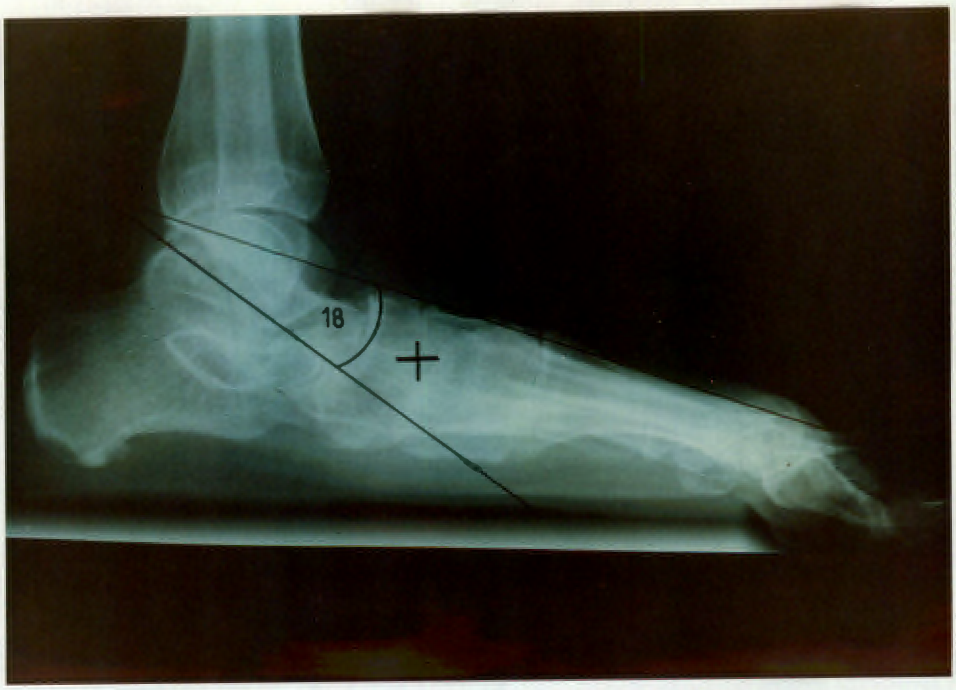


Fig. 27. Positive talometatarsal angle measured in a rheumatoid foot.

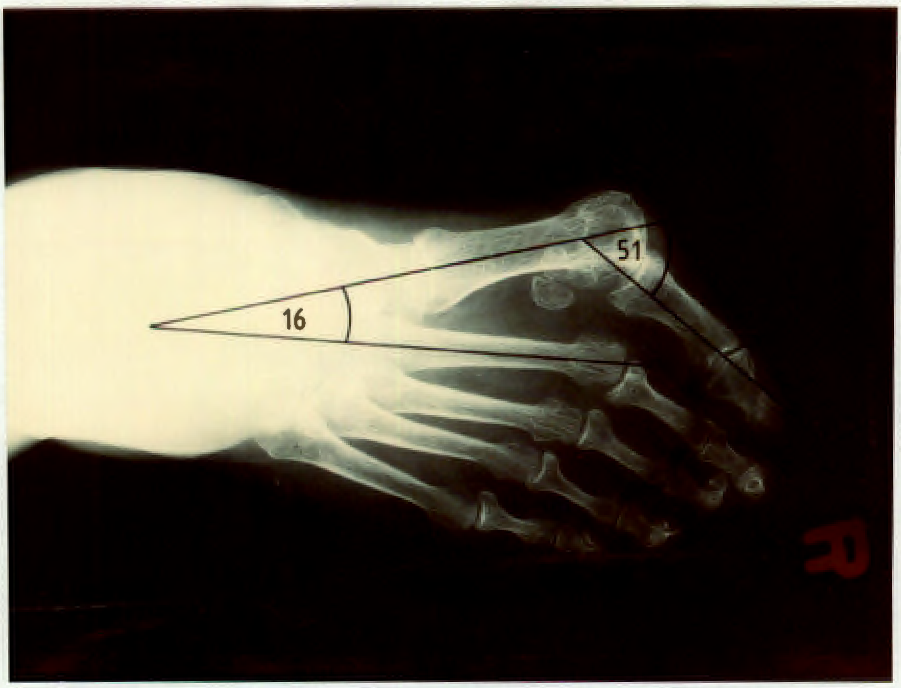


Fig. 28. Significantly increased metatarsal 1,2 and hallux valgus angles in a rheumatoid foot.

The functional status of rheumatoid and normal control subjects during walking was evaluated by concentrating on the kinematic and kinetic aspects of the foot and lower extremity. A digital camera system was used to evaluate parameters pertaining to the kinematic function of the foot and lower extremity in RA patients and normal control subjects. The force plate system at PAOH enabled me to assess kinetic aspects of the foot function.

Evaluation of function : digital camera. This system utilises the commerciably available Microneye camera (Micron Technology, Division Systems Group, 2805 East Colombia Rd., Boise, Idaho 83706, USA), which has as its operative part a dynamic random access memory (RAM) chip (see Fig. 29). This memory chip is sensitive to light, especially that coming to it from special retro-reflective markers. These markers are special in the sense that they only reflect light directly back to the source i.e. where the light was coming from originally. The markers were made up by covering ordinary table tennis balls with the retro-reflective material and sticking them onto small aluminium disks (see Fig. 30), which facilitated the attachment of the markers to the subjects' legs by means of double-sided tape. Because of the special reflective properties of the markers it meant that filming of the subjects could take place in normal ambient lighting conditions, provided that direct sunlight was shut out. The digital camera was situated between an array of three 150 watt light bulbs which provided the necessary illumination of the markers. The camera, with its array of lights, was mounted on a custom-built trolley and directly linked

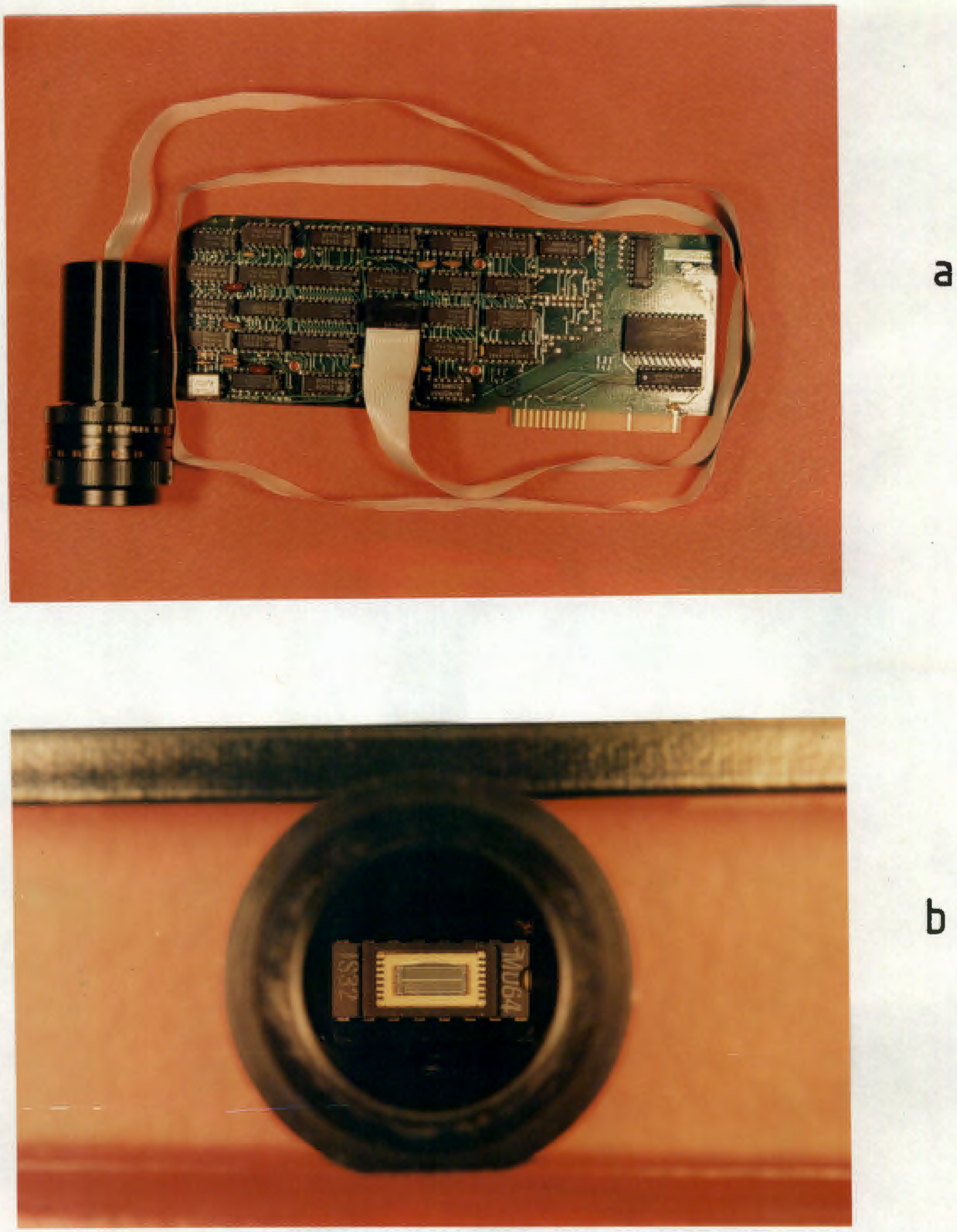


Fig. 29. (a) The Microneye digital camera with its computer interface and (b) the optic RAM chip within the barrel of the camera.

Fig. 30. Retro-reflective markers for use with digital camera.

to an Apple-compatible microcomputer also on the trolley (see Fig. 31). During filming, digital data on the 2D positions of the retro-reflective markers were sent from the camera to the microcomputer. Assembler and BASIC programs (see Appendix D) enabled me to collect the data, process it, and display the information on the screen or have it printed out. The specifications of the system are as follows :

- * a maximum of five (5) markers are allowed; however, I used only three i.e. one marker each at the hip, knee, and ankle joints on the lateral aspect of the left and the right leg. The subject was filmed in the sagittal plane, while walking from left to right and back (see Fig. 32);
- * scaled X, Y coordinates of the markers were ready to be displayed within 20 seconds of collecting the data;

Fig. 31. Custom-built trolley with microcomputer and array of three lights.

- the sampling frequency was 13 frames per second, while the memory of the computer had sufficient storage space for the data from 40 frames (about 3 seconds of recording time);
- as a result of the peculiar aspect ratio of the camera the field of view at a camera-to-subject distance of 10 m was approximately 5 m x 1.2 m;
- the accuracy with which a marker of 30 mm diameter could be located was better than 10 mm and the resolution was of the same order.

Fig. 32. Subject with reflective markers at the hip, knee, and ankle joints being filmed in the sagittal plane.

The results were calculated from data displayed in a number of different ways. The raw data were represented by plots of the 2D positions of the hip, knee, and ankle markers as a function of the distance walked while in the viewing field of the camera (see Fig. 33). From these raw data, stick figures were constructed by merely connecting up the coordinates of the hip, knee, and ankle markers which appeared in each frame (see Fig. 34). This was done by means of a special routine within the display program. The stick figure diagrams were used to determine the positions of consecutive heelstrikes of the ipsilateral leg. The number of

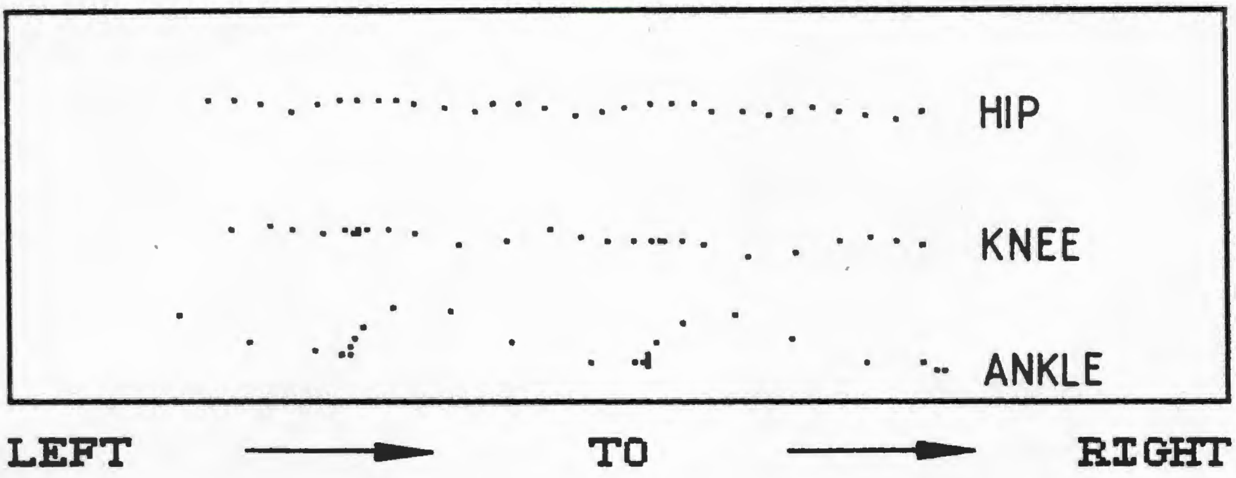


Fig. 33. Raw data generated by the digital camera. From the top the rows of dots represent the loci of the hip, knee, and ankle markers. Direction of walking is from left to right.

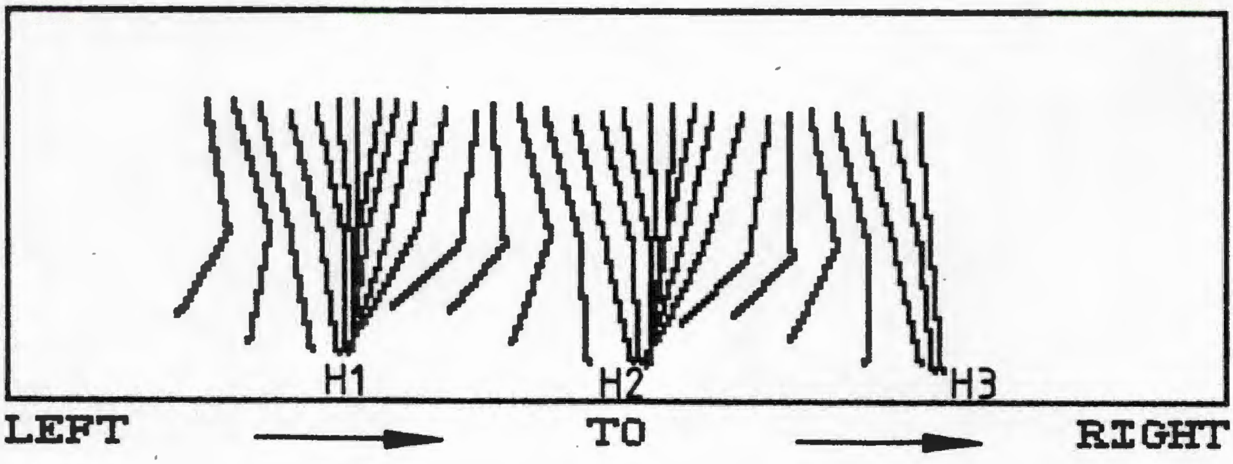


Fig. 34. The raw data converted to stick figures with consecutive heelstrikes of the ipsilateral leg denoted by H1, H2, and H3. Direction of walking is from left to right.

frames in between heelstrikes was used to calculate the amount of time which had elapsed. Using the distance and temporal information provided by the stick figures, the stridelength and walking speed could be calculated. However, before the stridelength and speed of rheumatoid and normal subjects could be compared, these parameters had to be normalised for height. The height of each subject was measured and the values for these two parameters expressed as a fraction of that person's stature. For example, a person with a stridelength of 0.7 statures would cover 70% of his stature in overground distance during one stride. If he were to do that in the space of 1 second, his speed would then be 0.7 statures/s.

It was also possible to extract angular displacement data from the raw data using some simple trigonometry in the display program. Flexion at the hip was so defined as to result in a positive thigh angle while extension caused the thigh angle to become negative (see Fig. 35). Flexion of the knee was defined as a positive angle while hyperextension resulted in a negative knee angle (see Fig. 35). These two angles were measured for each frame and then plotted against one another. The plots are called thigh-knee angle-angle diagrams, with the thigh angle as the X coordinate and the knee angle as the Y coordinate. One cyclical loop of such a diagram represented exactly one stride from heelstrike to heelstrike (see Fig. 36). This loop had a very characteristic pattern in the case of normal subjects and the range of motion at the hip and knee joints could be appreciated readily. It will be noted that this diagram is a mirror image about the X axis of Grieve's (1968) original diagrams (see Fig. 10). However, it was felt that the convention of having the increasing angle of knee flexion in the direction of the positive X axis was more satisfactory. The angle-angle diagram of more than one stride was displayed by plotting all the

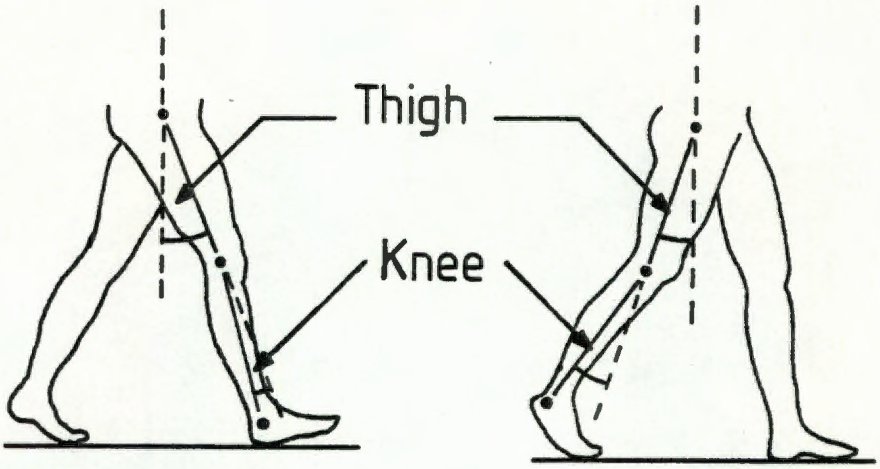


Fig. 35. The thigh and knee angles that were measured in order to produce angle-angle diagrams.

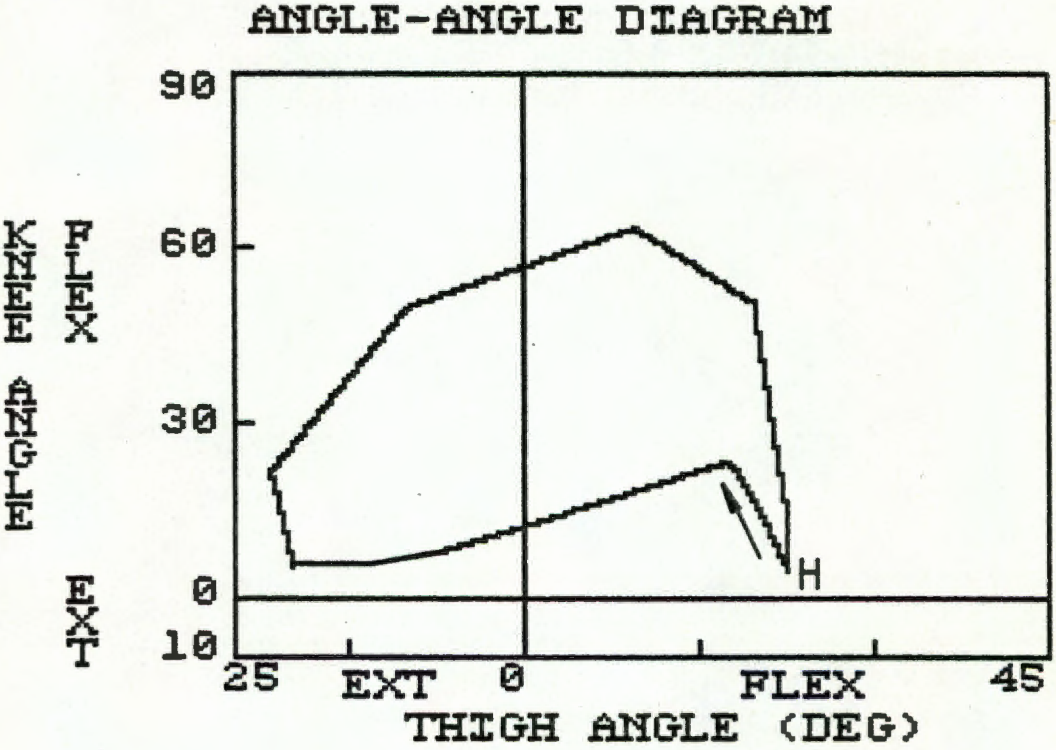


Fig. 36. Thigh-knee angle-angle diagram of a normal person. Read clockwise from heelstrike H.

data recorded during one walk past the camera by a subject. From the similarity between consecutive loops one could gain a visual impression of the repeatability of the gait pattern.

Evaluation of function : force plate. The force plate, which was used to study the function of the rheumatoid foot, is located at the Princess Alice Orthopaedic Hospital (PAOH) in Retreat, Cape Town. The system was designed and developed by Manley and Solomon (1979) and enables one to evaluate the plantar pressure profile as exhibited during the stance phase of walking. The force plate consists of 16 transparent Perspex beams next to each other, mounted at each end on a strain gauge load cell (see Fig. 37). These load cells are only sensitive to the vertical component of the applied loading. The magnitude and point of application of the resultant load on each beam is calculated electronically. At the same time, two video cameras record the visual data. The first camera records images of the plantar surface of the weightbearing foot through the transparent force plate. A second camera provides a lateral view of the subject's lower extremities. All this information is fed into a central controller/processor which assembles the video images and the force plate data into one composite video display (see Fig. 38). During recording a video picture is produced every 20 milliseconds. However, interlacing occurs which means that the force plate has an effective sampling rate of 25 frames per second. The three-tiered display shows the lateral view at the top, the plantar image of the foot with points of application of the resultant forces superimposed on it in the middle, and at the

Fig. 37. Close-up of the PAOH force plate.

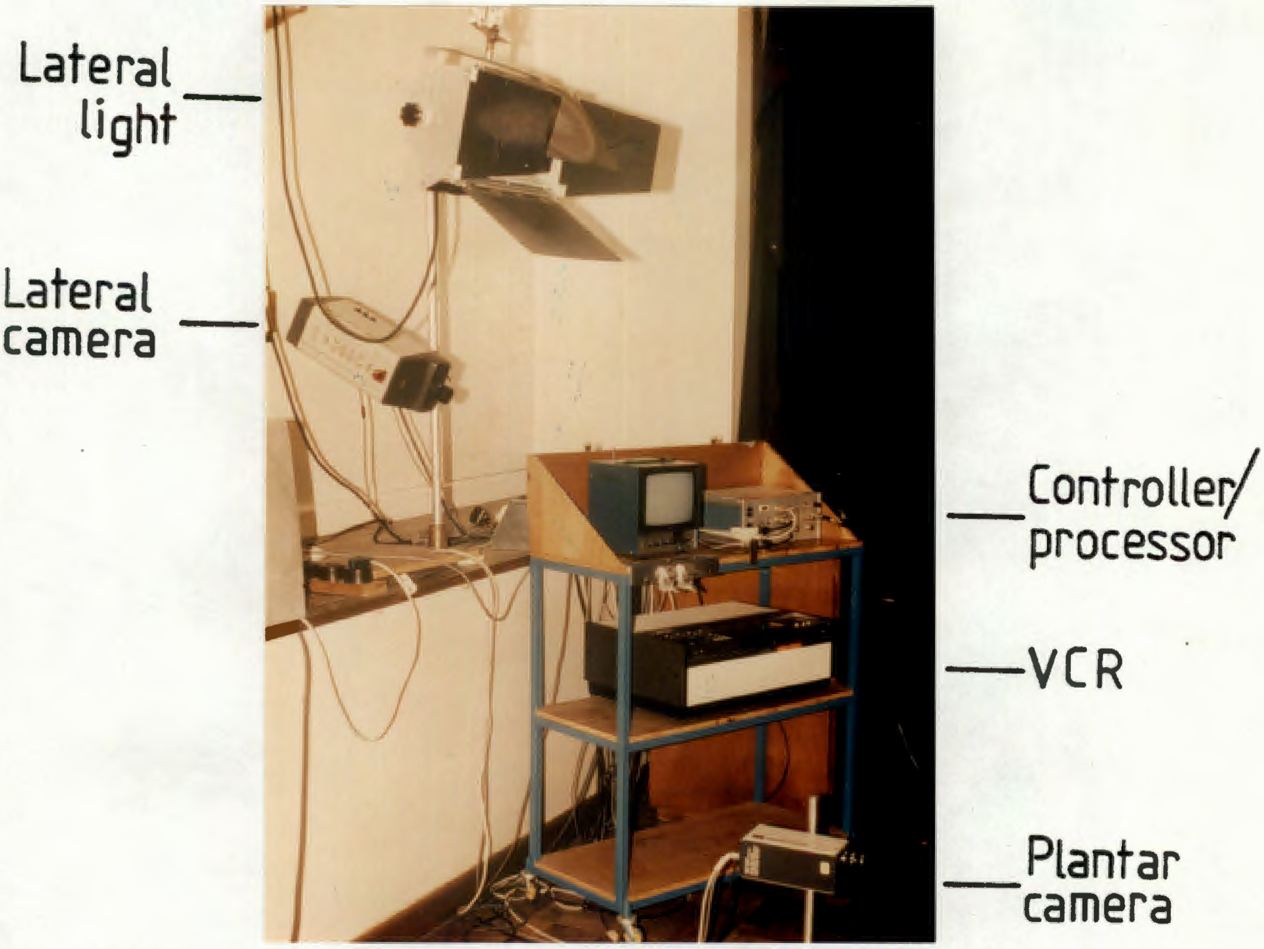


Fig. 38. The recording and display system used in conjunction with the PAOH force plate.

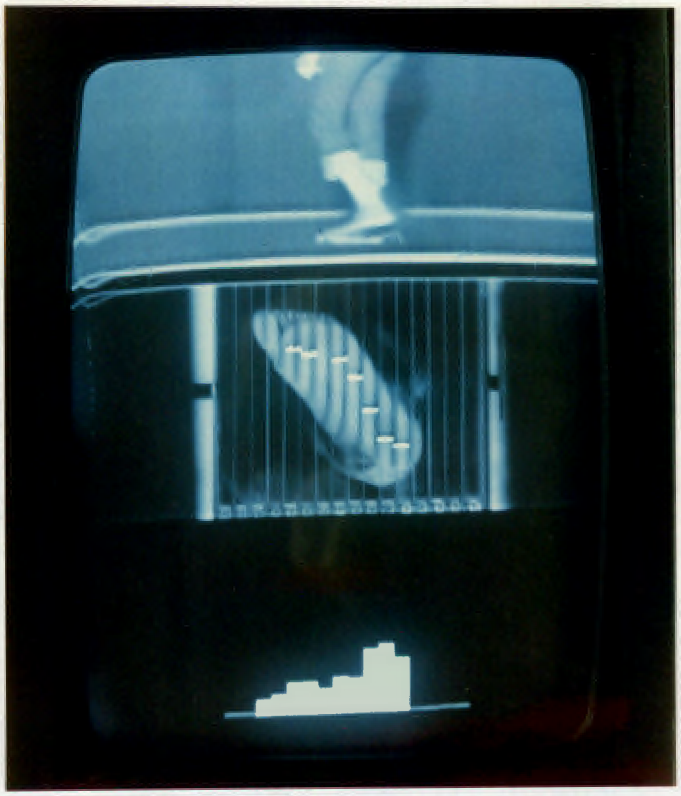


Fig. 39. A single video picture displaying the data generated by the PAOH force plate. Note the three-tiered format (cf. Fig. 20).

bottom a bar chart of the forces measured by each beam (see Fig. 39). This information is displayed on a video monitor and is immediately available for inspection. The information can also be stored on video tape. The rheumatoid and normal subjects taking part in this study were asked to walk diagonally across the force plate. This caused different beams to be loaded separately by individual metatarsal heads, which enabled me to calculate the forces experienced by each of these metatarsal heads. Two recordings were made of each foot with the best one being selected at a later stage for analysis. Because of limited space the subjects could only manage about three paces before stepping onto the force plate. This was not as negative a factor as it would have seemed at first glance. Although it did mean that people had little time at their disposal in which they could assume their natural gait, it also meant that there might not have been much difference between the walking speeds of normal and rheumatoid subjects. It is possible that this could have had some limiting effect on the speed dependence of the ground reaction forces as measured by the force plate. That the magnitude of ground reaction forces depended on the walking speed, was demonstrated quite conclusively by Vaughan et al (1985).

The relative bodyweights of 10 of the 15 rheumatoid patients and all the normal control subjects were measured. Five rheumatoid patients were not available for the bodyweight recordings which were done subsequent to the initial recordings of the foot forces during stance. Of these, one patient had died in the interim, another had been admitted to hospital due to a chronic illness, a third had received major foot surgery, and the last two were patients from out of town who only came to the clinic once every six months. In order to record their bodyweight, subjects had to stand on the force plate for a few seconds with both feet. These values were used to normalise the ground reaction forces which the foot experienced during the stance phase, i.e. all forces were expressed as a percentage of bodyweight. It was therefore possible to compare the data of the rheumatoid patients and normal control subjects.

Data Analysis

General. The small sample sizes necessitated the use of Student's t-test to ascertain whether significant differences existed between the mean values for the rheumatoid and normal control groups. The p value represents the level of confidence with which one can say that two samples were drawn from different populations. If $p > 0.05$ it meant that the observed difference between two means was not statistically significant. However, $p < 0.05$ meant that the difference could be regarded as significant and $p < 0.01$ indicated a highly significant difference. The product-moment correlation coefficient (r) was used to establish the degree of association existing between two parameters describing different aspects of the same group of subjects. In general, a coefficient of 1 indicates a perfect correlation, while a value between 0.75 and 0.99 indicates a high degree of correlation. However, if the number of pairs of items is 50 or less, the significance of r have to be obtained from a table of probabilities (p values) of r values. For this study, as before, $p > 0.05$ indicated no significant correlation between the two parameters, while $p < 0.05$ indicated a statistically significant and $p < 0.01$ a highly significant correlation. It should be remembered that a good correlation between two parameters did not necessarily indicate a causative relationship between them.

Evaluation of form. The contour diagram, iodine footprint, and antero-posterior X-ray for the same foot were compared visually to assess the closeness of fit between these representations, as well as the relationship between the internal structure of the foot and its external shape.

Correlation of the FFR with other parameters was done for only 29 rheumatoid feet because one patient had such a high-arched left foot that the narrowest waist part of the foot did not touch the ground. It was therefore unnecessary to calculate a ratio for that foot as a FFR of 0 did not have any meaning.

The mean FFR of the rheumatoid group was compared with that of the normal control group to see if there was any significant difference between these two values. The FFR was correlated with a clinical diagnosis of valgus heel to establish whether this ratio could in fact serve as a reliable indicator of flat feet in RA.

The FFR was also correlated with the Lequesne and contour indices to establish the degree of association between these three measures of flatfootedness.

The FFR was furthermore correlated with the talometatarsal angle in the sagittal plane and the hallux valgus angle in the transverse plane.

<u>Evaluation of function : digital camera.</u> From the stick figure diagrams for the left and right sides I was able to derive information on temporal parameters such as walking speed, cadence (stride frequency), and stridelength. Means were calculated for these parameters and Student's t-test was employed to detect significant differences between the values for rheumatoid patients and the normal control subjects. The angle of the thigh relative to the vertical was plotted against the knee angle of flexion. This yielded the so-called thigh-knee angle-angle

diagram which had a very characteristic pattern in the case of normal people (see Fig. 36). Hershler and Milner (1980) pointed out that one needed some quantitative parameters in order to perform statistical analyses on these angle-angle diagrams. As discussed in Chapter 2, they proposed three parameters which they thought to be fairly representative of the characteristics of the angle-angle diagram. These were :

* A - the area of one loop (i.e. the angle-angle diagram of one stride) which was representative of the combined range of motion at the hip and knee during that stride,
* P - the perimeter of the loop, which was a measure of the amount of coordination between movement at the hip and the knee,
* P_A - a dimensionless ratio ($P/\sqrt{A}$), which characterised the overall shape of the loop. The shape of the diagram was thought to be related to the neuro-musculo-skeletal control mechanisms in gait.

Means calculated for these three key parameters were compared for rheumatoid and normal control subjects in order to detect any significant differences between the two groups. The correlation between area A and the stridelength was also investigated in the case of both the rheumatoid and normal groups.

Evaluation of function : force plate. The foot was divided into the following areas of interest for the purpose of measuring the forces on its plantar surface : hindfoot, midfoot, metatarsal heads 1 - 5, and hallux.

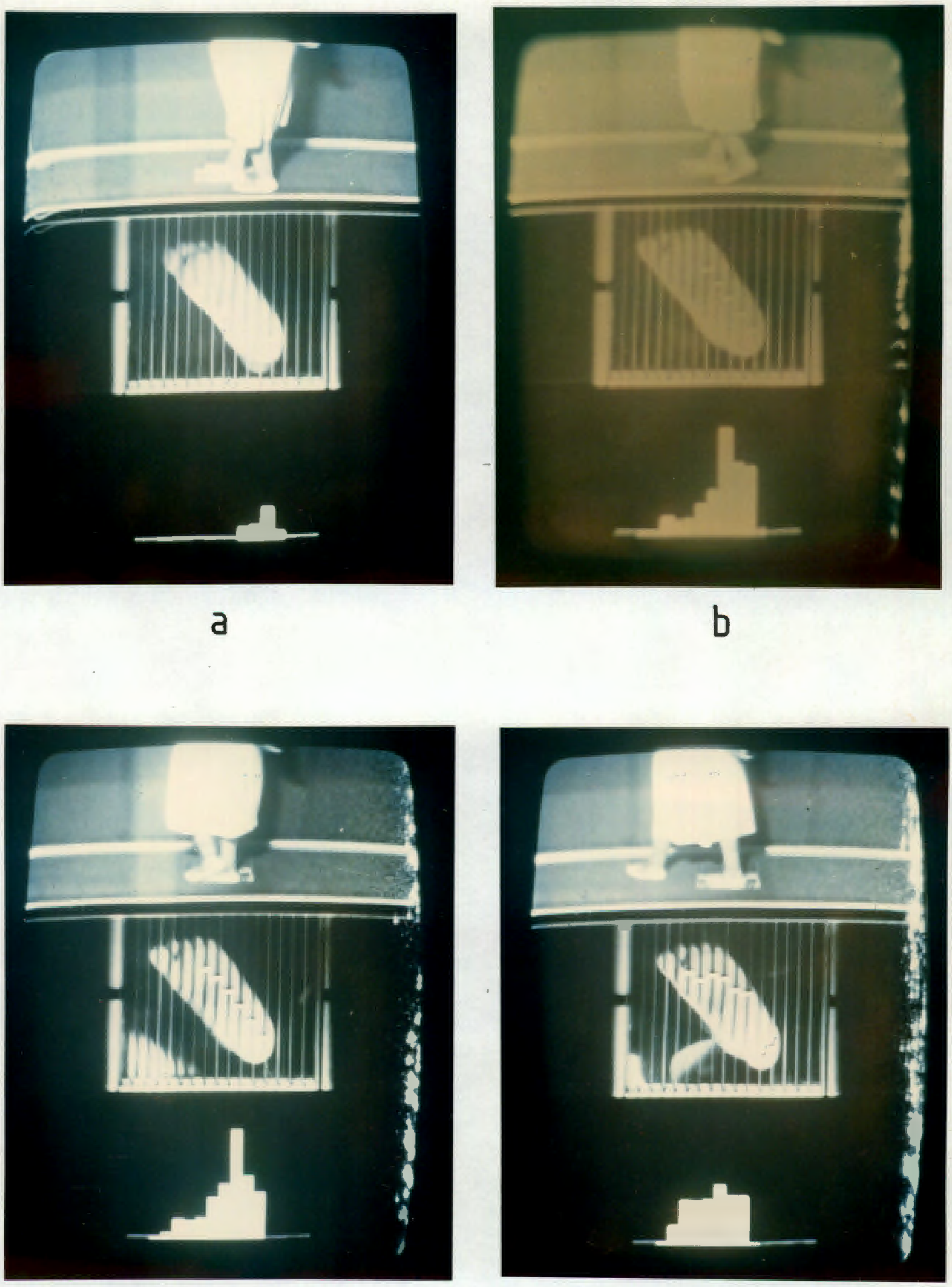
Colour slides of the video display of the force plate system at PAOH were taken at five easily identifiable stages of the stance phase (see Fig. 40). These stages were :

- heelstrike -- as soon as the heel struck the force plate and the force was indicated on the bar chart;
- footflat -- as soon as the forefoot touched the plate and the point(s) of the application appeared superimposed on the plantar image of the forefoot;
- midstance -- when the swinging foot was directly opposite the weightbearing foot;
- heelrise -- as soon as no more weight was borne on the hindfoot;
- toe-off -- just before the forefoot was lifted off the plate.

I used a photographic enlarger to obtain enlarged images of the slides which were taken of the video display at each of the five stages. Thereafter it was a simple case of measuring the heights of the bars on the bar charts to an accuracy of +- 1 mm using a steel ruler.

The foot was divided into eight areas of interest for the purpose of measuring the ground reaction forces on its plantar surface. These were the hindfoot (heel), midfoot, metatarsal heads 1 - 5 (MT1, MT2, ..., MT5), and hallux (Hx) (see Fig. 41). At three of the five stages i.e. at footflat, midstance, and heelrise these areas of interest were regarded in different combinations :

- footflat : hindfoot and mid-and-forefoot (the latter comprising the midfoot, metatarsal heads 1 - 5, and hallux),



a b

c d

Fig. 40. Video pictures of 4 of the 5 stages during stance i.e. (a) heelstrike, (b) footflat, (c) midstance, and (d) heelrise. Toe-off not shown.

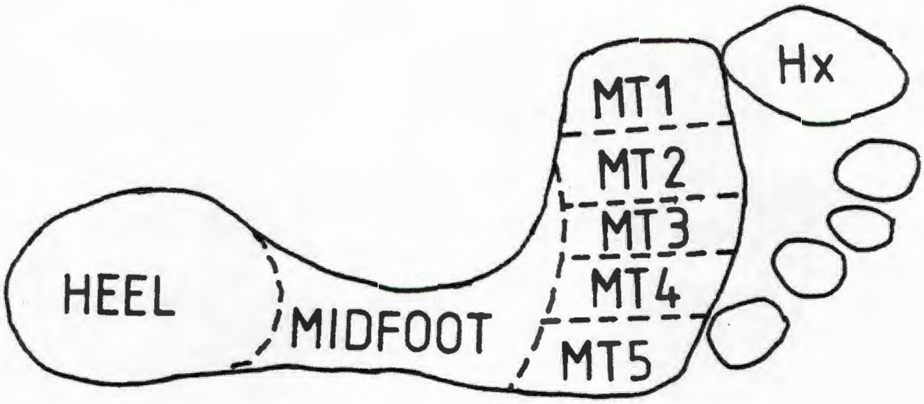


Fig. 41. Division of the plantar surface of the foot into eight areas of interest.

- * midstance : hindfoot, midfoot, metatarsal heads 1 - 5, and hallux,
- * heelrise : midfoot, metatarsal heads 1 - 5, and hallux.

Means were calculated for the forces that RA patients and normal control subjects experienced under the different parts of their feet during each of the five stages, as well as for the total force that rheumatoid and normal feet experienced during each stage.

It was sometimes quite difficult or impossible to separate out the forces experienced by adjacent sites of interest. The situation where five metatarsal heads fell on five separate beams of the force plate did not always materialise, as that depended a lot on the width of the foot and its placement on the force plate. Under those circumstances more than one metatarsal head could have contributed to the load measured by any single beam, while I was unable to sort out the relevant contribution of each. Not only the measurement of adjacent metatarsal heads suffered from this deficiency, but the same difficulties also arose when trying to separate the forces exerted on the hindfoot and midfoot, and the midfoot and metatarsal head 5. This gave rise to the method whereby adjacent sites were regarded in pairs and a cumulative value calculated for each pair. The pairs were hallux/MT1, MT1/MT2, ..., midfoot/hindfoot. The diagonal placement of the foot on the force plate, while generally quite helpful in analysing the forces on the forefoot, was not ideal as far as the hind- and midfoot were concerned.

CHAPTER 4

RESULTS AND DISCUSSION

Parameters describing some aspect of either the internal or external form of the foot or the function of the lower extremity, were chosen with the rheumatoid foot in mind. These parameters were therefore intended to quantify pathological features of the foot and lower extremity in RA. Such a parameter typically had a spread of values corresponding to the group of rheumatoid patients and these values could then be correlated with other parameters. Alternatively, the mean values of the parameter for the normal control and rheumatoid groups could be compared. The normal controls were, by definition, expected to have more or less the same value for a given parameter. Plotting two parameters for the normal group against one another tended to produce a cluster of points within the limits of normality, the corresponding statistical correlation between these two parameters being generally poorer than that of the rheumatoid group or not significant at all. Thus, instead of detracting from it, the pattern of good correlation in the rheumatoids and poor correlation in the normals for the same parameter, only served to confirm the ability of the parameter concerned to quantify some aspect of pathology in the rheumatoid foot and lower extremity. Throughout this study, whenever a correlation was done, it was done for both the normal control and rheumatoid groups and, unless otherwise stated, conformed to the above-mentioned pattern.

Evaluation of the Form of the Rheumatoid Foot

As set out in Chapter 3, different methods were used to study different aspects of the internal and external shape of the foot. The results from each of these methods will be discussed. Methods were sometimes combined to yield new insights, for example concerning the relationship between internal and external shape.

Footcasts. A contour diagram was obtained for each foot using the method described in Chapter 3 (see Fig. 25a). As was the case with the iodine footprints, the index derived from the contour diagrams (cf. Chapter 3) was an attempt to establish an objective but relatively simple quantitative index of flatfootedness. As set out in Table 1, the mean value was 10.3 +- 2.1 in the case of the normal control subjects and 7.8 +- 3.5 in the case of the rheumatoid patients . There was a significant difference between the means of these two groups ($p < 0.01$).

The indices, which were derived from the iodine footprints (FFR) and the contour diagrams (contour index) to indicate the degree of flatfootedness, were also correlated with each other in the case rheumatoid group. One pair of values had to be excluded as the FFR of that particular footprint could not be calculated. As explained in Chapter 3, the method for calculating the FFR involved measuring the heelpad distance as well as the narrowest waist distance. In one case the foot had such a high arch that it did not touch the ground and therefore no waist distance could be measured. This non-existent narrowest waist distance -- being the numerator in the FFR -- made it unnecessary to calculate a ratio for that foot as a FFR of 0 was meaningless. Another person, being from out of town, could not complete all the tests. Thus no footcasts were made of this person's feet and as a result no contour diagrams could be constructed. The correlation coefficient (r) for the rheumatoid group (n = 27 feet) was calculated to be -0.67 which meant that there was a highly significant negative correlation between the sets of values of the two indices ($p < 0.01$). The good correlation seemed to indicate quite a close agreement between these two methods for quantifying flatfootedness, despite the one (FFR) being essentially a 2D and the other (contour index) a 3D technique. It would therefore seem reasonable to suggest that the contour index, like the FFR, might be an objective way of quantifying flatfootedness in rheumatoid subjects. It is envisaged that this index could be used to quantify flatfootedness in other patient populations as well.

	Normal controls	Rheumatoid patients	Significant difference
Contour index	10.3 +- 2.1	7.8 +- 3.5	$p < 0.01$
FFR	0.14 +- 0.03	0.21 +- 0.09	$p < 0.01$
Lequesne index	0.29 +- 0.05	0.48 +- 0.20	$p < 0.01$

Table 1. Mean values of the three indices of flatfootedness for the normal control and rheumatoid groups and the significance of the differences between these values.

Footprints. The mean flatfootedness ratio (FFR) for the normal control subjects was 0.14 +- 0.03, and for the rheumatoid group 0.21 +- 0.09 according to Table 1. There was a significant difference between the FFR of the rheumatoid patients and that of the normal control subjects ($p < 0.01$). The FFR of the rheumatoids was also shown to be positively correlated with the clinical assessment of the hindfoot concerning the varus, neutral, or valgus position of the heel ($p < 0.05$). These two findings seemed to indicate that the FFR could be a useful objective and quantitative measure of the degree of flatfootedness in rheumatoid patients.

Lequesne et al (1984) suggested that the narrowest waist distance be expressed as a fraction of the width of the metatarsal pad in order to establish a quantitative index for the degree of flatfootedness in RA. According to Table 1 the mean values of the Lequesne index were 0.29 +- 0.05 and 0.48 +- 0.20 for the normal control and rheumatoid groups respectively. It was quite easy to show that the difference between the means for the two groups was highly significant ($p < 0.01$). The Lequesne index, as did the FFR, seemed to indicate a significantly more flatfooted stance than normal in the case of the rheumatoid patients. As far as the correlation between the two indices was concerned, there seemed to be a very good positive correlation between them for the rheumatoid group. The value of the product-moment correlation coefficient (r) was 0.96 ($p < 0.01$). This meant that the Lequesne index was at least as reliable as the FFR in quantifying the degree of flatfootedness.

The contour diagram and iodine footprint of the same foot

Fig. 42. Visual comparison between the contour diagram and iodine footprint of (a) a normal foot and (b) a rheumatoid foot.

were also visually compared on a light box in the case of each rheumatoid and normal subject (see Fig. 42). In general, there appeared to be a remarkably good fit between these two representations of the external form of the foot. This definitely added to the validity of the good statistical correlation which was found to exist between the contour index and FFR for the same foot.

X-rays. The mean values for the angles, which were measured on X-ray, are given in Table 2. It is evident that there were significant differences between the normal and rheumatoid groups in the case of the talometatarsal and hallux valgus angles ($p < 0.05$ and $p < 0.01$ respectively). In the case of the metatarsal 1,2 angle there was no significant difference between the normals and rheumatoids. There was a significant positive correlation between the talometatarsal angle and the FFR in the case of the rheumatoid patients ($r = 0.47$, $p < 0.01$).

	Normal controls	Rheumatoid patients	Significant difference
Angle (degrees):			
Talometatarsal	-5 +- 5	2 +- 11	$p < 0.05$
Metatarsal 1,2	10 +- 2	10 +- 4	$p > 0.05$
Hallux valgus	12 +- 4	26 +- 14	$p < 0.01$

Table 2. The mean values of angles measured on X-ray for the normal control and rheumatoid groups and the significance of the differences between these values.

This was matched by an equally significant negative correlation between the talometatarsal angle and the contour index for the rheumatoid patients ($r = -0.63$, $p < 0.01$). The statistically significant correlations between the two indices of flatfootedness and the talometatarsal angle were also clinically significant. It meant that, clinically, the degree of flatfootedness in RA could be quantified by simply measuring that angle on X-ray.

After having established the lateral talometatarsal angle as a quantitative clinical parameter concerning flatfootedness in RA patients, I was able to offer an explanation as to the rather large standard deviation of that angle in the case of the rheumatoid patients. The large spread of values pointed to the fact that not all rheumatoid feet were indeed flat. Some high-arched rheumatoid feet were in fact into the range of normal to cavus. However, on the whole there were far more flat than cavus rheumatoid feet. Hence, the mean talometatarsal angle for the rheumatoid group was found to be significantly larger than that of the normal group.

No significant correlation was found between the hallux valgus angle and the FFR or the contour index ($p > 0.05$ in both cases). Flatfeet in RA typically exhibit a pattern of progressive eversion of the hindfoot with the talus assuming a more medial and vertical position. This pattern was borne out by the highly significant positive correlation between the talometatarsal angle and the FFR as well as the contour index. The theory, held up to now, has been that hindfoot changes of that kind precipitated forefoot pathology such as hallux valgus. However, the fact that no significant correlation was found between the hallux valgus angle and either the FFR or the contour index in the rheumatoid group, would seem to dispel this theory of association between hindfoot and forefoot pathology in RA.

In the case of the rheumatoid patients there was a significant positive correlation between the metatarsal 1,2 angle

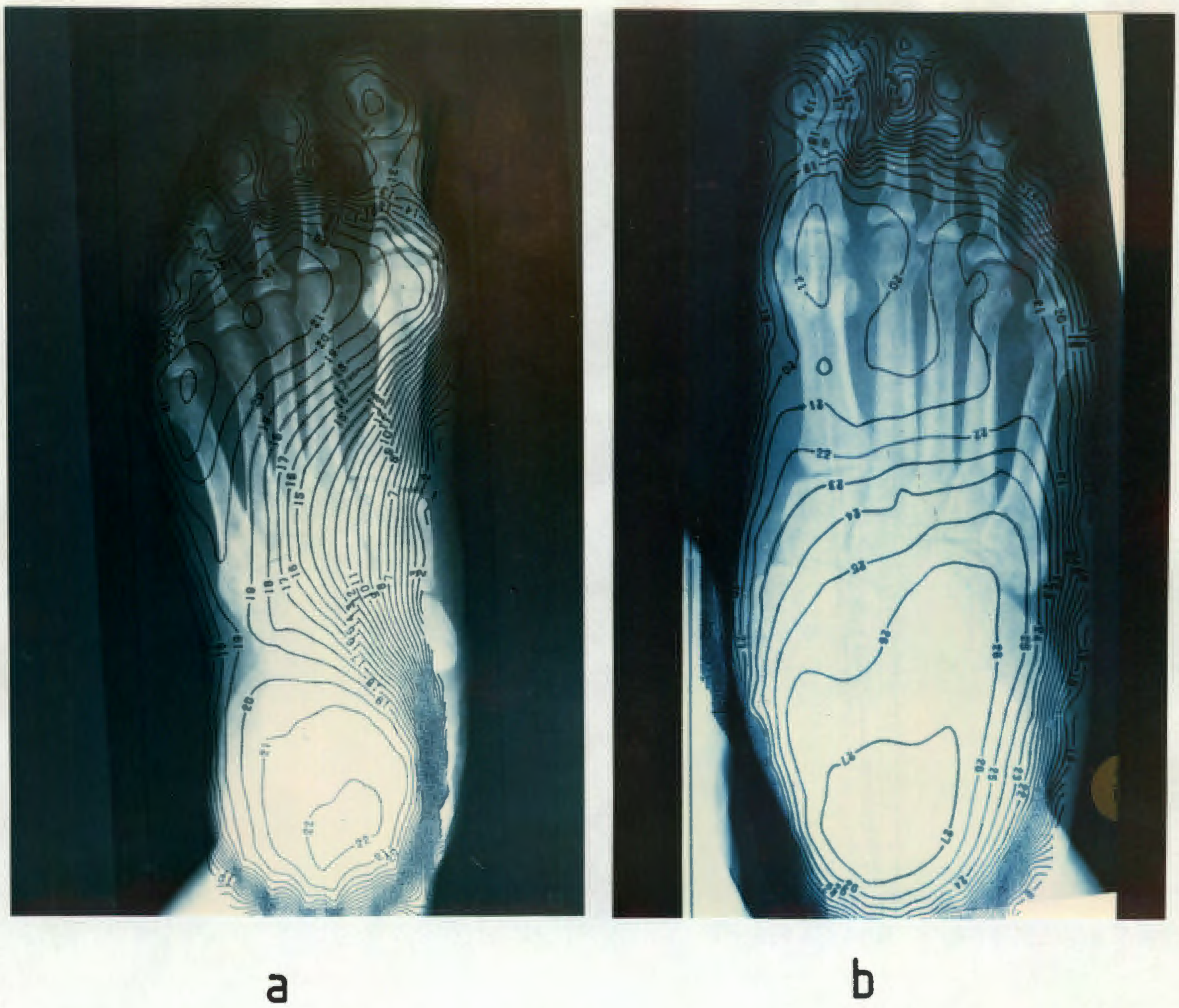


Fig. 43. Visual comparison between the contour diagram and the antero-posterior X-ray of (a) a normal foot and (b) a rheumatoid foot.

and the hallux valgus angle ($r = 0.49$, $p < 0.01$). However, despite the good correlation it was not possible to say whether increasing medial deviation of the first metatarsal was the cause or the effect of increasing hallux valgus. The fact that the mean metatarsal 1,2 angles were the same for the normal and rheumatoid groups, despite the existence of a highly significant difference between their respective mean hallux valgus angles, further confounded the issue.

The contour diagram and antero-posterior X-ray of the same foot were compared visually using a light box (see Fig. 43). High spots on the contour diagram could be matched up quite satisfactorily with corresponding bony reference points on the X-ray. Due to the angle at which the X-ray had been taken, features could only be meaningfully matched from the metatarsals onwards. This was a preliminary attempt to relate the internal structure of the foot to its external shape with the specific purpose of observing pathological features in rheumatoid feet.

Evaluation of the Function of the Rheumatoid Foot

The results produced by the digital camera concerned the functioning of the whole lower extremity which is that part of the body mainly responsible for the mechanical action of walking. The results from the force plate system focussed more closely on the foot itself and particularly on what was happening to it while it was on the ground during the stance phase of walking.

Digital camera system. The average height of the rheumatoid group was 1.60 +- 0.06 m and that of the normal control group 1.60 +- 0.05 m. The heights of 14 of the 15 rheumatoid patients were recorded which meant that the average speed and stridelength were calculated for this group of 14 patients. One patient died while the tests were in progress and her height was therefore not other temporal and distance parameters were calculated for the total group of 15 patients.

Mean values for walking speed and stridelength (after normalisation), and cadence are given in Table 3. In the case of both the speed and stridelength the differences between the means

	Normal controls	Rheumatoid patients	Significant difference
Cadence (steps/min)	111 +- 11	103 +- 11	$p < 0.05$
Speed (statures/s)	0.71 +- 0.11	0.50 +- 0.14	$p < 0.01$
Stridelength (statures)	0.77 +- 0.07	0.58 +- 0.12	$p < 0.01$

Table 3. Mean values of kinematic parameters for the normal control and rheumatoid groups and the significance of the differences between these values.

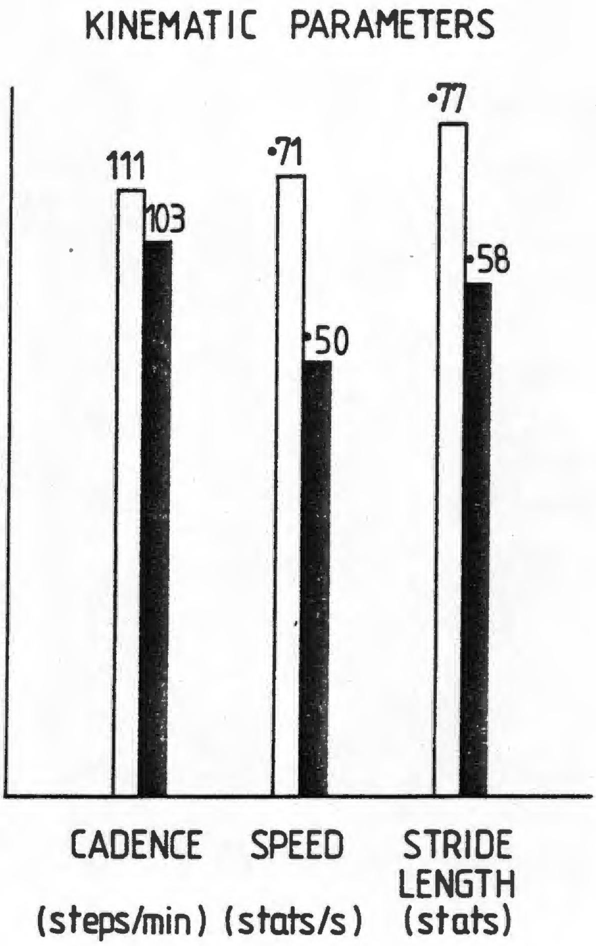


Fig. 44. Graphical representation of kinematic parameters for the normal control (□) and rheumatoid (■) groups.

for the normals and rheumatoids were highly significant ($p < 0.01$). Judging from the information in Table 3 and Fig. 44, the significant reduction in the average stridelength of the rheumatoid group seemed to be closely related to the equally significant reduction in walking speed. A highly significant correlation coefficient ($r = 0.94$, $p < 0.01$) confirmed the observed association between these two parameters. The average cadence for the rheumatoid group was somewhat less than the value for the normal group and, statistically speaking, the difference between the two means was significant ($p < 0.05$). However, it should be remembered that the calculation of cadence (cf. Chapter 3) depended on the number of frames between consecutive heelstrikes. The identification of these heelstrikes was prone to a certain amount of error (see Appendix B). This led me to disregard the apparent difference between the mean cadence for the normal control and rheumatoid groups and not to attach any clinical significance to it. It could therefore be argued that the reduction in walking speed experienced by the rheumatoid group was almost solely caused by a reduction in stridelength, because the cadence remained constant for both groups (walking speed = cadence x stridelength).

The angular displacement data generated by the digital camera were analysed by means of the mathematical parameters which Hershler and Milner (1980) proposed. Table 4 gives mean values of these three parameters for normals and rheumatoids. In the case of each of the three parameters there was a highly significant difference between the mean values for the rheumatoid and normal groups, i.e. in each case the value for the rheumatoid

	Normal controls	Rheumatoid patients	Significant difference
Perimeter P (deg)	340 +- 34	290 +- 44	$p < 0.01$
Area A (deg2)	5645 +- 1040	3598 +- 1574	$p < 0.01$
Ratio $\frac{P}{A}$	4.6 +- 0.3	5.2 +- 1.0	$p < 0.01$

Table 4. Mean values of angular displacement data for the normal control and rheumatoid groups and the significance of the differences between these values.

group was significantly reduced compared to the normal group. Perimeter P of the rheumatoid group, although smaller in absolute terms, was relatively larger than that of the normal group when compared to the amount of area it enclosed. This meant that the rheumatoid group, on average, exhibited more jerky and uncoordinated motion of the lower extremity than the normal group. However, because of the slow sampling rate of 13 Hz the angle-angle diagram assumed a rather jagged appearance during stance which was perhaps a little more exaggerated than the jerky motion could account for (see Fig. 45). The exaggerated outline of the angle-angle diagram during stance would have increased the the value of perimeter P for the rheumatoid group. The significant difference in the value of the ratio $\frac{P}{A}$ between normals and rheumatoids indicated that the shape of the rheumatoid angle-angle diagram was noticeably different to the normal shape. It should be noted that the perimeter P had a much larger influence than the area A on the value of $\frac{P}{A}$, so that a relatively small change in perimeter P could either have

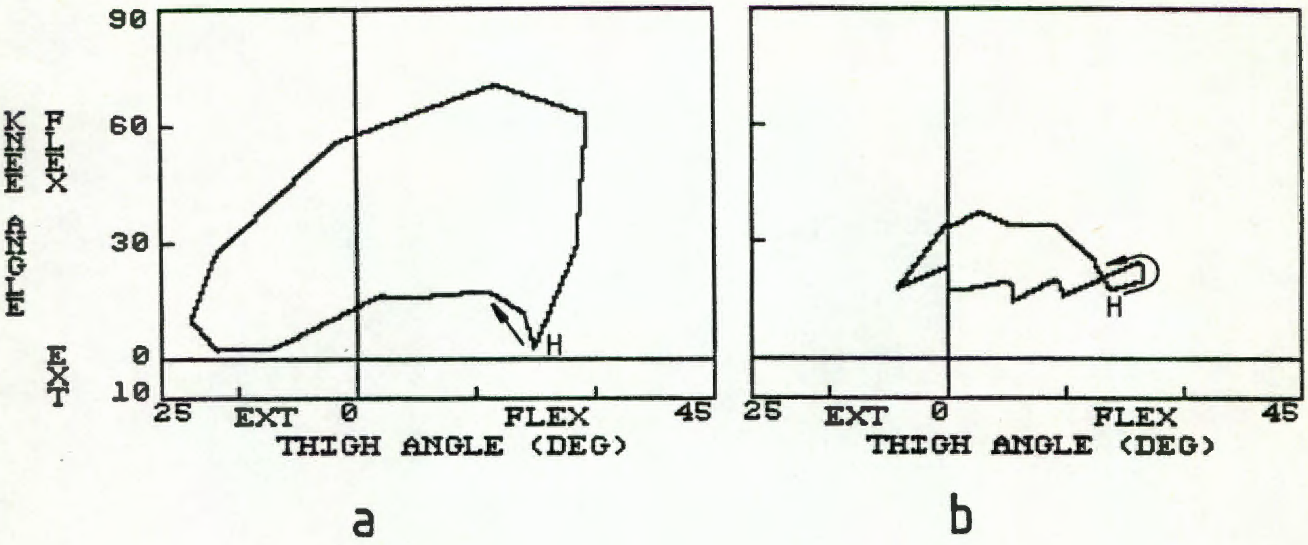


Fig. 45. Thigh-knee angle-angle diagrams of (a) a normal control subject and (b) a rheumatoid patient. Read the diagrams clockwise from heelstrike H. Note the instability of the rheumatoid patient at heelstrike and during stance.

cancelled out a relatively large change in the area A or caused the value of P_A to be changed by a substantial amount. The value of P_A should therefore be regarded with a suitable amount of caution. Hershler and Milner (1980) furthermore pointed out that P_A only reflected relative changes in shape and that it did not distinguish between the effects of walking speed and pathology on the shape of the angle-angle diagram.

It should be remembered that a reduced range of motion at the hip and knee -- as a result of pathology -- would have a definite limiting effect on the person's stridelength. This is supported the fact that a significant positive correlation for the rheumatoid group was found between the stridelength and area A of the angle-angle diagram ($r = 0.87$, $p < 0.01$). The significant reduction for the rheumatoid group in the value of the area A could therefore be indicative of such pathology of the hip and/or knee joints. Alternatively, the reduction for the rheumatoids in the value of area A could simply be a result of the reduction in stridelength. I think that the reason for the observed reduction in the range of motion at the hip and knee should be sought in a combination of the two above-mentioned factors. However, I cannot categorically disagree with Simkin (1981) when he maintained that the changes in the kinematic parameters of RA patients were not abnormal but such as could be expected from **normal** persons walking at a **reduced** speed.

At this point it should be noted that, as far as these aspects of the kinematic function of the rheumatoid foot were concerned, it was not possible to make a clear distinction between cause and effect.

A possible scenario from a kinematic and clinical perspective would be the following. Fear of falling as a result of instability and lack of confidence as well as the ever present pain could have caused the rheumatoid patients to walk significantly slower than normal. They could have achieved this by having a significantly reduced stridelength, compared to that of the normal group. The reduction in stridelength would have caused their range of motion at the hip and knee to be significantly reduced. Pathology in one or both of these joints would then in turn have exerted a further limiting influence on their range of motion at these joints. It is possible that the even more limited motion at the hip and knee could again have resulted in the stridelength being reduced even more as well. The further decrease in the stridelength would, in turn, have caused the patient to walk even slower. This cause-and-effect loop might well have resulted in the rheumatoid patient walking very slowly, having had to come to the point where that patient had to be willing to endure pain and instability for the sake of still being able to walk. Consideration of relevant kinetic parameters may clarify the issue somewhat and this will be discussed in the next section on the results of the force plate system.

Force plate system. Table 5 gives the normalised averages of the total force which the the foot experienced at each of five stages during the stance phase (see also Fig. 46).

	Normal controls	Rheumatoid patients	Significant difference
Heelstrike	24 +- 8	22 +- 7	$p > 0.05$
Footflat	65 +- 17	75 +- 16	$p > 0.05$
Midstance	92 +- 5	96 +- 8	$p > 0.05$
Heelrise	95 +- 7	78 +- 24	$p < 0.01$
Toe-off	15 +- 6	20 +- 9	$p > 0.05$

Table 5. Mean values of the total force which the foot experienced at each of the five stages during the stance phase and the significance of the differences between these values. All forces are expressed as a percentage of bodyweight.

As before, Student's t-test was used to ascertain the significance of the differences between the mean values of the

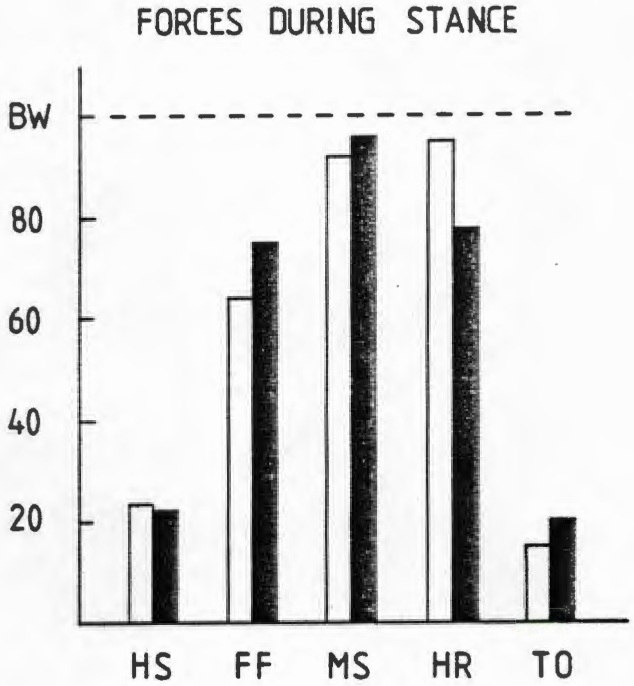


Fig. 46. The total ground reaction force, as a percentage of bodyweight, experienced by the foot at 5 stages during stance i.e. at HS - heelstrike, FF - footflat, MS - midstance, HR - heelrise, and TO - toe-off. Normal controls (☐), rheumatoid patients (■).

normal and rheumatoid groups. The result was that there were no significant differences between the various means ($p > 0.05$), except in one instance i.e. at heelrise where $p < 0.01$. This suggested that during the earlier and middle stages of the stance phase, normal and rheumatoid people experienced ground reaction forces of similar magnitude. However, during the latter stages, rheumatoids experienced significantly reduced ground reaction forces. A possible explanation would be that the rheumatoid patients seemed to refrain from pushing off on the forefoot as forcefully as the normal controls. The reason for exerting less force on the forefoot might be sought in the large proportion of rheumatoid patients (> 50%) suffering from forefoot pain, of which painful metatarsal heads seemed to be the most prevalent. If one's foot were painful one would take extra care when attempting to place a load on it. Unfortunately, because of the rather small sample size this correlation between the biomechanical (force) and the clinical (pain) factors could not be shown to be statistically significant.

At three of the five stages i.e. at footflat, midstance, and heelrise a distinction was made between different areas on the plantar surface of the foot (see Fig. 41) as well as the ground reaction forces which these areas were subjected to. All forces were expressed as a percentage of the bodyweight of the subject.

In order to analyse the forces on the foot at the **footflat** stage, the foot was divided into a hind section and a mid-and-fore section (see Table 6).

	Normal controls	Rheumatoid patients	Significant difference
Hindfoot	44 +- 14	49 +- 11	$p > 0.05$
Mid-and-forefoot	22 +- 5	26 +- 9	$p > 0.05$

Table 6. Mean values for the normal and rheumatoid groups of the loads on the foot at **footflat** and the significance of the differences between these values.

Looking at Table 6, it is clear that there were no significant differences between the values of the two groups for either the hindfoot or the mid-and-forefoot. These results suggested that the rheumatoid patients had not taken special care to decrease the load on their feet -- especially the heel -- at heelstrike and shortly thereafter. This was in spite of the fact that 7 out of 10 patients (9 out of 20 feet) reported painful hindfeet on clinical examination. It would therefore seem likely that painful hindfeet did not offer any real impediment to the gait pattern of rheumatoid patients as far as the initial stages of the stance phase were concerned.

The foot was divided up into eight areas of interest for the purpose of analysing the force pattern at the midstance stage. These were the hallux, metatarsal heads 1 to 5 (MT1, MT2, etc.), midfoot, and hindfoot (see Fig. 41). The average values of these regions of interest are shown in Table 7 (see Fig. 47).

	Normal controls	Rheumatoid patients	Significant difference
Hallux	8 +- 5	4 +- 5	$p < 0.05$
MT1	12 +- 4	10 +- 7	$p > 0.05$
MT2	20 +- 7	10 +- 6	$p < 0.01$
MT3	17 +- 5	11 +- 5	$p < 0.01$
MT4	13 +- 5	12 +- 5	$p > 0.05$
MT5	9 +- 4	12 +- 8	$p > 0.05$
Midfoot	3 +- 3	10 +- 11	$p < 0.01$
Hindfoot	10 +- 11	27 +- 22	$p < 0.01$

Table 7. Mean values for the normal control and rheumatoid groups of the forces on parts of the foot at midstance and the significance of the differences between these values.

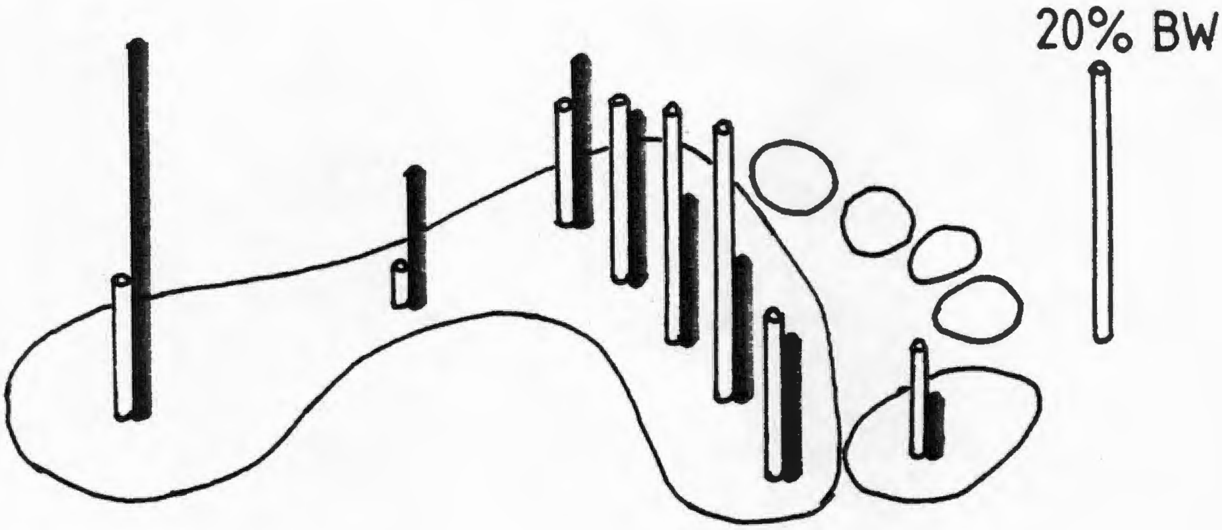


Fig. 47. Ground reaction forces on eight areas of the foot at midstance. Normal controls (□), rheumatoid patients (■). BW - bodyweight.

It is clear that there were significant differences between the mean values for the normal and rheumatoid groups at the sites of the hallux, metatarsal heads 2 and 3, midfoot, and hindfoot. It is important to note that at the hallux and metatarsal heads 2 and 3 the normal controls had the larger force values, while at the midfoot and hindfoot the rheumatoids had the larger force values.

Using the method of force pairs the pattern of force distribution, which had been observed when comparing individual sites, was confirmed with the pair MT4/MT5, the only one where no significant difference was found.

Earlier in this section on the force plate, it was pointed out that there had been no significant difference between the mean values for the total force experienced by the normal control and rheumatoid groups at midstance (cf. Table 5). The fact, which was noted earlier as well, that the distribution of force on the rheumatoid foot at midstance differed radically from that on the normal feet will now be considered. Compared to the normal controls, the forces on the hallux and medial metatarsal heads were significantly smaller in rheumatoids. Conversely, the forces on the midfoot and hindfoot were significantly larger in the rheumatoids. This meant that the rheumatoid patients had been purposely delaying the transferral of force from the hindfoot area to the forefoot area as the stance phase progressed. The pattern of prolonged midstance and minimised weight transfer to the forefoot was also noted by Gerber and Hunt (1985) and Simkin (1981). In summary one might say that the magnitude of the total force was the same for normals and rheumatoids but the distribution of force was significantly reversed.

The force distribution was also studied at heelrise. Once again the foot was divided up into the same regions of interest as that of midstance except for the hindfoot (see Fig. 41). By definition heelrise occurred as soon as no force was observed to be acting on the hindfoot. Table 8 summarises the mean values for all areas as well as whether significant differences existed between normals and rheumatoids (see also Fig. 48). It is clear that there were significant differences between the mean force values for normal and rheumatoids only at the hallux and metatarsal heads 2 and 3. However, despite these differences the pattern of force distribution at heelstrike was essentially the same for both groups. Earlier in this section it was mentioned

	Normal controls	Rheumatoid patients	Significant difference
Hallux	12 +- 5	7 +- 8	$p < 0.05$
MT1	15 +- 4	16 +- 10	$p > 0.05$
MT2	24 +- 7	16 +- 7	$p < 0.01$
MT3	20 +- 6	14 +- 6	$p < 0.01$
MT4	15 +- 5	12 +- 6	$p > 0.05$
MT5	9 +- 5	10 +- 9	$p > 0.05$
Midfoot	1 +- 2	3 +- 4	$p > 0.05$

Table 8. Mean values for the normal control and rheumatoid groups of the forces on parts of the foot at **heelrise** and the significance of the differences between these values.

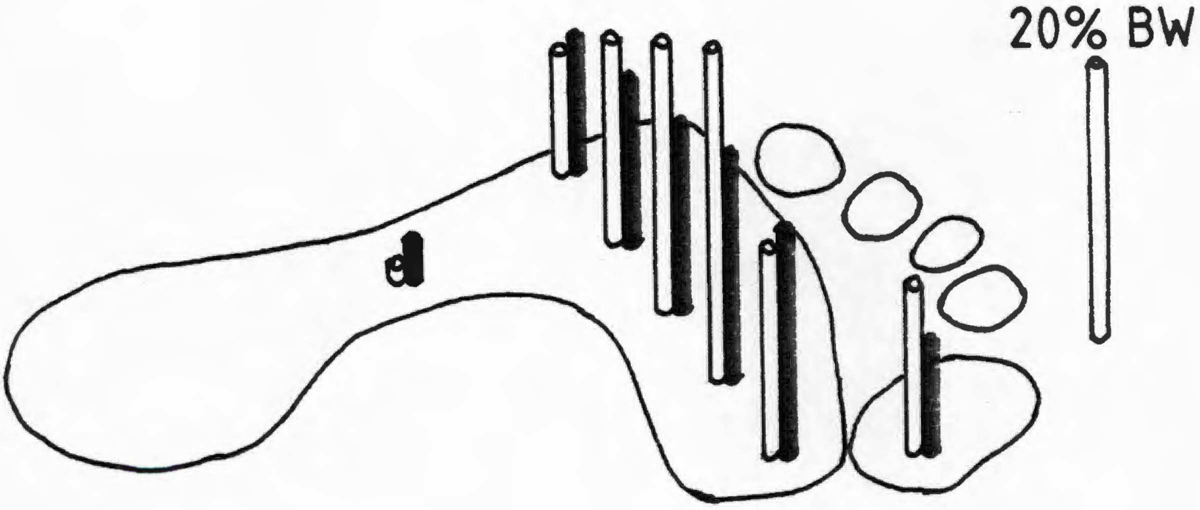


Fig. 48. Ground reaction forces on seven areas of the foot at heelrise. Normal controls (□), rheumatoid patients (■). BW - bodyweight.

that the total force at heelrise had been significantly smaller in the case of the rheumatoid group (cf. Table 5). In the light of the fact that the force distribution at heelrise was quite similar for normals and rheumatoids alike, it seemed highly probable that the decrease in the ground reaction forces at the hallux and metatarsals heads 2 and 3 could have accounted for the decrease in the total force at heelrise. Once again, as was the case during the analysis of forces at midstance, pairs were formed to circumvent the difficulty of trying to separate the forces acting on adjacent regions of interest. This arrangement did not reveal any new trends but served to confirm the pattern of force distribution which had been observed in Table 8. In summary one might say that the pattern of force distribution at heelrise was the same for normals and rheumatoids but the total force was significantly reduced in the case of the rheumatoid group.

During the discussion of the results of the digital camera system, mention was made of kinetic parameters which should also be brought into consideration when possible explanations are given concerning the gait pattern of people with RA. One of the most important kinetic factors is the ground reaction force which was studied extensively in this project.

As previously stated, a fear of falling as a result of a feeling of instability could have caused the rheumatoid patients to proceed more slowly and carefully than normal. Seeing that the rheumatoid patients' mean cadence remained more or less the same as that of the normal group, the stridelength was the only other parameter which could have been reduced in order to achieve the necessary reduction in walking speed. To achieve the reduction in stridelength would have necessitated, in turn, a reduction in the range of motion at the joints mainly responsible for gait i.e. the hip and knee. The reduced range of motion at the hip and knee joints of rheumatoid patients was reflected by the significantly reduced value of the area A when compared to the normal group. If a rheumatoid patient pushed off less forcefully than normal at the end of the stance phase (as was the case with the rheumatoid group in this study) a chain of events would be set into motion which could eventually result in a significant reduction in walking speed. This chain of events could perhaps run like this : a reduced push-off caused reduced linear and angular velocities of the lower extremity which caused reduced range of motion at the hip and knee joints which caused a reduced stridelength which eventually led to a reduction in walking speed. At each of these levels other contributing factors could be identified. For example, painful and stiff joints of the lower extremity -- keeping in mind that RA is a systemic disease -- would result in reduced range of motion at the affected joints. This could conceivably contribute to further reduction of the stridelength and walking speed. At the level of the ground reaction force, painful feet -- especially painful metatarsal heads -- could as a reasonable consequence, be partly or wholly responsible for a less forceful push-off at the end of the stance phase. Weakened calf muscles would certainly have contributed to the typically apropulsive gait of RA patients (Locke et al, 1984).

The effect of walking speed on ground reaction forces was minimised to the extent where it could have had very little influence on the magnitude of the forces measured with the PAOH force plate. Yet there were very definite and significant changes in the force distribution and total force on the rheumatoid foot at the different stages of the stance phase. These changes were shown in this and other studies (Gerber and Hunt, 1985 , Locke et al, 1984) to have strong associations with pathology of the lower extremity.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

Form of the rheumatoid foot. Statistical analayses of the results from the footprints and footcasts indicated that their respective flatfootedness indices correlated well with each other and with the clinical diagnosis of the flat feet. According to both indices rheumatoid feet were decidedly flatter, on average, than normal feet. On the basis of these findings I feel that the two indices concerned definitely go some way towards satisfying the need for techniques which enable one to express the degree of flatfootedness in RA in terms of quantitative parameters. A visual comparison between the X-ray, iodine footprint and contour diagram for the same foot revealed that there was indeed an obvious correlation between the internal structure of the foot and its external shape.

Function of the rheumatoid foot. Processing the digital camera data led me to observe the following pattern. Rheumatoids walked significantly slower than normal people with their stridelength significantly reduced as well. The fact that their combined range of motion at the hip and knee was also significantly reduced, tied in with the above-mentioned pattern i.e. this pattern confirmed the accepted and proven relationship between range of motion at the hip and knee and stridelength. Analysis of the force plate data revealed a general pattern in the case of the rheumatoid patients which differed significantly from that displayed by the normal control group. During the early stages of the stance phase there was no difference between the forces experienced by the two groups. However, at midstance the rheumatoid group exhibited a force distribution on the plantar surface of the foot that was quite different to the normal. Although the total force on the foot was more or less equal for both groups, the rheumatoids had a much larger proportion of their weight on the hindfoot than the normal controls and consequently, a much smaller proportion of their weight on the forefoot. One could say that the rheumatoids caused the transferral of weight from hindfoot to forefoot to be delayed, possibly to avoid the loading of a painful forefoot. At heelrise the rheumatoids experienced a significant reduction in the total force on the foot. However, the force distribution was essentially the same for both groups. The reduction in total force could be accounted for by the reduction in the forces experienced by the metatarsal heads 2 and 3. The reduced push-off, produced by the rheumatoids during the latter stages of the stance phase, once again seemed indicative of forefoot pathology and pain.

In order to have a more representative view of the function of the rheumatoid foot, the kinematic and kinetic parameters were considered to be acting in unison. Physical and also psychological factors could have had an influence on the gait pattern of the rheumatoid patients. Physical factors, such as forefoot pain, might have had a role to play in altering the pattern of ground reaction forces in rheumatoids. This would have led to a reduced stridelength and, eventually, to a reduction in walking speed. Diseased hip and knee joints would have had a further limiting influence on the stridelenth and walking speed. Psychological factors, such as a lack of confidence and a fear of falling, could also have caused the RA patients to slow down by forcing them to take smaller steps. Cadence never seemed to be of any major importance because, despite the complicating circumstances, the rheumatoids and normal controls had more or less the same cadence.

Conclusions

On the basis of the summary the following conclusions were reached :

- The incidence of flat feet in rheumatoid patients is significantly greater than in normal, non-rheumatoid subjects.
- Footcasts, footprints and any combination of these two methods with X-rays can provide the clinician with a better understanding of the form of the rheumatoid foot than X-rays alone.
- Physical and psychological factors can cause rheumatoid patients to adopt a gait pattern which is significantly different from that of normal, non-rheumatoid subjects.
- Forefoot pathology had a much larger role to play in changing rheumatoid gait, biomechanically speaking, than did hindfoot pathology.

* The combination of digital camera and force plate at the Princess Alice Orthopaedic Hospital can provide the clinician with a vastly improved understanding of the biomechanical function of the lower extremity when coupled with subjective visual inspection of the gait pattern.

Judging from these conclusions, it is clear that both hypotheses posed at the beginning of this study in Chapter 1 have been supported.

Recommendations

Future research of this kind into RA could prove even more valuable if it were done on a before-and-after basis -- i.e. before and after surgery and/or physiotherapy -- while still including the necessary normal control group as well. An extension of this could be serial studies where the object would be to study the progression of the disease. It would be advisable to have as large a sample of RA patients as is practically possible, because this would make for more meaningful and decisive statistics.

If the digital camera could be operated at an increased sampling rate it would increase the validity and reliability of the captured data.

Insight may be gained into the cause-and-effect relationship existing between certain kinematic and kinetic parameters by including the monitoring and analysis of electromyographic activity in future studies.

APPENDIX A

CALIBRATION OF TECHNIQUES

Digital Camera System

A 128 x 64 pixel array was used to reproduce the position of the retro-reflective markers on the screen. This arrangement allowed the digital camera to sample at its highest rate which was 13 Hz (i.e. 13 frames per second). Because the corresponding area per pixel changed as the camera-to-subject distances changed, scale factors pertaining to a particular distance had to be calculated for the X and Y axes. This was done by placing four markers in a diamond formation (see Fig. 49). The positions

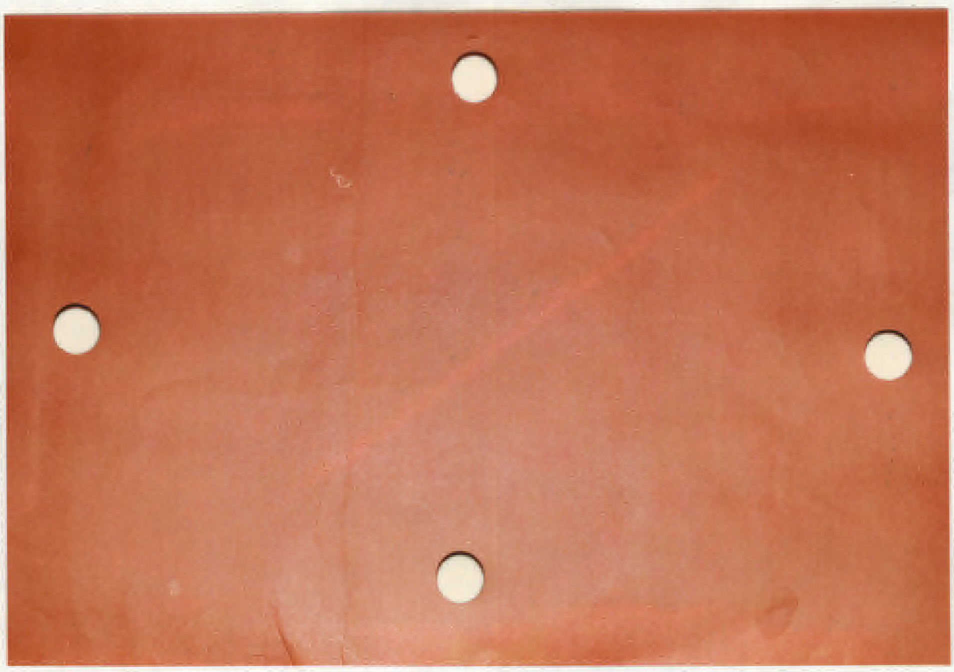


Fig. 49. Retro-reflective markers in diamond formation for calibration of digital camera.

of the markers were calculated by the camera in terms of the number of pixels counting from the bottom left hand corner of the screen. In order for marker separations to be calculated in terms of actual distances, a scale factor, as mentioned, had to be introduced for each axis. Due to the rectangular shape of the memory cells two scales were required, one for each of the axes. A series of scale factors for the X and Y directions was calculated for camera-to-subject distances ranging from 5 m to 10 m. The separation between the two markers in the X direction was held constant at 1.17 m. The separation in the Y direction was also held constant at 0.54 m except for the case where the camera-to-subject distance was 4.86 m. Here the Y separation was reduced to 0.47 m because of the limited vertical field of view of the digital camera (see Table 9).

Distance (m)	X separation (m)	Y separation (m)	X scale	Y scale
10.52	1.17	0.54	46.8	18.0
9.07	1.17	0.54	39.0	15.4
7.55	1.17	0.54	32.5	12.9
5.99	1.17	0.54	25.4	10.4
4.86	1.17	0.47	21.3	8.5

Table 9. Calculation of scale factors for the X and Y axes.

There existed highly significant positive correlations between the X and Y scale factors and the camera-to-subject distance (r = 0.9980 for X scale and 0.9999 for Y scale) which in turn suggested the existence of definite linear relationships between the scale factors and the distance. In order to normalise, the scale factors were divided by the distance, and the means of the normalised scale factors calculated. These were 4.334 +- 0.073 and 1.722 +- 0.019 for the X and Y directions respectively. The inclusion of these normalised scale factors in the programs for capturing and displaying the data meant that only the distance from camera to subject had to be measured in order to obtain the appropriate X and Y scale factors.

Provision was made for the camera to be aligned with the vertical. This was necessary because the thigh angle was measured with respect to the vertical. The procedure involved placing two markers, one above the other, along a vertical line of reference within the field of view of the camera. The difference in X values for these two markers reflected the amount by which the camera had strayed from the vertical. Slight adjustment of the camera on the trolley (see Fig. 50) made it possible to align the camera as near to the vertical as was possible within its limits of resolution and accuracy.

The algorithm for calculating the area A of an angle-angle diagram (see Appendix D) provided me with values having an accuracy better than 1%. The area of a hypothetical angle-angle diagram (2970 mm^2) was determined by drawing it on graph paper with 2 mm gradations. Comparing this value to that given by the algorithm (2962 mm^2) revealed a difference of only 0.3%.

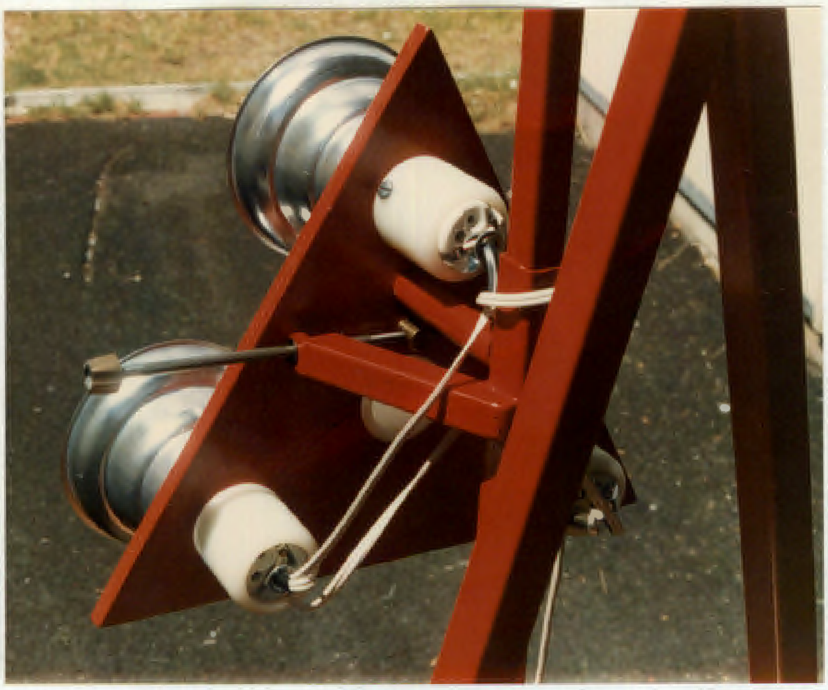


Fig. 50 Adjusting screw for aligning the digital camera with the vertical.

Force Plate System

A calibration procedure was carried out to ensure the reliability and repeatability of the measurements on the force plate. With the force plate unloaded, a calibration bar on the video monitor was always adjusted to a width of 10 mm prior to each session of recording. This set the sensitivity of the force plate to a pre-determined level. After each recording, the recorded force values had to be erased by pressing a button which removed any residual voltages and reset everything to zero.

The response curve of each beam of the force plate was investigated at three points -- i.e. in the middle of the beam and 2 cm from either end -- using a calibration jig (see Fig. 51). A satisfactory linear response was found in each case.

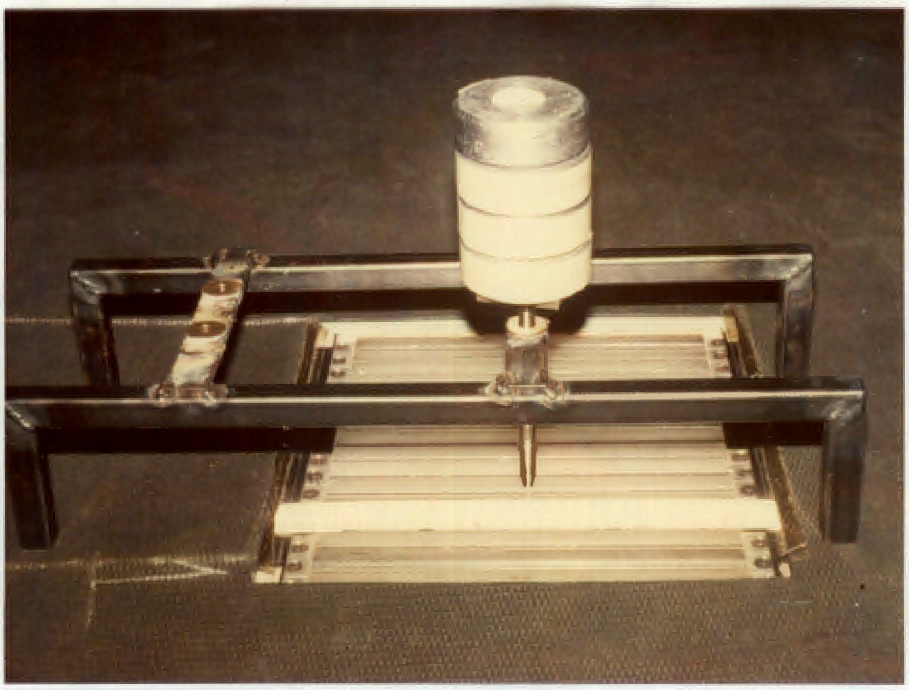


Fig. 51. Calibration jig for the PAOH force plate.

Beams were also compared with one another to ascertain whether a uniform sensitivity existed across the plate. No significant differences were found between any beams and it was concluded that the forces experienced by different beams could be used in statistical comparisons.

APPENDIX B

SOURCES OF ERROR

Evaluation of Form

Footcasts. The consistency of the casting sand might have differed from subject to subject, depending on the amount of talcum powder used and the period of time that elapsed from the mixing to making the imprint. The subject might have leant forward of backwards -- even though a chair was provided to hold onto -- or put more weight than usual on the foot of which the imprint was being taken. Any one of the above factors could have caused the imprint to be slightly deeper than normal in some areas. However, when analysing the casts, only the relative differences in height on the comtour diagrams were regarded as important. The absolute heights of the contours were therefore not of any real consequence. When lifting their feet from the sand, some fine features of the imprint were sometimes disturbed. Dusting off residual sand clinging to the Plaster of Paris cast with a brush, may also have smoothed-out some of the fine detail on the cast.

Digitising the footcasts required the placement of a fine pinpoint of light onto an image of the cast. Day-to-day differences in my own depth perception may have accounted for a variation of possibly not more than +- 0.5 mm in reading heights on the casts. The maximum of 400 points per casts, which could be digitised, put some restriction on exact reproduction of the contours of the cast itself. Around the edges, particularly at the heel, the interpolating polynomial created some artificially wavy contours. However, this did not have any significant influence on the information content of the contour diagram as a whole.

In calculating the contour index for each footcast, the high spots on the heel and first metatarsal head were selected as reference points. This was done by visual inspection of the contour diagrams. The placement of the reference points influenced the direction of the line connecting them, but the difference in the number of contours transected by this line in traversing the arch of the foot would not have been more than 2.

Footprints. The width of the foot at the arch (so-called narrowest waist distance) depended to some degree on how well the plantar surface had been wetted with iodine and whether the foot was rolled from side to side when putting it on or lifting it off the paper. The heelpad distance was also influenced by rolling the foot from back to front when placing it on the paper. Variation in the method for taking the measurements from the footprints may have provided the opportunity for some error to enter into the calculations.

X-rays. In measuring the hallux valgus and metatarsal 1,2 angles, lines were drawn along the shafts of the first and second metatarsals and the proximal phalanx of the hallux. This was done by visual inspection and the line of the long bones were estimated. This could have resulted in a possible error of approximately +- 5^o. In the case of the talometatarsal angle the line of the body of the talus also had to be estimated. This may have resulted in a similar error of +- 5°. The angles measured on the antero-posterior and lateral views of the foot would not have been adversely affected by the X-ray source not having been perpendicular to the plane of the angle concerned.

Evaluation of Function

Digital camera system. In obese rheumatoid patients identification of bony landmarks proved to be somewhat difficult, particularly the greater trochanter which was taken as being representative of the axis of the hip joint. Van Best et al (1984) suggested that the error involved in positioning a marker at a bony reference point on the body was between 10 mm and 20 mm. It was felt that while skin movement did also have some effect on the marker positions, the quality of the angular displacement data was not noticeably influenced by this.

Instructing people to walk as they usually do almost invariably had the opposite effect. They would walk slower, faster, try to hide their disability, or exaggerate it, etc. Even if the person had settled down and was able to walk the way he/she would walk when leaving the hospital, that person might still sub-consciously have been trying to "improve" his/her gait in order to please the gait analyst.

Depending on the ambient lighting conditions, i.e. whether the sun shone brightly outside or not, the exposure time per frame had to be increased from 10 ms to 15 ms. This meant that the effective sampling rate dropped from 13 Hz to 12 Hz.

However, this was still thought to be sufficient for the recording of walking subjects who typically display movements of a frequency not higher than 6 Hz.

In analysing the data the effect of the rather slow sampling rate was clearly seen. The determination of walking speed, stridelength and cadence relied heavily upon the accurate identification of consecutive heelstrikes. Due to the slow sampling rate, it was quite possible for one or both heelstrikes to fall in between frames. The effect of this was not so dramatic in the case of the stridelength. The walking speed and cadence, however, appeared to be much more sensitive to the number of frames in between heelstrikes because of the low sampling rate. The reason for this was that near to heelstrike, little distance was being added to the stridelength as the foot was moving quite slowly. In contrast to the small distance traversed, the time kept on increasing at the steady rate of 0.08 s per frame.

The thigh-knee angle-angle diagrams were not as smooth and rounded as they could have been with a higher sampling rate. The three quantitative parameters, devised by Hershler and Milner (1980), could have been influenced to a degree by this. Both the area A and perimeter P might have been increased somewhat due to the ragged outline of the angle-angle diagrams. The combination of these two factors might have had some influence on the value of the ratio $\frac{P}{A}$. However, the ragged appearance of the rheumatoid angle-angle diagrams during the stance phase could have been partly due to a lack of coordination and stability on the part of the RA patients.

Subjects walked twice in each direction and the averages of temporal, distance, and angular parameters were calculated for each subject. Intrasubject repeatability between the two trials on each side as well as between left and right was thought to be satisfactory for both the normal and rheumatoid groups.

Force plate system. There is an accepted and proven relationship between the walking speed and relative magnitude of the ground reaction forces during the stance phase (cf. Vaughan et al, 1985). Typically, walking speed has its most noticeable effects during the deceleration phase just after heelstrike, and during the acceleration phase before and at push-off, when a reduced walking speed will result in reduced ground reaction forces.

In this study, there was no reduction in the relative magnitude of the ground reaction forces during the earlier stages of the stance phase. Therefore, the significant reduction in the total force at heelrise, during the latter stages of the stance phase, could not have been the result of a reduced walking speed but rather of a refusal of the rheumatoid patients to load their painful forefeet. It would seem that in this case the reduction in the ground reaction forces was the cause of slower walking and not the result of it.

Working with the force plate the problem of targetting -- the subject changing his/her stridelength and/or cadence in order to step onto the plate correctly -- was a definite source of error. The artificiality of the test environment may have contributed to the problem of targetting by causing people to be even more anxious and nervous than what they would have been in a clinical environment.

Colour slides were taken of the monitor screen. The curvature of the cathode ray tube may have introduced a small error during the measurement stage when the measurements were taken on a flat surface. A photographic enlarger enabled me to measure the heights of the bars on the enlarged slides, using a steel ruler with 1 mm gradations. The heights were probably measured to an accuracy of +- 1 mm because of fuzzy edges -- a result of the enlargement.

The bodyweights of the subjects were recorded at a later date after the initial force recordings, which meant that the characteristics of the force plate might have changed in the interim. The slides of the bodyweight bar charts were also from a position slightly closer to the screen than the previous recordings. Consequently, the force values for the bodyweights had to be converted in order to be consistent with data from these previous recordings. The forces at the different stages were presented as a percentage of the bodyweight of each person, rounded off to the nearest integer.

Much more data than could reasonably be handled were generated by the force plate. A visual comparison was therefore made of the consecutive trials recorded for each subject and the most representative force patterns were chosen for the left and right feet respectively. However, this meant that intrasubject repeatability was only assessed qualitatively and not quantitatively.

APPENDIX C

PROGRAMS FOR EVALUATION OF FORM

This appendix contains the BASIC program and mainframe runstream respectively which were used to digitise the Plaster of Paris footcasts. The BASIC program was used in conjunction with the Reflex Metrograph to capture the data. The mainframe runstream, which was used to produce the contour diagrams, is part of the Sperry SACLANT graphics package. Program material was supplied by Prof. L.P. Adams of the U.C.T. Department of Surveying.

```
100 INIT
101 PRINT @32,26:2
110 PRINT "THIS IS LEON DU TOIT'S FOOTCAST PROGRAM"
120 PRINT "USING THE REFLEX METROGRAPH"
130 PRINT "START OBSERVING IN SINGLE SHOT MODE"
140 PRINT "WHEN YOU HAVE FINISHED OBSERVING, PRESS BREAK,BREAK"
150 PRINT "THEN RUN 500"
155 PRINT "G_G_G_G_"
160 DIM X(400), Y(400), Z(400)
170 CALL "CMINIT"
180 CALL "RATE",1200,4,0
190 CALL "EOLCHR",13,"START",0
200 CALL "RCRLF",1,2,0
210 FOR J = 1 TO 400
220 INPUT @40,13:A$
230 FOR M = 1 TO 3
240 N = M * 7 - 6
250 B$ = SEG(A$,N,6)
260 C = VAL(B$)
270 IF C < 500000 THEN  290
280 C = C - 1000000
290 C = INT(C) / 200
300 IF M = 2 THEN  340
310 IF M = 3 THEN  360
320 X(J) = C
330 GO TO 370
340 Y(J) = C
350 GO TO 370
```

```
360 Z(J) = C
370 NEXT M
375 PRINT "G_G_G_G_"
376 X(J) = -X(J)
379 PRINT J,X(J),Y(J),Z(J)
380 NEXT J
500 PRINT  "THE NUMBER OF POINTS OBSERVED =",J-1
510 FOR I = 1 TO J-1
520 PRINT @3,32: USING 530: I,X(I),Y(I),Z(I)
530 IMAGE 2X,3D,2X,5D.1D,2X,5D.1D,2X,5D.1D,(/,L)
540 NEXT I
550 PRINT "WHAT FILE DO YOU WANT DATA STORED ?"
551 INPUT T
552 FIND T
553 PRINT "WHAT IS THE LEAST VALUE OF Z ?"
554 INPUT Z1
560 FOR I = 1 TO J-1
570 PRINT @33: X(I),Y(I),Z(I)-Z1
580 NEXT I
590 END
```

```
@RUN,Z/N LEON,A0605-R002,FOOT,2,50
@SYM PRINT$,,RMTENG
@PRT,S FOOT.FOOT
@ASG,A FILENAME.
@ASG,G FILENAMEBP.
@USE RSPACED,FILENAME
@USE BLPOLY,FILENAMEBP.
@GDP*ABS.INPUT PLOTFILE.
@ADD,P SYS$*3D.XQT
RECTAN XMAX-XMIN,YMAX-YMIN
GRID 60,40
UCOORDS XMIN XMAX YMIN YMAX
NRNG4 4
@EOF
@EOF
@ADD,P SYS$*3D.XQT
RECTAN XMAX-XMIN,YMAX-YMIN
GRID 60,40
PEN CONTOUR,''PEN P1-BK/F ''
PEN 3D,''PEN P1-BK/F ''
TITLE ''FILE NAME''
CONTOUR
BLPOLY
UCOORDS XMIN XMAX YMIN YMAX
LEVINC 1 -1
NRNG 4
CAY 2
NARC 2
NDIV 2
@EOF
@EOF
```

APPENDIX D

PROGRAMS FOR EVALUATION OF FUNCTION

The Capture program makes use of three Assembler routines i.e. CAMASM.OBJ, CRUNCH.OBJ, AND SCALER.OBJ which were developed by D. Smith as part of a final-year engineering project.

```
100  REM   **************************************
110  REM
120  REM                  CAPTURE
130  REM
140  REM   THIS PROGRAM ALIGNS AND CALIBRATES
150  REM   THE MICRONEYE DIGITAL CAMERA,
160  REM   CAPTURES THE DATA, CHECKS IT, AND
170  REM   STORES IT TO DISK IF YOU WISH.
180  REM
190  REM   CREATED 19/4/85
200  REM   UPDATED 6/3/86
210  REM
220  REM   **************************************
230  REM
240  DIM X(4,40),Y(4,40),M(4,40)
250 XS = 1:YS = 1
260  HIMEM: 16383
270  REM  ************************* MENU *********************
280  HOME : VTAB 2: HTAB 18: INVERSE : PRINT "MENU": NORMAL
290  PRINT : PRINT : HTAB 5: PRINT "(1) CALIBRATE"
300  PRINT : HTAB 5: PRINT "(2) ALIGN CAMERA"
310  PRINT : HTAB 5: PRINT "(3) CAPTURE RAW DATA"
320  PRINT : HTAB 5: PRINT "(4) CHECK RAW DATA"
330  PRINT : HTAB 5: PRINT "(5) STORE DATA TO DISK"
340  PRINT : HTAB 5: PRINT "(6) QUIT"
350  PRINT : PRINT : PRINT "ENTER YOUR CHOICE NOW...": GET C: HOME
360  IF C = 1 THEN  GOSUB 430: REM  CALIBRATE
370  IF C = 2 THEN  GOSUB 1120: REM  ALIGN
380  IF C = 3 THEN  GOSUB 730: REM  CAPTURE
390  IF C = 4 THEN  GOSUB 1230: REM  CHECK
400  IF C = 5 THEN  GOSUB 930: REM  STORE
410  IF C = 6 THEN  END
420  GOTO 270
430  REM  ***************** CALIBRATION ************************
440  HOME : VTAB 5: PRINT "DO YOU WISH TO CALIBRATE USING FOUR     MARKERS? (Y/N
) ";
450  GET K$
460  IF K$ = "Y" THEN 570
470  HOME : VTAB 5: PRINT "NEW SCALE FACTORS? (Y/N) ";: GET K$
480  IF K$ = "N" THEN  RETURN :DS = 0
490  HOME : VTAB 5: INPUT "DISTANCE (m) = ";DS
500 XS = 0:YS = 0
510 XS = 4.334 * DS:YS = 1.722 * DS
520  HOME : VTAB 5: PRINT "XS = "; INT (XS * 100) / 100
530  PRINT : PRINT "YS = "; INT (YS * 100) / 100
540  PRINT : PRINT : PRINT "SATISFIED? (Y/N) ";: GET K$
550  IF K$ = "N" THEN 490
560  RETURN
570  PRINT : INPUT "ENTER SOAKTIME...";SK:FR = 5
580  HOME : PRINT : PRINT : HTAB 15: INVERSE : PRINT "CALIBRATING": NORMAL
590  GOSUB 1440: REM  MICRONEYE ROUTINES
600 XL = 0:XR = 0:YT = 0:YB = 0
610 XS = 0:YS = 0
620  FOR I = 0 TO 4:XL = XL + X(1,I):XR = XR + X(2,I):YT = YT + Y(0,I):YB = YB +
 Y(3,I): NEXT I
630 T0 = (XR - XL) / 5
640 T1 = (YT - YB) / 5
650  HOME : VTAB 5: INPUT "ENTER X SEPARATION (MM)...";XS
660  HOME : VTAB 5: INPUT "ENTER Y SEPARATION (MM)...";YS
```

```
670 XS = XS / T0:YS = YS / T1
680  PRINT : PRINT : PRINT "XS = ";XS
690  PRINT : PRINT "YS = ";YS
700  PRINT : PRINT : PRINT "SATISFIED? (Y/N) ": GET K$
710  IF K$ = "N" THEN 580
720  RETURN
730  REM  ******************** CAPTURE DATA *******************
740  HTAB 10: INVERSE : PRINT "LOADING CAMASM.OBJ": NORMAL
750  PRINT  CHR$ (4);"BLOAD CAMASM.OBJ,A$8000"
760  HOME : VTAB 5
770  INPUT "ENTER SOAKTIME IN MSEC...";SK
780  PRINT : PRINT
790  INPUT "ENTER NUMBER OF FRAMES...";FR
800  POKE 769,SK: POKE 770,FR:GE = 32768
810  CALL GE
820  HOME : PRINT : PRINT : HTAB (10): INVERSE : PRINT "LOADING CRUNCH.OBJ": NOR
MAL
830  PRINT  CHR$ (4);"BLOAD CRUNCH.OBJ,A$8000"
840  POKE 770,FR
850  CALL GE
860  HOME : PRINT : PRINT : HTAB 10: INVERSE : PRINT "LOADING SCALER.OBJ,A$8000"
: NORMAL
870  PRINT  CHR$ (4);"BLOAD SCALER.OBJ,A$8000"
880  HOME
890  POKE 769,FR
900  CALL GE
910  POKE 33,40
920  RETURN
930  REM  ***************** STORE RAW DATA *******************
940  PRINT : INPUT "PATIENT NO  ";PN
950  PRINT : INPUT "VISIT NO  ";VN
960  PRINT : INPUT "NAME  ";N$
970  PRINT : INPUT "HOSPITAL NO:  ";H$
980  PRINT : INPUT "TODAY'S DATE IS ";D$
990  PRINT : PRINT : INPUT "NAME OF FILE TO STORE DATA..";S$
1000  PRINT  CHR$ (4);"OPEN"S$
1010  PRINT  CHR$ (4);"WRITE"S$
1020  PRINT SK: PRINT FR
1030  PRINT PN: PRINT VN
1040  PRINT N$: PRINT H$
1050  PRINT D$
1060  FOR I = 0 TO FR - 1: FOR J = 0 TO 4
1070  PRINT X(J,I)
1080  PRINT Y(J,I)
1090  NEXT J: NEXT I
1100  PRINT  CHR$ (4);"CLOSE"S$
1110  RETURN
1120  REM  ******************* ALIGN CAMERA ******************
1130  HOME : VTAB 5: INPUT "SOAKTIME IN MSEC...";SK:FR = 1
1140 X(0,0) = 0:X(1,0) = 0
1150 DI = 0
1160  HOME : VTAB 5: INVERSE : PRINT "ALIGNING CAMERA": NORMAL
1170  GOSUB 1440: REM  MICRONEYE ROUTINES
1180 DI = X(0,0) - X(1,0): REM  DIFFERENCE IN X VALUES
1190  HOME : VTAB 5: PRINT "X-TOP = ";X(0,0): PRINT : PRINT "X-BOTTOM = ";X(1,0)
: PRINT : PRINT "DIFFERENCE = ";DI
1200  PRINT : PRINT : INPUT "SATISFIED? (Y/N) ";K$
1210  IF K$ = "N" THEN 1140
1220  RETURN
1230  REM  ***************** CHECK RAW DATA ******************
1240  FOR I = 0 TO FR - 1
1250  PRINT I;" ";X(0,I);" ";Y(0,I);" ";X(1,I);" ";Y(1,I);" ";X(2,I);" ";Y(2,I)
1260  NEXT I
```

```
1270  PRINT : PRINT "ANY PROBLEMS? (Y/N)..": GET K$
1280  IF K$ = "N" THEN  RETURN
1290  PRINT : PRINT "ANY NEIGHBOURING FRAMES? (Y,N)": GET K$
1300  IF K$ = "N" THEN 1350
1310  INPUT "FIRST PROBLEM FRAME #..";PF
1320  FOR J = 0 TO 2:X(J,PF) = X(J,PF - 1) + (X(J,PF + 2) - X(J,PF - 1)) / 3:Y(J
,PF) = Y(J,PF - 1) + (Y(J,PF + 2) - Y(J,PF - 1)) / 3
1330 X(J,PF + 1) = X(J,PF - 1) + (X(J,PF + 2) - X(J,PF - 1)) * 2 / 3:Y(J,PF + 1)
 = Y(J,PF - 1) + (Y(J,PF + 2) - Y(J,PF - 1)) * 2 / 3: NEXT J
1340  GOTO 1410
1350  PRINT : INPUT "PROBLEM FRAME #..";PF
1360  IF PF = 0 THEN 1390: IF PF = FR - 1 THEN 1390
1370  FOR J = 0 TO 2:X(J,PF) = (X(J,PF - 1) + X(J,PF + 1)) / 2:Y(J,PF) = (Y(J,PF
 - 1) + Y(J,PF + 1)) / 2: NEXT J
1380  GOTO 1410
1390  INPUT "EQUATE TO FRAME #..";GF
1400  FOR J = 0 TO 2:X(J,PF) = X(J,GF):Y(J,PF) = Y(J,GF): NEXT J
1410  PRINT "FINISHED? (Y,N)..": GET K$
1420  IF K$ = "Y" THEN  RETURN
1430  GOTO 1290
1440  REM  **************** MICRONEYE ROUTINES ****************
1450  PRINT  CHR$ (4);"BLOAD CAMASM.OBJ,A$8000"
1460  POKE 769,SK: POKE 770,FR:GE = 32768
1470  CALL GE
1480  PRINT  CHR$ (4);"BLOAD CRUNCH.OBJ,A$8000"
1490  POKE 770,FR
1500  CALL GE
1510  PRINT  CHR$ (4);"BLOAD SCALER.OBJ,A$8000"
1520  POKE 769,FR
1530  CALL GE
1540  RETURN
```

```
100  REM  **********************************
110  REM
120  REM                    DISPLAY
130  REM
140  REM  THIS PROGRAM READS RAW DATA FROM
150  REM  DISK, PLOTS STICK FIGURES, CONSTRUCTS
160  REM  ANGLE-ANGLE DIAGRAMS, CALCULATES
170  REM  TEMPORAL AS WELL AS OTHER ANGLE-ANGLE
180  REM  PARAMETERS.
190  REM
200  REM   CREATED 22/4/85
210  REM   UPDATED 6/3/86
220  REM
230  REM  **********************************
240  REM
250  DIM X(4,40),Y(4,40),H(40),A(40),K(40),P(40),R(40)
260  HIMEM: 16383
270  HOME : PRINT : PRINT
280  REM  ****************** MENU *********************
290  HOME : VTAB 2: HTAB 18: INVERSE : PRINT "MENU": NORMAL
300  PRINT : PRINT : HTAB 5: PRINT "(1) READ DATA FROM DISK"
310  PRINT : HTAB 5: PRINT "(2) SET SCALE FACTORS TO PLOT"
320  PRINT : HTAB 5: PRINT "(3) PLOT RAW DATA"
330  PRINT : HTAB 5: PRINT "(4) PLOT STICK FIGURES"
340  PRINT : HTAB 5: PRINT "(5) PLOT A-A DIAGRAM"
350  PRINT : HTAB 5: PRINT "(6) CALCULATE SPEED ETC."
360  PRINT : HTAB 5: PRINT "(7) PLOT KNEE ANGLE VS. TIME"
370  PRINT : HTAB 5: PRINT "(8) CALCULATE A-A PARAMETERS"
380  PRINT : HTAB 5: PRINT "(9) QUIT"
390  PRINT : PRINT : PRINT "ENTER YOUR CHOICE NOW...": GET C: HOME
400  IF C = 1 THEN  GOSUB 510: REM  READ DISK
410  IF C = 2 THEN  GOSUB 3380: REM  SCALE FACTORS
420  IF C = 3 THEN  GOSUB 660: REM  PLOT DOTS
430  IF C = 4 THEN  GOSUB 930: REM  PLOT STICKS
440  IF C = 5 THEN  GOSUB 1220: REM  PLOT A-A
450  IF C = 6 THEN  GOSUB 1930: REM  TEMP PARMS
460  IF C = 7 THEN  GOSUB 2590: REM  KNEE ANGLE
470  IF C = 8 THEN  GOSUB 3090: REM  A-A PARMS
480  IF C = 9 THEN  END
490  GOTO 270
500  PRINT : PRINT
510  REM   ****************** READ DATA FROM DISK *********
520  PRINT : INPUT "NAME OF FILE TO BE READ..";R$
530  PRINT  CHR$ (4);"OPEN"R$
540  PRINT  CHR$ (4);"READ"R$
550  INPUT SK: INPUT FR
560  INPUT PN: INPUT VN
570  INPUT N$: INPUT H$
580  INPUT D$
590  FOR I = 0 TO FR - 1: FOR J = 0 TO 4
600  INPUT X(J,I)
610  INPUT Y(J,I)
620  NEXT J: NEXT I
630  PRINT  CHR$ (4);"CLOSE"R$
640  POKE 33,40
650  RETURN
660  REM  *************** PLOT RAW DATA ********************
670  PRINT : PRINT : PRINT "(S)CREEN DISPLAY OR (P)RINTOUT?": GET K$
680  IF K$ = "S" THEN 830
```

```
690  PRINT
700  PRINT  CHR$ (4);"PR#1 "
710  PRINT : HTAB 4: PRINT "SUMMARY OF PATIENT INFORMATION": GET K$
720  IF K$ = "Y" THEN  GOSUB 1740
730  GOSUB 1820: REM  CHARGEN
740  HGR2 : HCOLOR= 3: HPLOT 0,45 TO 279,45 TO 279,145 TO 0,145 TO 0,45
750  GOSUB 2230: REM  LABEL DOTS
760  SPEED= 230
770  FOR I = 0 TO FR - 1: FOR J = 0 TO 4: HPLOT X(J,I) / FX,145 - Y(J,I) / FY
780  NEXT J: NEXT I: GET A$: TEXT : SPEED= 255
790  PRINT  CHR$ (9);"G2"
800  PRINT
810  PRINT  CHR$ (4);"PR#0 "
820  GOTO 910
830  PRINT : HTAB 4: PRINT "SUMMARY OF PATIENT INFORMATION": GET K$
840  IF K$ = "Y" THEN  GOSUB 1740
850  GOSUB 1820: REM  CHARGEN
860  HGR2 : HCOLOR= 3: HPLOT 0,45 TO 279,45 TO 279,145 TO 0,145 TO 0,45
870  GOSUB 2230: REM  LABEL DOTS
880  SPEED= 230
890  FOR I = 0 TO FR - 1: FOR J = 0 TO 4: HPLOT X(J,I) / FX,145 - Y(J,I) / FY
900  NEXT J: NEXT I: GET A$: TEXT : SPEED= 255
910  HOME
920  RETURN
930  REM  ****************** PLOT STICK FIGURES ************************
940  PRINT "(S)CREEN DISPLAY OR (P)RINTOUT?": GET K$
950  IF K$ = "S" THEN 1110
960  PRINT
970  PRINT  CHR$ (4);"PR#1"
980  GOSUB 1820: REM  CHARGEN
990  HGR2 : HCOLOR= 3: HPLOT 0,45 TO 279,45 TO 279,145 TO 0,145 TO 0,45
1000  GOSUB 2290: REM  LABEL STICKS
1010  SPEED= 230
1020  FOR I = 0 TO FR - 1: FOR J = 0 TO 1
1030  IF Y(J,I) > 1340 THEN Y(J,I) = 1340
1040  IF X(J,I) = 0 OR X(J + 1,I) = 0 OR Y(J,I) = 0 OR Y(J + 1,I) = 0 THEN I = I
 + 1: IF I = FR - 1 THEN X(J + 1,I) = X(J,I)
1050  HPLOT X(J,I) / FX,145 - Y(J,I) / FY TO X(J + 1,I) / FX,145 - Y(J + 1,I) /
FY
1060  NEXT J: NEXT I: GET A$: TEXT : SPEED= 255
1070  PRINT  CHR$ (9);"G2"
1080  PRINT
1090  PRINT  CHR$ (4);"PR#0 "
1100  GOTO 1200
1110  GOSUB 1820: REM  CHARGEN
1120  HGR2 : HCOLOR= 3: HPLOT 0,45 TO 279,45 TO 279,145 TO 0,145 TO 0,45
1130  GOSUB 2290: REM  LABEL STICKS
1140  SPEED= 230
1150  FOR I = 0 TO FR - 1: FOR J = 0 TO 1
1160  IF Y(J,I) > 1340 THEN Y(J,I) = 1340
1170  HPLOT X(J,I) / FX,145 - Y(J,I) / FY TO X(J + 1,I) / FX,145 - Y(J + 1,I) /
FY
1180  IF X(J,I) = 0 OR X(J + 1,I) = 0 OR Y(J,I) = 0 OR Y(J + 1,I) = 0 THEN I = I
 + 1
1190  NEXT J: NEXT I: GET A$: TEXT : SPEED= 255
1200  HOME
1210  RETURN
1220  REM  ********************** PLOT A-A DIAGRAM **********************
1230  PRINT : INPUT "FOR WHICH LEG?  ";L$
1240  PRINT : INPUT "BEGIN WITH FRAME # (COUNT FROM 0)..";BE
1250  PRINT : INPUT "END WITH FRAME # (COUNT BACK FROM 29).";EN
1260  GOSUB 3500: REM  CALCULATE KNEE ANGLE
```

```
1270  FOR I = BE TO EN
1280  IF Y(0,I) = Y(1,I) THEN H(I) = 1.5708: GOTO 1390
1290 H(I) =  ATN ((X(1,I) - X(0,I)) / (Y(0,I) - Y(1,I)))
1300  IF L$ = "L" THEN H(I) = ( - 1) * H(I)
1310 H(I) = (H(I) / 1.222) * 186 + 146
1320 K(I) = 153 - (K(I) / 1.745) * 150
1330  NEXT I
1340  HOME : VTAB 5
1350  PRINT "(S)CREEN DISPLAY OR (P)RINTOUT?": GET K$
1360  IF K$ = "S" THEN 1550
1370  PRINT
1380  PRINT  CHR$ (4);"PR#1"
1390  GOSUB 1820: REM  CHARGEN
1400  HGR2 : HCOLOR= 3: HPLOT 80,18 TO 266,18 TO 266,168 TO 80,168 TO 80,18
1410  HPLOT 80,153 TO 266,153
1420  HPLOT 146,18 TO 146,168
1430  HPLOT 80,63 TO 84,63: HPLOT 80,108 TO 84,108: HPLOT 106,164 TO 106,168: HP
LOT 186,164 TO 186,168: HPLOT 226,164 TO 226,168
1440  GOSUB 2350: REM  LABEL A-A
1450  SPEED= 230
1460  FOR I = BE TO EN
1470  IF I = EN THEN H(I + 1) = H(I)
1480  IF I = EN THEN K(I + 1) = K(I)
1490  HPLOT H(I),K(I) TO H(I + 1),K(I + 1)
1500  NEXT I: GET A$: TEXT : SPEED= 255
1510  PRINT  CHR$ (9);"G2"
1520  PRINT
1530  PRINT  CHR$ (4);"PR#0 "
1540  GOTO 1730
1550  GOSUB 1820: REM  CHARGEN
1560  PRINT : PRINT "(L)INE DRAWING  OR  (D)OTS?..": GET C$
1570  HGR2 : HCOLOR= 3: HPLOT 80,18 TO 266,18 TO 266,168 TO 80,168 TO 80,18
1580  HPLOT 80,153 TO 266,153
1590  HPLOT 146,18 TO 146,168
1600  HPLOT 80,63 TO 84,63: HPLOT 80,108 TO 84,108: HPLOT 106,164 TO 106,168: HP
LOT 186,164 TO 186,168: HPLOT 226,164 TO 226,168
1610  GOSUB 2350: REM  LABEL A-A
1620  SPEED= 100
1630  FOR I = BE TO EN
1640  IF I = EN THEN H(I + 1) = H(I)
1650  IF I = EN THEN K(I + 1) = K(I)
1660  IF C$ = "D" THEN 1690
1670  HPLOT H(I),K(I) TO H(I + 1),K(I + 1)
1680  GOTO 1700
1690  HPLOT H(I),K(I)
1700  NEXT I: GET A$: TEXT : SPEED= 255
1710  HOME : PRINT : PRINT "DRAW AGAIN?  (Y,N)..": GET K$
1720  IF K$ = "Y" THEN 1550
1730  RETURN
1740  REM  ******************* PATIENT INFO *******************
1750  PRINT : HTAB 8: PRINT "PATIENT NO:  "PN
1760  PRINT : HTAB 8: PRINT "VISIT NO:  "VN
1770  PRINT : HTAB 8: PRINT "NAME:  "N$
1780  PRINT : HTAB 8: PRINT "HOSPITAL NO:  ";H$
1790  PRINT : HTAB 8: PRINT "VISIT DATE:  "D$
1800  PRINT : HTAB 8: PRINT "DATA FILE:  ";R$
1810  RETURN : GET K$
1820  REM  **************** CHARACTER GENERATOR ***************
1830 CR = 26112:XP = 26113:YP = 26114
1840  PRINT : PRINT : PRINT  CHR$ (4);"BLOAD CHARGEN.BIN"
1850  RETURN
1860  REM  ***************** STRING PRINTING ******************
```

```
1870  FOR I = 1 TO  LEN (MSG$)
1880  POKE YP,YS: POKE XP,(XS - 1) + I
1890  POKE CR, ASC ( MID$ (MSG$,I,1))
1900  CALL 26117: REM  CHARGEN
1910  NEXT I
1920  RETURN
1930  REM  ************** CALCULATE TEMP PARMS **************
1940  INPUT "FOR WHICH LEG?  ";L$
1950  PRINT
1960  INPUT "FIRST FRAME  ";FI
1970  PRINT
1980  INPUT "LAST FRAME  ";LA
1990 ST = (X(2,LA) - X(2,FI)) / 1000
2000  IF L$ = "L" THEN ST = ( - 1) * ST
2010 TI = (LA - FI) * (0.067 + (SK / 1000))
2020 VE = ST / TI
2030 CA = 60 / TI
2040  HOME
2050  PRINT : PRINT "(S)CREEN DISPLAY OR (P)RINTOUT?...": GET K$
2060  IF K$ = "S" THEN 2150
2070  PRINT : PRINT  CHR$ (4);"PR#1 "
2080  PRINT : PRINT : PRINT : HTAB 5: PRINT "TEMPORAL PARAMETERS :";
2090  PRINT : PRINT : HTAB 15: PRINT "STRIDELENGTH = ";( INT (ST * 100)) / 100;"
 m"
2100  PRINT : HTAB 15: PRINT "VELOCITY = ";( INT (VE * 100)) / 100;" m/s"
2110  PRINT : HTAB 15: PRINT "CADENCE = ";2 * ( INT (CA * 100)) / 100;" steps/mi
n"
2120  PRINT : HTAB 5: PRINT "(FIRST FRAME = ";FI;"   LAST FRAME = ";LA;")"
2130  PRINT : PRINT  CHR$ (4);"PR#0 "
2140  GOTO 2220
2150  PRINT : PRINT : PRINT : HTAB 5: PRINT "TEMPORAL PARAMETERS :";
2160  PRINT : PRINT : HTAB 15: PRINT "STRIDELENGTH = ";( INT (ST * 100)) / 100;"
 m"
2170  PRINT : HTAB 15: PRINT "VELOCITY = ";( INT (VE * 100)) / 100;" m/s"
2180  PRINT : HTAB 15: PRINT "CADENCE = ";2 * ( INT (CA * 10)) / 10;" steps/min"
2190  PRINT : HTAB 5: PRINT "(FIRST FRAME = ";FI;"   LAST FRAME = ";LA;")"
2200  PRINT : PRINT "CONTINUE? (Y/N)..": GET K$
2210  IF K$ = "Y" THEN  RETURN
2220  RETURN
2230  REM  **************** LABEL DOTS GRAPH ****************
2240 MSG$ = "SAGITTAL PLANE":XS = 13:YS = 12: GOSUB 1860
2250 MSG$ = "RAW DATA":XS = 16:YS = 28: GOSUB 1860
2260 MSG$ = "LEFT                    TO                  RIGHT":XS = 0:YS = 155: GOSUB 18
60
2270 MSG$ = "DIRECTION OF WALKING":XS = 10:YS = 171: GOSUB 1860
2280  RETURN
2290  REM  *************** LABEL STICKS GRAPH ***************
2300 MSG$ = "SAGITTAL PLANE":XS = 13:YS = 12: GOSUB 1860
2310 MSG$ = "STICK FIGURES":XS = 13:YS = 28: GOSUB 1860
2320 MSG$ = "LEFT                    TO                  RIGHT":XS = 0:YS = 150: GOSUB 18
60
2330 MSG$ = "DIRECTION OF WALKING":XS = 10:YS = 171: GOSUB 1860
2340  RETURN
2350  REM  ***************** LABEL A-A GRAPH *****************
2360 MSG$ = "ANGLE-ANGLE DIAGRAM":XS = 12:YS = 1: GOSUB 1860
2370 MSG$ = "90":XS = 9:YS = 18: GOSUB 1860
2380 MSG$ = "K F":XS = 4:YS = 57: GOSUB 1860
2390 MSG$ = "60":XS = 9:YS = 59: GOSUB 1860
2400 MSG$ = "N L":XS = 4:YS = 65: GOSUB 1860
2410 MSG$ = "E E":XS = 4:YS = 73: GOSUB 1860
2420 MSG$ = "E X":XS = 4:YS = 81: GOSUB 1860
2430 MSG$ = "A":XS = 4:YS = 97: GOSUB 1860
```

```
2440 MSG$ = "30":XS = 9:YS = 104: GOSUB 1860
2450 MSG$ = "N":XS = 4:YS = 105: GOSUB 1860
2460 MSG$ = "G":XS = 4:YS = 113: GOSUB 1860
2470 MSG$ = "L":XS = 4:YS = 121: GOSUB 1860
2480 MSG$ = "E":XS = 4:YS = 129: GOSUB 1860
2490 MSG$ = "O":XS = 10:YS = 148: GOSUB 1860
2500 MSG$ = "E":XS = 6:YS = 148: GOSUB 1860
2510 MSG$ = "X":XS = 6:YS = 156: GOSUB 1860
2520 MSG$ = "10":XS = 9:YS = 162: GOSUB 1860
2530 MSG$ = "T":XS = 6:YS = 164: GOSUB 1860
2540 MSG$ = "25      0              45":XS = 11:YS = 170: GOSUB 1860
2550 MSG$ = "EXT":XS = 15:YS = 172: GOSUB 1860
2560 MSG$ = "FLEX":XS = 28:YS = 172: GOSUB 1860
2570 MSG$ = "THIGH ANGLE (DEG)":XS = 17:YS = 183: GOSUB 1860
2580  RETURN
2590  REM  ************** ANGLE/FRAME NO GRAPH **************
2600  PRINT : INPUT "BEGIN WITH FRAME #.."；BE
2610  PRINT : INPUT "END WITH FRAME #.."；EN
2620  GOSUB 3500: REM  CALC. KNEE ANGLE
2630  HOME : PRINT "(S)CREEN DISPLAY OR (P)RINTOUT?": GET K$
2640  IF K$ = "S" THEN 2770
2650  PRINT : PRINT  CHR$ (4)；"PR#1 "
2660  GOSUB 1820: REM  CHARGEN
2670  HGR2 : HCOLOR= 3: HPLOT 63,32 TO 273,32 TO 273,162 TO 63,162 TO 63,32
2680  HPLOT 63,149 TO 273,149
2690  HPLOT 63,71 TO 67,71: HPLOT 63,110 TO 67,110
2700  HPLOT 105,158 TO 105,162: HPLOT 147,158 TO 147,162: HPLOT 189,158 TO 189,1
62: HPLOT 231,158 TO 231,162
2710  GOSUB 2860: REM  LABEL KNEE/TIME
2720  FOR I = BE TO EN: HPLOT I * 5.25 + 63,149 - (K(I) / 1.745) * 130: NEXT I
2730  GET A$: TEXT
2740  PRINT  CHR$ (9)；"G2"
2750  PRINT : PRINT  CHR$ (4)；"PR#0 "
2760  RETURN
2770  GOSUB 1820: REM  CHARGEN
2780  HGR2 : HCOLOR= 3: HPLOT 63,32 TO 273,32 TO 273,162 TO 63,162 TO 63,32
2790  HPLOT 63,149 TO 273,149
2800  HPLOT 63,71 TO 67,71: HPLOT 63,110 TO 67,110
2810  HPLOT 105,158 TO 105,162: HPLOT 147,158 TO 147,162: HPLOT 189,158 TO 189,1
62: HPLOT 231,158 TO 231,162
2820  GOSUB 2860: REM  LABEL KNEE/TIME
2830  FOR I = BE TO EN: HPLOT I * 5.25 + 63,149 - (K(I) / 1.745) * 130: NEXT I
2840  GET A$: TEXT
2850  RETURN
2860  REM  ************** LABEL ANGLE/FRAME NO. GRAPH **************
2870 MSG$ = "KNEE-ANGLE VS. TIME":XS = 13:YS = 8: GOSUB 1860
2880 MSG$ = "90":XS = 7:YS = 32: GOSUB 1860
2890 MSG$ = "K":XS = 0:YS = 57: GOSUB 1860
2900 MSG$ = "N    F":XS = 0:YS = 65: GOSUB 1860
2910 MSG$ = "60":XS = 7:YS = 67: GOSUB 1860
2920 MSG$ = "E    L":XS = 0:YS = 73: GOSUB 1860
2930 MSG$ = "E    E":XS = 0:YS = 81: GOSUB 1860
2940 MSG$ = "X":XS = 5:YS = 89: GOSUB 1860
2950 MSG$ = "A":XS = 0:YS = 97: GOSUB 1860
2960 MSG$ = "N":XS = 0:YS = 105: GOSUB 1860
2970 MSG$ = "30":XS = 7:YS = 106: GOSUB 1860
2980 MSG$ = "G (DEG)":XS = 0:YS = 113: GOSUB 1860
2990 MSG$ = "L":XS = 0:YS = 121: GOSUB 1860
```

```
3000 MSG$ = "E":XS = 0:YS = 129: GOSUB 1860
3010 MSG$ = "E":XS = 5:YS = 142: GOSUB 1860
3020 MSG$ = "O":XS = 8:YS = 144: GOSUB 1860
3030 MSG$ = "X":XS = 5:YS = 150: GOSUB 1860
3040 MSG$ = "10":XS = 7:YS = 156: GOSUB 1860
3050 MSG$ = "T":XS = 5:YS = 158: GOSUB 1860
3060 MSG$ = "0    .5     1    1.5     2    2.5":XS = 9:YS = 166: GOSUB 1860
3070 MSG$ = "TIME (S)":XS = 20:YS = 182: GOSUB 1860
3080  RETURN
3090  REM  ********************* CALCULATE A-A PARMS **********************
3100  REM  ************** PERIMETER (P), AREA (A), RATIO (PA) ***************
3110 PE = 0
3120  INPUT "BEGINNING OF LOOP, FRAME #  ";BE
3130  PRINT
3140  INPUT "END OF LOOP, FRAME #  ";EN
3150  FOR I = BE TO EN
3160  IF I = EN THEN H(I + 1) = H(BE): IF I = EN THEN K(I + 1) = K(BE)
3170 P(I) =  SQR ((H(I + 1) - H(I)) ^ 2 + (K(I + 1) - K(I)) ^ 2)
3180 PE = PE + P(I)
3190  NEXT I
3200  REM  ********************************
3210 AR = 0
3220  FOR I = BE TO EN
3230  IF I = BE THEN H(I - 1) = H(EN)
3240  IF I = EN THEN H(I + 1) = H(BE)
3250 R(I) = K(I) * (H(I + 1) - H(I - 1))
3260 AR = AR + R(I)
3270  NEXT I
3280 AR =  ABS (AR) / 2
3290  REM  ********************************
3300 PA = 0
3310 PA = PE /  SQR (AR)
3320  HOME
3330  PRINT : HTAB 8: PRINT "PERIMETER = ";( INT (PE * 100)) / 100;" degrees"
3340  PRINT : HTAB 8: PRINT "AREA = ";( INT (AR * 100)) / 100;" (degrees)2"
3350  PRINT : HTAB 8: PRINT "RATIO (PA) = ";( INT (PA * 100)) / 100
3360  GET K$
3370  RETURN
3380  REM  ******************** SET SCALE FACTORS TO PLOT *******************
3390 FX = 0:FY = 0
3400  PRINT : PRINT : HTAB 5: PRINT "(1) GSH,RCCH   (2) PAOH   (3) BME": GET K
3410  IF K = 1 THEN 3440
3420  IF K = 2 THEN 3460
3430  IF K = 3 THEN 3480
3440 FX = 15.45:FY = 8.41
3450  RETURN
3460 FX = 19.98:FY = 11.01
3470  RETURN
3480 FX = 22.63:FY = 13.38
3490  RETURN
3500  REM  ***************** CALCULATE KNEE ANGLE *****************
3510  HOME : PRINT : PRINT : VTAB 5: HTAB 15: INVERSE : PRINT "CALCULATING": NOR
MAL
3520  FOR I = BE TO EN
3530 A(I) = ((X(1,I) - X(0,I)) * (X(2,I) - X(1,I)) + (Y(1,I) - Y(0,I)) * (Y(2,I)
 - Y(1,I))) / ( SQR (((X(1,I) - X(0,I)) ^ 2 + (Y(1,I) - Y(0,I)) ^ 2) * ((X(2,I)
- X(1,I)) ^ 2 + (Y(2,I) - Y(1,I)) ^ 2)))
3540 K(I) =  -  ATN (A(I) / ( SQR ( - (A(I) ^ 2) + 1))) + 1.5708
3550  NEXT I
3560  RETURN
```

APPENDIX E

DATA CONCERNING THE FORM OF NORMAL AND RHEUMATOID FEET

Appendix E contains tables of raw and processed measurements concerning the form of normal and rheumatoid feet. Note that the abbreviation S.D. is used to denote the standard deviation in each case. All distances and angles are expressed in terms of millimetres and degrees respectively.

Footcasts

Normal controls				
Subject	H	T	A	Contour index
1	23	25	14	10.0
	20	19	7	12.5
2	22	18	9	11.0
	25	23	13	11.0
3	26	21	9	14.5
	28	21	14	10.5
4	29	21	18	7.0
	22	20	14	7.0
5	28	23	17	8.5
	27	22	13	11.5
6	25	20	14	8.5
	24	20	11	11.0
			Mean	10.3
			S.D.	2.1

Table 10. Measurements taken from the contour diagrams of normal control subjects in order to calculate their respective contour indices. H - height of the heel, T - height of the first metatarsal head, and A - height of the arch of the foot.

Rheumatoid patients

Subject	H	T	A	Contour index
1	25	21	19	4.0
	34	22	20	8.0
2	23	26	12	12.5
	25	25	11	14.0
3	26	18	18	4.0
	30	22	16	10.0
4	30	30	18	12.0
	22	22	12	10.0
5	21	16	15	3.5
	23	18	16	4.5
6	26	18	18	4.0
	27	21	21	3.0
7	21	21	12	9.0
	29	29	18	11.0
8	26	21	9	14.5
	29	20	10	14.5
9	17	17	12	5.0
	21	17	14	5.0
10	17	19	13	5.0
	24	29	21	5.5
11	24	19	13	8.5
	24	21	15	7.5
12	30	23	17	9.5
	33	25	20	9.0
13	14	9	8	3.5
	19	14	12	4.5
14	28	28	19	9.0
	23	25	16	8.0
15	*	*	*	*
			Mean	7.8
			S.D.	3.5

Table 11. Measurements taken from the contour diagrams of the rheumatoid patients in order to calculate their respective contour indices. * - patient did not complete all the tests (see Chapter 3).

Footprints

		Normal controls			
Subject	NW	HP	MT	FFR	Lequesne index
1	22	198	90	0.11	0.24
	24	197	87	0.12	0.28
2	19	197	88	0.10	0.22
	17	198	85	0.09	0.20
3	34	191	97	0.18	0.35
	29	193	94	0.15	0.31
4	33	184	90	0.18	0.37
	30	186	88	0.16	0.34
5	27	205	99	0.13	0.27
	25	203	96	0.12	0.26
6	30	198	94	0.15	0.32
	32	196	91	0.16	0.35
		Mean		0.14	0.29
		S.D.		0.03	0.05

Table 12. Measurements taken from the iodine footprints of the normal control subjects in order to calculate their respective FFR and Lequesne indices. NW - narrowest waist distance, HP - heel pad distance, and MT - metatarsal pad width. FFR - flatfootedness ratio.

Rheumatoid patients

Subject	NW	HP	MT	FFR	Lequesne index
1	36	204	#	0.18	#
	56	206	#	0.27	#
2	30	190	81	0.16	0.40
	32	190	83	0.17	0.39
3	59	187	79	0.32	0.75
	41	190	80	0.22	0.51
4	12	185	70	0.06	0.17
	22	187	74	0.12	0.30
5	62	201	85	0.31	0.73
	60	196	89	0.31	0.69
6	84	210	100	0.40	0.84
	84	201	95	0.43	0.89
7	30	187	#	0.19	#
	32	193	#	0.21	#
8	24	182	#	0.13	#
	*	200	#	*	#
9	42	202	96	0.21	0.44
	43	208	92	0.10	0.35
10	50	197	97	0.25	0.52
	58	201	94	0.29	0.62
11	26	201	95	0.13	0.27
	33	199	93	0.17	0.35
12	33	182	86	0.18	0.38
	32	182	87	0.18	0.37
13	49	196	88	0.25	0.56
	43	196	87	0.22	0.49
14	16	185	73	0.09	0.22
	19	186	72	0.10	0.28
15	36	173	#	0.21	#
	37	184	#	0.20	#
			Mean	0.21	0.48
			S.D.	0.09	0.20

Table 13. Measurements taken from the iodine footprints of the rheumatoid patients in order to calculate their respective FFR and Lequesne indices. * - NW of this footprint could not be measured as the midfoot part of this high-arched foot did not touch the ground. # - these iodine footprints were too faded for MT to be measured.

X-rays

Normal controls

Subject	TMT	MT 1,2	HV
1	0	9	18
	0	8	12
2	-1	10	13
	-8	10	14
3	-12	10	16
	-10	11	13
4	-8	9	10
	-13	9	8
5	-2	14	5
	-2	10	10
6	-2	9	12
	-2	8	10
Mean	-5	10	12
S.D.	5	2	4

Table 14. Angles measured on the relevant X-rays of the normal control subjects. TMT - talometatarsal angle, MT 1,2 - metatarsal 1,2 angle, and HV - hallux valgus angle.

Rheumatoid patients

Subject	TMT	MT 1,2	HV
1	20	12	30
	29	10	11
2	-3	0	21
	-5	2	14
3	2	14	17
	-17	11	23
4	0	15	25
	0	14	34
5	0	11	30
	0	11	38
6	18	11	13
	18	5	11
7	2	12	35
	2	17	54
8	-23	10	34
	-12	15	40
9	24	10	33
	12	12	27
10	6	10	38
	1	12	46
11	-7	9	12
	-8	5	13
12	4	12	56
	0	9	46
13	4	8	10
	10	8	12
14	0	7	8
	-2	7	7
15	-4	6	35
	0	10	19
Mean	2	10	26
S.D.	12	4	14

Table 15. Angles measured on the relevant X-rays of the rheumatoid patients.

APPENDIX F

DATA CONCERNING THE FUNCTION OF NORMAL AND RHEUMATOID FEET

This appendix contains raw and processed data concerning the function -- kinematic and kinetic -- of the normal control and rheumatoid feet. Note that the abbreviation S.D. is used throughout to denote the standard deviation. An explanation was given in Chapter 3 for some of the rheumatoid patients not appearing in all the tables.

Digital Camera System

Normal controls

Subject	Cadence (steps/min)	Stridelength (m)	Walking speed (m/s)
1	111	1.20	1.12
	108	1.21	1.09
2	95	1.06	0.84
	92	1.10	0.87
3	112	1.22	1.13
	125	1.26	1.31
4	116	1.12	1.07
	120	1.11	1.11
5	98	1.45	1.17
	108	1.33	1.19
6	120	1.34	1.34
	125	1.35	1.40
Mean	111	1.23	1.14
S.D.	11	0.12	0.17

Table 16. Values of kinematic parameters generated for the normal control subjects by the digital camera.

Rheumatoid patients

Subject	Cadence (steps/min)	Stridelength (m)	Walking speed (m/s)
1	111	0.96	0.90
	120	0.93	0.93
2	95	0.76	0.60
	108	0.76	0.68
3	92	0.75	0.57
	92	0.89	0.68
4	81	0.84	0.56
	89	0.73	0.54
5	114	1.13	1.07
	105	1.24	1.09
6	116	1.09	1.05
	120	1.19	1.18
7	98	1.00	0.82
	104	1.04	0.90
8	97	0.98	0.79
	98	0.96	0.78
9	100	0.84	0.70
	97	0.76	0.62
10	92	0.96	0.74
	95	1.03	0.81
11	92	1.05	0.80
	95	1.04	0.82
12	89	0.65	0.48
	101	0.59	0.50
13	113	0.96	0.90
	108	0.95	0.86
14	120	1.30	1.29
	120	1.28	1.28
15	98	0.78	0.63
	108	0.73	0.65
Mean	103	0.94	0.81
S.D.	11	0.18	0.22

Table 17. Values of kinematic parameters generated for the rheumatoid patients by the digital camera.

Normal controls

Subject	Height (m)	Stridelength (statures)	Walking speed (statures/s)
1	1.56	0.86	0.86
		0.86	0.90
2	1.53	0.73	0.70
		0.73	0.73
3	1.63	0.65	0.52
		0.68	0.54
4	1.59	0.77	0.71
		0.79	0.82
5	1.67	0.87	0.70
		0.80	0.71
6	1.61	0.75	0.70
		0.75	0.68
Mean	1.60	0.77	0.71
S.D.	0.05	0.07	0.11

Table 18. Heights of the normal control subjects as well as the values of their respective normalised kinematic parameters.

Rheumatoid patients

Subject	Height (m)	Stridelength (statures)	Walking speed (statures/s)
1	1.71	0.56	0.53
		0.54	0.54
2	1.60	0.48	0.38
		0.48	0.43
3	1.59	0.47	0.36
		0.56	0.43
4	1.56	0.54	0.36
		0.47	0.35
5	1.49	0.76	0.72
		0.84	0.73
6	1.55	0.70	0.68
		0.77	0.76
7	*	*	*
8	1.68	0.58	0.47
		0.57	0.46
9	1.69	0.50	0.42
		0.45	0.37
10	1.57	0.61	0.47
		0.66	0.52
11	1.62	0.65	0.50
		0.64	0.51
12	1.59	0.41	0.30
		0.37	0.32
13	1.56	0.62	0.58
		0.61	0.55
14	1.65	0.79	0.78
		0.78	0.78
15	1.60	0.49	0.39
		0.46	0.41
Mean	1.60	0.58	0.50
S.D.	0.06	0.12	0.14

Table 19. Heights of the rheumatoid patients as well as the values of their respective normalised kinematic parameters. * - patient died before completing all the tests.

Normal controls

Subject	Perimeter P	Area A	Ratio PA
1	330	5910	4.3
	322	4645	4.7
2	315	5373	4.3
	305	5147	4.2
3	353	4570	5.3
	319	4546	4.7
4	295	4414	4.4
	313	5709	4.2
5	378	6093	4.8
	393	6450	4.9
6	382	7894	4.3
	381	6989	4.6
Mean	340	5645	4.6
S.D.	34	1040	0.3

Table 20. Values for the three key parameters which were obtained by mathematical manipulation of the respective angle-angle diagram of each normal control subject.

Rheumatoid patients

Subject	Perimeter P	Area A	Ratio PA
1	299	4482	4.5
	310	4311	4.7
2	268	3063	4.8
	237	2883	4.4
3	206	752	7.6
	227	1738	5.5
4	269	3035	4.9
	264	3207	4.7
5	356	5812	4.7
	399	6755	4.9
6	353	4950	5.0
	379	6624	4.7
7	334	5133	4.7
	313	5794	4.1
8	250	3080	4.5
	287	2505	5.8
9	253	2919	4.7
	231	1573	6.0
10	301	3184	5.4
	302	3789	4.9
11	282	3668	4.7
	252	2238	5.4
12	297	1523	7.6
	275	1023	8.6
13	264	3353	4.6
	284	3460	4.8
14	323	5576	4.3
	334	5431	4.5
15	274	2789	5.2
	280	3284	5.1
Mean	290	3598	5.2
S.D.	44	1574	1.0

Table 21. Values of the three key parameters which were obtained by mathematical manipulation of the respective angle-angle diagram of each rheumatoid patient.

Force Plate System

All the ground reaction forces, which had been recorded by means of the PAOH force plate, were expressed as a percentage of the particular person's bodyweight.

Normal controls

Subject	HS	FF	MS	HR	TO
1	16	81	99	96	13
	32	100	96	96	15
2	20	65	94	107	17
	21	63	93	108	7
3	23	58	94	92	9
	36	66	95	93	18
4	28	49	91	97	8
	17	47	91	91	18
5	10	55	92	95	8
	15	49	89	89	16
6	30	52	94	94	21
	35	90	79	79	29
Mean	24	65	92	95	15
S.D.	8	17	5	7	6

Table 22. Total ground reaction forces experienced by the normal control subjects at five stages during the stance phase of walking. HS - heelstrike, FF - footflat, MS - midstance, HR - heelrise, and TO - toe-off.

		Rheumatoid patients			
Subject	HS	FF	MS	HR	TO
2	20	76	87	84	37
	15	79	86	85	30
3	18	72	102	50	21
	20	94	90	103	8
4	12	53	88	87	11
	13	66	90	31	16
5	22	70	80	89	32
	20	62	90	89	31
9	21	74	89	90	12
	28	94	100	55	13
10	28	60	99	99	14
	21	107	104	100	30
11	16	57	100	89	17
	19	69	95	96	20
12	23	65	106	13	8
	29	48	111	60	20
13	28	70	103	79	14
	18	91	96	79	20
14	46	89	99	104	31
	29	101	103	73	19
Mean	22	75	96	78	20
S.D.	7	16	8	24	9

Table 23. Total ground reaction forces experienced by rheumatoid patients at five stages during the stance phase.

Normal controls

Subject	Hindfoot	Mid-and-forefoot
1	57	24
	70	29
2	46	19
	46	18
3	41	22
	48	25
4	28	12
	27	21
5	33	21
	30	19
6	25	27
	64	27
Mean	44	22
S.D.	14	5

Table 24. Ground reaction forces which were imposed on the feet of the normal control subjects at **footflat** (FF).

Rheumatoid patients		
Subject	Hindfoot	Mid-and-forefoot
2	56	21
	47	33
3	49	22
	60	34
4	37	17
	47	20
5	37	32
	42	20
9	59	16
	70	24
10	29	32
	54	54
11	38	19
	53	17
12	46	20
	30	17
13	41	28
	61	30
14	60	29
	65	37
Mean	49	26
S.D.	11	9

Table 25. Ground reaction forces which were imposed on the feet of the rheumatoid patients at **footflat** (FF).

Normal controls

Subject	Hx	MT1	MT2	MT3	MT4	MT5	Mid	Hind
1	10	16	22	10	10	5	5	22
	9	17	24	17	8	2	4	16
2	3	12	15	15	20	10	0	19
	11	12	25	23	8	3	2	8
3	13	13	29	14	9	12	4	0
	12	13	31	21	13	6	0	0
4	2	5	10	18	10	9	9	29
	9	7	22	30	14	9	0	0
5	3	7	14	16	14	11	6	22
	17	17	10	10	16	15	5	0
6	7	11	18	18	25	11	4	0
	4	14	16	16	14	15	0	0
Mean	8	12	20	17	13	9	3	10
S.D.	5	4	7	5	5	4	3	11

Table 26. Ground reaction forces which were imposed on the respective areas of interest of the feet of the normal control subjects at **midstance**. Hx - hallux, MT1 - metatarsal head 1, ..., MT5 - metatarsal head 5, Mid - midfoot, and Hind - hindfoot.

Rheumatoid patients

Subject	Hx	MT1	MT2	MT3	MT4	MT5	Mid	Hind
2	0	0	3	5	12	34	16	17
	0	7	15	11	13	13	10	18
3	0	9	7	16	9	5	5	50
	8	16	19	18	13	16	0	14
4	0	7	7	18	19	18	10	10
	0	5	5	8	8	10	0	55
5	0	3	5	13	9	8	28	15
	6	15	4	14	12	0	10	0
9	0	0	0	4	12	6	18	47
	0	8	9	11	7	8	20	37
10	0	25	15	12	25	12	11	0
	7	24	18	13	18	7	7	12
11	11	7	20	10	14	9	0	30
	17	12	17	6	6	27	0	10
12	0	0	9	3	9	10	0	75
	0	20	2	2	9	9	0	70
13	5	8	9	10	18	16	23	14
	2	5	5	5	11	0	41	27
14	5	19	19	15	10	12	0	18
	12	11	17	15	8	14	7	21
Mean	4	10	10	11	12	12	10	27
S.D.	5	7	6	5	5	8	11	22

Table 27. Ground reaction forces which were imposed on the various areas of interest of the feet of the rheumatoid patients at **midstance**.

Normal controls

Subject	Hx	MT1	MT2	MT3	MT4	MT5	Mid
1	19	22	28	12	12	4	0
	14	22	29	22	10	0	0
2	11	19	23	21	24	8	0
	21	17	32	28	9	2	0
3	15	16	31	14	8	8	0
	9	11	31	21	13	9	0
4	10	13	22	30	14	9	0
	9	8	23	30	14	9	0
5	12	11	20	21	18	12	0
	17	17	10	10	16	15	5
6	7	12	18	19	25	11	4
	4	14	16	16	14	15	0
Mean	12	15	24	20	15	9	1
S.D.	5	4	7	6	5	5	2

Table 28. Ground reaction forces which were imposed on the various areas of interest of the feet of the normal control subjects at **heelrise.**

Rheumatoid patients

Subject	Hx	MT1	MT2	MT3	MT4	MT5	Mid
2	0	0	14	17	15	35	3
	0	18	28	15	14	10	0
3	4	12	9	16	7	2	0
	16	22	25	22	12	7	0
4	0	9	9	21	21	19	10
	0	7	7	7	6	5	0
5	4	8	23	15	12	20	17
	9	22	19	19	14	7	0
9	0	20	16	27	10	17	0
	7	16	15	14	3	0	0
10	13	13	15	12	25	12	11
	0	42	22	14	17	3	3
11	23	10	27	10	12	6	0
	22	15	27	7	7	24	0
12	0	0	10	0	4	0	0
	0	32	4	4	11	5	8
13	11	13	13	13	19	7	3
	5	12	12	12	15	13	13
14	11	27	27	20	11	11	0
	19	28	13	12	4	4	0
Mean	7	16	16	14	12	10	3
S.D.	8	10	7	6	6	9	4

Table 29. Ground reaction forces which were imposed on the various areas of interest of the feet of the rheumatoid patients at **heelrise**.

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