CLINICAL EVALUATION OF NORMAL AND ARTHRITIC KNEES BY A NON-INVASIVE VIBRATORY TECHNIQUE

by

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ABSTRACT

Following a pilot investigation into the basic concepts of vibration and transfer pickup responses, a mechanical measuring system with an electronic velocity feedback for experimentally determining the Input and Transfer impedances of a knee joint are described. The system incorporated commercially available equipment for the excitation, observation, and analysis of measurements. The results for the input and transfer impedances between normal and arthritic subjects are compared. The patterns of the transfer impedance curves between the left and right knees were similar and distinctive for each of the pickup positions, but nevertheless characteristic to each subject. Large differences were observed in the transfer impedance amplitudes through a large frequency span should a subject suffer from arthritis in one knee and the other knee is normal. It is concluded that with the present setup, further studies could be directed to investigating bone porosity, fracture or union of bones and patella disorders.
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CONTENTS

Abstract i
Acknowledgement ii
Contents iii
List Of Symbols v

Chapter I Introduction 1
Anatomical, Physiological And Clinical Factors Which Determine Joint Degeneration 2
1.10 Articular Cartilage 3
1.11 Histological Structure 3
Pathology Of Osteoarthritis And Rheumatoid Arthritis
1.20 Osteoarthritis 4
1.21 Clinical Features And Anatomical Alterations 6
1.22 Rheumatoid Arthritis 7
1.30 Survey Of Techniques 8
1.31 Discussion 11

Chapter II Feasibility Studies Of Vibratory Techniques 16
2.10 Survey Of Previous Work Using Vibratory Technique In Biological Studies 16
2.20 The Knee Joint 19
2.21 Anatomy Of A Knee Joint 19
2.30 The Effects Of Mechanical Vibration On The Human Body 20
2.40 Summary Of Specifications 22
Chapter III Preliminary Investigation
3.10 Introduction 23
3.20 Apparatus And Experimental Set-Up 24
3.30 Experimental Procedure 34
3.40 Results And Discussion 35

Chapter IV Clinical Evaluation Of Knee Joints Using A Vibratory Technique 45
4.10 Modifications To Instrumentation Mountings, Attachments And A Seating Arrangement Of Subjects 45
4.20 Theoretical Measurement Of The Mechanical Impedance 52
4.21 Impedance Measuring System 54
4.22 Electrical Measuring System 55
4.23 Calibration Of Set-Up 59
4.24 Transfer Impedance 63
4.25 Vibration Data Analysis 63

Chapter V Clinical Evaluation Of Knee Joints Using A Vibratory Technique — Results And Discussion 65
5.10 Results 65
5.20 Discussion 135
5.30 Conclusions 137
5.40 Suggestions For Future Work 138

Appendix I References 139

Appendix II Analytical Considerations Of A Linear One Dimensional Mass-Spring-Damper System With Mass Excitation 144
**List Of Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F$</td>
<td>Force</td>
</tr>
<tr>
<td>$V$</td>
<td>Velocity</td>
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<tr>
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<td>Mechanical Impedance</td>
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<td>Frequency</td>
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<tr>
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<td>Damping Constant</td>
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<tr>
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<td>Mass</td>
</tr>
<tr>
<td>$f_r$</td>
<td>Resonant Frequency</td>
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INTRODUCTION

Degenerative joint disease is a disorder which affects a large percentage of the population, particularly the elderly. The nature of the disease has been well documented, examples having been isolated in mammal fossils dating back millions of years. The causes and classifications of osteoarthritis are still the subject of much research and discussion. It is generally regarded as a wear and tear phenomenon, somehow related to abnormal joint mechanics or as an inevitable concomitant of ageing. Many working days are lost each year as a result of the crippling nature of the disease, inflicting great personal distress with obvious social and economic repercussions.

Arthritis is a disease which affects the diarthrodial articulations of the human body. Histopathological studies on the tissues of patients with very early joint degeneration are seldom reported because the majority of patients are seen for the first time after the disease has been present for many months or even years. This is because articular cartilage is aneuria, and is insensitive to the weight it bears. Except in its deepest layers, adjacent to the bone, it is devoid of blood vessels and lymphatics. Articular cartilage has no perichondrium and is not covered by synovial membrane. Furthermore, it never ossifies and, apart from the layer immediately adjacent to the bone, it does not calcify. The complex structural changes that characterize arthritis commences with the disorganisation and loss of substances from the articular surfaces. These effects are not felt by the patient until the latter stages of the disease when medical advice would be sought. By this time, gross deformation by
proliferation of tissues in and adjacent to the articulating surfaces would have taken place. Treatment for the alleviation of suffering and the arresting of progressive degeneration has had some limited success, but in extreme cases joint replacements are inevitable. Extreme discomfort is brought to bear upon a patient waiting for an operation and the costs of such treatment are high. It is therefore advantageous, both economically and for the patient that early detection of the disease be made in order that treatment can be initiated.

As yet, there is no specific diagnostic tool available which would enable a doctor to detect and evaluate an osteoarthritic joint in the early stages of the disease. Any such tool should be able to ascertain rapidly the changes which have occurred in the joint as a result of any treatment. The aim of the proposed project is to carry out a critical appraisal of the problem, and to devise equipment for quantitative comparisons between normal and arthritic patients.

ANATOMICAL, PHYSIOLOGICAL AND CLINICAL FACTORS WHICH DETERMINE JOINT DEGENERATION

The accomplishment of movement between segmented parts of the human body is achieved through joints. It is the synovial joint (diarthrosis) that is capable of free motion within a joint space which is closed off by a capsule which holds the bone ends together, and into which ligaments and tendons enter. This ligamentous capsule tissue is lined by synovial membrane; where the bone ends articulate, they are covered by cartilage, which in most diarthrosis is smooth and hyaline. The extent of the articular cartilage on each bone end corresponds in general to the area of functional contact between the opposed bones.
1.10 Articular Cartilage

Normal articular cartilage is devoid of blood vessels, lymphatics and nerves. The cartilage cells receive their nourishment by means of the diffusion of tissue fluid through the intercellular substance. The chief source of nutriment for the articular cartilage is the synovial fluid, through an intricate mechanism of joint movement.

The colour of the cartilage covering the bone ends of diarthrodial joints varies with the age of the subject. In a young adult the cartilage appears white and glossy. By middle age, the colour of the articular cartilage has usually changed to yellowish white and with further ageing it tends to take on a yellowish brown colour.

The thickness of normal articular cartilage in adult is usually about 2 or 3 mm, except in special locations, such as on the patella where it may exceed 5 mm, and on the phalanges where it is usually not more than 1 mm. The thickness of articular cartilage is dependent on joint size as well as its functional characteristics.

1.11 Histological Structure

On microscopic examination, articular cartilage is found to be composed of cells (chondrocytes) which are embedded in an intercellular matrix. The cartilage matrix consists essentially of collagenous fibrils set in a homogeneous ground substance. The ground substance in which the fibrils are set consists largely of mucopolysaccharide and chondroitin sulphate, and has a high water content.

The entire thickness section of articular cartilage of a large joint of an adult, reveals a tendency toward stratification, and an arrangement of the cartilage cells into four, roughly distinct zones. The first three
zones are set apart from each other by differences in the slant and grouping of their cells. The fourth zone, the deepest, is further distinguished from the others by the presence of calcium in the intercellular matrix. The most superficial of the four zones is termed the "Tangential" zone. Here, the cells are flattened and lie parallel to the articular surface. Beneath the tangential zone is the broader "Transitional" zone. Its cartilage cells are roundish and appear clumped into groups. The broadest is the third zone, or the "Radial" zone, where the cells are flattened laterally and arranged in short rows vertically or radially to the surface of the cartilage. Adjacent to the bony end plate is the fourth, "Calcified" zone, named by virtue of the calcification of its matrix.

PATHOLOGY OF OSTEOARTHRITIS AND RHEUMATOID ARTHRITIS

There are many different types of arthritis but for two major types, namely osteoarthritis and rheumatoid arthritis, their causes are not yet known.

1.20 Osteoarthritis

Osteoarthritis is a non inflammatory disorder of movable joints, characterized by the deterioration and abrasion of articular cartilage, and also by the formation of new bone at the articular surface. This degenerative joint disease is usually subclassified into primary and secondary osteoarthritis.

Primary osteoarthritis is due to the initial change caused by the degeneration of the articular cartilage. It is intrinsic and the changes are associated with senescence. This deterioration of the cartilage may
have its basis in alterations relating to the rate of production and chemical composition of the matrix of the cartilage. The matrix is produced by the chondrocytes and is composed of chondromucin enmeshed by a network of collagen fibres. Superimposed upon the degenerative changes in the articular cartilage are excess local mechanical or functional stresses which are needed to create the pathological changes characteristic of osteoarthritis.

Secondary osteoarthritis is of the type in which the alterations of the articular tissues are secondary to minor anatomical variations in the joint, i.e. a traumatic incident, or some pre-existing inflammatory or even noninflammatory disease process involving one or both articular bone ends.

Articular cartilage usually shows the most striking microscopic changes with advancing age. In the course of senescence, it becomes somewhat thinned and discoloured to a yellowish-brown tint but remains smooth and glossy. More positive evidence of degeneration is characterized by a roughened surface with cracks penetrating to various depths in more grossly fibrillated areas. Physical changes at the articular surfaces lead to an increase in friction during functional contact, and the gradual rubbing away of the fibrillized cartilage produces an eroded superficial surface. With continued abrasion, the fibrillation extends deeper into hitherto intact cartilage, and further erosion follows. In this way, all the cartilage may eventually be worn away in some places, and the subchondral bone may be exposed. Microscopic examination reveals initial changes in the interstitial substance of the matrix. Since the polysaccharide is responsible for the stiffness of the tissue and for binding collagen fibres together, this dissolution is followed by a reduction in the strength
of the matrix and the cartilage becomes soft. The consequence of loading the cartilage at this point would be further wear. Hence, it is the belief of most investigators that abnormal joint mechanics is the main cause of excessive wear of the cartilage.

The pathological condition of large joints affected with primary osteoarthritis is characterized by alterations in the cartilage and subchondral bone, leading to deformation of the contour of the articular surfaces. These changes consist essentially of:

1. erosion of portions of the articular cartilage
2. sclerosis of the bone underlying the damaged cartilage
3. grinding down of exposed subchondral bone
4. formation of bony overgrowths at the margins of the articular cartilages and in some places the shifting and reduplication of the bone-cartilage border, resulting in bumpiness of the articular surface.

1.21 Clinical Features And Anatomical Alterations

The disease shows a wide variation in severity and in the speed with which it develops. Complaints of early morning stiffness are often noted but this symptom diminishes in the course of daily motion, only to increase again towards the end of the day. In the early stages of the disease, disturbances of mobility are not prominent. Nevertheless, in severe cases, the range of motion may become very much limited. This limitation is due mainly to the incongruity of the joint ends or the blocking by exostoses. Some restriction of joint movement may at first, be induced directly by muscle spasm. Degeneration of ligaments and the tearing and fraying of degenerated menisci or of tendons near the affected joints can further
handicap movement. Pain is mainly registered in weight bearing joints and is aggravated by prolonged use of the joint. Pain in the joint (the knee for example) may be brought about by the breaking off and jamming of bits of cartilage or bone between the articulating ends of the joint. Tenderness is another feature which is pronounced, especially over marginal exostoses and thickened synovium. When the arthritic changes have become more advanced, the joint region may show obvious enlargements.

1.22 Rheumatoid Arthritis

Rheumatoid arthritis is initiated by non-suppurative inflammation in the synovial membrane of affected joints. It normally occurs in a symmetrical fashion, running a prolonged course of exacerbation and remission. There is as yet no histological evidence to show whether the inflammatory reaction is a response to a primary injury to cells of the synovial lining cell layer or whether the initial injury is to the underlying connective tissue with a secondary involvement of the surface cells. Hence, the cause of the disease remains unknown. Chronicity of the inflammatory changes in the synovial membrane is nearly always associated with damage to the articular cartilage. The process is slow in evolving, commencing with the periphery of the cartilage which meets the inflammed synovial membrane. Gradual spreading of the inflammatory pannus from the synovial membrane causes large areas of the cartilage surface to be eroded. The pannus may reach the subchondral bony end plate in those places in which the cartilage has been entirely destroyed. The precise nature of the eventual subchondral changes depends largely upon the severity of the inflammation in the synovial membrane and the degree of damage undergone by the articular cartilage.
The biological changes that accompany rheumatoid arthritis may eventually manifest themselves as secondary osteoarthritis. These contributory factors are attributed to ageing, together with the wear and tear phenomena already discussed above.

Clinically, the disease features localised pain, redness, heat and swelling with frequent complaints of stiffness.

1.3 Survey Of Techniques

Physical differences between normal and degenerative cartilages have been studied, their origins established and their courses traced. Additional knowledge of the mechanical properties of biological tissue has been required prior to the replacement of any function of defective biological material with an implant device. The physical properties of articular cartilage have thus been the subject of detailed study in many classical ways, these being generally proposed by the various properties of linear elastic and visco-elastic materials. In fact, there is no shortage of literature dealing with the structure and permeability of articular cartilage.

Tests have been carried out in which impact and continuous tensional, compressional and shearing forces are brought to bear on whole anatomical units or cut specimens. The different loading conditions were aimed at giving a better understanding of cartilage deformations and properties during joint movement. The anatomical and chemical differences between normal and degenerative cartilage have also been well documented. The pathology of degenerative joint disease derives from an interaction between the biological properties of cartilages and the mechanical uses being made of them. Mechanical factors are suspected, at least in part,
as being responsible for the lesions of degenerative joint disease. Permeability studies have been directed at understanding the lubricating mechanism between the synovial fluid and that of the articulating surfaces. Various lubrication theories and models have been put forward, but are still the subject of much research and conjecture.

The quantification of arthritis is often based on the appearance of joints, rather than any dependable parameter of measurement. Joint evaluation is concerned with the course of the disease insofar as it relates to the range of motion, swelling, tenderness, stiffness, heat and deformity. It gives however very little information as to the general state of the patient. Also it often fails to distinguish between present (active) disease and the effects of old (extinct) disease. Nevertheless, the qualitative assessment of joint evaluation, especially over long periods is vital and indispensable to the medical practitioner. These limitations require a more objective and quantitative assessment of the mobility of joint degeneration, in the provision of improved clinical treatments.

Standard hospital practice for the evaluation of joint disease has hitherto been X-ray techniques. The use of radiology in rheumatic diseases has received considerable attention, but has several disadvantages, particularly in that it is really only useful for the comparison of grossly deformed joints over extended periods. Early detection of joint disease is not possible as routine examination is impractical for fear of radiation damage.

**Literature Survey.** To determine whether a joint is diseased or normal, it is necessary to monitor the progress of a pathological condition over a period of time. Structural changes present in arthritis often
result in the common symptoms noted above. It is these mechanical factors that previous researchers have attempted to monitor, with some degree of success in the hope that some parameter would ultimately quantify the total systemic manifestation of the disease. Early morning stiffness is an exceedingly common complaint of active arthritis sufferers of all ages. It is the stiffening which affects the essential dynamics of the joint, that medical practitioners have used for a long time as a subjective parameter.

Lansbury (1956) noted the daily duration of this stiffness in his patients, and used it as a clinical index. His method involved the recording of statements from patients, as to the number of hours during which stiffness persist each day from the time they wake up. The disadvantages of this method are:

1. The subjective judgements of stiffness by patients are not dependable as to consistency, and in many cases it is not possible to distinguish between stiffness and pain.

2. Stiffness is prominent only when arthritis is in an advanced state, and therefore early assessment of the disease is not possible.

3. Many factors unconnected with the arthritic process may influence the stiffness response. Stiffness is inconsistent between patients, the severity of which depends upon the progress of the disease.

Hence, Lansbury's method is invalid for use as an objective basis of assessment during treatment.

Ingpen and Kendall (1968) devised a simplified method to quantify stiffness at the metacarpophalangeal joint, by measuring the time taken to fall freely through an arc of ten degrees. This method allowed free
movement, devoid of pain, and was not controlled by the patient in any way. It is applicable to small finger joints only.

Following on, Wright, Dowson and Longfield (1969) developed an "arthograph", to measure the stiffness of the metacarpophalangeal joint. The joint is rotated at various amplitudes and frequencies. The force required to impose such a sinusoidal motion is displayed on an oscilloscope as a torque in relation to displacement.

Goddard, Dowson and Longfield (1968) extended the principle of the "arthograph" to the knee joint. Here again a torque versus displacement curve is extracted.

1.31 Discussion

The attempts at measuring metacarpophalangeal and knee joint stiffness, utilised the resistance effects on induced oscillating motion and comprised of three components, viz:

1. A single frictional component proportional to the normal force between joint surfaces. The roughness of the articular cartilage would be the essential factor.

2. An elastic component in which the resisting torque is proportional to the angular displacement, being governed by the surrounding tissues which constitute the joint.

3. A viscous component in which the viscous torque is proportional to the relative angular velocity of the joint surfaces, this resulting from the shear of the synovial fluid film, which lubricates the joint surfaces.

The qualitative assessments of the above methods are questioned by the following considerations. It is generally acknowledged that a joint
in locomotion comprises of a multitude of forces acting across the articulating surfaces, additionally of the mechanical properties of body elements and muscle forces that accompany joint movements of any sort. The above methods do not, therefore, measure specifically the factors which attribute to stiffness alone, nor do they alone specify the origin of the disease in relation to the torque and displacement curves. Furthermore, the application of the "arthrograph" is impractical for fear of inducing further pain in patients with advanced arthritis.

A major milestone in the development of an acoustical technique has leant its application to the evaluation of knee joint cartilage. The only relevant publication was present in letter form, at the 27th ACEMB conference by Chu, Gradisar, Raily and Bowling (1974). This non-invasive acoustical setup used an electronic sound retrieval system to pick up distinguishing acoustical signatures of sound emitted from normal and pathological knee joints. Background noise is minimised through the noise cancellation technique adopted, employing a double microphone-differential amplifier. The data is recorded on tape and the loop technique is used in the analysis. This method has claimed unique results for three types of knee joint condition. No attempts however have been made at explaining the characteristics of the resulting waveform to that of the knee joint condition.

Lately however, ultrasonics have been extensively used in the analysis and evaluation of bone properties. But this is still a relatively new technique and further studies are required.

The effects of shock and vibrational forces on man have been the subject of popular studies for the purpose of protection, by the determination of tolerance criteria of the structure and properties of the human body,
which is regarded as a mechanical as well as a biological system. In recent years, non-invasive techniques have been sought to determine the mechanical properties of bone and surrounding tissues. One of these is the mechanical impedance technique. Mechanical impedance is a quantitative measure of the effect of vibratory force on a structure. If a linear elastic structure is excited by a sinusoidal force, and the resulting sinusoidal velocity is measured, the frequency-dependent ratio of the exciting force to the resulting velocity is defined as mechanical impedance. The mechanical impedance method was adopted in most cases, and experiments indicated definite advantages over X-ray and other destructive and invasive methods. In most cases of impedance testing a corresponding mathematical model (models) was developed through which numerical values of the parameters defining the model could be ascertained, the objective being either to determine material properties or to diagnose disease conditions.

Gierke and Franke (1950) were the first pioneers to investigate the effects of vibration on the surface of the human body. They studied the behaviour of a body surface when it was exposed to vibration, and obtained a quantitative picture of the processes of absorption, propagation and attenuation in tissue. The method was then used to study the mechanical properties of the body surface in terms of mass, stiffness and friction as functions of frequencies.

Jurist (1970) has investigated the area of impedance testing and analysis of the human ulna. He reported a correlation between the osteoporotic state of the ulna and a clinically measurable quantity FL. (F=resonant frequency, L=length) The vibratory properties of the ulna was modelled on the fundamental equation describing a vibrating bar. The reproducibility of the frequency measurement was studied and it was found
to be dependent on the geometrical factors, boundary conditions and the mode of vibration of the ulna.

Thompson (1973) studied the loading and boundary conditions for the ulna by maximising its dependance on ulna properties rather than the characteristics of soft tissues or joints. A range of static preload forces between 200 and 600 grams were applied to the vibrating probe, creating a stiffening effect on the overlying soft tissue. He discovered that a static coupling force of 400 grams was sufficient to raise the stiffness of the skin layer above the effective bending stiffness of the ulna.

Orne (1974, 1975) worked in conjunction with Thompson's results to produce a linear viscoelastic beam model of the human ulna. The soft tissue squeezed between the impedance head and the ulna is modelled as a tri-parameter viscous solid whose material constants are functions of the static component of the forcing functions. Theoretical impedance curves obtained using the model are in better agreement with Thompson's impedance data. He later modified the model, to include the resistance to lateral vibration which is provided by the surrounding musculature.

Finally, Markey and Jurist (1974) developed an objective method to evaluate fracture union by measurement of bone resonant frequency. The purpose of that study was to analyse the relationship between the tibial response spectra following fracture and during healing. They adopted a standard engineering analysis which suggested that the square of the ratio of the resonant frequency of the fracture tibia to that of the intact tibia would provide an index of the strength of union relative to that of an intact bone. The use of this ratio allowed compensation for geometrical factors when comparing results obtained from different individuals.
The above survey presents a comprehensive picture of the various techniques hitheto used, along with their advantages and disadvantages, in the evaluation of bone and joint properties. Complications exist as a result of the large variations in human physical characteristics of which no two people are the same.

Bearing in mind the above mentioned difficulties, a non-invasive technique is sought which qualitatively and quantitatively defines the progress of the pathological condition. Ideally, this method would possess no side effects in routine examination, inflict no pain during tests and yet be economically feasible for possible use in mass scanning.

The measurement of mechanical changes in joint pathology could possibly be achieved by ultrasonic, acoustical technique or mechanical impedance method. The mechanical impedance method was used in this research.
FEASIBILITY STUDIES OF VIBRATORY TECHNIQUE

The response of biological materials to mechanical vibrations can be described in terms of lumped values of mass, stiffness and dissipation. An analogue of the human body may be taken to consist of multitudes of interconnected masses, springs and dampers and should, therefore, behave as a dynamic system with many degrees of freedom. If lumped parameters of this system could be determined, a mechanical or electrical analogue of satisfactory completeness and precision might be developed from which a better understanding of the human body could be studied using the vibratory technique. This technique had been used to study various aspects of the anatomy which bear some relevance to this research. However, no significant vibrational study had been carried out on the mechanical properties of joints.

2.1 Survey Of Previous Works Using Vibratory Technique In Biological Studies.

Franke (1951) studied the driving point mechanical impedance of the surface of the human body and proposed the form of a model for the system. He investigated problems concerning the transmission of energy into the body and calculated the absorption coefficients from the equations of impedance. Using the impedance measurements, he established that the mechanical responses of the tissues to vibration can be described by a set of two coefficients, i.e. shear viscosity and shear elasticity.

Corliss and Koidan (1955) determined the resistive and reactive components of the impedance of the human head and mastoid. This facilitated the design of equipments for the calibration of bone conductors under conditions
representing the threshold of hearing.

Hodson and Nakamura (1968) investigated the impact characteristics of the human zygoma. The mechanical impedance technique was employed to provide an awareness of the part played by inertia, elasticity, damping and the resonant characteristics of the zygoma-head system in response to steady state vibratory forces.

Noyes, Clark and Watson (1968) established a correlation between an aspect of mechanical impedance and the looseness of teeth in vivo. A clinically suitable instrument was developed which objectively measured tooth mobility. The suspensory apparatus of the tooth was represented in model form, and consisted of several equivalent springs and dampers.

Cameron, Jurist, Sonenson and Mozess (1969) estimated bone elasticity by measuring the speed of sound propagation in bone. Four approaches were used:

1. The timing of impulse propagation along the bone. Two vibration accelerometers were strapped at known distances to a long bone.
2. Measurement of the phase shift per unit length of bone for fixed vibrational frequencies.
3. Measurement of the resonant frequency for a particular length of bone. The product of these was found to be proportional to the speed of sound in bone.

The detailing of each of the approaches was carried out by Jurist et al. in their later publications.

Gurdjian, Hodgson and Thomas (1970) studied the relationship between the frequency response of the human head to sinusoidal vibrations and impact
time sensitivity, hence developing a better understanding of the head injury mechanism. The response of the head was monitored by means of multiple accelerometers and plots of amplification factor were derived. The amplification factor here is the ratio of acceleration responses at the input, and helps to demonstrate various modes of vibratory bending assumed by the head as a force generator is swept through the frequency range.

Suggs and Abrams (1971) evaluated the dynamic characteristics of biological materials with mechanical impedance techniques. They illustrated how mechanical impedance might be used to evaluate the dynamic behaviour of a variety of systems.

Abrams (1971) furthered the versatility of the driving point mechanical impedance method by modelling the vibrational characteristics of the human hand. This is particularly useful in the design of hand-held power tools. If incorrectly produced, excessive vibration could be transmitted to the hand or arm, causing annoyance or even be hazardous to health.

Much of the above works have described the complexity of determining the mechanical and physical properties of the tissues forming the human body. The experimental data obtained should be useful to the theoretician in formulating more accurate mathematical models of the human body; to the bioengineer designing the implantation devices; to the experimentalist in the construction of physical models; and perhaps, ultimately, to the establishment of injury threshold criteria.

It had been established that the cause for arthritis originated with the degeneration of articular cartilage. It commences with a reduction in the mucopolysaccharide content in the matrix which effectively reduces the stiffness and strength of the cartilage. By means of a vibratory technique this research hopes to demonstrate differences in mechanical properties
between normal and arthritic joints. Effectively, a known and controllable vibratory input is fed in at one end of a joint and the output is picked up on the other side of the joint. The amount of vibration transmitted across the joint would inevitably be depended on the joint properties. One of the main factors which effectively limits the amount of vibration transmitted is the stiffness of the cartilage. Since articular cartilage covers both the bony ends of the joint. The stiffness of articular cartilage could be represented in terms of the vibratory amplitude at the pickup. The peaks of these amplitude which occurred at various frequencies could be termed resonances. Hence, it is these resonances which could be used as an indication of the mechanical differences between normal and arthritic joints.

Vibrational techniques were chosen for the detection of these mechanical changes in joint degeneration, mainly because it is a non-invasive method. In addition, tests could be carried out on both normal and arthritic patients without inflicting pain or inducing any injury to the joint itself. This non-invasive vibratory technique is free from artifacts of any sort and hence routine examination is possible. The advantage with this method is that the equipment used is readily available on the commercial market.
2.20 The Knee Joint

There can be little doubt that the form of transport most taken for granted is walking, and any deficiencies in the lower limbs, such as derangements of the knees for example, can cause both physical and psychological difficulties. If research were to be directed toward the study of human knees, which could in any way be of benefit to those with a pathological knee condition, by the indication of small differences between normal and arthritic knees, this would be adequate justification for the carrying out of such work.

The three most accessible joints for the measurement of mechanical properties are the knee, elbow and phalangeal. After the small joints of the hand, the knee is perhaps the joint most commonly affected by arthritis. The knee joint was chosen for study in this thesis for the following reasons:

1. Being a weight bearing joint, the forces are larger and therefore easier to measure.
2. It is the largest of the joints and would be more comfortably utilised in as far as the patient under examination is concerned.

2.21 Anatomy Of A Knee Joint

The knee is not a simple hinge joint and its movement is helicoid or spiral in character. It consists of three articulars: two condyloid joints between the condyles of the femur and the semilunar cartilages (menisci) and condyles of the tibia; and a third between the patella and the femur. Flexion and extension involve the tibia in a winding course set by the configuration of the medial condyle of the femur. The spiral movement of the knee is guided by a mechanism of cruciate ligaments and semilunar cartilages.
The cruciates act as guide ropes to keep the tibia on its winding path when the knee extends and flexes. The medial hamstrings are directed from the ischial tuberosity downward and their action is to rotate the tibia inwardly while flexing the knee. The anatomic arrangement and continuity of the cruciates with the semilunar cartilages suggest that the function of guiding rotation is shared in the figure of eight manner. This rotator mechanism distributes the overall weight over an area of maximum congruencies of articulating surfaces.

In order that the results be comparable between patients, a suitable criteria for a knee joint is needed. The above anatomical description of a knee joint dictated that a subject in a standing position would have difficulty in positioning his weight evenly over both knee joints. Also, the effects of joint lubrication under loading would vary from normal and arthritic joints and is dependent with time. To minimise these effects, a subject under test should remain seated. However, the knee joint under test should be in a 90° flexion with the foot medially rotated to ensure maximum congruencies of the articulating surfaces. This would then be the configuration of the subjects under tests.

2.3 The Effects Of Mechanical Vibrations On The Human Body

Medical and human considerations of vibratory effects can be classified into three main categories. These being forces at the vibrator input, sensitivity at the output and side effects induced by vibration on the human body.

There is very little reliable information on the magnitude of the forces required to produce mechanical damage to the human body. This is because experiments have been carried out mainly on animals or human cadavers,
neither of which resemble accurately to the living body. For the purpose of this research, however, the threshold of pain is taken as the ultimate magnitude of vibrator force. In fact, this limit is not reached during the course of experiments. Biological systems may, of course be influenced by vibration at all frequencies if the amplitude is sufficiently great. The literature survey of vibratory studies on the human body indicated that the typical amplitude of vibration does not exceed $\pm 2.5$ mm (0.1 inch), peak to peak, and the frequency ranges between 20 to 5000 Hz. In practice, the mechanical force and vibrator amplitudes to which the human body is exposed must be clearly defined in terms of duration and intensity. For safety reasons, a device should be incorporated into the circuitry which limits the maximum voltage being delivered to the vibrator.

Vibration measurement of the body's response can be obtained meaningfully only if measurement methods and instrumentations are adapted to ensure minimal interference of the measurement with the system's behaviour. This behaviour may be physical, physiological or psychological. Vibration pickups are placed in contact with the body for the measurement of the body's response. Hence, they must be small and light enough so as not to introduce a distorting mechanical load. This usually places a maximum weight limitation on the pickup of a few grams, dependent on the frequency range of interest and the effective mass to which the pickup is attached. The lack of rigidity of the human body as a supporting structure makes measurement of acceleration usually preferable to those of velocity or displacement.

The effects and behaviour of vibration on biological systems are not at all clearly understood. Gierke (1951) made an attempt at explaining the dissipation phenomena and vibratory characteristics of the human body, much of which is still a matter of conjecture. There is no evidence to suggest
that short duration and very low intensity vibration may be harmful to the body. Jankovich (1972) reported that vibration actually enhances growth and rigidity. He explained that vibration constituted a continuous, but alternating load on bone which resulted in continuous muscular exercise. These effects are contrary to those of hypodynamia, such as bed rest and immobilisation. In conclusion, therefore, physical activity within the comfort limit of the subject tends to have more beneficial than undesirable side effects.

2.4 Summary Of Specification

The above discussion listed the vibratory force, amplitude and frequency range used by previous investigators for the measurement of the body's responses. The work in this research will use these specifications as guidelines in determining the feasibility of the vibratory technique. Modifications will be carried out on the existing equipments to suit a clinical evaluation of normal and arthritic knees.

Principal specifications are:

1. Maximum vibrator displacement (amplitude) is ± 2.5 mm (0.1 inch)
2. Operational frequency range is 20 to 5000 Hz

The duration of vibratory exposure of the subject is kept to a minimum, and the intensity of vibration does not reach the threshold of pain.
CHAPTER III

PRELIMINARY INVESTIGATIONS

3.1 Introduction

The published work of Jurist et al. and other users of the vibratory technique have not stated the technical difficulties encountered in the measurement of the body's responses. For a better understanding of the overall problems, similar apparatus to those used by Jurist (1969) were constructed by Carter (1973) at Surrey University.

Continuing, these apparatus were experimented along the lines described by Jurist et al. in establishing the resonant frequency tests for the ulna. The following observations were made.

1. The measured resonant frequency is dependent on the instruments, such as frequency sweep speed and recorder printing speed.
2. The reproducibility of the measurement is critically dependent on the positioning of the bone relative to both the accelerometer pickup and the vibrator.
3. Boundary conditions, including the forces exerted on the soft tissue, interposed between the bone and the vibrator or accelerometer pickup maybe critical in the reproducibility of experimental results.

The above technical difficulties could be overcome with suitable modifications to the apparatus. It was felt that the practicality of the vibratory technique could be extended for use in a clinical evaluation of normal and arthritic joints. The vibratory technique utilises the principle that the amount of vibration being transmitted across any media would depend on the properties of that media (Shock and Vibration Handbook, Vol. 1). Chapter 1 has dealt with the chemical changes which effectively alter the
stiffness and damping characteristics of the articular cartilage along with other tissues surrounding the joint. Nevertheless, it is hoped that the changes in stiffness of articular cartilage would be most significant in early detection and diagnosis of arthritis. In vibratory terms, damping is the property which limits the amount of vibration being transmitted, and stiffness is responsible for the resonant frequency of the system, (Appendix 11). It is these two main changes in the knee joint that are most accessible when using the vibratory technique.

The feasibility of the vibratory technique is studied before financial justification in obtaining the monitoring equipment and constructing an apparatus which is clinically suitable to patients. It was necessary to first conduct preliminary tests on the knee joint with minor modifications to existing equipments. The tests were performed on both normal and arthritic patients with a view to observing two main characteristics, namely:

1. Vibrations with variable amplitudes and frequencies can be detected across a joint.

3.2 Apparatus And Experimental Setup

A schematic representation of a general setup in the preliminary tests is shown in Figure 1. Basically the apparatus consisted of an electrodynamic vibrator mounted onto a dexion frame. Characteristics of vibration transmitted through the knee joint are picked up by a piezoelectric accelerometer transducer. The extent of the design factors and monitoring circuitry surrounding these two devices depended on a number of factors, the important ones being:
WEIGHTS

FIG: 3.1. SCHEMATIC REPRESENTATION OF PRELIMINARY TEST SETUP
The Vibrator: a sinusoidal force is applied through the vibrator, with a maximum force output of 1 - 2 lbf, at the medial border shaft of the tibia. Based on the inconsistency of experimental results, observations were centered on the contact area between the vibrator head and tibia. It is concluded that the change in vibratory amplitude with frequency produced an effect whereby the reactionary force between patient and vibrator ceased to be constant and consistent. The patient either exerted too much or too little push against the vibrator, depending on the sensitivity felt at that moment. The amount of push required to produce consistency is somewhat overcome with a plastic guard surrounding the vibrator head, as shown in Figure 3.2. This guard ensures and also limits the longitudinal movement of the vibrator when the leg is pressed against it. There is also sufficient clearance between shaft and guard to prevent contact during scanning.

The size and shape of the vibrator head constituted another important factor. It was redesigned to minimise the sharp sensation felt by the patient. The surface area of the vibrator head is enlarged into a flat circular disc thus reducing the exerted pressure.

The Pickup: attachment of pickup is normally achieved with an elastic band. This method proved to be clumsy and disadvantageous. Firstly, repeatability is inconsistent with varying elastic tension (depending on wrist or knee diameter), hence uncertainty in obtaining a normal, constant reactionary force. Secondly, location of an exact position is not always achieved with occasional slipping and therefore necessary adjustment is required. Thirdly, the versatility of the elastic band is limited with difficulty in attaching the pickup at some positions.

Modifications were made to attach the pickup onto the knee surface through a 3-dimensional clipex arrangement and universal clamps. A constant
FIG. 3.2 PLASTIC GUARD ON VIBRATOR ENSURES A CONSTANT DEFLECTION

FIG. 3.3 PICKUP MOUNTED ON A LEAF SPRING
reaction force on the pickup is ensured with a leaf spring (bended cantilever) attached to one end of the clipex, Figure 3.3. This static preload of the knee pickup should reach a certain level in order that the original aim of the test be satisfied, that is to maximise the dependence of results on cartilage properties rather than the characteristics of soft tissues that surround the joint. This static preload level is at present indeterminate and would vary for each subject. However, the problem is overcome if the static preload being applied is maintained at a constant level but sufficiently high to achieve the above aims.

Interference from vibrator to pickup is minimised by having the pickup attachment separated from that of the dexion frame.

Definite positions are required on the patient's knee for repeatability purposes and ease of location. The lateral condyle and epicondyle of the femur is chosen. The patella is also used but its large surface area presents difficulty in defining the exact location of the pickup.

Auto Scan: the frequency of vibration was manually scanned between 0 - 500 Hz. This oscillatory circuit was built by Carter (1973) and has two main limitations. These being:

1. The frequency range is limited between 0 - 500 Hz
2. It is not possible to produce constant frequency sweep manually, thus hindering the repeatability of the setup.

To overcome the above objections, the 8038 Intersil Waveform Generator was used which is a monolithic integrated circuit capable of producing sine, square, triangular, saw-tooth or pulse waveforms. The frequency range can be selected by varying a capacitance externally from less than 0.0001 Hz to more than 1 MHz. The frequency ranges used were 10 - 100 Hz, 100 - 1000 Hz and 100 - 2000 Hz with capacitance values of 0.22 μF, 0.022 μF and 0.01 μF.
FIG: 3.4 CONNECTIONS FOR FREQUENCY SWEEP

C1 = 0.22 μF  C2 = 0.022 μF  C3 = 0.01 μF

FIG: 3.5 CONNECTIONS FOR INPUT TO X-Y PLOTTER
respectively as shown in Figure 3.4.

The voltage output from the 8038 Generator is too high for full scale deflection on the graph plotter. A reduction network employing an operational amplifier is used, shown in Figure 3.5.

Frequency variation is caused by the change in resistance of the potentiometer at pin 8, Figure 3.4. Frequency scanning is then achieved by rotating the potentiometer at a constant speed. This is done by connecting the potentiometer shaft to a geared Crouzet motor which rotates at 10 revolutions per minute. Figure 3.6 shows the circuit diagram of the motor circuit. The micro-switch in the circuit automatically stops the motor on completion of the frequency scanning range, through an off-set cam mounted directly on the potentiometer coupling.

Figure 3.8 shows the resonant frequency monitoring circuit for the preliminary tests.
FIG: 3.7 PHOTOGRAPH OF THE RESONANT FREQUENCY CIRCUIT AND AUTO-SCAN PANEL
FIG: 3.8 RESONANT FREQUENCY MONITORING CIRCUIT FOR THE PRELIMINARY TESTS
Loading A Knee Joint

The difference between a loaded and an unloaded knee joint (through joint movement) have been hypothesised as a basis of joint lubrication. Nevertheless, excessive loading through abnormal joint mechanics has been explained as the main cause of joint degeneration. The knee tests have been carried out when the subjects were seated, hence the knee joint is unloaded except by its own internal forces and weight of the thigh. Loading the knee joint (subjects remaining seated) with dead weights, and repeating the experiments, could verify the hypothesis on light lubrication and possibly assist a simulation of the normal knee becoming arthritic. This loading action effectively squeezed the articular cartilage resulting in a change of its stiffness properties and hence inhibiting the vibration transmission measurements. Loading is applied through the cantilever mechanism shown in Figure 3.9. The loading pad resting on the knee is attached onto a screw
threaded lever, which ensures a normal loading force.

3.3 Experimental Procedure

In a seated posture with knees bared, the leg is strapped onto the Dexion frame resulting in a 90° flexion at the knee joint. The vibrator is then moved up against the leg until the plastic guard completes the depression of the vibrator probe. The subject is then requested to maintain this contact on the plastic guard throughout the tests. The accelerometer pickup is next placed onto one of the chosen pickup and automatic recording at the pickup. A plot of frequency (X-axis) against accelerometer pickup amplitude (Y-axis) is displayed on the pen-recorder. After each completed frequency sweep, the pen on the recorder is lifted and the frequency dial returned to the starting frequency. This procedure is repeated for each pickup position.

A follow up to this test is carried out, subjecting normal and abnormal knees to mechanical loads in vivo. Dead weights from 1 - 20 lbs., with 1 lb. increments, were used. For each loading, manual scanning is carried out for successive 1 minute intervals up to a maximum of 10 minutes. A period of 10 minutes is allowed for the knee to stabilise before additional loading or reloading at other pickup positions.

Prior to the comparison of experimental results, it is necessary to define a normal and an arthritic subject. A subject is considered normal when he/she has no experience of stiffness, swelling, heat or deformity at the knee joint (or any other joints) whether it may be caused through accidents or ageing. Ageing is also considered to be a contributory factor to the changes in articular cartilage. Here, difficulty arises in drawing the line as to when is articular cartilage 'normal' with regard to age, when none of the above abnormalities are experienced by the subject. It is for this reason that the normal subjects
used for these tests are those within the age group of 18 - 30 years old.
The arthritic subjects used in these tests are those supplied by the Royal
Surrey County Hospital with a documented history of arthritic complaints.

Results And Discussion

A selection of the results involving accelerometer pickup responses
for both normal and arthritic subjects, are shown in Figure 3.10 - 3.16.

Resonating peaks of pickup amplitudes were observed at particular
frequencies for certain pickup positions. These peaks were somewhat repeatable
even though the pickup amplitudes were not always consistent, Figure 3.10.
The resonant frequencies, at certain pickup positions, were observed to remain
consistent for similar pickup positions with other normal subjects.

As a follow up, normal and arthritic knees were subjected to mechanical
loading in vivo. An example of which is shown in Figure 3.11 - 3.14 for
the normal subject and Figure 3.15 for the arthritic subject. It is generally
observed that after 5 minutes of loading, there is little variation in
both amplitude and resonating frequency. Also, above 10 lbs, dead weight,
there is little if any variation in the graphs obtained with further increased
weights, Figure 3.13 - 3.14. This has a 'saturisation' effect to loading
in the response of the knee joint. Here again, two distinct parameters
were observed to affect the results; firstly, the time interval between
successive loadings before stabilisation is achieved and also the magnitude
of weights needed to reach saturisation. It is not always possible to
determine this saturation level without first inducing pain onto the subjects,
especially those with arthritic knees. However when comparing results of
normal and arthritic cases, for loaded and unloaded knees, the main
differences observed were:
1. Increase in amplitude and bandwidth at the pickup for abnormalities.

2. Resonating peaks occurred at higher frequencies for similar pickup positions of abnormalities.

An example of these observations are given in Figure 3.10 and Figure 3.16, for similar pickup position at the patella.

3. The very positive change with time after loading for both normals and abnormalities.

From these main changes, the following conclusions were drawn. First, vibrations of controllable amplitude and frequency can be transmitted across a joint. Second, resonating peaks occurring at a particular frequency depend on the conditions of the joint and the pickup positions. Third, the effects of loading were observed to be dependent on time and the amount of weight used. On loading, a joint underwent changes with the effect of squashing the articular cartilage. After a while, stabilisation is attained when the squashing force equals the internal forces of the joint. This squashing action currently altered the stiffness of the articular cartilage and hence inhibiting the vibration transmission measurements. Above a certain loading weight and with further increase in weights, no variation in the curves were observed. This could be explained that the articular cartilage were fully squashed to its limits. Excessive loadings were not performed in these experiments for fear of inflicting pain onto patients and even permanent damages might be caused for the articular cartilage and other knee joint properties.

The results obtained demonstrate the responses of a knee joint under unloaded conditions. The variations in the results could possibly be interpreted in terms of the physiological parameters that reflect the condition of the joint under mechanical loadings or degenerative joint disease. But the results from these tests were somewhat inconclusive.
This could be attributed to the fact that much finer details in experimental setup might be required in order to produce reliable and repeatable results.

The apparatus used in the preliminary tests was constructed from Dexion and it was not clinically suitable. In addition, it only accommodated one foot at a time and suffered from an interference between vibrator and pickup. Hence the pickup was mounted separately from the frame. Its main drawback was that the patient's leg has to be secured against the vibrator. The pickup attachment consisted of the bent cantilever design. This was clumsy and placed limitations on the ease with which it could be located.

In conclusion, therefore, the beneficial aspects of the preliminary tests were noted with particular modifications needed for instrumentation mountings, attachments and the seating arrangement of subjects.
PICKUP POSITION: MEDIAL CONDYLE OF FEMUR

PICKUP POSITION: PATELLA

PICKUP POSITION: LATERAL CONDYLE OF FEMUR

SUBJECT: NORMAL

FIG: 3.10 GRAPH OF ACCELEROMETER PICKUP
SUBJECT: NORMAL

PICKUP POSITION: LATERAL CONDYLE OF FEMUR

FIG: 3.11 GRAPH OF KNEE JOINT LOADED WITH 10 lbs. wt.
Subject: Normal
Pick-up position: Lateral Condyle of Femur

FIG: 3.12  GRAPH OF KNEE JOINT LOADED WITH 10 lbs. wt.
Subject: Normal

Pick-up position: Lateral Condyle of Femur

FIG: 3.13 GRAPH OF KNEE JOINT LOADED WITH 20 lbs, wt.
Subject: Normal

Pick-up position: Lateral Condyle of Femur

FIG: 3.14 GRAPH OF KNEE JOINT LOADED
WITH 20 lbs. wt.
PICKUP POSITION: PATELLA

SUBJECT: ABNORMAL

FIG: 3.15  GRAPH OF REPEATABILITY FOR ACCELEROMETER PICKUP
FIG: 3.16 GRAPH OF KNEE JOINT LOADED
WITH 10 lbs. wt.
CLINICAL EVALUATION OF KNEE JOINTS USING A VIBRATORY TECHNIQUE

4.1 Modifications To Instrumentation Mountings, Attachments And The Seating Arrangement Of Subjects

The general arrangement of the apparatus and experimental setup is shown in Figure 4.1. This comprised a complete redesign of the seating arrangement for subjects, vibrator and pickup mounting equipment plus their respective monitoring equipment. Each of these will in turn be described below.

The previous setup involved moving the subject up against the vibrator and pickup. This method is clumsy and places limits when accommodating arthritic subjects with severe disorders. The present arrangement involves a chair with special leg mountings to secure the subject's leg, against which the pickup and vibrator is attached, Figure 4.2. The leg is secured to the chair through strapping three positions, namely; the thigh, ankle and the metatarsal region of the foot. The foot can be fully rotated medially, and then locked. The advantage of medial rotation of the leg in a fully flexed position is that it ensures maximum congruencies of the articulating surfaces and also provides a known and repeatable condition of the knee.

Vibrator mounting, alignment and stiffness comprises another area of attention. Because of the varied leg sizes and angle of medial rotation, the vibrator is mounted on a rig which can be adjusted in all three axes, Figure 4.3. The vibrator stand is mounted on slide tables, which enables accurate positioning of the vibrator against the tibial
FIG: 4.1  A GENERAL ARRANGEMENT OF THE APPARATUS AND EXPERIMENTAL SET-UP
FIG: 4.2 A CHAIR WITH SPECIAL LEG MOUNTINGS
FIG: 4.3 VIBRATOR STAND
FIG: 4.4  PLAN VIEW OF VIBRATOR STAND
UNIVERSAL CLIP EX
ARRANGEMENT
ACCELEROMETER PICKUP

FIG: 4.5 THE PICKUP ARRANGEMENT
shaft of the leg. The horizontal angle of the vibrator can be further adjusted at the support screws of the trunnion to obtain a flush surface contact with the tibia. The height of the vibrator is adjusted through the jack handle mounted at the top of the stand, Figure 4.4. The rig is on wheels and can be locked through nylon brakes at the rear.

Because of the contact stiffness between vibrator head and leg, the amplitude of vibration does not remain constant with increase in frequency. This is clearly seen when a linear variable differential transformer is mounted between the vibrator shaft and vibrator. In addition, to avoid unnecessary risks to subjects, the limits of human tolerance to mechanical forces must be such that the amplitude is safe. Hence the mechanical force environment to which the human body is exposed is clearly defined through a force and accelerometer transducer termed an Impedance Head (model B&K Type 8001), which is mounted in between the vibrating piston and vibrator. Because of the weight imposed by the impedance head on the vibrator shaft, a larger vibrator (model 200 series) was chosen.

Requirements for shakers include adequate safety precautions, accurate control of exposure and sufficient load capacity for subjects. A plastic guard surrounding the vibrating piston head forms an integral unit which safeguards the contact stiffness. This is achieved by placing the guard against the subject's leg and maintaining its contact throughout the period of vibration.

Vibration measurements of the body's responses are made by pickups in contact with the body. This is dependent on two main factors, these being:

1. The size and weight limitation of the pickup depending on the frequency range of interest and the effective mass to which
the pickup is attached.

2. A static preload, above which the results are dependent of the soft tissues that surround the joint.

The lack of rigidity of the human body as a supporting structure makes measurement of acceleration preferable to those of velocity and displacement. A miniature piezo-electric accelerometer, model BQ35 weighing 4.5 grams is used. A static preload of 600 grams is maintained on the pickup against anyone of the pickup positions. A modification to the bent cantilever consists of a spring loaded plunger and universal clipex clamp. This unit is attached onto an adjustable bar which swivel about a fixture, underneath the knee pads. This is shown in Figure 4.5.

4.2 Theoretical Measurement Of The Mechanical Impedance

The purpose of this research was to provide basic information concerning the mechanical responses of a knee joint considered as a system. This information will be of value in the determination of arthritis and aid in the design and development of artificial knee joint replacement.

Certain physical characteristics such as apparent mass, damping and stiffness influence the dynamic response of a knee joint. These characteristics are a function of frequency and can be determined by Mechanical Impedance Measurement Techniques. The reader should consult Harris and Crede "Shock and vibration handbook" Vol. 1, chapter 10, for further references on the theoretical considerations of the mechanical impedance technique.

Mechanical impedance is a measure of the response (motion) of a mechanical structure to excitation by an applied sinusoidal force. By definition, it is equal to the applied force at the excitation point
divided by the resulting velocity at the response point of the structure. When the velocity and force are measured at the same point, the impedance is called the Point Impedance. If the measurements are carried out at two different points of the structure, the impedance is called the Transfer Impedance.

The force, \( F \), and the velocity, \( V \), are expressed as

\[
F = F_0 e^{j(wt + \phi)} \quad \text{...............}(1)
\]

and

\[
V = V_0 e^{jwt} \quad \text{...............}(2)
\]

where \( F_0 \) and \( V_0 \) are the peak values or magnitudes of the respective signals, \( w \) is the excitation frequency in radians per second, \( \phi \) is the phase-angle difference of the force with respect to the velocity in radians, and \( t \) is time in seconds.

The Mechanical Impedance, \( Z \), is defined as

\[
Z = \frac{F}{V} = \frac{F_0 e^{j\phi}}{V_0} = \bar{Z} e^{j\phi} \quad \text{...............}(3)
\]

where \( \bar{Z} \) is the modulus or absolute value and is the ratio of the force magnitude to the velocity magnitude.

In general, a plot of impedance versus frequency will show large fluctuations in impedance magnitude with a number of peaks and valleys. The valleys, points of low impedance, indicate ease of motion and correspond to a resonant condition in the structure. The peaks, points of high impedance, correspond to antiresonant conditions.

Mechanical impedances can be determined analytically, but as the complexity of the structure increases, the estimation of structure parameters and their computations become exceedingly difficult. Furthermore, at any point in a structure, rectilinear displacements are possible in any one of
the three mutually perpendicular axes. The mechanical impedance then, becomes an array of nine complex quantities conveniently expressed in matrix form. However, motions in directions not coincident with the forcing direction can be neglected. The velocity at the transfer point is then considered as the "Resultant Velocity" at that point. This is because the pickup surface is not always orthogonal to any of the three mutually perpendicular axes. Also, most of the vibratory energy is propagated through the tissue in the form of transverse shear waves and longitudinal compression waves, the nature of which is not at all clearly understood. In addition, some energy is propagated along the body surface in the form of surface waves. The following describes the measuring system developed to determine mechanical impedance experimentally, using commercially available equipment.

4.21 Impedance Measuring System (Procedure)

A subject is seated on the chair with knees bared. The knee supports are adjusted horizontally and the legs supports vertically, thus, ensuring a right angle flexion at the knee before the whole leg is rigidly secured against the chair. The leg to be tested is then medially rotated and locked.

The vibrator stand is moved to the subject and locked. The height of the vibrator is adjusted through the jack handle until it is about 150 mm from the tip of the tibial shaft. With variations in leg lengths, this value of 150 mm is maintained. Obvious advantages lie in this method over the alternative, which involves working out the ratio of leg length to the point of attachment. The vibrator is then adjusted horizontally for a flush surface contact with the medial shaft of the tibial. Finer adjustments are possible in both horizontal axes through the slide tables.
The pickup is next placed on one of the chosen pickup positions and a static preload applied. Each of the above procedure is carefully performed so as not to induce pain onto the subject. The subject is now ready for test runs.

Each scan lasts 15 seconds and the whole test lasts about 30 minutes. This includes repetitive scans for each pickup position and for both knees. For each subject, a detailed description form is completed. A sample of this form is shown in Table 4.1. This included a case history of each arthritic subject supplied by the Royal Surrey County Hospital.

4.22 Electrical Measuring Circuit

A block diagram of the electrical measuring circuit is shown in Figure 4.6.

The force transducer of the Impedance Head between the vibrator and the leg gives as electrical signal proportional to the applied force, the accelerometer transducer gives electrical signal proportional to the motion. Appropriate transducer sensitivities are taken into consideration by setting these on their corresponding charge amplifier.

From equation 3, it is observed that to make a complete recording of the modulus of impedance versus frequency, the modulus of velocity is required to be kept constant. This is achieved through amplification and integration of the acceleration signals from the Impedance Head, to a velocity signal in the Vibration Pickup preamplifier (1606). The signal is then fed into the Audio Frequency Spectrometer (2110) which is displayed on its electronic voltmeter. From the A.F.S. it is fed into the compressor input of the Beat Frequency Oscillator. This in turns governed the amount of current going into the vibrator for a constant velocity at the vibrating piston. This close-loop system is controlled by
TABLE 4.1

TO BE COMPLETED BY THE PATIENT

1) Date:
2) Name:
3) Hospital Code No:
4) Sex:
5) Age:
6) Weight:
7) Height:
8) Profession:
9) Activity (Hobbies) - particular type of exercise:

10) If retired, years since retirement:
11) Date when first consulted Doctor:

TO BE COMPLETED BY THE DOCTOR

1) Is this a Polyarthritis or an Oligoarthritis
2) Is it symmetrical or not
3) Does it effect large or small joints
4) Are these systemic features
5) Duration and location of any other arthritic joints
6) Types of arthritis at the knee joint location
7) How much does it interfere with the patient's life
8) General notes on particular pathology
Examination of the knee

i) Analysis of function.
   a) Knee in full extension, side view.
   b) Knee flexed to 90°, side view.
   c) Normal alignment of knees, front view.
   d) Valgus deformity of both knees, front view.
   e) Varus deformity of both knees, front view.

ii) Observation of general physical appearances of the knee.
   1) Swelling
   2) Skin colouring
   3) Temperature
   4) Amount of sweating of the overlying skin
   5) Consistency with the other knee
FIG: 4.6 BLOCK DIAGRAM OF THE ELECTRICAL MEASURING CIRCUIT
<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>MAKE</th>
<th>TYPE</th>
<th>QUANTITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beat Frequency Oscillator</td>
<td>B &amp; K</td>
<td>1022</td>
<td>1</td>
</tr>
<tr>
<td>Audio Frequency Spectrometer</td>
<td>B &amp; K</td>
<td>2110</td>
<td>1</td>
</tr>
<tr>
<td>Level Recorder</td>
<td>B &amp; K</td>
<td>2305</td>
<td>2</td>
</tr>
<tr>
<td>Vibration Pickup Preamplifier</td>
<td>B &amp; K</td>
<td>2625</td>
<td>1</td>
</tr>
<tr>
<td>Vibration Pickup Preamplifier</td>
<td>B &amp; K</td>
<td>1606</td>
<td>1</td>
</tr>
<tr>
<td>Electronic Voltmeter</td>
<td>B &amp; K</td>
<td>2409</td>
<td>1</td>
</tr>
<tr>
<td>Impedance Head</td>
<td>B &amp; K</td>
<td>8001</td>
<td>1</td>
</tr>
<tr>
<td>Charge Amplifier</td>
<td>Kistler</td>
<td>5001</td>
<td>1</td>
</tr>
<tr>
<td>Minature Piezo - Electric Accelerometer</td>
<td>E. E.</td>
<td>EQ35</td>
<td>1</td>
</tr>
<tr>
<td>Vibrator</td>
<td>Ling Dynamic</td>
<td>System 200</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 4.7  Instrumentations For Measurement Of Mechanical Impedance Of A Knee Joint.

The settings on the Audio Frequency Spectrometer, whose maximum limit depends on the compressor capability of the Beat Frequency Oscillator. It is for this reason, that the pre-determined maximum force settings, in turn specify a maximum frequency scan range of between 0-2 KHz.

Amplification signals from the force transducer of the Impedance Head, are fed via both the Charge Amplifier (5001) and the Electronic Voltmeter (2409) into the input socket of the Level Recorder (2305). This recorder is mechanically driven by the Beat Frequency Oscillator and commences on depression of the Recorder switch. This automatically activates the drive system of the Beat Frequency Oscillator and at the same time scans the frequency range. On completion of the scanning range, the recorder is switched off and the frequency dial disengaged for
resetting. The whole procedure is repeated for each scan. The accelerometer pickup above the knee has its signals amplified and integrated through the Vibration Pickup Pre-amplifier (2625) and then fed into the input socket of the other Level Recorder (2305). This Recorder is switched on simultaneously with the other (force) recorder. With practice synchronization of both recorders could be achieved with relative ease. The instruments used in the clinical set-up are listed in Figure 4.7.

4.23 Calibration of the Set-up

Each of the instruments for measurement of the mechanical impedance are individually calibrated according to the instructions set in their respective hand books. However, the calibrations carried out for the input amplitude to the Level Recorder from both the Impedance Head and the pickup are herein described.

Although there are many calibration techniques which have been used for calibrating a transducer, the two most widely used are:

1. substituting a voltage proportional to a known transducer sensitivity, and
2. exciting a reference structure whose characteristics are exactly known.

The latter technique is used in this set-up. The impedance head is calibrated by firmly attaching it to the vibrator and the frequency from the Beat Frequency Oscillator set at 160 Hz. At this frequency, the acceleration signal at 10 m/s\(^2\) velocity signal at 0.01 m/s equaled the \(\triangleleft\). Additionally, from the calibration chart for the impedance head, an acceleration sensitivity of 3.34 mV/ms\(^{-2}\) is quoted. The electronic voltmeter reading from the accelerometer socket of the impedance head is 0.003 volt at 160 Hz excitation.
At 160 Hz, the input impedance is

\[ Z = 20 \log_{10} F - 20 \log_{10} V \]

\[ = 20 \log_{10} 0.6944 - 20 \log_{10} 0.0008982 \]

\[ = -3.168 + 60.932 \]

\[ = 57.766 \text{ dB} \]

Figure 4.8(a) shows a force plot of the Impedance Head with a constant velocity of 0.0008982 m/s. Since the velocity is constant, the force plot becomes an impedance plot (Equation 3). This curve has a steady slope at 6 dB per octave.

Calibration of the pickup amplitude on the Level Recorder involved attaching the pickup onto the piston of the vibrator with some plasticine. Excitation at 160 Hz gives an acceleration output of 28.00 mV. With a quoted sensitivity of 2.28 mV/g for the accelerometer pickup, the acceleration is

\[ = \frac{28.00 \times 9.81}{2.28} \]

\[ = 120.5 \text{ m/s}^2 \]

Therefore, the velocity is 0.1205 m/s, from the above relationship.

Hence, in dB scales,

\[ V (\text{dB}) = 20 \log_{10} V \]

\[ = 20 \log_{10} 0.1205 \]

\[ = -18.4 \text{ dB} \]

A logarithmic scale is used for the frequency axes (abscissas) because the impedance and velocity magnitude may be plotted over a greater range of frequencies than with linear frequency axes.
Therefore the acceleration $\ddot{a} = \frac{0.003}{0.00334} = 0.8982 \text{ m/s}^2$

Hence from the relationship the corresponding velocity is $0.0008982 \text{ m/s}$. This velocity magnitude is held constant throughout the whole frequency scanning range by a network of built-in electronics within the compressor unit of the Beat Frequency Oscillator. To verify that a constant velocity is achieved, the miniature accelerometer pickup is attached on the vibrating probe with some plasticine. The output from the pickup is recorded on the Level Recorder, as shown in Figure 4.8(b). The result shows a maximum velocity variation of $4 \text{ dB}$ throughout the frequency range of $2 \frac{1}{2} \text{ Hz} - 2.0 \text{kHz}$.

Also, at $160 \text{ Hz}$, the force transducer of the Impedance Head produced an output of $300 \text{ mV}$ on the electronic voltmeter. The force transducer is quoted with a sensitivity of $432 \text{ mV/N}$. Thus the force generated at $160 \text{ Hz}$ is $300/432 \text{ Newtons}$ or $0.6944 \text{ N}$.

To convert the force and velocity output into decibels, the following relationships are applicable.

\[ \text{dB} = 20 \log_{10} F \quad \text{...............(4)} \]

\[ \text{and} \quad \text{dB} = 20 \log_{10} V \quad \text{...............(5)} \]

But from (3), the impedance, $Z = \frac{F}{V}$. Therefore in dB scales, impedance becomes

\[ \text{dB} = 20 \log_{10} Z \quad \text{...............(6)} \]

\[ = 20 \log_{10} \frac{F}{V} \]

\[ = 20 \left( \log_{10} F - \log_{10} V \right) \]

\[ = 20 \log_{10} F - 20 \log_{10} V \quad \text{...............(7)} \]
FIG: 4.8 (a) A FORCE PLOT OF THE IMPEDANCE HEAD WITH CONSTANT VELOCITY.

FIG: 4.8 (b) A CONSTANT VELOCITY PLOT OF THE IMPEDANCE HEAD.
4.24 Transfer Impedance

The Transfer Impedance of a knee joint is defined as equal to the applied sinusoidal force at the tibial shaft divided by the resulting velocity at the pickup. The pickup could be at anyone of the pickup positions mentioned above.

Hence,

\[ \text{Transfer Impedance, } Z_T = \frac{F_{\text{input}}}{V_{\text{output}}} \] .................(8)

But in dB scales, (from equation 7)

\[ Z_T (\text{dB}) = 20 \log_{10} F - 20 \log_{10} V_{\text{pickup}} \] ..............(9)

From equation 9, it is noted that the total transfer impedance could be obtained by subtracting the Force signal at the input with the Velocity signal at the pickup. This could be achieved electronically with an Impedance analyser. But for the purpose of this research, the transfer impedance is obtained manually, by subtracting the Force input graph with its corresponding Velocity pickup graph. This is performed at 10 Hz intervals between 20 - 100 Hz and then at 100 Hz intervals between 100 - 2 KHz. The results are shown and discussed in chapter V.

4.25 Vibration Data Analysis

The main analysis of the Impedance method often resolves to one of a visual and graphical nature. This involved:

1. Determination of natural frequencies and mode shapes.
2. Measurement of specific material properties such as damping or dynamic stiffness.
3. A basis of an analytical model.
The mode shapes associated with each resonance denotes an understanding of exactly how a knee, as a structure is deforming. The magnitudes of the response peaks can be used to define certain effects of the vibration by considering systematically the properties of the system and relating the peak and valley responses to such properties. These properties are damping, stiffness and mass. Here, mass is an inconsistent factor because of the varied leg sizes between subjects. Hence it is not discussed in this research.

From the measurements of the impedances of individual pickup positions, it is possible to compare the behaviour of a knee to that of combined systems, in a manner completely analogous to the study of complex systems involving masses, springs and dampers. An analytical description of exactly how a normal and arthritic knee is behaving is thus possible with structural modelling. This would make available virtually all the information necessary to predict the dynamic response of a knee for any defined forcing function input. One technique available for extracting precise numerical information from the measured test results is to curve fit the data in the form of some pre-defined expression, such as the impedance equation for a single degree of freedom system of mass excitation (Appendix II). The purpose of fitting equations are:

1. To summarise a mass of data in order to obtain interpolation formulae or calibration curves.
2. To confirm or refute a theoretical relation, to compare several sets of data in terms of constants in their representative equations, and possibly aid in the choice of a theoretical model for a normal and an arthritic knee.
5.1 Results

Results for eighteen subjects ranging from 21 to 82 years of age and of both sexes were recorded in this thesis. Of these, twelve are arthritic subjects with varying pathological knee and the remaining six are normal subjects whose average age is less than thirty years old. A great many other subjects were tested in the first series of experiments. In fact 39 normal subjects were tested and in many cases, these tests were repeated several times over a period of a few weeks.

Table 5.1 shows the sex, age, height, weight and profession of these eighteen subjects. Subjects A - L are arthritic, and subjects M - R are normal. Table 5.2 shows the history of these arthritic subjects as supplied by the Royal Surrey County Hospital. Table 5.3 shows the physical observations of these arthritic subjects prior to the tests.

Figure 5.1 and 5.2 show a sampling of the repeatability of the Input Impedance (or force, impedance being force divided by a constant input velocity) between the first scan and after the eighth scan. This is followed by Figure 5.3, which shows two main differences observed in the Input Impedance curves between that of a normal and arthritic subject. Figure 5.4 - 5.6 show the repeatability of the pickup at three positions namely the Medial Condyle of the femur, patella and Lateral Condyle of the femur.

Figure 5.7 - 5.51 show the transfer impedance curves for the three
pickup positions respectively, of subjects A - R. The notations on
Figure 5.7, of which dots represent the tracing for the right knee and
crosses represent that of the left knee, is applicable throughout.

The input impedance curve shows an increase in the resonant frequency
with repetitive scanning, but stabilised after the fourth scan. This is
observed for both normal and arthritic subjects. Nevertheless, the
frequency at which resonance occurs varies between subjects. It is
generally observed that the resonant frequency for the young and exercised
limbs to be higher than those of the weak and older limbs, Figure 5.3.
This could be attributed to the stiffness of the bone, which acts as a
resistance against the input vibratory force. In addition, the magnitude
of impedance at which resonance occurs is lower for weak and older limbs
than those of strong and younger limbs. In vibratory terms, this is related
to the damping coefficient which the legs have against the vibratory force.
To investigate in detail, all the possibilities with which the Input
Impedance has to offer, would defer from the main purpose of this research.
It would require a special mounting for the vibrator and pickup attachment
so that this technique could be adapted to other anatomical positions.
Hence the main context will be mainly on the differences in Transfer
Impedances between a normal and arthritic knee.

Velocity pickup responses at the three pickup positions have two
main noticeable differences. They are the amplitude and bandwidth of these
responses. However, it is not possible to characterise a response
pattern for any particular pickup position that is similar for every test
subject. However, it is observed that the shapes and sizes of these
resonances, and their harmonics, do bear a close resemblance between a
subject's right knee to that of his left knee. This could be explained in
the similarities which exist between the left and right knee of a subject, of which no two subjects are the same. Pictorial comparisons of these velocity pickup responses do little, if anything, to correlate them to the well established characteristics of mechanical elements such as spring, damper and mass. It is therefore more meaningful to convert these pickup responses with the input force to obtain the Transfer Impedance.

A general survey of the transfer impedances obtained for both normal and arthritic subjects revealed six main categories. For each category, a subject is chosen as a representative case and they are:

1. Subject J with Rheumatoid Arthritis in both knees, Figure 5.34
2. Subject C with Osteoarthritis in both knees, Figure 5.13
3. Subject D with Osteoarthritis in the right knee only, Figure 5.16
4. Subject A with Rheumatoid Arthritis in both knees and a metal probe in the right femur, Figure 5.07
5. Subject G with Rheumatoid Arthritis in both knees and a Gunston knee prosthesis in the left knee, Figure 5.25
6. Subject M is normal, Figure 5.43

The analysis of the above curves in this research is based on an impedance equation for a single degree of freedom system of mass excitation. This is chosen mainly for simplicity, and to correlate the curves to the, by now, well established properties of a theoretical spring, damper and resonance of the system. This, however, does not mean that a knee is a single degree of freedom system. But since the number of degrees of freedom system that could represent a knee joint is at present indeterminate, such a system is chosen as a starting point. If this proves conclusive, perhaps structural modelling might prove necessary for detailed study.

Prior to the study of transfer impedance curves for arthritic
subjects, it is essential to observe the characteristics of the normal results. This can then be used as a reference datum with which comparisons are made.

It is observed that the general feature of the transfer impedance curves for normal subjects are similar at the three pickup positions. For this reason, subject M is arbitrarily chosen as representative of normals on which the following observations are noted, Figure 5.43 - 5.45. With the pickup at the medial condyle of the femur, the response is highly damped with an impedance value of 50 dB at 20 Hz. The curve is fairly flat until 400 Hz at which point the impedance increases with frequency. With the pickup at the patella, the response started at a lower impedance value of 25 dB but quickly increased in value. A resonance occurred at 300 Hz but with further increased in frequency to 400 Hz, the impedance started to increase again. With the pickup at the lateral condyle of the femur, the response commenced at an impedance value of 15 dB, the lowest of the three pickup position. It then gradually increased with increased in frequency. A resonance also occurred at 300 Hz and the impedance increased with increased in frequency. It is noted that for subject M, a main resonance occurred at 300 Hz, after which the curve is identical for the three pickup positions. The impedance value at resonance varied between 45 dB and 53 dB.

For subject J, with rheumatoid arthritis in both knees, the impedance value at 20 Hz varied between 40 and 50 dB. Resonance is observed to occur at about 70 Hz and the valley of the impedance curve exist between 20 and 100 Hz. The impedance at resonance occurred between 38 and 45 dB. After resonance, the curves bore the same features for the three pickup positions.
For subject C, with osteoarthritis in both knees, the impedance value at 20 Hz varied between 34 and 51 dB. There is a resonance which occurred at 25 Hz for the left knee and at 30 Hz for the right knee. This, however, does not show up on the curves when the pickup is at the patella and the medial condyle of the femur. The amplitudes above 200 Hz are similar for the three pickup positions.

With rheumatoid arthritis in both knees and a metal probe in the right femur, subject A's curves started at 24 dB and 31 dB with the pickup at the lateral condyle of the femur. Resonance varied between 50 and 80 Hz for the three pickup positions. It is observed that the impedance amplitude of the right knee is higher than that of the left knee. This could perhaps be explained by the presence of the metal probe in the femur which effectively reduces the impedance of the left knee. This is not the case with the pickup at the patella.

Subject G incurred rheumatoid arthritis in both knees. In addition, a Gunston knee prosthesis is implanted in the left knee. At the time of this test, subject G is due for another knee prosthesis implantation. At 20 Hz, an impedance value of 9 dB is noted for the pickup at the lateral condyle position. The impedance amplitude is higher for the left knee than the right knee between 20 and 70 Hz. Further increases in frequency showed an increased in impedance amplitude of the right knee over the left knee. The curves for the patella and medial condyle positions are quite similar, especially after 300 Hz. Nevertheless, the impedance amplitude for the left knee is less than that for the right knee with the pickup at the patella. This could also be interpreted by the more rigid surface contact, provided by the Gunston knee prosthesis, between the femur, tibia and patella. Little difference existed between the
curves of the left and right knee. Perhaps, because of the degenerative state of both knees, the Gunston had done little to change the total impedance of the knee.

Subject D has a ten years history of osteoarthritis in the right knee caused by an injury in a football match. He had since undergone removal of the cartilage both medially and laterally. Hydrocortizone injection and manipulation have also been effected. The main observations are large differences in the impedance amplitude between the left and right (arthritic) knee curves for all three pickup positions. These separations in amplitude existed through a large frequency span of 20 to 500 Hz. The impedance amplitude for the right knee is much lower than that of the left knee. This could be reasoned that due to the wear and tear phenomena od osteoarthritis, a more rigid surface contact existed between the femur, patella and tibia. In addition, the removal of articular cartilage could have effectively reduced the damping properties which it provided.
Table 5.1

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>SEX</th>
<th>AGE</th>
<th>HEIGHT (feet)</th>
<th>WEIGHT (Kg)</th>
<th>PROFESSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>F</td>
<td>58</td>
<td>5' 7½</td>
<td>61</td>
<td>Clerical</td>
</tr>
<tr>
<td>B</td>
<td>F</td>
<td>70</td>
<td>5' 5½</td>
<td>83</td>
<td>Catering</td>
</tr>
<tr>
<td>C</td>
<td>F</td>
<td>82</td>
<td>5' 0</td>
<td>56</td>
<td>Housewife</td>
</tr>
<tr>
<td>D</td>
<td>M</td>
<td>32</td>
<td>5' 10</td>
<td>72</td>
<td>Engineer</td>
</tr>
<tr>
<td>E</td>
<td>F</td>
<td>52</td>
<td>5' 4</td>
<td>82</td>
<td>Catering &amp; Cleaning</td>
</tr>
<tr>
<td>F</td>
<td>F</td>
<td>72</td>
<td>5' 3</td>
<td>62</td>
<td>Housewife</td>
</tr>
<tr>
<td>G</td>
<td>F</td>
<td>66</td>
<td>5' 1½</td>
<td>49</td>
<td>Physiotherapist</td>
</tr>
<tr>
<td>H</td>
<td>F</td>
<td>75</td>
<td>5' 3</td>
<td>46.5</td>
<td>Shop Assistant</td>
</tr>
<tr>
<td>I</td>
<td>M</td>
<td>27</td>
<td>5' 9</td>
<td>69</td>
<td>Teacher</td>
</tr>
<tr>
<td>J</td>
<td>F</td>
<td>43</td>
<td>5' 4</td>
<td>57</td>
<td>Clerical</td>
</tr>
<tr>
<td>K</td>
<td>M</td>
<td>23</td>
<td>5' 8</td>
<td>73</td>
<td>Labourer</td>
</tr>
<tr>
<td>L</td>
<td>F</td>
<td>63</td>
<td>5' 1</td>
<td>46</td>
<td>Housewife</td>
</tr>
</tbody>
</table>

NORMAL

<p>| M   | M   | 38  | 6' 2         | 83          | Technician            |
| N   | M   | 28  | 6' 0         | 75          | Student               |
| O   | M   | 28  | 5' 10        | 62          | Managing Director     |
| P   | M   | 21  | 5' 10        | 73          | Student               |
| Q   | M   | 24  | 6' 0         | 81          | Student               |
| R   | M   | 26  | 6' 0         | 76          | Student               |</p>
<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>DURATION OF ARTHRITIS (YEARS)</th>
<th>POLYARTHRITIS OR OLIGARTHRITIS</th>
<th>LARGE OR SMALL JOINTS AFFECTED</th>
<th>TYPES OF ARTHRITIS AT THE KNEE JOINT</th>
<th>GENERAL NOTES ON PARTICULAR PATHOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>39</td>
<td>Polyarthritis</td>
<td>Both</td>
<td>Rheumatoid</td>
<td>Metal probe in right femur. (Fracture at condyle of femur) Hydrocortizone injected in both knees.</td>
</tr>
<tr>
<td>B</td>
<td>30</td>
<td>Oligarthritis</td>
<td>Large</td>
<td>Osteoarthritis</td>
<td>Right leg is 2 inches shorter than left leg. Patella is badly worn away and right leg could not be straightened.</td>
</tr>
<tr>
<td>C</td>
<td>Unknown</td>
<td>Polyarthritis</td>
<td>Both</td>
<td>Osteoarthritis</td>
<td>Trouble coming mainly from patella. No invasive treatment.</td>
</tr>
<tr>
<td>D</td>
<td>10</td>
<td>Oligarthritis</td>
<td>Large</td>
<td>Secondary</td>
<td>Removed cartilage both medially and laterally. Hydrocortizone injection and manipulation.</td>
</tr>
<tr>
<td>E</td>
<td>9</td>
<td>Oligarthritis</td>
<td>Large</td>
<td>Rheumatoid</td>
<td>Patella removed in left knee. Osteotomy performed in left knee.</td>
</tr>
<tr>
<td>F</td>
<td>7</td>
<td>Polyarthritis</td>
<td>Large</td>
<td>Rheumatoid</td>
<td>Gunston knee prosthesis in right knee.</td>
</tr>
<tr>
<td>SUBJECT</td>
<td>DURATION OF ARTHRITIS (YEARS)</td>
<td>POLYARTHRITIS OR OLIGARTHRITIS</td>
<td>LARGE OR SMALL JOINTS</td>
<td>TYPES OF ARTHRITIS AT THE KNEE JOINT</td>
<td>GENERAL NOTES ON PARTICULAR PATHOLOGY</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------------</td>
<td>--------------------------------</td>
<td>----------------------</td>
<td>--------------------------------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>G</td>
<td>Unknown</td>
<td>Polyarthritis</td>
<td>Both</td>
<td>Rheumatoid</td>
<td>Gunston prosthesis in left knee. Metatarsal removed in left knee. Sensitive in left knee since operation.</td>
</tr>
<tr>
<td>H</td>
<td>3</td>
<td>Oligarthritis</td>
<td>Large</td>
<td>Osteoarthritis</td>
<td>Knee injury caused mainly through falling.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Right knee only</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>6</td>
<td>Oligarthritis</td>
<td>Large</td>
<td>Secondary Osteoarthritis</td>
<td>Cartilage removed in left knee. Hydrocortizone injection and manipulation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left knee only</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>15</td>
<td>Polyarthritis</td>
<td>Large</td>
<td>Rheumatoid</td>
<td>Two artificial hip joints. A pin in left ankle and synovectomy in both knees.</td>
</tr>
<tr>
<td>K</td>
<td>4</td>
<td>Oligarthritis</td>
<td>Large</td>
<td>Rheumatoid</td>
<td>Stiffness is the main complaint.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left knee only</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>15</td>
<td>Polyarthritis</td>
<td>Both</td>
<td>Rheumatoid</td>
<td>Due for knee joint prosthesis in right knee. Left ankle is badly affected.</td>
</tr>
<tr>
<td>SUBJECT</td>
<td>SWELLING</td>
<td>TEMPERATURE</td>
<td>ANALYSIS OF FUNCTION</td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>----------</td>
<td>-------------</td>
<td>---------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>R</td>
<td>Slight</td>
<td>Cold on medial side</td>
<td>Varus deformity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>Medium</td>
<td>Warm</td>
<td>Varus deformity</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>R</td>
<td>None</td>
<td>Warm</td>
<td>Varus deformity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>None</td>
<td>Normal</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>R</td>
<td>Slight</td>
<td>Warm knee, warm patella</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>Slight</td>
<td>Cold knee, warm patella</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>R</td>
<td>Slight</td>
<td>Warm</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>None</td>
<td>Normal</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>R</td>
<td>Large</td>
<td>Cold knee, normal patella</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>Large</td>
<td>Cold knee, normal patella</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>R</td>
<td>Normal</td>
<td>Cold</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>Slight</td>
<td>Cold</td>
<td>Varus deformity</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>R</td>
<td>Slight</td>
<td>Warm</td>
<td>Varus deformity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>R</td>
<td>Slight</td>
<td>Cold</td>
<td>Varus deformity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>Medium</td>
<td>Normal</td>
<td>Varus deformity</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>R</td>
<td>None</td>
<td>Normal</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>None</td>
<td>Normal</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>R</td>
<td>Slight</td>
<td>Cold - warm in places</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>Slight</td>
<td>Cold - warm in places</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>R</td>
<td>Normal</td>
<td>Cold</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>Slight</td>
<td>Warm</td>
<td>Normal alignment</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>R</td>
<td>Medium</td>
<td>Cold</td>
<td>Valgus deformity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>Normal</td>
<td>Cold</td>
<td>Normal alignment</td>
<td></td>
</tr>
</tbody>
</table>
SUBJECT: NORMAL

FIG: 5.01 GRAPH OF REPEATABILITY FOR INPUT IMPEDANCE
FIG: 5.02 GRAPH OF REPEATABILITY FOR

SUBJECT: NORMAL
FIG: 5.03 DIFFERENCES IN THE INPUT IMPEDANCE RESPONSE CURVES BETWEEN A NORMAL AND ARTHRITIC SUBJECT.
SUBJECT: NORMAL
PICKUP POSITION: MEDIAL CONDYLE OF THE FEMUR

FIG: 5.04 .GRAPH OF REPEATABILITY FOR VELCLTY PICKUP
SUBJECT: NORMAL

PICKUP POSITION: PATELLA

FIG: 5.05. GRAPH OF REPEATABILITY FOR VELOCITY PICKUP
SUBJECT: NORMAL
PICKUP POSITION: LATERAL CONDYLE OF THE FEMUR

FIG: 5.06  GRAPH OF REPEATABILITY FOR VELOCITY PICKUP
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: A

RIGHT KNEE: RHEUMATOID ARTHRITIS; METAL PROBE IN FEMUR
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.07 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: A

RIGHT KNEE: RHEUMATOID ARTHRITIS; METAL PROBE IN FEMUR
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.08 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: A

RIGHT KNEE: RHEUMATOID ARTHRITIS; METAL PROBE IN FEMUR
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.09 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: B

RIGHT KNEE: OSTEARTHRITIS

LEFT KNEE: NORMAL

FIG: 5.10. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: B

RIGHT KNEE: OSTEOARTHRITIS
LEFT KNEE: NORMAL

FIG: 5.11 . GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: B

RIGHT KNEE: OSTEOARTHRITIS
LEFT KNEE: NORMAL

FIG: 5.12 .GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: C

RIGHT KNEE: OSTEOARTHRITIS

LEFT KNEE: OSTEOARTHRITIS

FIG: 5.13 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: C

RIGHT KNEE: OSTEOARTHRITIS
LEFT KNEE: OSTEOARTHRITIS

FIG 5.14. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: C

RIGHT KNEE: OSTEARTHRITIS
LEFT KNEE: OSTEARTHRITIS

FIG: 5.15 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: D

RIGHT KNEE: OSTEOARTHRITIS
LEFT KNEE: NORMAL

FIG: 5.16 .GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: D

RIGHT KNEE: OSTEOARTHRITIS
LEFT KNEE: NORMAL

FIG : 5.17 . GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: D

RIGHT KNEE: OSTEOARTHRITIS
LEFT KNEE: NORMAL

FIG. 5.18 .GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: E

RIGHT KNEE: RHEUMATOID ARTHRITIS

LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.19  GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: E

RIGHT KNEE: RHEUMATOID ARTHRITIS

LEFT KNEE: RHEUMATOID ARTHRITIS; PATELLA REMOVED

FIG: 5.20. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: E

RIGHT KNEE: RHEUMATOID ARTHRITIS
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.21. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: F

RIGHT KNEE: RHEUMATOID ARTHRITIS; GUNSTON KNEE PROSTHESIS
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.22. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: F

RIGHT KNEE: RHEUMATOID ARTHRITIS; GUNSTON KNEE PROSTHESIS

LEFT KNEE: RHEUMATOID ARTHRITIS

FIG:5.23 .GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: F

RIGHT KNEE: RHEUMATOID ARTHRITIS; GUNSTON KNEE PROSTHESIS
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 524 .GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: G

RIGHT KNEE: RHEUMATOID ARTHRITIS

LEFT KNEE: RHEUMATOID ARTHRITIS; GUNSTON KNEE PROSTHESIS

FIG: 5.25. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: G

RIGHT KNEE: RHEUMATOID ARTHRITIS
LEFT KNEE: RHEUMATOID ARTHRITIS; GUNSTON KNEE PROSTHESIS

FIG: 5.26  GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: G

RIGHT KNEE: RHEUMATOID ARTHRITIS
LEFT KNEE: RHEUMATOID ARTHRITIS; GUNSTON KNEE PROSTHESIS

FIG: 5.27 .GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: H

RIGHT KNEE: OSTEOARTHRITIS

LEFT KNEE: NORMAL

FIG: 5.28 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: H

RIGHT KNEE: OSTEOARTHRITIS
LEFT KNEE: NORMAL

FIG: 5.29 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: H

RIGHT KNEE: OSTEOARTHRITIS
LEFT KNEE: NORMAL

FIG 5.30 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: 1

RIGHT KNEE: NORMAL

LEFT KNEE: OSTEOARTHRITIS; CARTILAGE REMOVED

FIG. 5.31. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: I

RIGHT KNEE: NORMAL

LEFT KNEE: OSTEOARTHRITIS; CARTILAGE REMOVED

FIG: 5.32 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: 1

RIGHT KNEE: NORMAL
LEFT KNEE: OSTEOARTHRITIS; CARTILAGE REMOVED

FIG: 5.33 .GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: J

RIGHT KNEE: RHEUMATOID ARTHRITIS
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.34. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: J

RIGHT KNEE: RHEUMATOID ARTHRITIS
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.35. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: J

RIGHT KNEE: RHEUMATOID ARTHRITIS
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.36  GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: K

RIGHT KNEE: NORMAL
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.37 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: K
RIGHT KNEE: NORMAL
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.38. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: K

RIGHT KNEE: NORMAL
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.39 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.

TRANSFER IMPEDANCE, DB
FREQUENCY, HZ
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: L

RIGHT KNEE: RHEUMATOID ARTHRITIS

LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.40 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: L

RIGHT KNEE: RHEUMATOID ARTHRITIS
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG : 5.41 . GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: L

RIGHT KNEE: RHEUMATOID ARTHRITIS
LEFT KNEE: RHEUMATOID ARTHRITIS

FIG: 5.42 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: M

RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 5.43 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: M
RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 5.44. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: M

RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 5.45 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
SUBJECT: N
RIGHT KNEE: normal
LEFT KNEE: normal

FIG. 5.46
GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.

TRANSFER IMPEDANCE, dB.

FREQUENCY, Hz
SUBJECT: N
RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG 5.47 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: N

RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 5.48 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: O

RIGHT KNEE: NORMAL

LEFT KNEE: NORMAL

FIG: 5.49. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: O

RIGHT KNEE: NORMAL

LEFT KNEE: NORMAL

FIG: 5.50 . GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: O

RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 5.51 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: P

RIGHT KNEE: NORMAL

LEFT KNEE: NORMAL

FIG: 5.52 .GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: P

RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 5.53 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: P

RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 5.54 .GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: Q

RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 5.55 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT PATELLA

SUBJECT: Q
RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 5.56 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: Q

RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 5.57 .GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT MEDIAL CONDYLE OF FEMUR

SUBJECT: R

RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 5.58 GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
SUBJECT: R
RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 559. GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
PICKUP AT LATERAL CONDYLE OF FEMUR

SUBJECT: R

RIGHT KNEE: NORMAL
LEFT KNEE: NORMAL

FIG: 5.60 .GRAPH OF TRANSFER IMPEDANCE OF KNEE JOINTS.
5.2 Discussion

The tests were performed over a limited frequency range of 20 to 2000 Hz. The results indicated that the first resonance occurred between 20 and 100 Hz for most normal and arthritic subjects. It is therefore unnecessary to scan the knee joint beyond 2.0 KHz as second order resonance are not considered.

The transfer impedance curve obtained by extrapolating the force and velocity curves were tedious and somewhat inaccurate. An impedance analyser that automatically performs the above task accurately is recommended for clinical application of the Transfer Impedance Method.

Pickup positions are presently located on a subject's knee manually. Difficulty arose when an arthritic knee is tested, especially those which are swollen and deformed. A device is thus needed which could accurately locate the pickup positions and simultaneously quantify the pickup distance relative to the input vibrator.

The ease with which the pickup is located on the knee involves considerable manipulation. An improvement would be to mount the pickup separately from the chair altogether, perhaps it could be mounted independently on a rig similar to that of the vibrator stand.

In view of the above mentioned differences in curves obtained for left and right knees and also between normal and pathological knees, three outstanding points have arisen out of these experiments. Namely:

1. There is good repeatability of the force input and velocity pickup response curves. This verifies the reliability of the set-up, demonstrating that modifications carried out on the vibrating probe and the pickup attachment have been justified.
With such consistencies in the force input curves, it is felt that further investigation be centred around the Input Impedance. The potential of this method could be utilised in the analysis of bone porosity and in the determination of fracture or union of bone (an alternative method to X-ray). By shifting the vibrator probe on to the patella, and measuring the input impedance of the patella, early diagnosis of patella disorders might be achieved.

2. For any subject, the transfer impedance curves are distinctive for each of the pickup positions. The patterns between the left and right knees at each of the pickup positions are similar, but nevertheless, characteristic to each subject. The reasons have been explained earlier and are based on the fact that no two subjects have the same size and shape of knees.

3. It is observed that if a subject should suffer from arthritis in one knee, be it osteoarthritis or rheumatoid arthritis, and the other knee is normal, then there are large differences in the transfer impedance amplitudes through a large frequency span. This could perhaps be used as an important factor in diagnosing knee arthritis.

However the results for subjects with both knees normal or arthritic are not clear-cut, thereby rendering limitations upon the transfer impedance technique with the present set-up.
5.3 Conclusions

The pilot investigations of the vibratory technique have showed definite changes in the accelerometer pickup response with time, under loading. Stabilization of the knee joint is achieved after about five minutes of loading and, above a certain load no further change is observed.

Modifications made to the original apparatus were justified with reproducible results.

The resonant frequency of the input impedance is observed to shift with repeatitative scanning, but stabilized after about the fourth scan. Also, the resonant frequency is observed to shift to a higher level for normal subjects; similarly the amplitudes also moves to a higher level.

There were differences in the transfer impedance amplitude over a large frequency range, between the left and right knee of an arthritic patient, should one knee be in a more degenerated state than the other.

The vibratory technique has no visible and detectable side effects. This is because it is a non-invasive method and biological measurements are not made. Hence it is free from artifacts which would naturally occur when materials are removed from their natural surroundings.
5.4 Suggestions For Future Work

All components of the measuring system used in the Input and Transfer Impedances are commercially available, making it easy for the measuring technique described to be duplicated and adopted by others.

With the available apparatus and minor modification to the set-up, further work could be directed to determine:

1. Bone porosity; this would correlate the stiffness, damping and resonant characteristics of bone as it undergoes changes.
2. Fracture or union of bones; the resonant frequency and stiffness properties would dominate.
3. Patella disorders; direct input impedance on the patella would eliminate the complex structures encountered with the present transfer impedance method. The direct surface contact between patella and femoral condyle surfaces would perhaps initiate detection of any changes or commencement of an arthritic state.
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APPENDIX II

ANALYTICAL CONSIDERATIONS OF A LINEAR ONE DIMENSIONAL MASS-SPRING-DAMPER SYSTEM WITH MASS EXCITATION

One analytical technique available to visualize how a normal or arthritic knee is behaving is thus by structural modelling it with a single degree of freedom system of mass excitation. The following theory will enable curve fitting of the theoretical curve to that obtained by the input and transfer impedance curves of a knee joint. Three main constants governed the curve fittings, these being mass, stiffness and damping.

Mechanical impedance testing is usually steady state by nature, and an assumption of linearity must usually be applicable. Sinusoidal testing involves providing a sinusoidal input to an unknown system, a "black box" approach, allowing the output to become a steady state sinusoidal and then measuring the phase and amplitude of the output. The input is the driving force and the output is the resulting motion of the driven point.

![Diagram of a linear one-dimensional mass-spring-damper system with infinite rigid foundation]
The mechanical impedance of the three ideal elements, mass, spring and damper are:

- **Mass**: \( Z_m = jw m \)
- **Spring**: \( Z_k = \frac{-jk}{w} \)
- **Damper**: \( Z_c = c \)

The impedance of the above are functions of frequency and can be represented on graph paper with logarithmic impedance and frequency scales.

Consider the linear, one-dimensional system shown above. The equation of motion is

\[
f(t) = m \frac{dv}{dt} + cv + k \int_0^t v \, dt \quad \text{.........}(10)\]
Applying Laplace Transforms and solving for the ratio of transformed force to transformed velocity, the impedance is

\[ Z(s) = \frac{F(s)}{V(s)} = \frac{ms^2 + cs + k}{s} \]  \hspace{1cm} (11)

For steady state sinusoidal behaviour,

\[ s \rightarrow jw \]

where \( \omega \) is the angular frequency of the sinusoidal force and motion. Therefore equation 11 becomes;

\[ Z(j\omega) = \frac{F(j\omega)}{V(j\omega)} = c + j\left( \frac{mw}{w} - \frac{k}{w} \right) \hspace{1cm} (12) \]

In general, \( Z \) is a complex quantity, the real part being the mechanical resistance and the imaginary part being the reactance. As with any complex quantity, the impedance can be expressed as a magnitude and a phase angle and as such equation 12 becomes;

\[ Z(j\omega) = \sqrt{c^2 + \left( \frac{mw}{w} - \frac{k}{w} \right)^2} \tan^{-1} \frac{\frac{mw}{w} - \frac{k}{w}}{c} \]  \hspace{1cm} (13)

This can be represented graphically with logarithmic scales as shown below.
From equation 13 and the above graph, it is noted that at the frequency of

$$f_r = k/m$$

the imaginary term is zero. This frequency, $f_r$, is the resonant frequency; the impedance, $Z$, is real and is at a minimum value equalled to $c$. At very low frequencies, $Z$ approaches the spring impedance and the system is said to be "stiffness controlled". At high frequencies, $Z$ approaches the mass impedance and the system is "mass controlled".