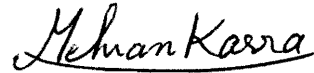


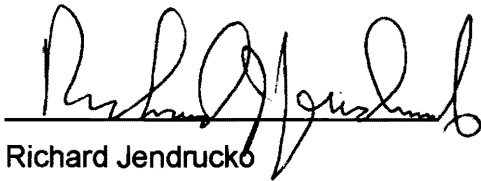
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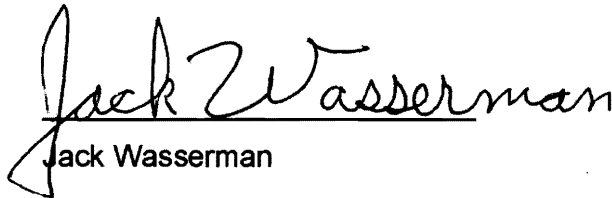


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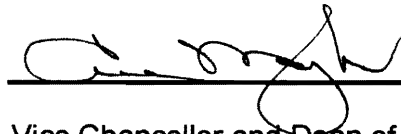


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*Dynamic Response Analysis of the
Human Knee Joint*

A Thesis Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

Brandi Lyn Bohleber
May 2005

Dedication

I would like to dedicate this thesis to my friends and family that encouraged and supported me throughout my graduate studies and helped to keep to me motivated. I would like to thank my Dad, Ken, for his help and insight for all of my engineering queries. I would like to thank my Mom, Terry, for her help and knowledge about anatomy and physiology. I would also like to thank my best friend, Ric, for his company on all those late nights to finish this.

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Abstract

Objective. To perform frequency response analysis of passive intact and meniscectomized human knee joints under body mass. The knee dynamic system parameters and their alterations with different preloads and displacement amplitudes will be determined.

Design. Using an Instron Mechanical Testing System, specially designed fixtures, and the following softwares: WaveMaker, Excel, LabView, and Matlab, the knees were dynamically tested and analyzed.

Background. Studies have been performed to analyze the dynamic behavior of the human knee. However, no experimental study has investigated the dynamic response of the knee joint under an axial compressive dynamic loading condition considering the effect of the upper body mass.

Methods. Ten human knee joints were each placed in fixtures and secured in the Instron equipment, with an added mass to simulate body weight. The dynamic testing sequence consisted of creep tests, a series of frequency sweeps at increasing amplitudes, and relaxation tests. This testing series was performed with the knee in full extension, and at a 25-degree flexion angle. A meniscectomy was performed on each specimen, and the testing trial was performed again. The data from testing was then analyzed, and the joint response was obtained.

Results. The results indicated that the resonance frequency is significantly affected by change in preload and flexion angle. Increase in preload resulted with an increase in resonant frequency, but flexing the knee resulted in a decreased resonant frequency. The stiffness also decreased significantly when the knee was flexed. The joint compliance response increased up to two fold at resonant frequency compared with that of 1 Hz frequency at different joint conditions.

Conclusion. The compliance graphs had similar shapes and had interesting trends that yielded results that can be used as reference data for future studies

and rehabilitation means. The analysis indicated that there is a range in the dynamic factors depending on the testing conditions. The meniscectomy had a significant effect on the joint response as well.

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Chapter 1: Introduction

Background

It is recognized that mechanical factors play an important role in the cause of knee injuries and diseases such as osteoarthritis. While performing daily activities such as walking, running, and climbing as well as during occupational and sport activities, the joint is exposed to vibrations and multiple impacts. There is some evidence that the cumulative effect of these impact forces may be harmful. For instance, researchers showed that repeated impulse loadings could produce degenerative changes in cartilage [Radin et al. 1973]. There is also a high risk of osteoarthritis in occupations involving repeated squatting and lifting tasks [Holibkova et al., 1989; Cooper, 1995]. Premature and posttraumatic osteoarthritis is common in elite athletes participating in sport activities involving multiple impacts on the knee joint such as soccer, cross-country skiing, ice hockey [Roos, 1998; Sandmark, 1996] as well as heavy weight-bearing such as weight lifters [Spector et al., 1996]. Even teenagers in high school sports are very susceptible to traumatic knee injury; with 60.3% of all United States school sports injuries requiring surgery involving the knee [Powell et al., 1999]. According to an individual's age, fitness, and weight, these activities may cause the joint load, stiffness, and damping to reach critical limits initiating or accelerating different knee disorders.

The knee joint is a complex nonlinear dynamic system acting as the main shock absorber of the body. Its shock absorbing property depends on the material behavior of its constituents such as meniscus, cartilage, and bones, etc. The knee joint dynamic behavior is the main determinant of how ground impact forces are transmitted to the other upper main load-bearing joints such as hip and spine. A reduced dynamic performance at the knee joint level not only has a deteriorating affect on different constituents like bone, cartilage, etc. of the knee joint itself but may also adversely affect hip joint and spine, increasing the risk of osteoarthritis and low-back pain [Wolfe et al., 1996]. The prevalence of knee OA

increases with age throughout the elderly years [Felson et al., 1987]. Elderly persons at high risk of developing radiographic knee OA include obese persons and those who are physically active. There is also an increase in rate of OA following meniscectomy in young population [Neyret et al., 1994] and damage to the ACL. An increase in weight correlated directly with the risk of developing OA [Felson et al., 1997].

Musculoskeletal disorders, of which osteoarthritis (OA) is the most common, cause significant economic, social, and psychological costs. Costs of illness have risen over recent decades accounting for up to 1-2.5% of the gross national product for those countries studied so far, including the USA, Canada, UK, France and Australia [March et al., 1997]. Statistics show that over two million cases of knee injury occur in the United States each year. Inadequate understanding of the knee joint dynamic behavior results in poor preventive measures and management of these injuries. This will further increase the number of population suffering from knee osteoarthritis [Cooper, 1995; Roos, 1998; Spector et al., 1996] and the consequent low back pain [Wolfe et al., 1996]. Osteoarthritis is the most common form of arthritis targeting elderly as well as active age groups in the population. It can result in severe pain and disability and is becoming one of the great healthcare challenges of the future [Felson, 1996; Dieppe, 1993]. About 5% of the United States population is affected with hip or knee osteoarthritis. Because of the frequency, associated pain, and disability of this disease, osteoarthritis accounts for much of the disability in lower extremities. More than 70% of total hip and knee replacements are performed for osteoarthritis [Felson, 1996]. Osteoarthritis is one of the most important diseases as it frequently affects the active age group of the population and is the source of considerable loss of working hours and of disability in the elderly as well as active age group and the use of costly health care services.

Overweight people are at higher risk of developing knee osteoarthritis (OA). Furthermore, being overweight is considered as a risk factor in accelerating

disease progression in knee OA. The health-related economic cost of obesity to U.S. business in 1994 was estimated to total \$12.7 billion. Osteoarthritis of the knee shares a substantial amount of this cost [Thompson et al., 1998]. Unfortunately, studies of metabolic factors linked to obesity have not provided an explanation for these findings [Felson et al., 1997]. In this case, the role of mechanical factors seems to be very important. Therefore, investigating the role of upper body mass and weight applied on the knee joint and its dynamic response may help develop a better understanding of the knee.

Previous studies

In preliminary studies performed on human knee joints, the passive knee joint was studied more often than a dynamic joint. In one study, cadaver knees were subjected to an applied load by testing equipment to determine movement of the knee in the anterior-posterior and medial-lateral directions, as well as varus-valgus angulation. No mass was present for inertial effect, and the knee was not loaded in the upright condition [Markolf et al., 1981]. Another study investigated the impedance of the human knee by use of a displacement generator, and found that the knee behaved similar to a Kelvin body [Crowninshield et al., 1976]. A study investigating knee stiffness and damping characteristics used an electrogoniometer to record oscillations of live knees in varying degrees of flexion. Stiffness and damping were found to increase for males, and also decrease with age [Oatis, 1993]. Impact loading on the knee joint was also studied, but a mass representing body weight was not considered. A mathematical model was created to investigate the three-dimensional dynamic behavior of the human knee joint under impact loading. This model included constraints of various ligaments, and used sinusoidally decaying forcing pulses with different durations and different magnitudes to simulate impact to the tibial center of mass in the posterior direction. They found that increasing load level caused a decrease in joint stiffness [Abdel-Rahman et al., 1998]. A finite

element model was also created to understand the behavior of the knee joint. The response of the passive knee joint under anterior-posterior forces was investigated. Tibial rotation measurements were found, and the ACL and PCL ligaments were found to constrain this movement [Bendjaballah, 1998; Pfeiler, 2004]. Whole body vibration (WBV) was also studied to determine the effects on knee extension strength and speed of movement. The amplitude of vibration was 2.5 – 5.0mm, and frequency was 35 – 40Hz. By WBV training for 24 weeks on a vibration platform, knee extension strength and speed of movement through resistance was improved [Roelants et al., 2004]. No study has investigated the dynamic response of the human knee under an axial compressive dynamic loading condition under the body mass. The above studies did not consider the joint response in terms of resonant frequency, stiffness, and other properties we are measuring under a dynamic axial load. This experimental study will investigate how a simulated body mass applied to the joint affects the joint response under dynamic loading. The results can also verify mathematical and finite element models that have been previously created.

Anatomy of the knee

The knee joint is considered to be the largest and most unstable joint in the human body [Figure 1]. The joint is complex; it consists of several tissues, ligaments, and bone structures. The main bones in the knee are the femur, tibia, patella, and fibula. The femur and tibia are the main weight-bearing bones. The femur slants medially at the knee, whereas the tibia is almost vertical. The contact surfaces between the tibia and femur are the [femoral and tibial] condyles. The condyles consist of an outer thin layer of articular cartilage with a very low coefficient of friction. This property allows the knee to flex and move in a fluid motion. The femur, tibia, patella, and fibula have an outer shell of cortical bone and an inner body of trabecular bone. The cortical bone is the strongest and most dense type of bone in the body. Both types of bone support loading.

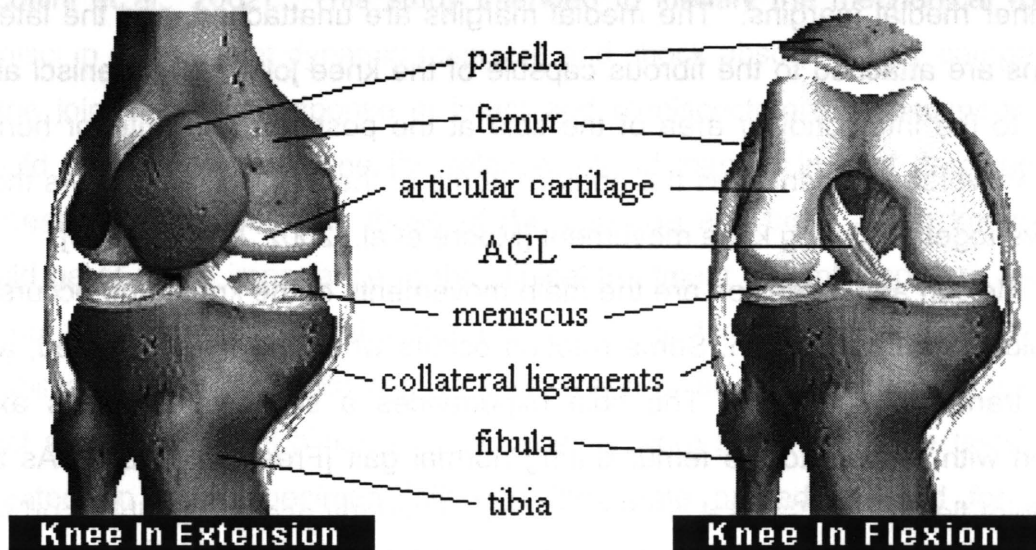


Figure 1: Anterior view of knee in flexion and extension

Several ligaments help to hold the knee joint together. The medial and lateral collateral ligaments basically attach the femur to the tibia (although the LCL attaches to the head of the fibula) and prevent excessive mediolateral movements during varus-valgus movements. The patellar ligament, a thick fibrous band, attaches to the distal part of the quadriceps tendon, passing and connecting over the patella to the tibial tuberosity. This ligament allows the patella to move mediolaterally during knee movement. The cruciate ligaments, anterior and posterior, join the femur and tibia between the condyles. They criss-cross obliquely to form the letter "X", and provide stability to the joint. The anterior cruciate ligament (ACL) is slack during a flexed knee, and taut during knee extension; the opposite is true for the posterior cruciate ligament. These ligaments prevent excess movement of the knee during flexion and extension. The menisci of the knee joint are crescent shaped plates of fibrocartilage on the articular surface of the tibia. [Moore et al., 2002; Netter, 1998] They act as lubrication, stabilization, load transfer, and shock absorbers for the knee joint [Meakin et al., 2003]. The menisci are thicker at their lateral margins, and taper

to thinner medial margins. The medial margins are unattached, and the lateral margins are attached to the fibrous capsule of the knee joint. The menisci also attach to the intercondylar area of the tibia at the posterior and anterior horns. The transverse ligament joins the anterior horns of the menisci, and allows them to move together during knee movement [Moore et al., 2002; Netter, 1998].

Flexion and extension are the main movements of the knee, and occurs at the tibiofemoral connection. Some rotation occurs when the knee is flexed, and some translation as well. The tibia experiences a slight varus-valgus axial rotation with respect to the femur during normal gait [Freeman, 2001]. As the knee joint flexes, the femoral condyle slides posteriorly across the tibial surface. Walking also causes the lateral condyles to experience a slight lift-off causing a temporary loss of contact between the surfaces, especially in persons with OA [Komistek et al., 1998]. The medial condyles of the tibia and femur typically bear slightly more weight than the lateral condyles [Kirsch et al., 1998].

Role of the musculature system

In this study, as a first step, the contribution of knee joint constituents (cartilage, meniscus, etc.) is investigated in the joint dynamic response. During an impact, the time duration is shorter than the time required for a muscle to react to the sensory signal [Nigg, 1978; 1986]. However, before an impact the muscle exertion may already exist in anticipation of the impact. Therefore, although muscle activity remains unchanged during the impact but the already activated muscles would significantly influence the joint loading and stability in impact. The influence of muscle activities has been accounted for in this study by constraining the joint flexion angle and considering different preload values.

Role of menisci

The detrimental effects of meniscectomy in altering joint mechanics and initiating degenerative OA have been well documented by many clinical reports

[Cicuttini et al., 2002]. This study intended to identify the mechanical role of menisci in overall joint dynamic response and shock absorption. By comparison of the joint dynamic response in intact and meniscectomized specimens, one should be able to determine the relative role of menisci in joint damping and stiffness as compared with those of the cartilage and bone. Such knowledge would be of prime importance in the clinical treatment of joint disorders, with or without the menisci, in the total joint arthroplasty, and in the design of appropriate rehabilitation exercises following an intervention or an injury. Following tests on intact specimens, total bilateral meniscectomy were performed. The tests were repeated on each specimen following the same procedure used for intact specimens. Dr. H. Cates, an orthopaedic surgeon, performed the initial meniscectomy procedure. The research student performed all subsequent meniscectomy procedures.

Objective

The objective of this experimental study is to develop an understanding of the dynamics of the passive knee joint with special attention on the effect of upper body mass. The frequency response analysis will be performed of passive intact and meniscectomized human knee joints under body mass. The knee dynamic system parameters (stiffness, resonant frequency, dynamic magnification factor, etc.) and their alterations with preloads and loading amplitude will be determined. The data to be obtained in this study is expected to lead to research and development of new techniques for prevention and rehabilitation of osteoarthritis. The data can also be used for qualitative validation of finite element models. The study can improve designs of preventive methods of osteoarthritis and its progression. It can also help in the future design and maintenance of total joint replacement systems as well as rehabilitation equipment and exercises. Finally, the study can provide the basic

knowledge for designing a diagnostic vibration-testing tool for early detection of osteoarthritis.

Chapter 2: Materials and Methods

Knee preparation

Five pairs of human knees were received from the Human Donor Program of the State of Texas. There were 3 female pairs and 2 pairs of male knees. The average age of the males was 58.5, and the standard deviation was 5.5. The average age of the females was 61.7, and the standard deviation was 0.94. The overall age average was 60.4, and the standard deviation was 3.88. The knees were not prepared for testing upon arrival, so they were transported to the Tissue Preservation Laboratory at the University of Tennessee College of Veterinary Medicine. There, after partial thawing, the knees were cut 5 inches distally and proximally to the joint with a bone saw. The knees were then thawed for excising the tissue. Using a scalpel and filet knife, tissue was excised approximately 2-3 inches distally and proximally to the joint in order to expose the bone distal to the joint. This was done so that the joint could be easily secured in polymethylmethacrylate within the testing fixtures. The knees were then labeled according to patient number and age. Each knee joint was placed in a labeled zippered plastic bag, and the pairs were kept together in similarly labeled drawstring plastic bags. X-rays were taken of one female and one male knee joint at the veterinary school [Figures A1 - A4]. The x-ray allowed for discovery of fracture, osteoporosis, or other anomalies of the knee joint. X-rays can later be taken after testing to detect any change in the knee joint due to the vibration procedure. Once completed, the knees were transported back to the laboratory and stored in the upright freezer. All remaining excised tissue were placed in doubled drawstring bags with respective labels, and also stored in the freezer (-40°C).

Fixture designs

In order to stabilize the knee joint in the Instron mechanical testing system, new fixtures needed to be designed. Two aluminum cups were

designed to hold the femur and tibia in place, which will later be referred to as the femur and tibial cups. These cups also allowed for stainless steel bone screws to fix the bones into a desired location within the cup. The objective for placement of the bone screws relative to top of the cup (0.25in) was to get as close to the knee joint as possible. The bone screws were threaded through the cup and firmly into the tibia or femur. The tibial cup allowed for a guide block to attach beneath. Both cups had the same design. The guide blocks allowed for translation in the x and y planes, parallel to the tibial surface. A roller bearing was also used to allow for rotation about the z-axis (in the axial direction). A flexion plate was also designed to allow for full extension and 25-degree flexion of the knee joint for testing. Adapter plates were also designed in order to attach the two guide blocks and roller bearing to the tibial cup. In order to simulate body mass, 4 weights were also designed and created. These weights were designed with a specific mass, 20 kilograms each, and were designed to fit to one another. An additional adapter plate was designed for the attachment between the four weights and the load cell. The load cell required this adapter plate in order for the pressure sensor to read the load during testing. All of these fixtures were designed to fit within the Instron equipment and attach to one another [Figure A5].

Fixture set-up

Additional fixtures, as referenced above, needed to be ordered to complete the fixture set up. Two lockable Versa-mount needle roller bearing guide blocks, guide block rails, and connecting components were purchased [McMaster-Carr. Atlanta, GA]. The guide blocks were purchased so that the knee joint could translate freely in the x and y direction (horizontal) during testing. The lockable feature on the guide blocks was intended for investigating whether change in range of motion would affect the dynamic response. A cast iron

flange-mount steel ball bearing (Abec-1) was purchased so that the knee joint could rotate freely about the z direction (femoral-tibial axial direction).

Experimentation set-up

In order to secure the knee joint within the Instron equipment, the fixtures were assembled. The 40kN load cell was threaded into the Instron actuator. Four 20kg weights were then attached below the load cell. This mass represented the upper body mass. Considering the weight of fixtures and mould on top of the specimen (~5 Kg), the upper body mass was approximately 45 Kg. The joint resonant frequency should be within the frequency range of 1- 40 Hz, including the effect of body mass, and should also be within the range of in-vivo values. The 45 Kg upper mass represented the mass in a two-leg stand of a heavy person (90 Kg) or in a one-leg stand of a light individual (45 Kg). The flexion plate was then attached below the weights. The knee joint fixture assembly (aluminum cups with the knee joint) was attached below the flexion plate. The guide blocks and rails were attached below the knee joint, each guide block and rail assembly separated by an adapter plate. The roller ball bearing was attached at the bottom of the entire assembly, and screwed into the base of the Instron [Figure A5].

In order to secure the knee joint within the fixture assembly and Instron equipment, the joint needed to be secured first in the cups. The human femur was first placed into the femur cup. Bone screws were then threaded through the cup and into the bone to secure the bone into place, near the center of the cup. Epoxy was then poured in to fill the space [Ivoclar Vivadent, Inc. Buffalo, NY]. The epoxy was made by mixing a batch of 12 scoops of powder and approximately 110 mL of liquid. Once the epoxy set, the human tibia was ready to be placed into the tibial cup. The femoral cup was threaded to the flexion plate and weights. The tibia was then lowered into the tibial cup, which was already attached to the slider assembly on the Instron. The tibia was then set with bone

screws. The epoxy mixture for the tibial cup consisted of approximately 11 scoops of powder and 90mL of liquid. This mixture was then poured in, and the epoxy was allowed to fully set. Gauze was wrapped around the knee joint, and a 0.9% saline mixture was sprayed onto the knee to prevent dehydration during testing. The joint was then ready to be tested within a complete fixture assembly.

Testing procedure

All tests were programmed to run on the Instron 1800.11 machine [Instron Corporation. Canton, MA]. Software packages from National Instruments were used since they were compatible and written for the Instron machine [National Instruments Corporation. Austin, TX]. Two software packages, WaveMaker Editor and WaveMaker Runtime, were used for data acquisition and machine control. WaveMaker Editor allowed the user to write a function program in order to perform specific tests using the Instron machine. WaveMaker Runtime allowed the user to open and run the WaveMaker Editor programs written. Runtime then sent this program data to the Instron, and the machine performed the tasks as specified in WaveMaker Editor. Data was then sent from the load cell to the computer and stored in files as specified in Editor. Several different programs, composed of quasi-static and oscillating forces, were written in WaveMaker Editor: creep tests, frequency sweeps, and relaxation tests. These tests simulated compressive forces on the knee joint under vibration loading and the initial joint condition upon a step impact during jumping and running [Nigg, 1978].

Creep tests were written in order to precondition the knee joint before running the frequency sweep. The creep test was first performed by applying a step load of 2 seconds rising time and 5 minutes hold duration at a specified preload. The next preconditioning step for the creep test was applied in 10 cycles of triangular ramp loading with a rising time of 500 ms (2 Hz) for bringing the joint to a steady state condition. Three different creep tests were written in order to

condition the knee at different preloads: 400N, 800N, and 1200N. The preload magnitudes were chosen to be nondestructive, considering that forces experienced by the knee in daily-living activities can reach up to 6 times the body weight [Taylor et al., 1998, 2004; Nilsson and Thorstensson, 1989]. The rising time and hold duration still remained the same for all preloads. This preload difference could change the response of the knee joint, and could later be seen in the resonant frequency. Previous studies [Kasra et al., 1998; Kasra et al., 1992] indicated that the joint stiffness was not sensitive to changes in loading speed or frequency up to 100 folds. Therefore, the initial joint stiffness induced by a preload of 500ms rising time was expected to simulate the stiffness in walking (100-150ms) as well as in more strenuous activities such as jumping and running (10-15 ms) [Shepherd and Seedhom, 1997; Payne, 1978].

Frequency sweeps were performed after each randomly applied preload test, and consisted of 3 different amplitudes. The sweep at each preload was performed automatically by programming the testing machine. All the frequency sweep tests at each preload were performed with a 0.04mm dynamic amplitude except for the case of 400 N preload, where the effect of different dynamic amplitudes (0.04mm, 0.06mm, and 0.08mm) were investigated [Figure 2]. These amplitudes were chosen to generate a linear response and used to investigate whether the amplitudes have an effect on changing the knee resonance. The specimens were subjected to axial sinusoidal force with frequencies ranging from 1 to 40Hz. The frequency-sweep technique was employed to collect compliance and viscoelastic data. The frequency sweep consisted of 1-Hz intervals at frequencies distant from resonant frequency and at 0.5-Hz intervals at frequencies approaching the resonant frequency. The data sampling rate was 1kHz from 1-8Hz, 1.667kHz from 9-30Hz, and 2.5kHz from 31 to 40Hz. After each frequency sweep test, the preload was removed and the specimen repositioned to the original position before testing to allow recovery to the baseline configuration (5 minutes) before the next preload was applied.

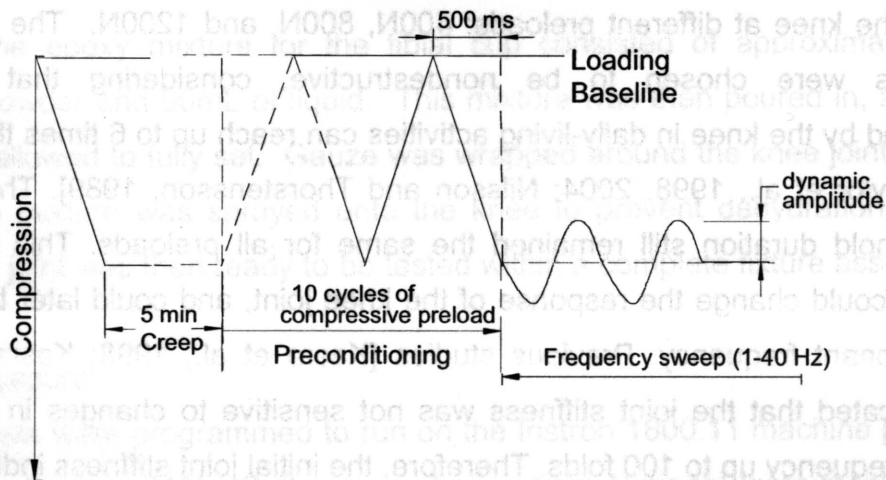


Figure 2: General pattern of loading condition with frequency sweep

Three relaxation test programs were written to relax the knee joint at different rates after the creep and frequency sweep tests. Relaxation testing could provide more insight into the viscoelastic behaviour of the knee joint. A maximum axial displacement of 1.5 mm (d_0) from an initial position of 0 mm was randomly applied at different rates of 0.1 s, 1.0 s and 10.0 s. The displacement was chosen to induce a compression load of no more than 1000 N. The specimen was then allowed to relax and hold at this displacement for approximately 5 minutes. After each test, the specimen was brought back to its baseline (original position). A resting time of 5 minutes was given for recovery between each relaxation test. Flexion angles of 0° (full extension) and 25° (knee flexion) were performed for each complete test trial – creep trials, frequency sweeps, and relaxation tests [Figure 3].

The tests for the intact specimen were completed in one day, and the meniscectomy procedure and subsequent testing on the following day. During preparation and the testing procedure, the specimens were kept moist by wrapping them lightly in gauze soaked with saline. The moisture was sustained by continuously spraying saline water on the specimen gauze between each test.

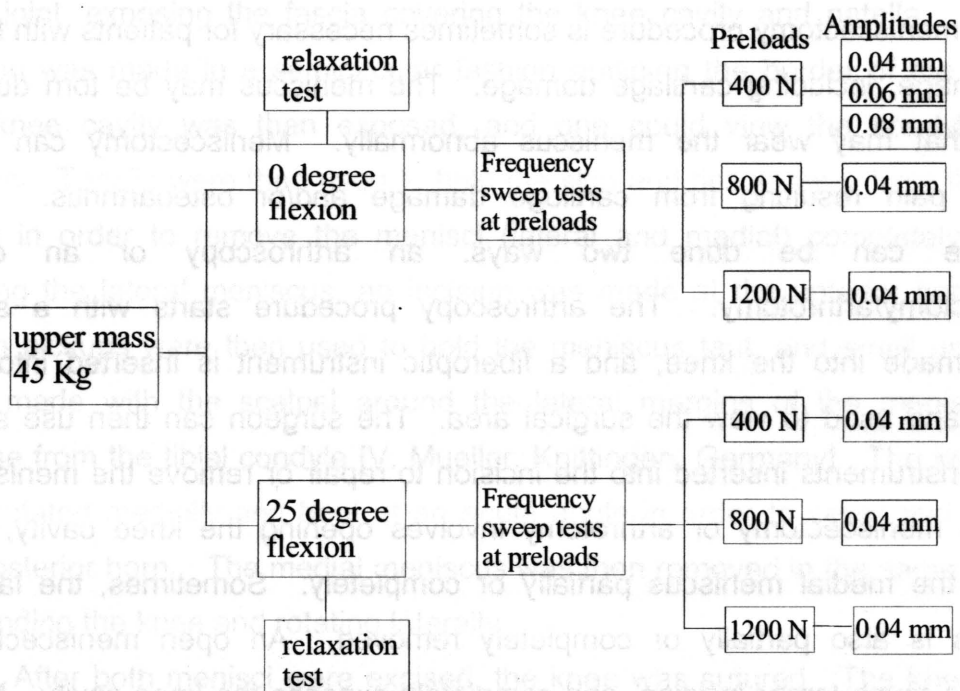


Figure 3. Dynamic testing protocol.

After testing, the joint–fixture assembly was dismantled and stored in deep freeze. On the following day, the menisci were removed and the loading protocol was repeated. Therefore, each specimen was tested two times in two days, having two cycles of freezing and thawing. The mechanical effect of refrigeration has previously been investigated. No influence on the pattern of load transmission was found when the same knee was tested "fresh" and again after freezing and thawing [Hoshino and Wallace, 1987; Jans et al., 1988]. Furthermore, freeze-thawing cycles have little effect on the mechanical properties of cartilage or subchondral bone [Kempson, 1979; Sedlin et al., 1966].

Meniscectomy

A meniscectomy procedure is sometimes necessary for patients with knee joint damage, including cartilage damage. The meniscus may be torn due to activity that may wear the meniscus abnormally. Meniscectomy can also alleviate pain resulting from cartilage damage and/or osteoarthritis. This procedure can be done two ways: an arthroscopy or an open meniscectomy/arthrotomy. The arthroscopy procedure starts with a small incision made into the knee, and a fiberoptic instrument is inserted into the opening and used to view the surgical area. The surgeon can then use small surgical instruments inserted into the incision to repair or remove the meniscus. An open meniscectomy or arthrotomy involves opening the knee cavity, and excising the medial meniscus partially or completely. Sometimes, the lateral meniscus is also partially or completely removed. An open meniscectomy involves a much larger incision, and completely exposes the knee cavity. More complicated situations such as bone fracture and ligament damage may require this invasive procedure [Gray et al., 1995]. This study will involve a complete bilateral meniscectomy.

It is recognized that a meniscectomy procedure can significantly affect knee joint performance. Thus, this study investigated the change in dynamic response of the knee joint due to a meniscectomy procedure. Finite element models were also available that can simulate this condition and output the stress in the knee joint as compared to a normal knee [Meakin et al., 2003]. For this study, an open meniscectomy procedure was utilized. The knee was completely thawed out after removing from the freezer for 18 hours. The knee joint was placed in an approximate 90-degree angle (between the tibia and femur) for surgery. Using a scalpel with a #10 stainless steel blade, an incision was made midline of the knee joint, from the quadriceps/femoral tendon to the patellar tendon (~4-5 inches) connecting to the tibial tuberosity [Feather Safety Razor Co. Ltd. Seki, Japan]. Brown pickups were used to hold the outer tissue taut away

from the joint. Using the scalpel, the superficial tissue was cut away from the knee joint, exposing the fascia covering the knee cavity and patella. Another incision was made in a semicircular fashion outlining the border of the patella. The knee cavity was then exposed, and one could view the condyles and menisci. Tonsils were then used to hold the skin and tissue away from the knee cavity in order to remove the menisci (lateral and medial) completely. After locating the lateral meniscus, an incision was made at the anterior horn. The Brown pickups were then used to hold the meniscus taut, and small undercuts were made with the scalpel around the lateral margins of the meniscus for release from the tibial condyle [V. Mueller. Knittingen, Germany]. The knee was then rotated medially and bent at an acute angle in order to sever and release the posterior horn. The medial meniscus was then removed in the same fashion by bending the knee and rotating laterally.

After both menisci were excised, the knee was sutured. The knee cavity was closed and sutured first to maintain stability of the knee. An Ethibond #1 nonabsorbable polyester reverse cutting suture with an attached needle was used [Ethicon, Inc. Somerville, New Jersey]. The knee cavity had 6 double sutures, each with 6 knots. The knots were made in an alternating fashion to create square knots that would not slip. The sutures were placed approximately 0.5 inches apart. Suture scissors were used after completion of each suture to cut the thread between sutures. The skin and outer tissue were then sutured together to completely enclose the knee joint as it was before meniscectomy. Here, 4 double sutures were made with 6 knots each, spaced approximately an inch apart. The knee was again wrapped in gauze and sprayed with the saline mixture for hydration. The same testing procedure was then used to compare a meniscectomized knee to normal conditions.

Data analysis process

All data was stored as comma delimited files from the Instron machine. This data was then converted into Excel text files, and columns of data were set up: time, block, load and position [Excel 2000. Microsoft Office Corp. Seattle, WA]. The block number corresponded to the frequency that the data was collected. Load and position data were normalized at zero in order to provide a clearer visual of the data response. These text files were then run through Matlab programs created to separate the data according to frequency [Matlab 7.0. The MathWorks, Inc. Natick, MA]. That is, each frequency was separated with its corresponding time, load, and position data in its own file. These text files were then analyzed in LabView with a lowpass filter [LabView. National Instruments. Austin, TX]. This LabView program passed all frequencies from 1 to 200Hz, removing the high frequency noise content of the force/displacement signals. The program also made charts displaying the filtered load and position data. The resulting filtered data was stored as new filtered text files and run through another Matlab program. This program read in all of the text files and calculated the compliance, load amplitude, displacement amplitude, and phase angle at each frequency. All calculated data for a frequency sweep (1-40Hz) was collected into one text file by the Matlab program, and compliance and phase angle curves could then be created. Stiffness, magnification factor, and dampening could then be calculated from these values. This was done for each specimen at the different amplitudes and preloads prescribed earlier.

Chapter 3: Results

One main objective of this study was to obtain the resonant frequency of the knee joint through compliance curves. All 10 specimens were analyzed at the 400N preload and 0.04mm displacement for all 4 conditions: intact with full extension, intact with flexion angle of 25 degrees, meniscectomized with full extension, and meniscectomized with flexion angle. Once analyzed, the compliance and phase angle curves were created, and resonant frequency, phase angle at resonant frequency, magnification factor, compliance at 1Hz, and stiffness could be obtained and calculated. The magnification factor was calculated by dividing the compliance at resonant frequency by the compliance at 1Hz for that specific condition. The stiffness was calculated by inverting the compliance at 1Hz.

Compliance data

The compliance charts for the specimens were similar in shape [Figures 4, A6 – A148 (even)]. One can see that there was an initial flat line followed by a small rise and fall, then a large rise and fall corresponding to resonant frequency, and finally another small rise and fall near the end of the frequency sweep. The phase angle curves were also similar in shape for the specimens. There was an initial flat line, a small rise and fall, and then a sharp peak, and a continuation of curve at this peak for a short interval of frequency, another sharp fall, and then perhaps another small rise and fall at the end of the frequency sweep [Figures 5, A7-149 (odd)]. The compliance graphs also showed a difference when changing the condition under the same preload and amplitude. The compliance changes for the following conditions: from intact full extension to flexion angle, meniscectomized full extension to flexion angle, intact full extension to meniscectomized full extension, and intact with flexion angle to meniscectomized with flexion angle for specimen 7 with a 400N preload and 0.04mm displacement

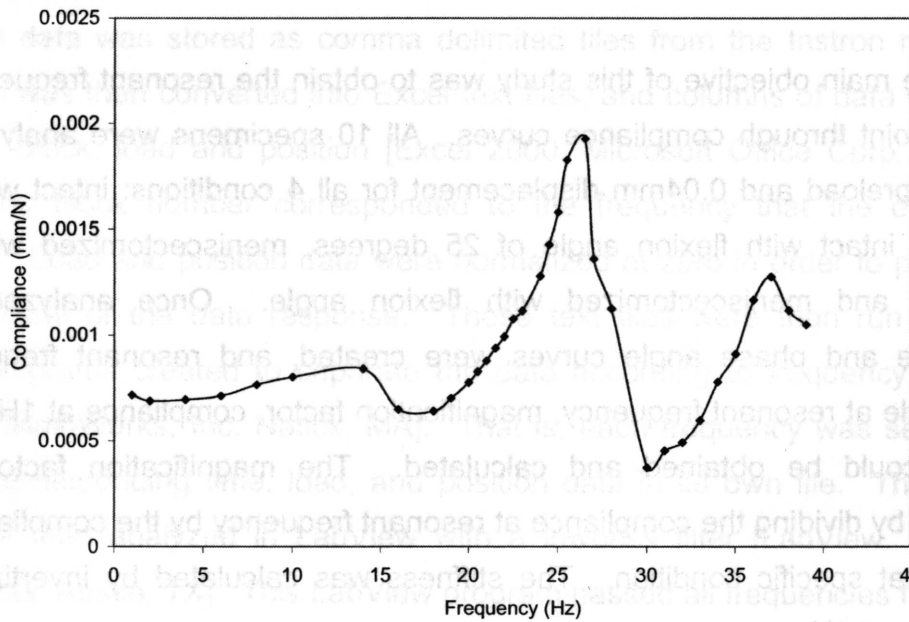


Figure 4: Specimen 7 intact full extension with 400N preload, 0.04mm amplitude

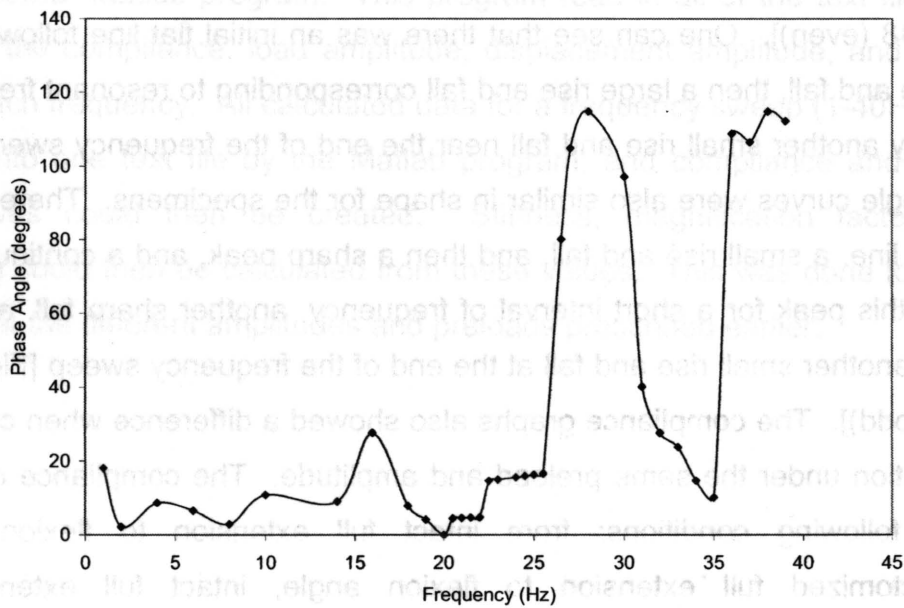


Figure 5: Specimen 7 intact full extension condition phase angle curve for 400N preload and 0.04mm amplitude

[Figures A150 – A153]. For the intact condition, the flexion angle caused the compliance to rise compared to full extension, but the resonant frequency decreased, and the same is true for the meniscectomized condition. When comparing the intact and meniscectomized conditions, one can see that for the full extension test, the meniscectomized knee had a higher compliance and lower resonant frequency. For the flexion test, the curves were more similar, but the meniscectomized knee had a very slightly lower resonant frequency, and the compliance curve was slightly higher and lower in places.

Complete analysis

A complete analysis of specimen 10 was completed for all preloads and changes in amplitude for all conditions tested. The compliance trend across the preloads (400, 800, and 1200N) for all 4 conditions with a 0.04mm displacement showed somewhat similar trends [Figures A154 – A157]. The intact full extension and flexion angle showed that compliance decreased with increase in preload. For both cases, resonant frequency increased with increase in preload. The meniscectomized full extension and flexion angle showed that 400N preload had the greatest compliance, followed by 800 and then 1200N. The flexion angle graph curves for the 800 and 1200N were somewhat similar in shape. Most had a noticeable change in compliance between preloads, though there was not a distinct change in compliance for the meniscectomized full extension condition.

The resonant frequency showed a general trend of increasing with increase in preload. The phase angle trend across the preloads for all 4 conditions all showed that the general phase angle curves decreased with an increase in preload [Figures A158 – A161]. The compliance trends at the 400N preload with change in amplitude for all 4 conditions demonstrated that an increase in displacement amplitude resulted in a general increase in compliance [Figures A162 – A165], and these results compares well with the finite element

model predictions [Pfeiler, 2004]. The full extension curves for the intact and meniscectomized conditions were similar in shape, as were the flexion angle curves for both conditions. The resonance frequencies for change in amplitude were also similar corresponding to testing condition. That is, for full extension, the resonance frequencies were 26.5, 25.5, and 26Hz for 0.04, 0.06, and 0.08mm displacement, respectively. The phase angle curves also showed a general trend: an increase in displacement amplitude resulted in a general increase in the phase angle curve, though the full extension phase angle curves did not show as much of a distinct increase [Figures A166 – A169].

Dynamic response factors

Bar charts were then created to show how each condition changed the response in resonant frequency, compliance at resonant frequency, magnification factor, and stiffness at 1Hz. These bar charts consisted of all the specimens with a 400N preload and a 0.04mm displacement. The average and standard deviation was shown for each condition given the analysis considered. For the resonant frequency, the flexed condition showed a decreased resonance before and after meniscectomy when compared to full extension [Figure 6]. The resonance frequencies were similar between the full extension and flexed conditions before and after meniscectomy. That is, the average resonant frequency for the intact full extension condition was 26.5Hz, and 25.7Hz for the meniscectomized full extension condition. Statistical analysis for all specimens was also done in SPSS [SPSS 12.0, SPSS Inc., Chicago, IL]. A paired samples t-test was used for all dynamic response factors (significance level $p < 0.05$). The resonance frequency for full extension was significantly higher than the flexion angle condition for both the intact ($p = 0.012$) and meniscectomized ($p = 0.008$) conditions.

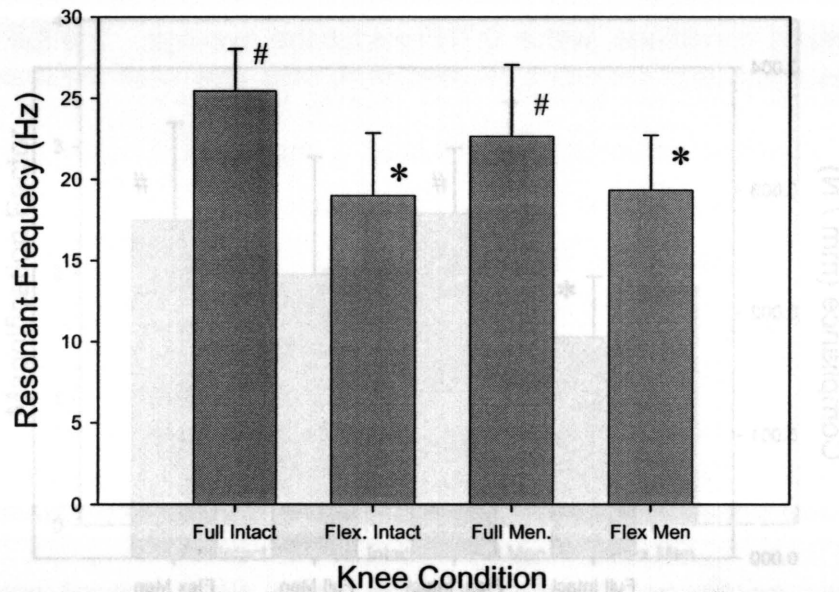


Figure 6: Average resonant frequency for all specimens with 400 N preload and 0.04 mm amplitude. Groups with different symbols (#, *) are significantly different ($P < .05$).

The bar chart for the compliance at resonant frequency also shows an interesting trend [Figure 7]. The flexed condition for both intact and meniscectomized knees illustrated a higher compliance than the full extension condition, which correlated to a lower stiffness. An increase in compliance is directly related to a lower stiffness since stiffness is the inversion of compliance. The compliances also showed a significant difference with a paired samples t-test. The results indicated that the compliance was significantly lower for the full extension intact condition than all other conditions. The intact full extension condition was significantly lower than the intact flexion angle ($p = 0.008$), lower than the meniscectomized full extension condition ($p = 0.022$), and lower than the meniscectomized flexion angle (0.028).

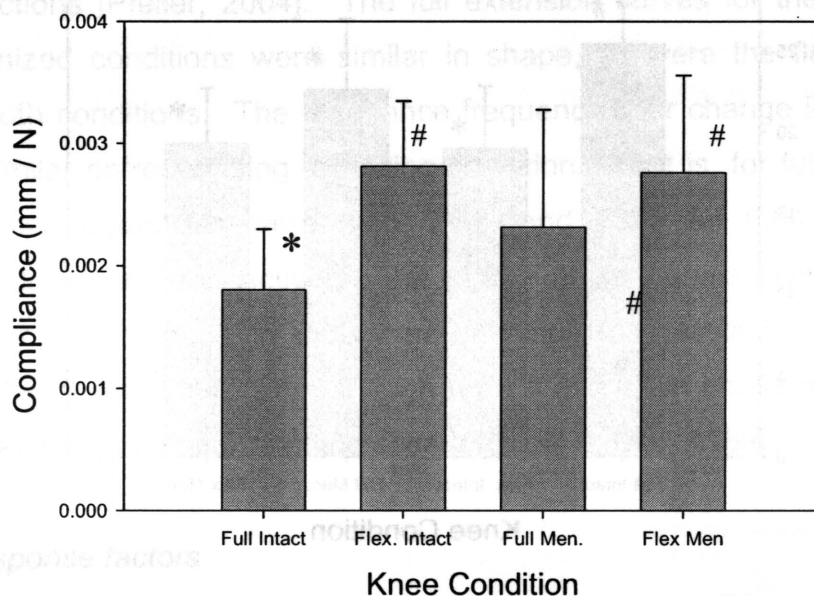


Figure 7: Average compliance at resonance for all specimens with 400 N preload and 0.04 mm amplitude. Groups with different symbols (# ,*) are significantly different.

The magnification factor analysis shows similarity between all the conditions except for the full extension meniscectomized condition [Figure 8]. This magnification factor was approximately 2.6, whereas the others were around 2 ± 0.1 . This showed that the full extension meniscectomized condition has the greatest range in compliance between 1Hz and resonant frequency. The paired samples t-test did not show any significant difference between any of the conditions.

The stiffness at 1 Hz analysis showed a similar trend as that of the resonant frequency [Figure 9]. The stiffness at 1 Hz simulated the stiffness in the knee at static loading, whereas the stiffness at resonant frequency was more representative of dynamic loading. The flexed condition showed a decreased stiffness compared to the full extension for both the intact and meniscectomized knees. The flexed condition was almost exactly the same between the intact and

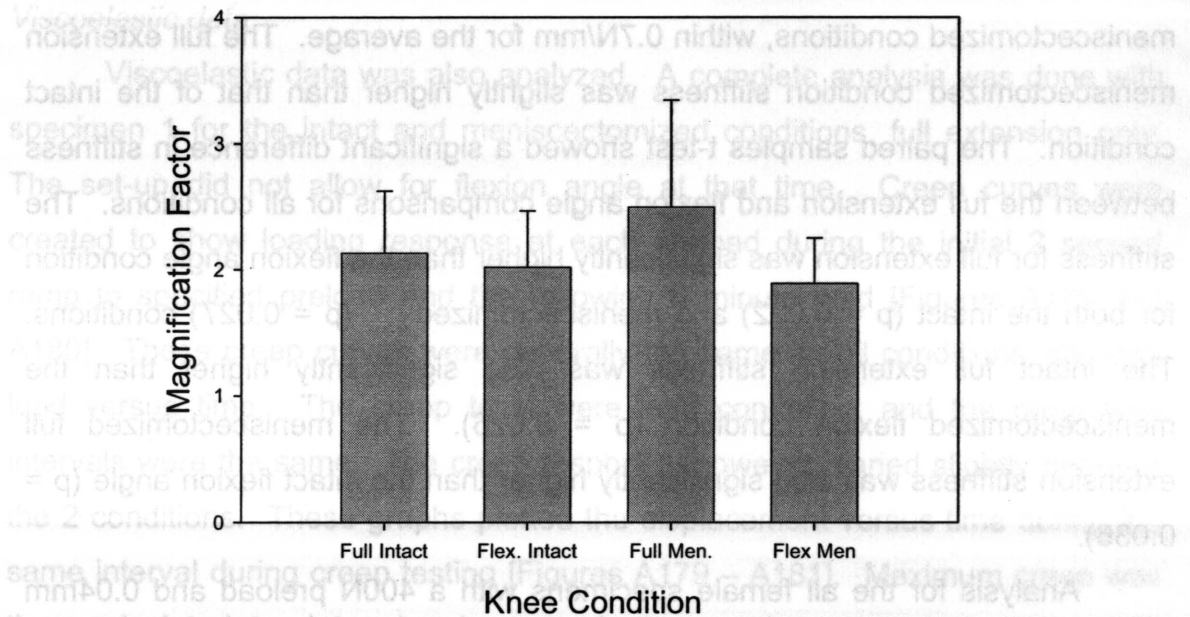


Figure 8: Average magnification factor for all specimens with 400 N preload and 0.04 mm amplitude. There was no significance between the groups.

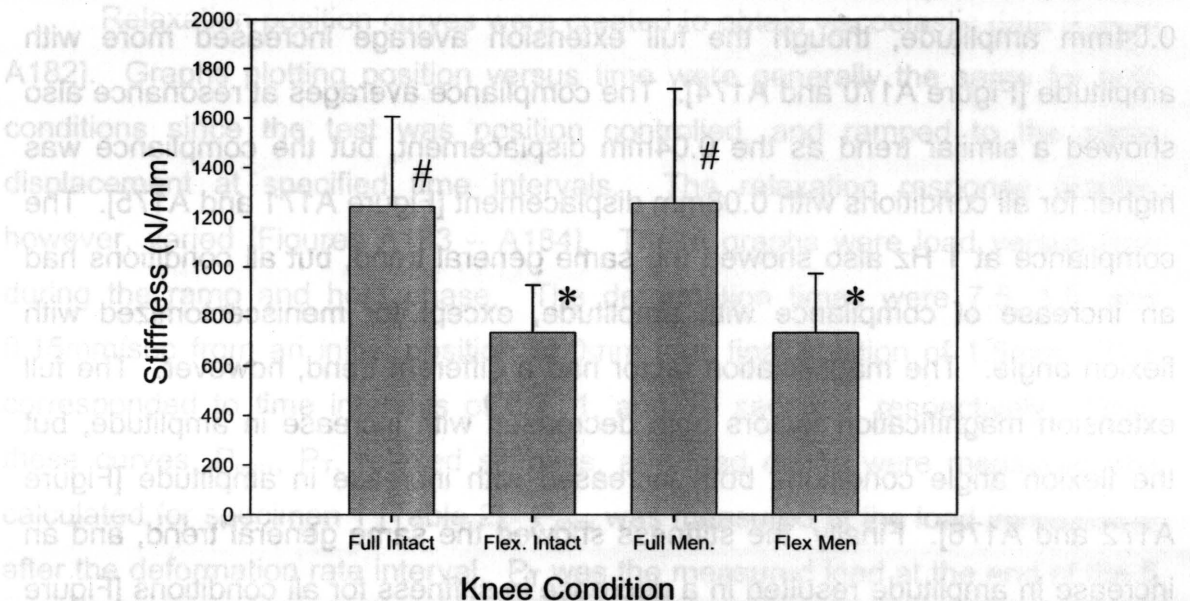


Figure 9: Average stiffness for all specimens with 400 N preload and 0.04 mm amplitude. Groups with different symbols (#, *) are significantly different.

meniscectomized conditions, within 0.7N/mm for the average. The full extension meniscectomized condition stiffness was slightly higher than that of the intact condition. The paired samples t-test showed a significant difference in stiffness between the full extension and flexion angle comparisons for all conditions. The stiffness for full extension was significantly higher than the flexion angle condition for both the intact ($p = 0.022$) and meniscectomized ($p = 0.027$) conditions. The intact full extension stiffness was also significantly higher than the meniscectomized flexion condition ($p = 0.026$). The meniscectomized full extension stiffness was also significantly higher than the intact flexion angle ($p = 0.036$).

Analysis for the all female specimens with a 400N preload and 0.04mm and 0.08mm displacement was performed [Figures A170 – A177]. This was done to determine whether a change in amplitude had an effect on the properties we are calculating, although only for the female specimens. The resonant frequency averages for the 0.08mm followed the same trend as that of the 0.04mm amplitude, though the full extension average increased more with amplitude [Figure A170 and A174]. The compliance averages at resonance also showed a similar trend as the 0.04mm displacement, but the compliance was higher for all conditions with 0.08mm displacement [Figure A171 and A175]. The compliance at 1 Hz also showed the same general trend, but all conditions had an increase of compliance with amplitude, except for meniscectomized with flexion angle. The magnification factor had a different trend, however. The full extension magnification factors both decreased with increase in amplitude, but the flexion angle conditions both increased with increase in amplitude [Figure A172 and A176]. Finally, the stiffness showed the same general trend, and an increase in amplitude resulted in a decrease in stiffness for all conditions [Figure A173 and A177].

Viscoelastic data

Viscoelastic data was also analyzed. A complete analysis was done with specimen 1 for the intact and meniscectomized conditions, full extension only. The set-up did not allow for flexion angle at that time. Creep curves were created to show loading response at each preload during the initial 2 second ramp to specified preload and the following 5 minute hold [Figures A178 and A180]. These creep curves were generally the same for all conditions, showing load versus time. The creep tests were load controlled, and the ramp time intervals were the same. The creep response, however, varied slightly between the 2 conditions. These graphs plotted the displacement versus time during the same interval during creep testing [Figures A179 – A181]. Maximum creep was then calculated to determine how much the specimen crept under each preload during the 5 minute hold [Table 1]. These calculations were made by subtracting the final load at the end of the hold by the initial load at the beginning of the hold.

Relaxation position curves were created to obtain viscoelastic data [Figure A182]. Graphs plotting position versus time were generally the same for both conditions since the test was position controlled, and ramped to the same displacement at specified time intervals. The relaxation response graphs, however, varied [Figures A183 – A184]. These graphs were load versus time during the ramp and hold phase. The deformation times were 7.5, 1.5, and 0.15mm/sec from an initial position of 0mm to a final position of 1.5mm. This corresponded to time intervals of 0.2, 1, and 10 seconds, respectively. From these curves, P_{max} , P_T , relaxed stiffness, and load decay were measured and calculated for specimen 1 [Table 2]. P_{max} was measured at the load immediately after the deformation rate interval. P_T was the measured load at the end of the 5 minute hold. The relaxed stiffness was calculated by dividing P_T by the displacement of 1.5mm. The load decay was calculated by dividing P_{max} by P_T . The relaxation response showed that the load response on the meniscectomized

Table 1: Maximum Creep Calculations for Specimen 1

	Intact	Meniscect.
Preload (N)	Max Creep (mm)	Max Creep (mm)
400	0.278181	0.9163134
800	0.485692	0.547993
1200	0.70533	2.272277

Table 2: Relaxation Response Calculations

Intact				
Deformation Rate (mm/s)	P_{max} (N)	P_T (N)	Relaxed Stiffness (N/mm)	Load Decay
7.5	477.174295	317.59423	211.72949	1.5024653
1.5	502.743755	331.04082	220.69388	1.518676
0.15	455.22143	335.32376	223.54917	1.3575579
Meniscectomized				
Deformation Rate (mm/s)	P_{max} (N)	P_T (N)	Relaxed Stiffness (N/mm)	Load Decay
7.5	320.3746	167.14595	111.43063	1.9167356
1.5	296.0193	182.61687	121.74458	1.6209855
0.15	285.1342	191.5559	127.70393	1.4885169

knee was much lower than the intact knee [Figure A184]. The creep response curves were somewhat similar between conditions, though the displacement for the meniscectomized knee was a little higher for the 1200N preload during the 5 minute hold [Figure A181].

Meniscus grading

During the meniscectomy procedure, each knee was given a grade corresponding to the level of osteoarthritis and wear of cartilage the individual had. These grades were based on the Kellgren-Lawrence grading scale. This scale gave the following grades and conditions: 0 - normal, 1 - fibrillation of superficial layer of cartilage; no loss of cartilage, 2 - fissuring and loss of tissue, 3 - calcified cartilage exposed, tide mark exposed to surface, 4 - deep lesions into bone, 2/3 of lost cartilage. All specimens received a grade of at least a 2 [Beattie K et al., 2005, Table 3]. For specimen 8, one can see that the cartilage was mainly intact, shiny, and in relatively good condition, which warranted a grade of 2 [Figure A185]. The lateral and medial menisci were in relatively good condition as well [Figure A186]. Specimen 7 showed relatively bad cartilage condition, warranting a grade of 4 [Figure A187]. The lateral and medial menisci are not in good condition, either [Figure A188].

Table 3: Specimen Grading Summary

Specimen	Patient No.	Gender	Age	Left/Right Knee	Grade of OA
1	42305	Female	63	Right	2
2	43287	Male	53	Left	3
3	45328	Female	61	Left	3
4	43457	Female	61	Right	3
5	45016	Male	64	Left	3
6	42305	Female	63	Left	3
7	43287	Male	53	Right	4
8	45328	Female	61	Right	2
9	45016	Male	64	Right	4
10	43457	Female	61	Left	2

Chapter 4: Discussion

Objective

This research concentrated on finding the dynamic response of the human knee joint under an axial dynamic load. The study entailed designing special fixtures that would allow natural movement of the knee joint under compression leading to an accurate representation of the data and results that were desired. The knees were prepared, preconditioned, and tested in a dynamic manner that incorporated body mass for physiological accuracy, and then tested in relaxation to gain insight to the viscoelastic behavior of the joint. The changes in relaxation testing corresponded to finding joint relaxation properties at changing deformation rates. The meniscectomy procedure was used in order to gain more knowledge of the intact knee condition as well as determine the effects in the joint response with the absence of the menisci. The change in flexion angle was used to simulate the knee angle at foot-strike in running (25 degrees) and determine how this affected the dynamic response. The findings in this study will lead further research in the behavior of the knee joint, as well as aid in knee product design and rehabilitation means.

Clinical applications

The inclusion of an upper body mass marked this project as the first in its category. No other study has incorporated an upper body mass to investigate the mechanical properties of the knee. This test was the first to apply a dynamic load with a body mass to simulate different physiological conditions such as walking, running, and impact loading and obtain dynamic response factors for the whole knee joint. The finite element model previously created in conjunction with this study can also be validated by the resulting experimental data. The model predicted movements of the joint in response to different loads, and the stresses that resulted [Pfeiler, 2004]. This study validated the model by showing how the joint responded in resonant frequency, stiffness, magnification factor, etc. This

study can be applied to physical conditions such as osteoarthritis or sports injuries. For example, knowing the body mass of the individual, condition of the body, and the activities the person is involved in, the chance of developing OA can be predicted as well as developing preventative measures or rehabilitation means, by predicting risk enhancing movements. The OA condition can also be predicted using data from this study in conjunction with mathematical and finite element models already created. Further research beyond this study by referring to this data can lead to improvement in knee implant design as well as treatment, preventative measures, and rehabilitation means for conditions relating to the knee.

Frequency response

The pattern of the compliance curves was generally similar, as shown in the Appendix. The difference in rise and falls in the compliance curves may be related to different modes of the knee motion during testing. These modes can be explained by vibrational theory. Since the knee joint was loaded axially, the main compression force was along the superior-inferior direction (z-axis). The knee was allowed to rotate about the z-axis, and translate in the x-y plane (mediolaterally and anteroposteriorly). These non-axial, non-constraint movements could have caused some cross contamination in the data [McConnell K, 1995]. The contamination results from the movement causing a small amount of load or force on the knee that is not in the axial direction. Thus, the additional modes seen in the compliance graphs corresponding to the initial and final peaks could be attributed to this contamination. The initial peak could be attributed to translation and rotation, the middle peak was the compression mode since the knee was primarily in compression, and the last mode may have been a combination of rotation and compression or translation. The middle mode has the highest compliance, corresponding to the resonant frequency, and was the highest peak since the testing was position controlled. Due to this, the

displacement amplitude was controlled to stay constant during the frequency sweep, and the load was allowed to change depending on the frequency and response of the knee. When the load reached a minimum, the compliance reached a maximum. The load approached a minimum during resonance since the stiffness of the knee decreases to a minimum at resonance. The knee is most unstable at this frequency since there is no resistance, and therefore has a low stiffness.

The shape of the phase angle curves also followed this trend in modes. The initial rise and fall may be related to a cross-contamination mode, but the sharp rise was related to the resonant frequency. The initial phase angle measurements were during low frequencies, and the testing simulated a quasi-static loading condition. When the resonant frequency occurred, normally at higher frequencies, the phase angle would jump to approximately 90 degrees, perhaps more in some cases. This was due to the shift in the load and position curve peaks.

The decreased resonant frequency in all the bar charts for the flexed condition compared to full extension could be attributed to the knee becoming more unstable, and thus having a lower stiffness, since the condyles did not have as much surface area contact. The absence of the menisci also decreased the surface area contact, and the load was not as evenly distributed across the tibial plateau. Therefore, the joint was more apt to move extraneously and had less support, leading to a lower stiffness. In full extension, however, the joint was more stable, and the load was distributed more evenly between the condyles. Therefore, the stiffness was higher for the full extension conditions than that of the flexed conditions, and the resonant frequency occurred at slightly higher frequencies. Stretched ligaments in different conditions could have caused the increased stiffness.

As for the changes in amplitudes for specimen 10 with 400N preload, a large difference in resonant frequency was not apparent. The resonant

frequency difference was only ± 1 Hz. The change in amplitude showed a slight shift in compliance, directly relating to stiffness, which was expected. The change in preload, however, showed a larger change in resonant frequency. As the preload increased, the resonant frequency increased, which corresponded to an increase in stiffness. The joint was subjected to a higher load, becoming stiffer, and behaving as a Kelvin body as suggested by earlier studies.

The magnification factor did not seem to have a significant difference between any conditions in the paired samples t-test. Most were the same, 2 ± 0.1 , except for the full extension meniscectomized condition. The full meniscectomized condition had the highest magnification factor average and standard deviation for all tests analyzed. More knees would need to be tested to determine whether there is a significant difference in magnification factor.

The stiffness at 1 Hz showed a similar trend as that of the resonant frequency bar chart. This showed that the data during the dynamic loading condition was validated by similar data during the static loading condition. That is, the response relationship between quasi-static and dynamic loading were somewhat linear, which can show that results from the dynamic loading were expected to occur. If the response was nonlinear, then mathematical models could not be as easily validated by these findings. Since the trends were similar between static and dynamic loading, then the resonance frequencies found can be held as quality reference data, due to linearity.

Viscoelastic data

The viscoelastic data calculations for specimen 1 also showed trends corresponding to increases in preload. For intact and meniscectomized conditions, the maximum creep calculated increased with an increase in preload. The most significant increase was for the 1200N preload, meniscectomized condition. This may have been attributed to the absence of the meniscus and not having the load absorption qualities as that of the intact condition. The

relaxation response showed that increase in deformation rate had the same effect for both conditions: the relaxed stiffness increased and load decay decreased. This can be attributed to the knee having more time to relax, and thus the knee was not as stiff and the load did not reach as high a peak for a larger decay to occur [Table 2, Figures A183 and 184].

Osteoarthritis grading

The grades given to the knees for osteoarthritis and condition of the cartilage can be attributed to several factors: lifestyle of the individual, daily activities of the individual such as athletic to bedrest, as well as genetics and age. The individuals that had higher muscle content, notably the males, had more cartilage wear. The females with less muscle tissue and more fat, which can be attributed to less physically stressful lifestyles, had better cartilage conditions.

Future work

This study was intended to gain fundamental data from the response of the knee joint under a dynamic load. These findings can be used as reference data for future studies that incorporate body mass or need the compliance, resonance, or viscoelastic data to complete a model or design a new project or product. Continuation of analyses for this study can be done to have a complete understanding of the specimens considered overall. That is, viscoelastic data and the change in preloads for all specimens can be completed to get a better understanding of how the joint responds. This study also allowed the knee to move freely during testing. Future studies can be done that do not allow the knee to move, and determine how that changes the joint response. Better testing equipment could also be utilized. This study used older software that had to be worked with extensively to get the correct parameters and obtain cleaner

responses. Newer equipment can also run more sophisticated tests and obtain data quicker and in better resolution.

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APPENDIX

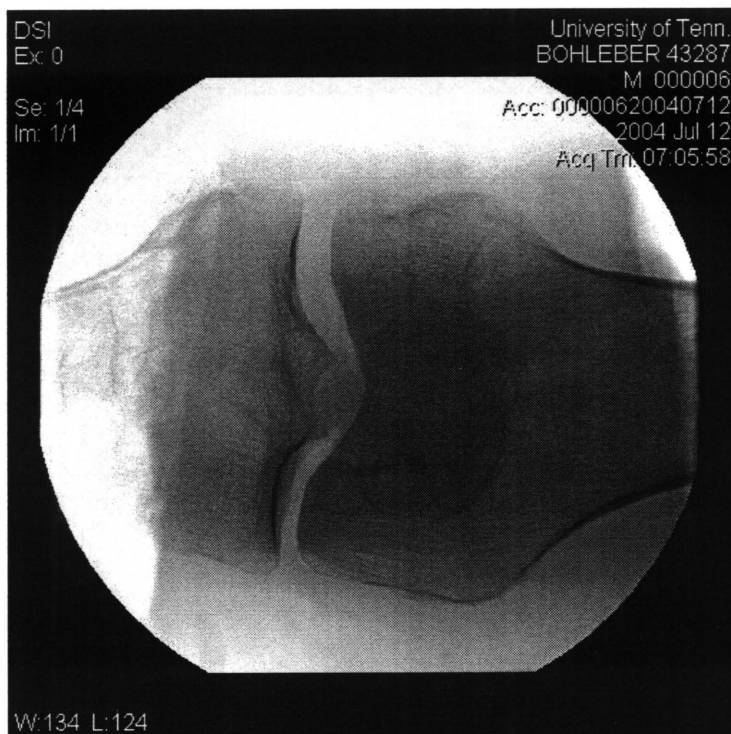


Figure A1: Specimen 2 male x-ray, anteroposterior view, left knee

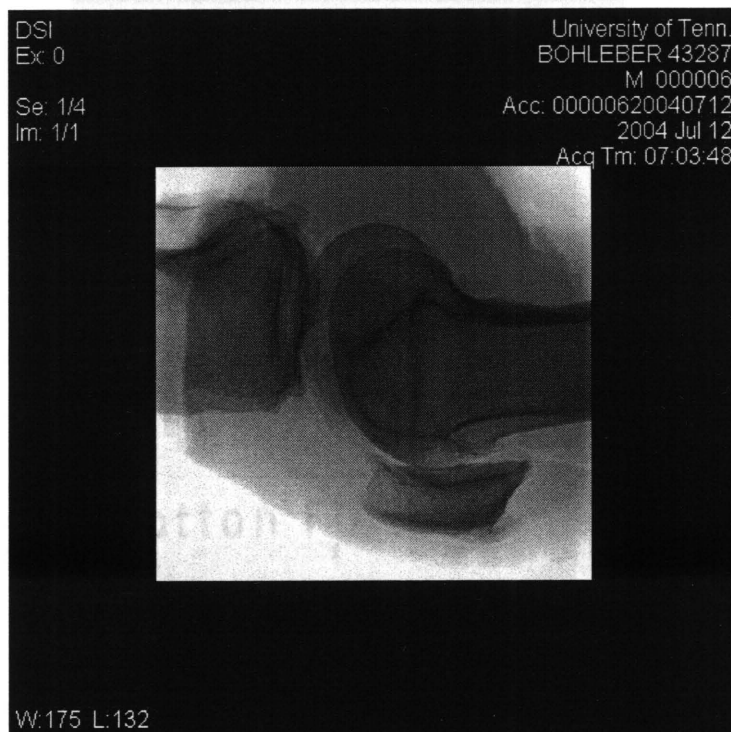


Figure A2: Specimen 2 male x-ray, mediolateral view, left knee



Figure A3: Specimen 10 female x-ray, anteroposterior view, left knee



Figure A4: Specimen 10 female x-ray, mediolateral view, left knee

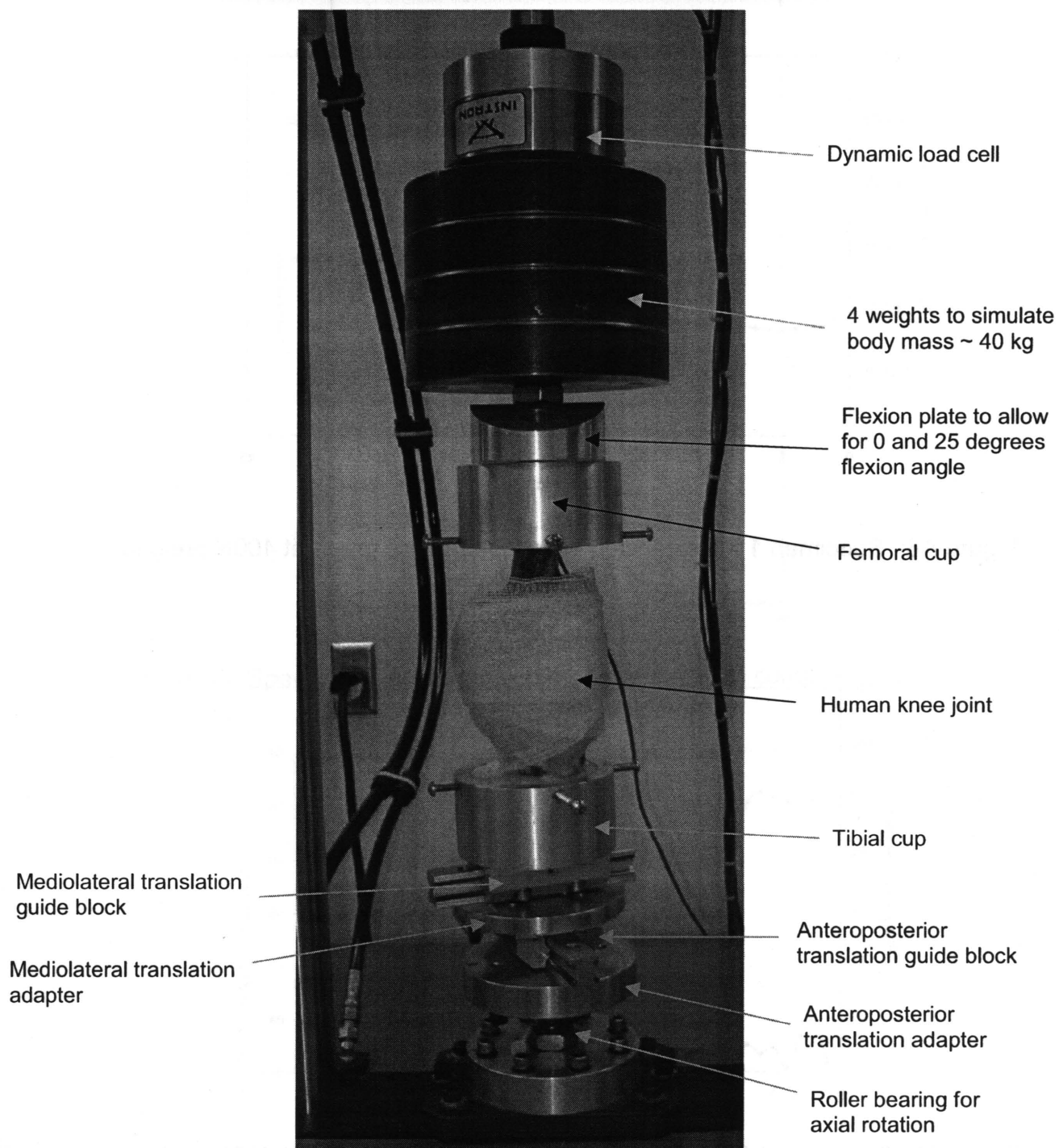


Figure A5: Complete schematic of dynamic loading fixtures, knee joint, and Instron equipment with assembly notes

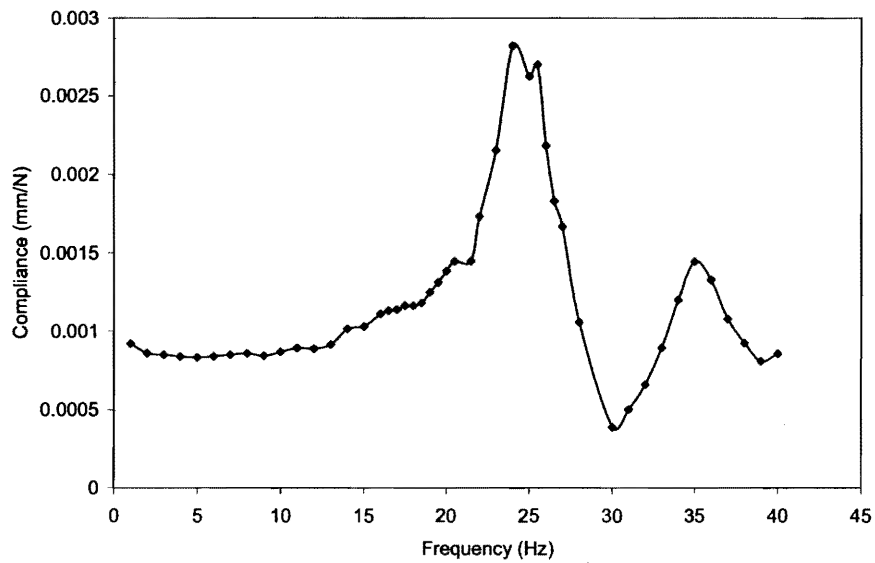


Figure A6: Specimen 1 full extension intact compliance graph at 400N preload, 0.04 mm amplitude

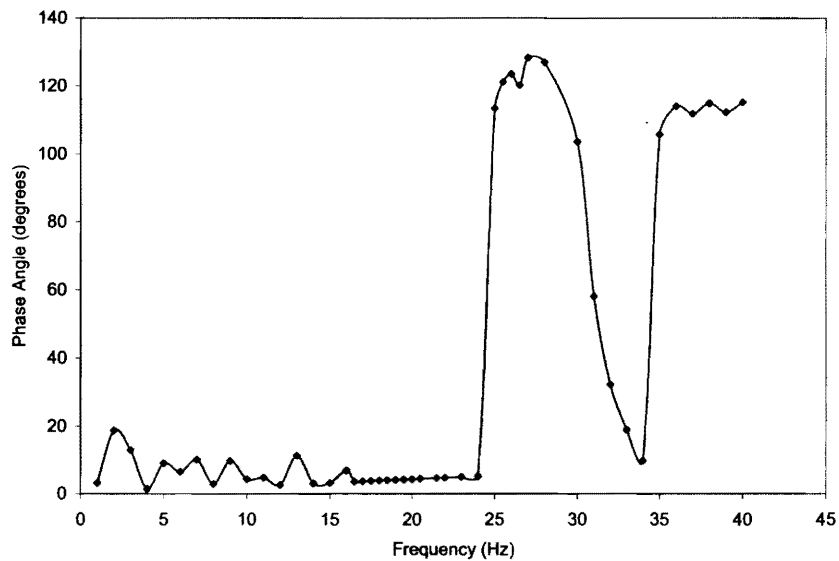


Figure A7: Specimen 1 full extension intact phase angle graph at 400N preload, 0.04 mm amplitude

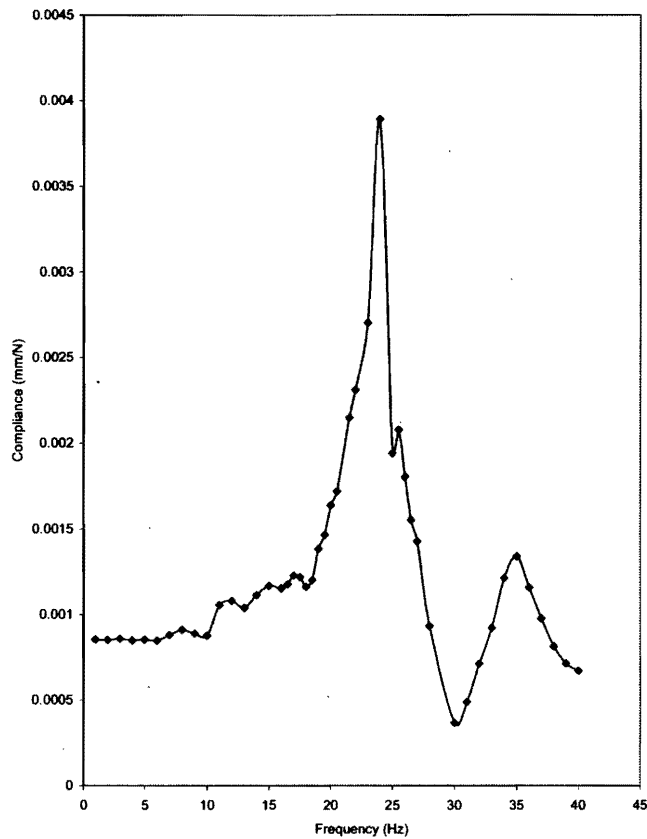


Figure A8: Specimen 1 full extension meniscectomized compliance at 400N preload, 0.04 mm amplitude

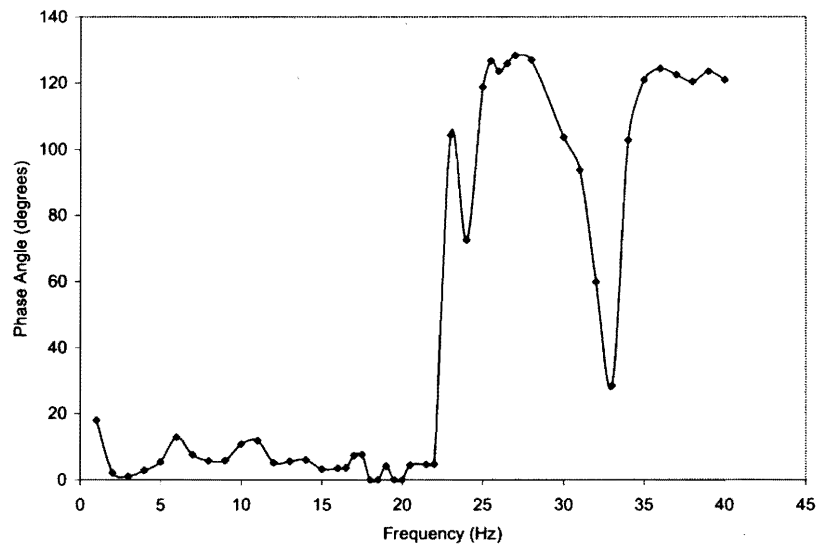


Figure A9: Specimen 1 full extension meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

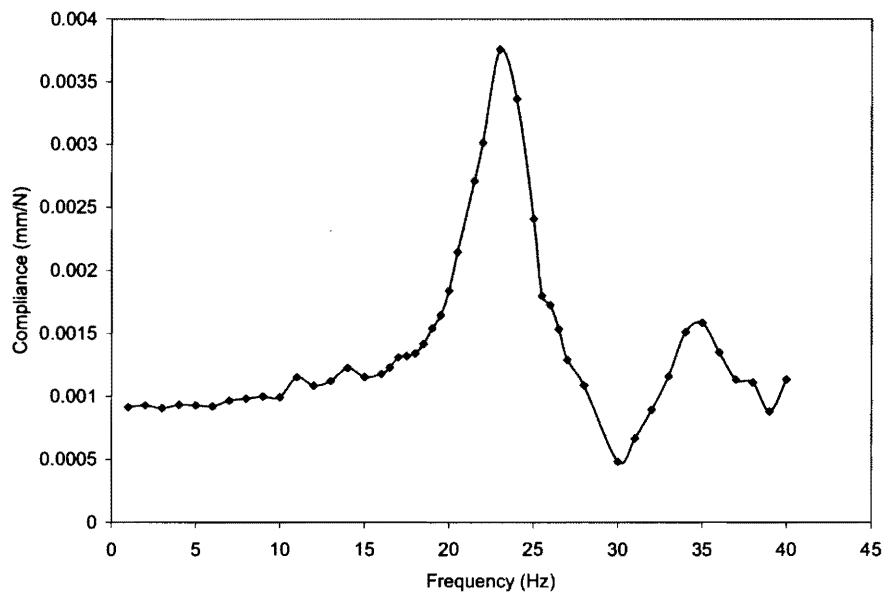


Figure A10: Specimen 1 full extension meniscectomized compliance at 400N preload, 0.06 mm amplitude

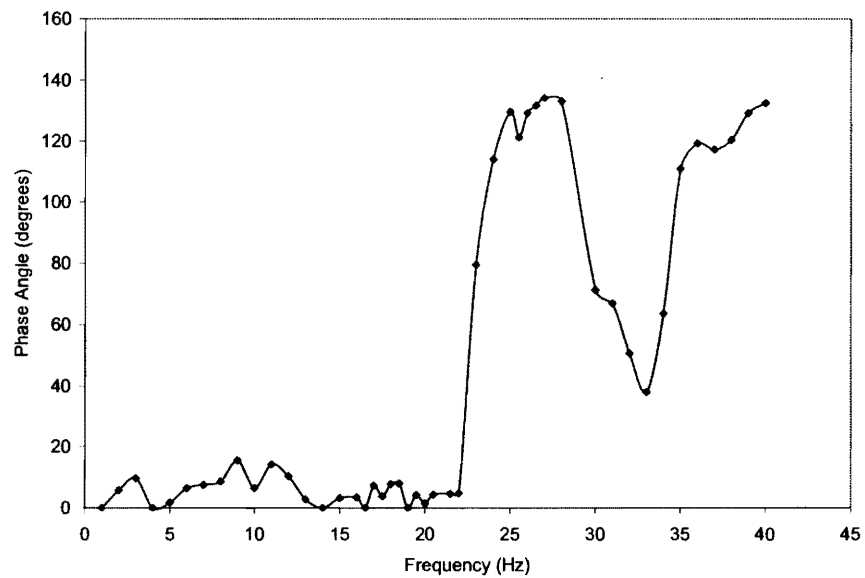


Figure A11: Specimen 1 full extension meniscectomized phase angle graph at 400N preload, 0.06 mm amplitude

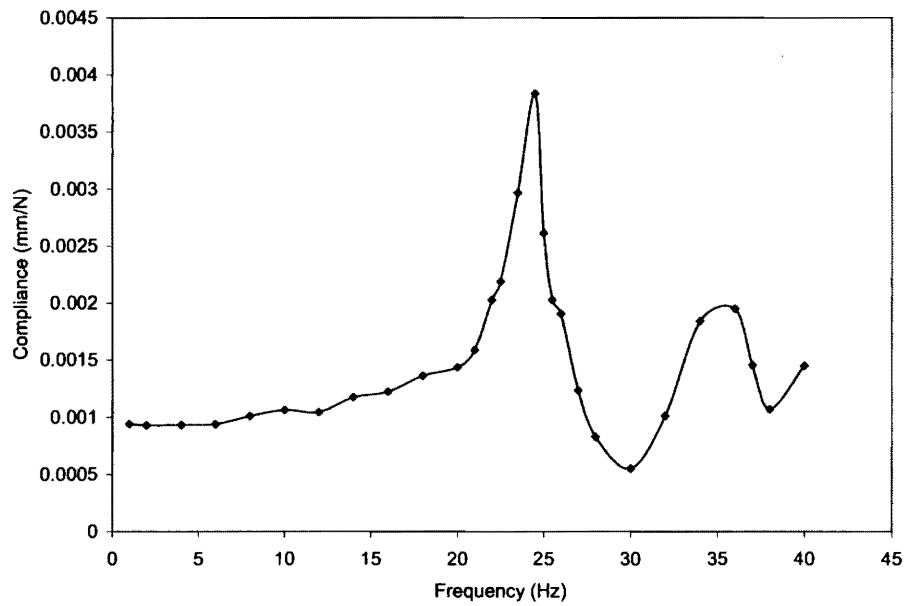


Figure A12: Specimen 1 full extension meniscectomized compliance graph at 400N preload, 0.08 mm amplitude

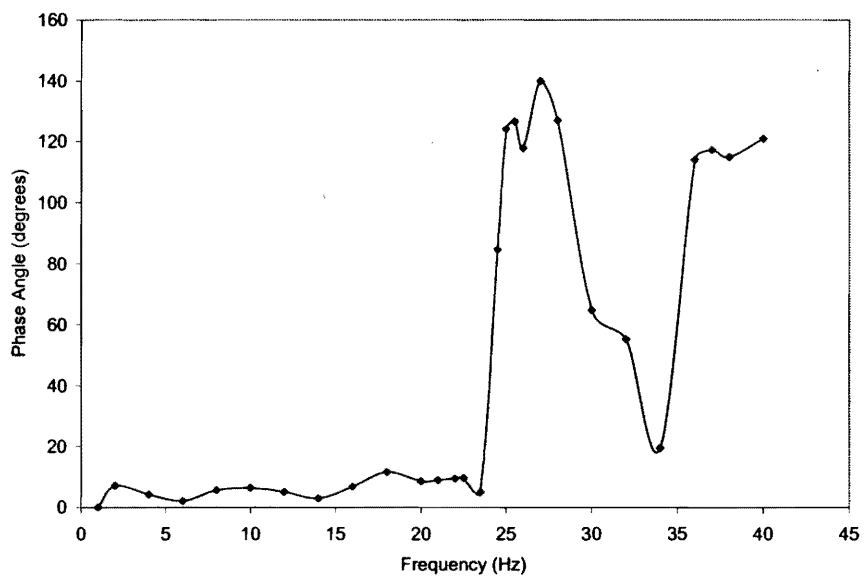


Figure A13: Specimen 1 full extension meniscectomized phase angle graph at 400N preload, 0.08 mm amplitude

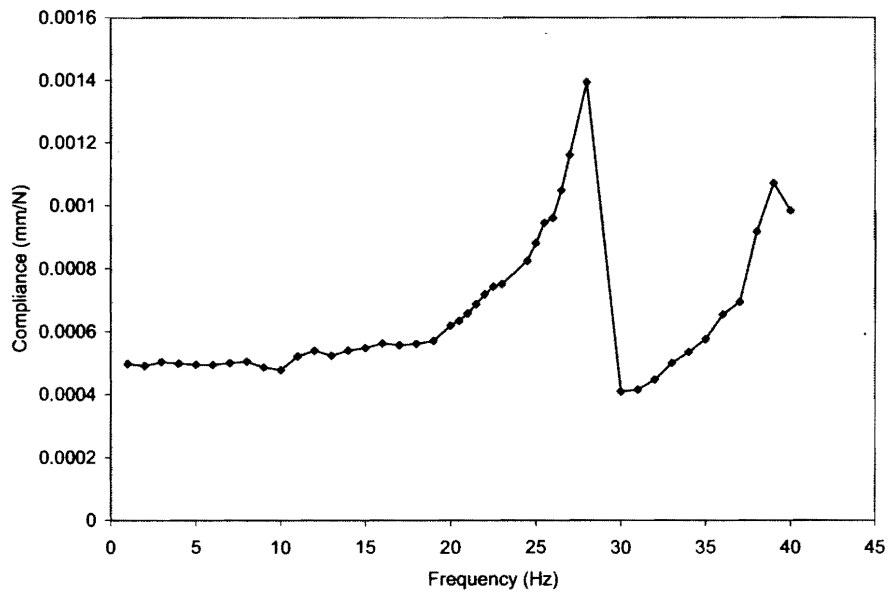


Figure A14: Specimen 2 full extension intact compliance graph at 400N preload, 0.04 mm amplitude

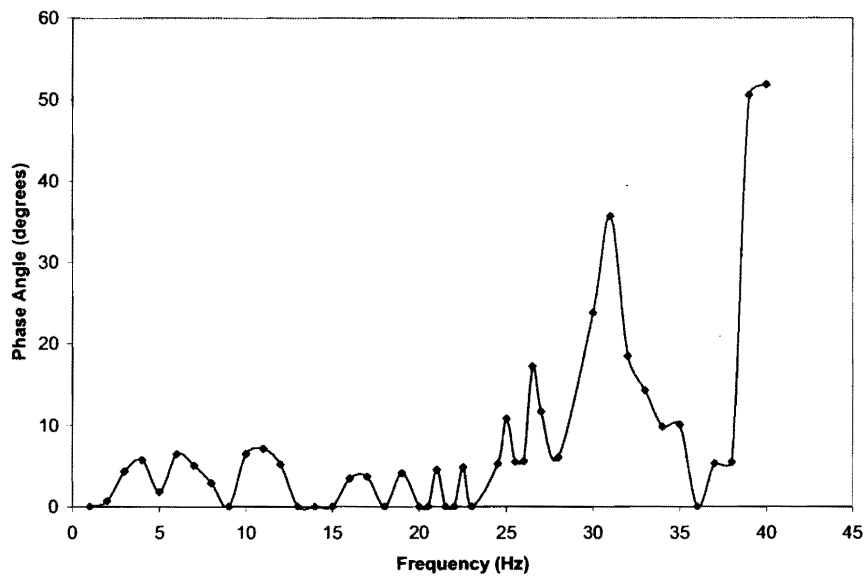


Figure A15: Specimen 2 full extension intact phase angle graph at 400N preload, 0.04 mm amplitude

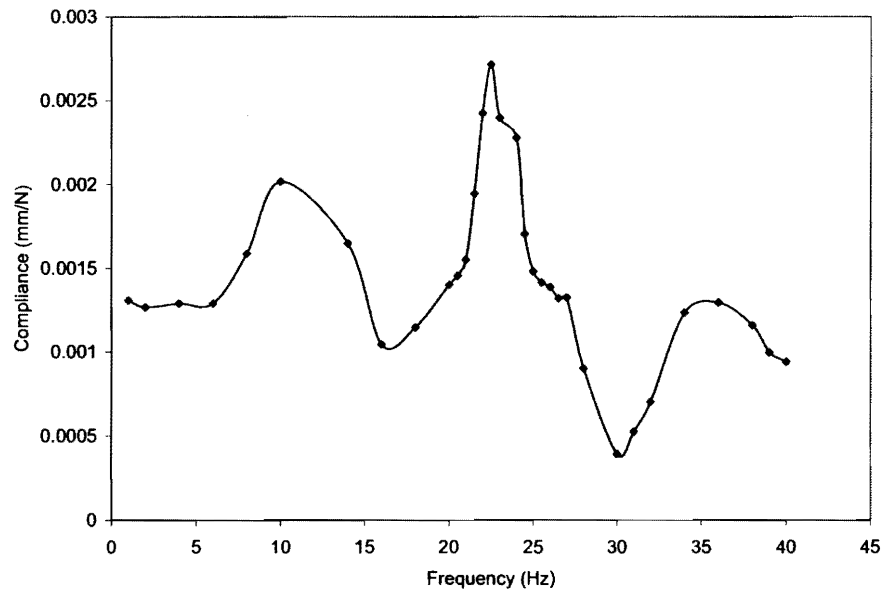


Figure A16: Specimen 2 flexion angle intact compliance graph at 400N preload, 0.04 mm amplitude

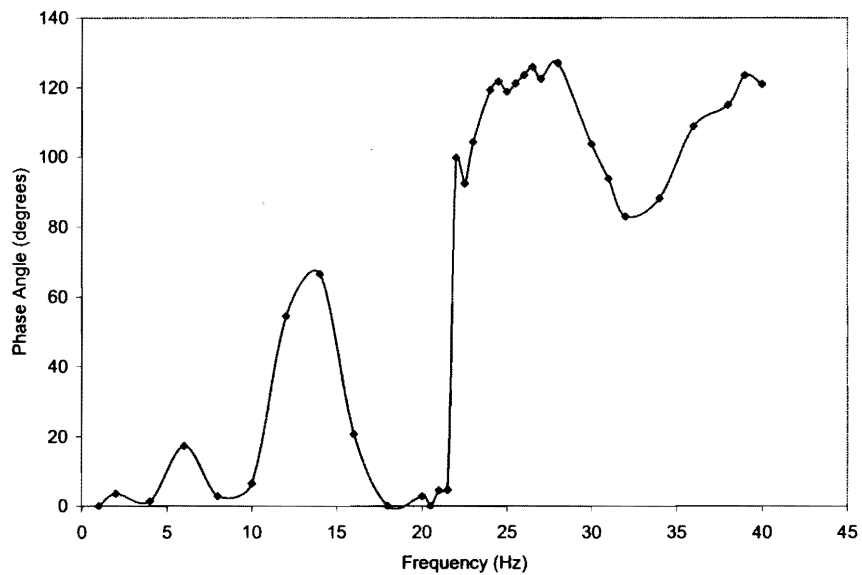


Figure A17: Specimen 2 flexion angle intact phase angle graph at 400N preload, 0.04 mm amplitude

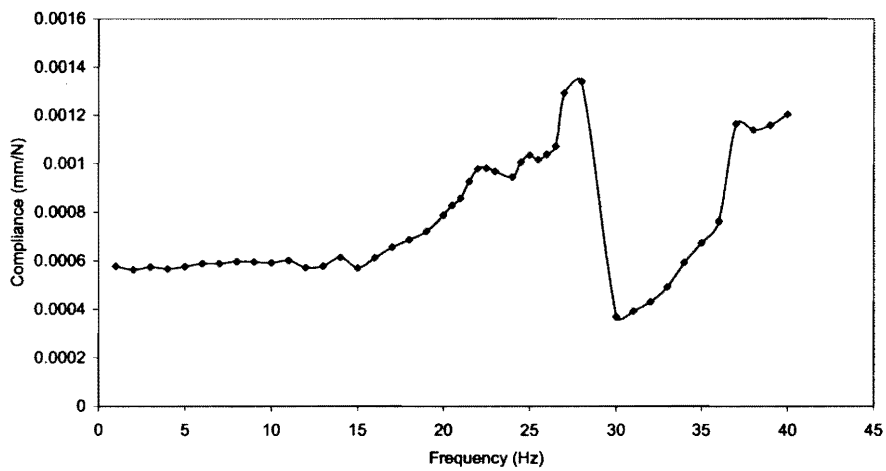


Figure A18: Specimen 2 full extension meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

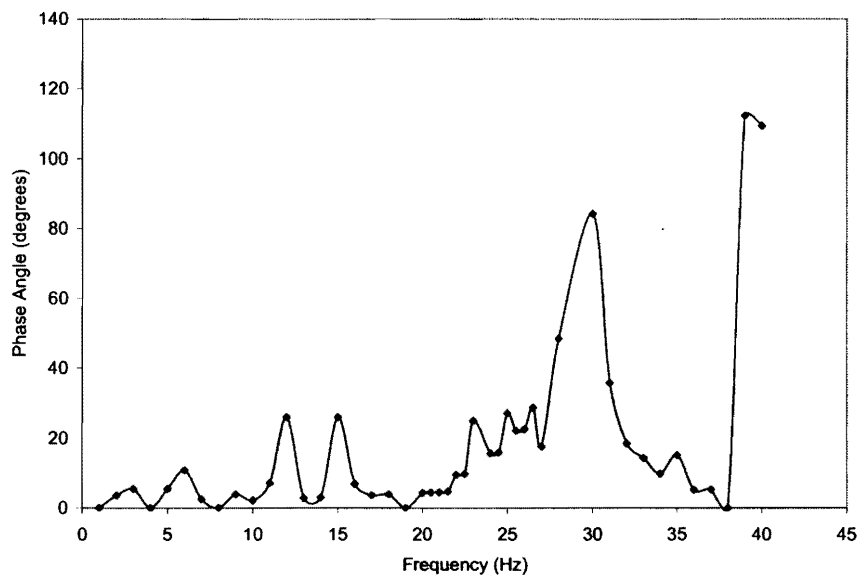


Figure A19: Specimen 2 full extension meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

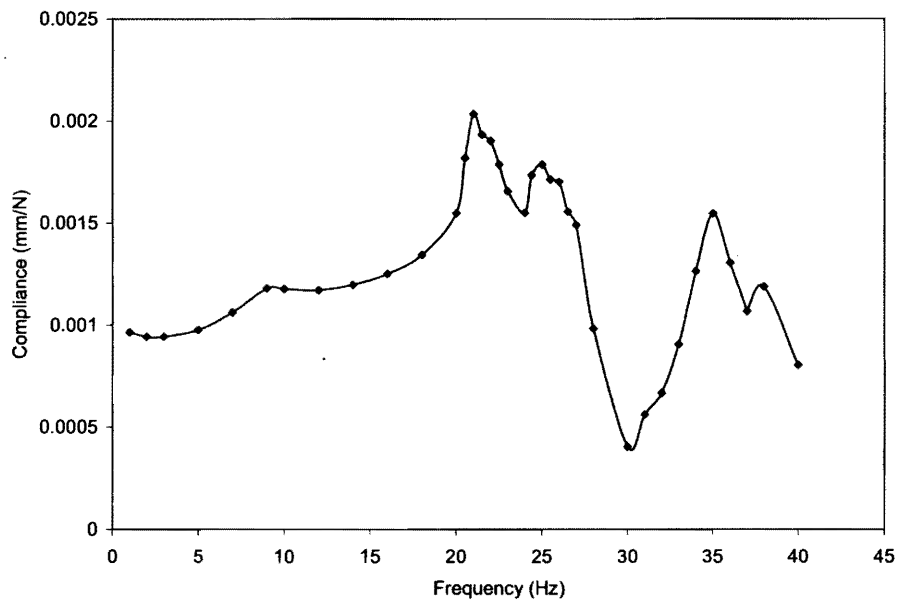


Figure A20: Specimen 2 flexion angle meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

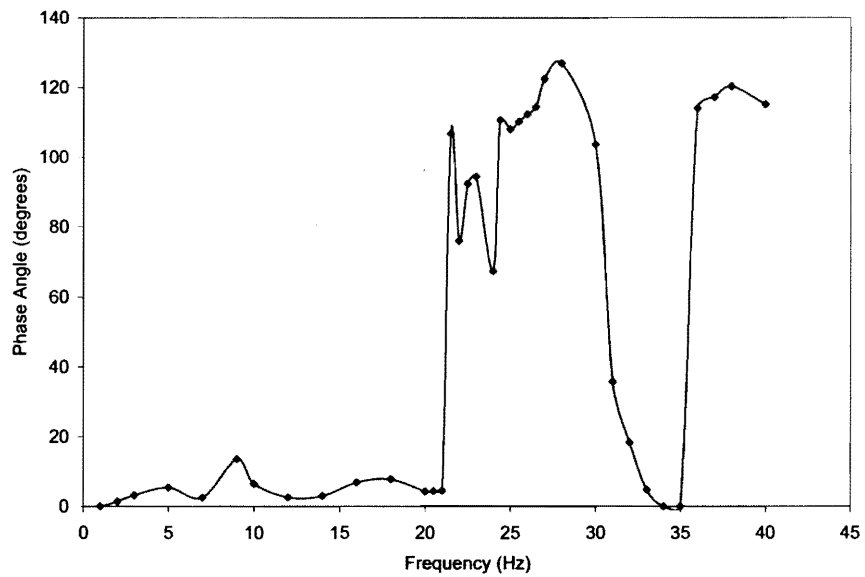


Figure A21: Specimen 2 flexion angle meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

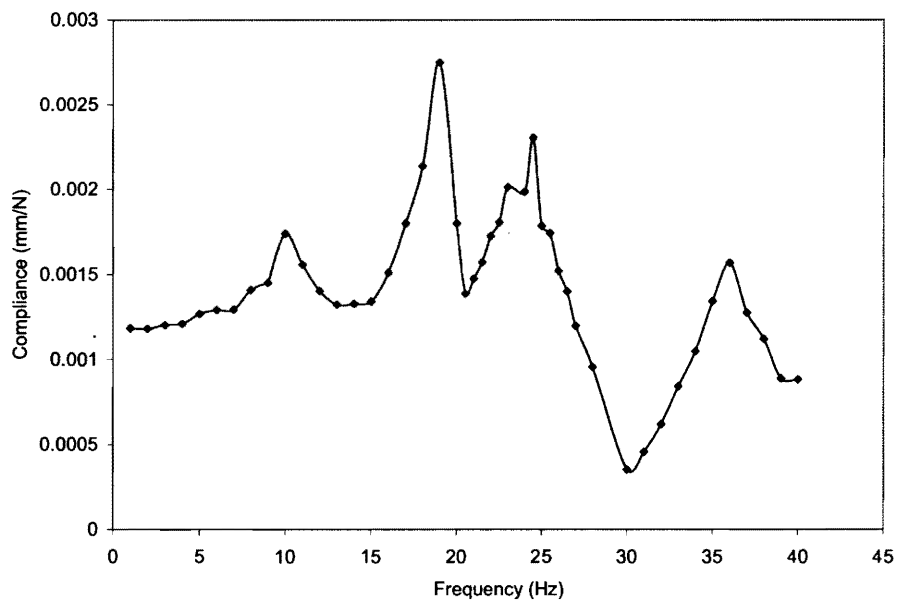


Figure A22: Specimen 3 full extension intact compliance graph at 400N preload, 0.04 mm amplitude

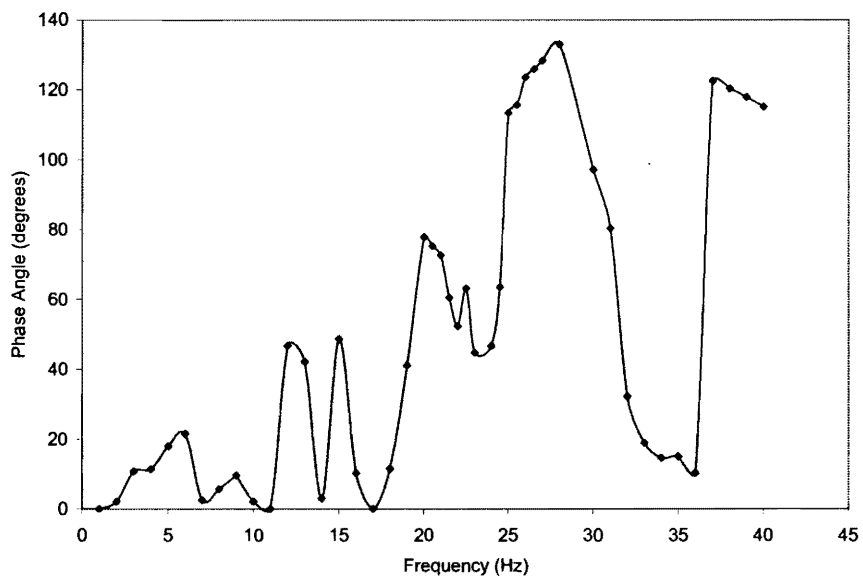


Figure A23: Specimen 3 full extension intact phase angle graph at 400N preload, 0.04 mm amplitude

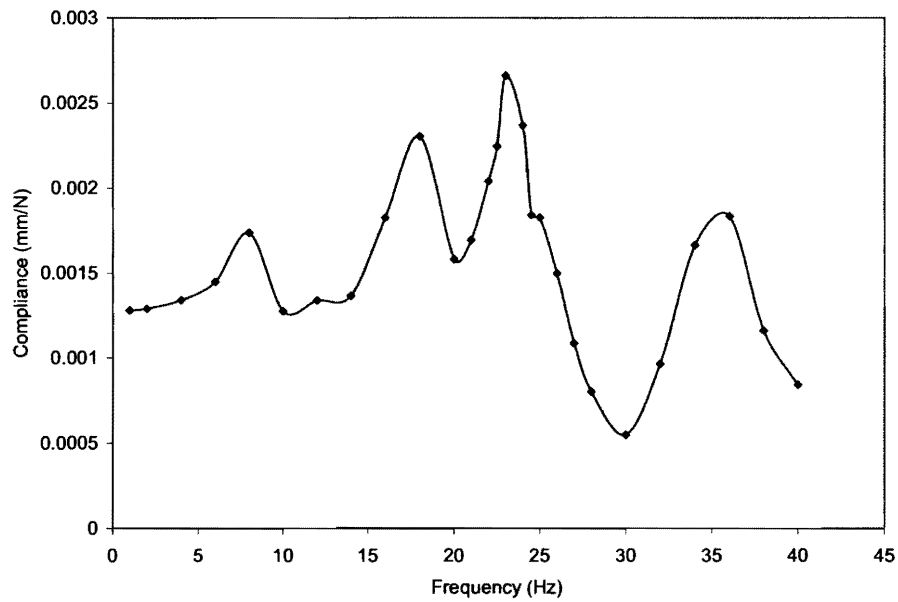


Figure A24: Specimen 3 full extension intact compliance graph at 400N preload, 0.08 mm amplitude

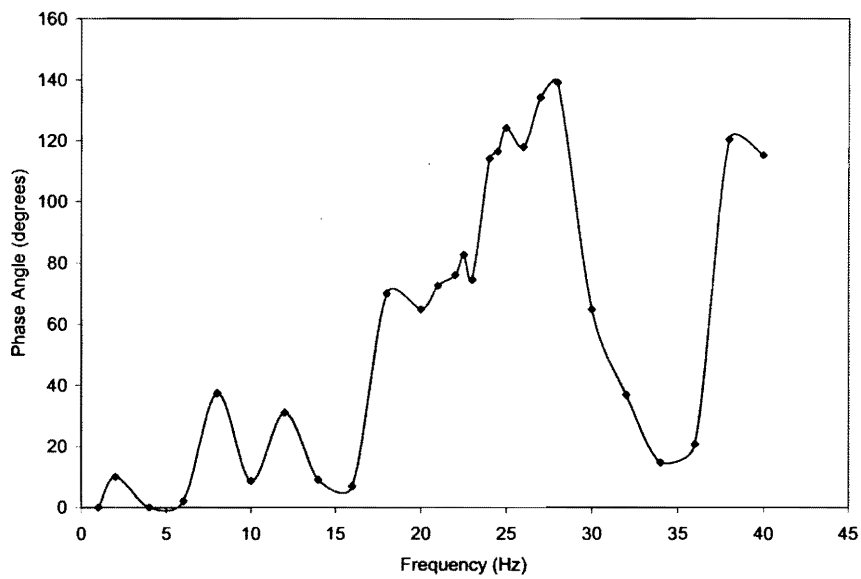


Figure A25: Specimen 3 full extension intact phase angle graph at 400N preload, 0.08 mm amplitude

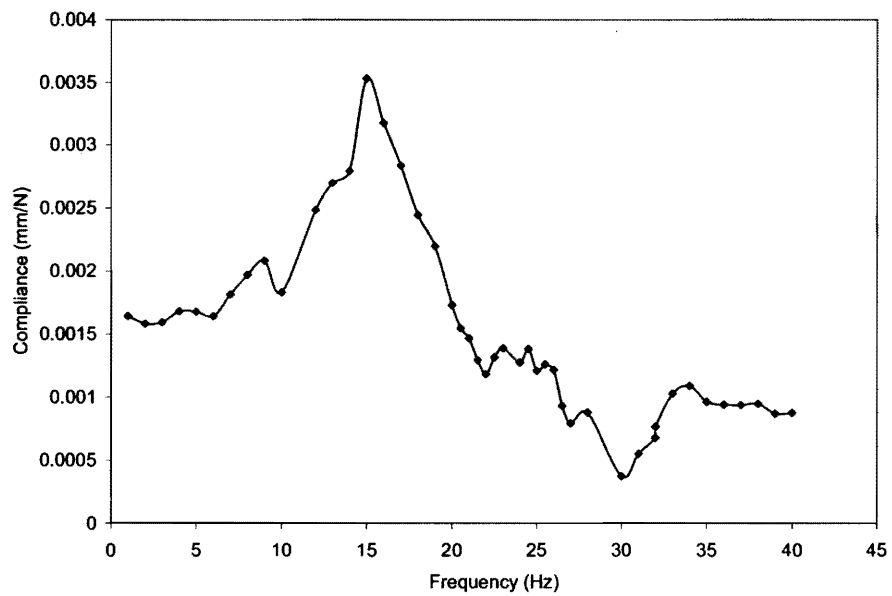


Figure A26: Specimen 3 flexion angle intact compliance graph at 400N preload, 0.04 mm amplitude

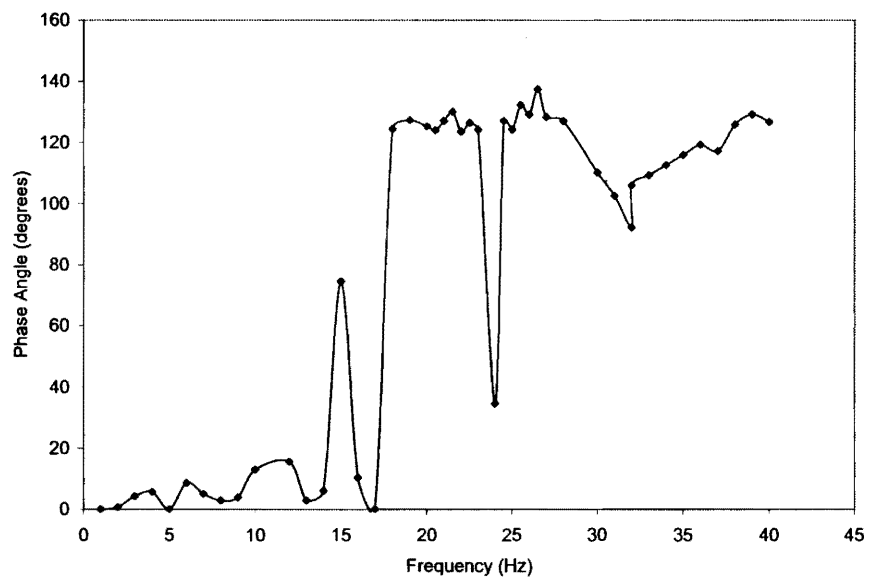


Figure A27: Specimen 3 flexion angle intact phase angle graph at 400N preload, 0.04 mm amplitude

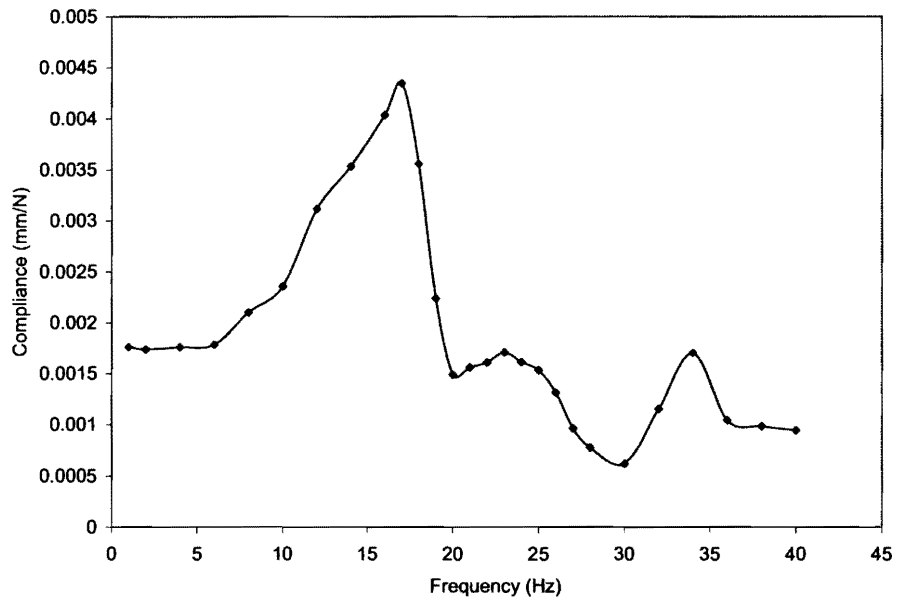


Figure A28: Specimen 3 flexion angle intact compliance graph at 400N preload, 0.08 mm amplitude

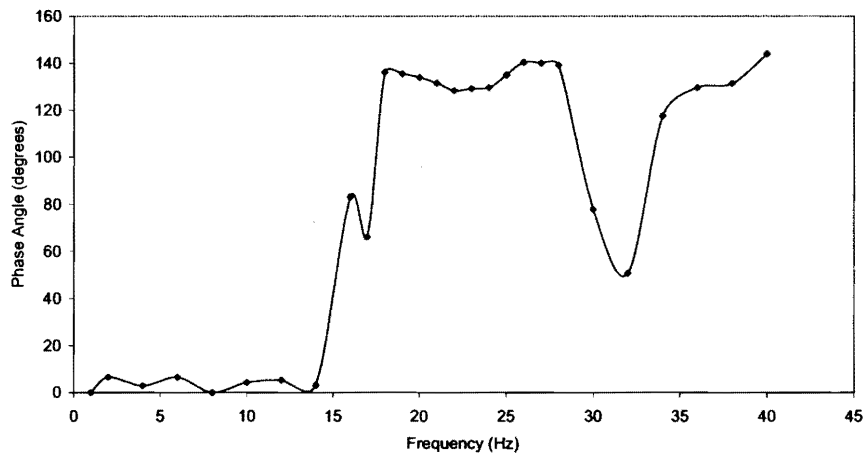


Figure A29: Specimen 3 flexion angle intact phase angle graph at 400N preload, 0.08 mm amplitude

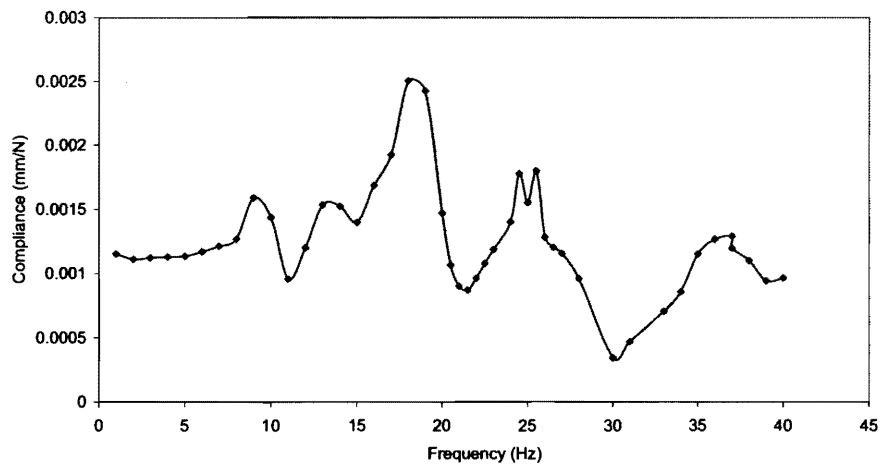


Figure A30: Specimen 3 full extension meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

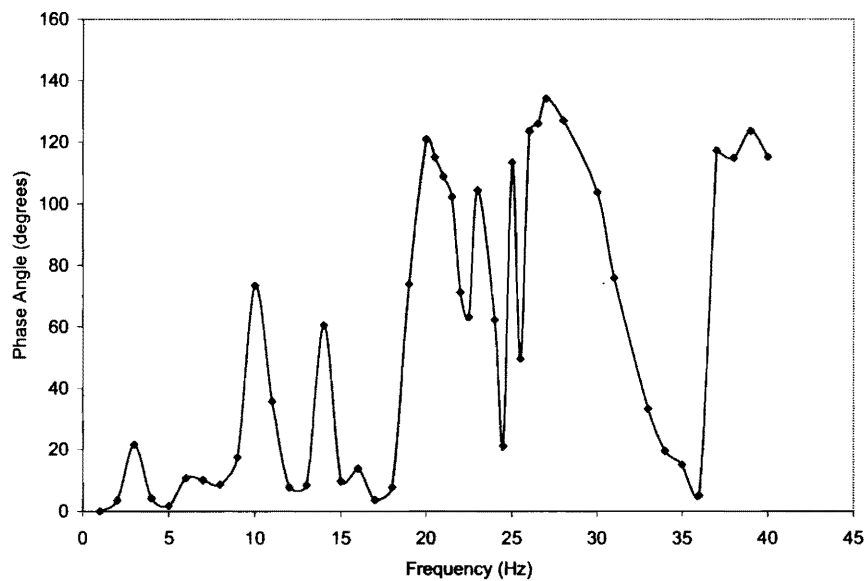


Figure A31: Specimen 3 full extension meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

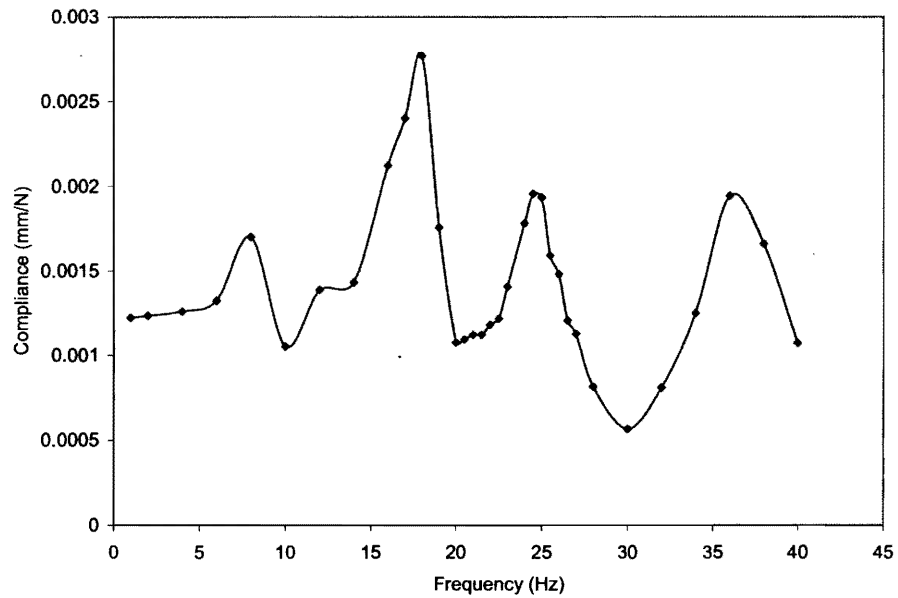


Figure A32: Specimen 3 full extension meniscectomized compliance graph at 400N preload, 0.08 mm amplitude

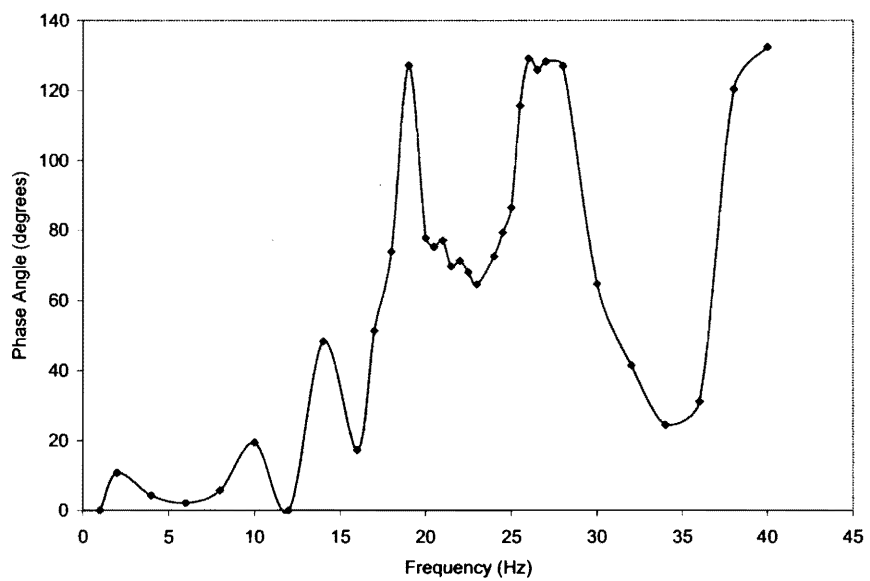


Figure A33: Specimen 3 full extension meniscectomized phase angle graph at 400N preload, 0.08 mm amplitude

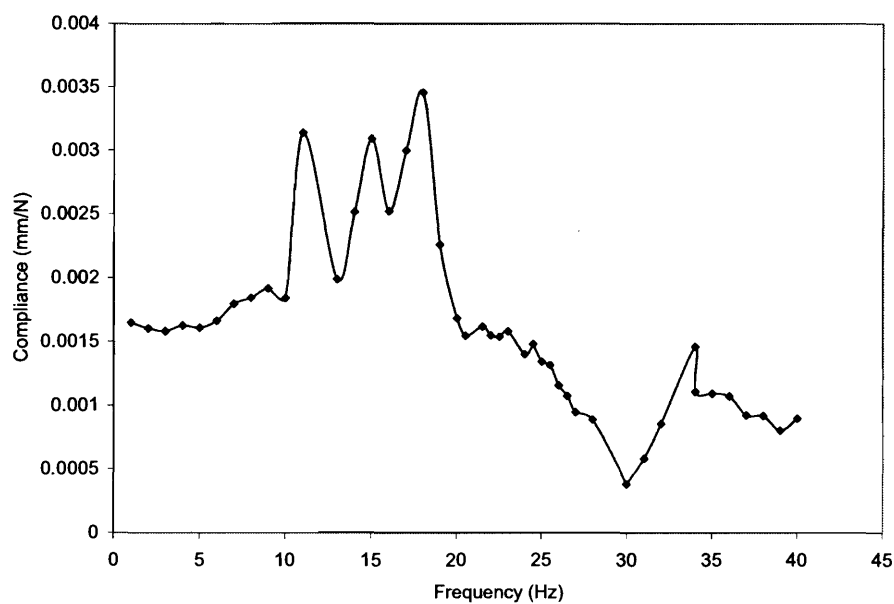


Figure A34: Specimen 3 flexion angle meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

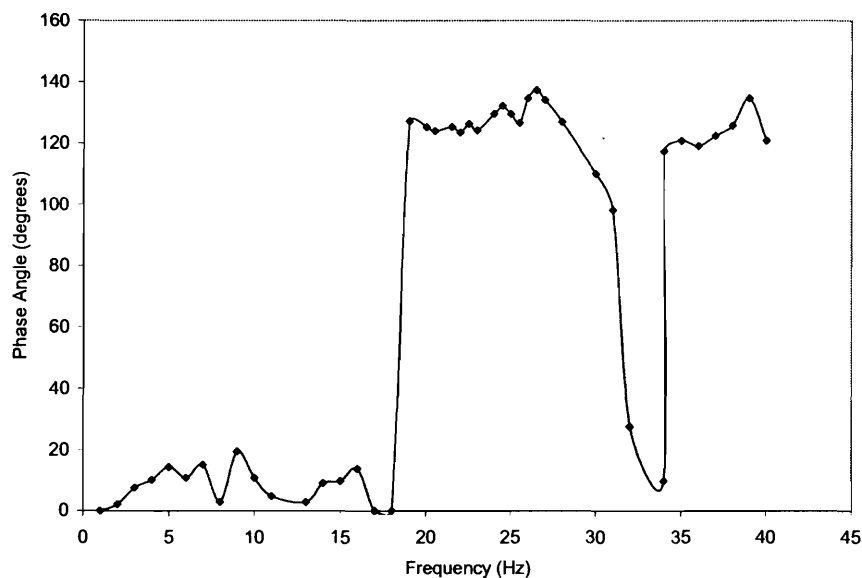


Figure A35: Specimen 3 flexion angle meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

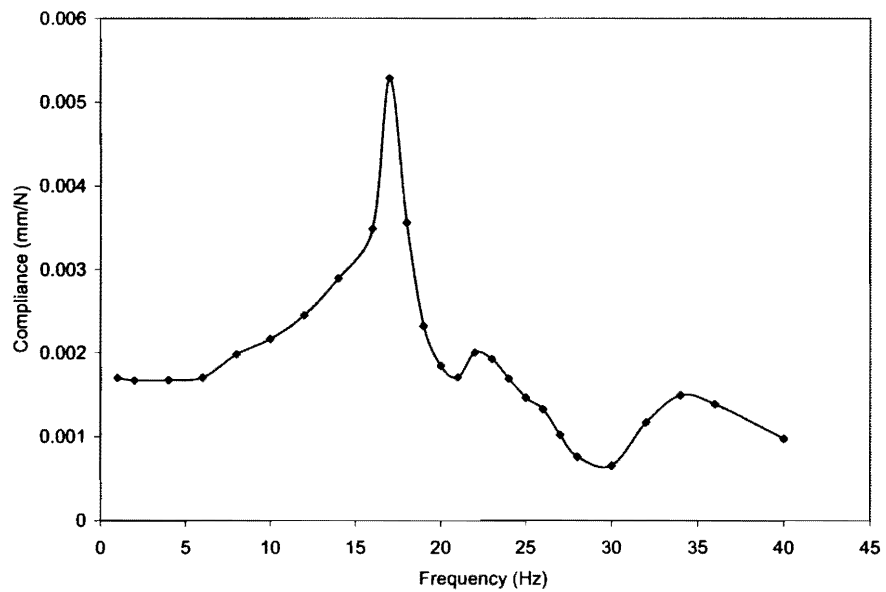


Figure A36: Specimen 3 flexion angle meniscectomized compliance graph at 400N preload, 0.08 mm amplitude

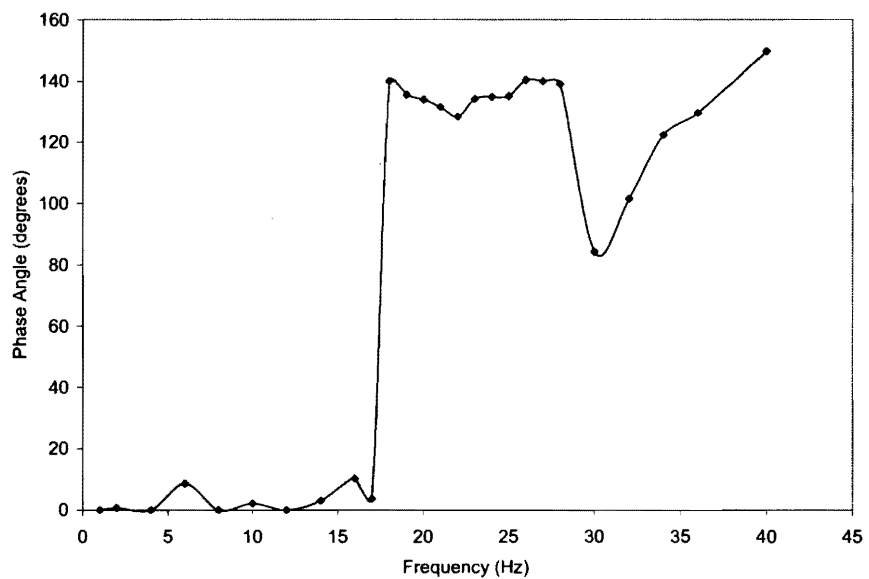


Figure A37: Specimen 3 flexion angle meniscectomized phase angle graph at 400N preload, 0.08 mm amplitude

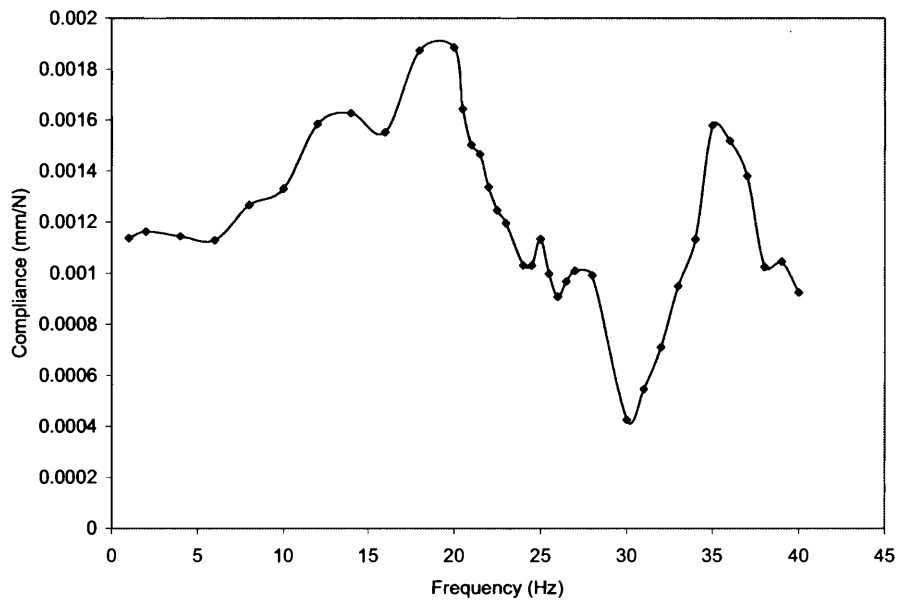


Figure A38: Specimen 4 full extension intact compliance graph at 400N preload, 0.04 mm amplitude

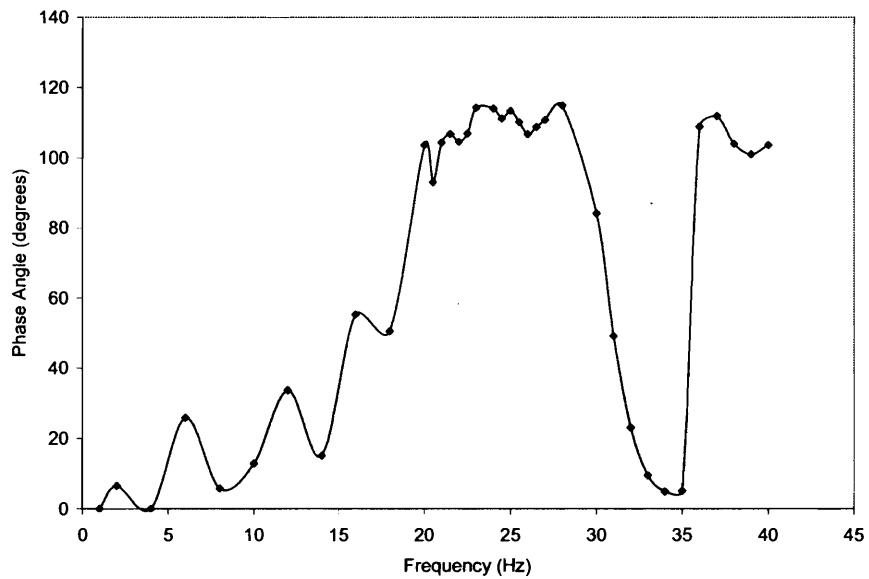


Figure A39: Specimen 4 full extension intact phase angle graph at 400N preload, 0.04 mm amplitude

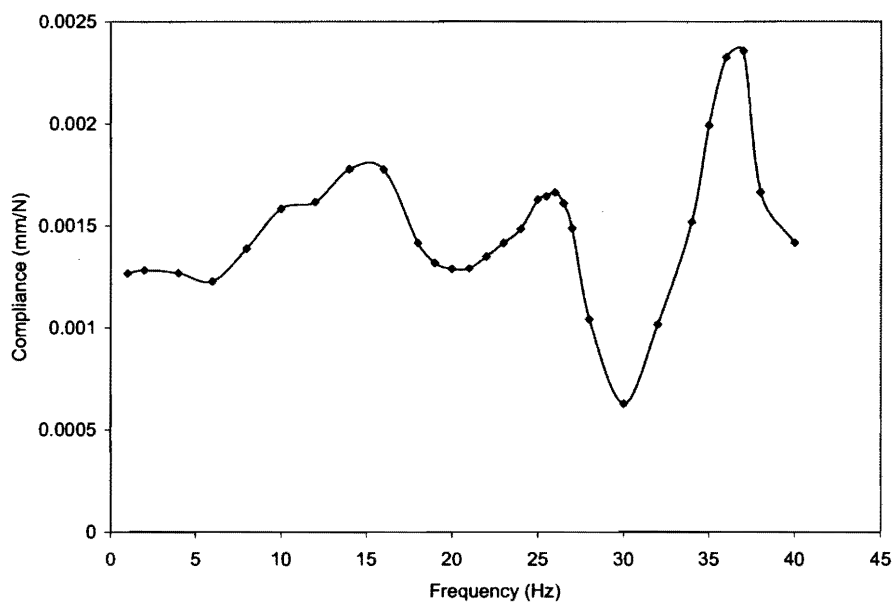


Figure A40: Specimen 4 full extension intact compliance graph at 400N preload, 0.08 mm amplitude

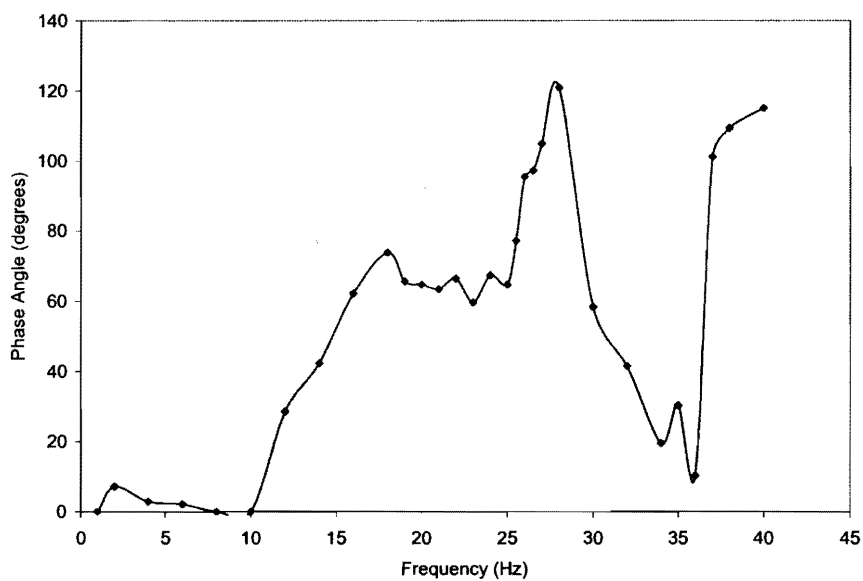


Figure A41: Specimen 4 full extension intact phase angle graph at 400N preload, 0.08 mm amplitude

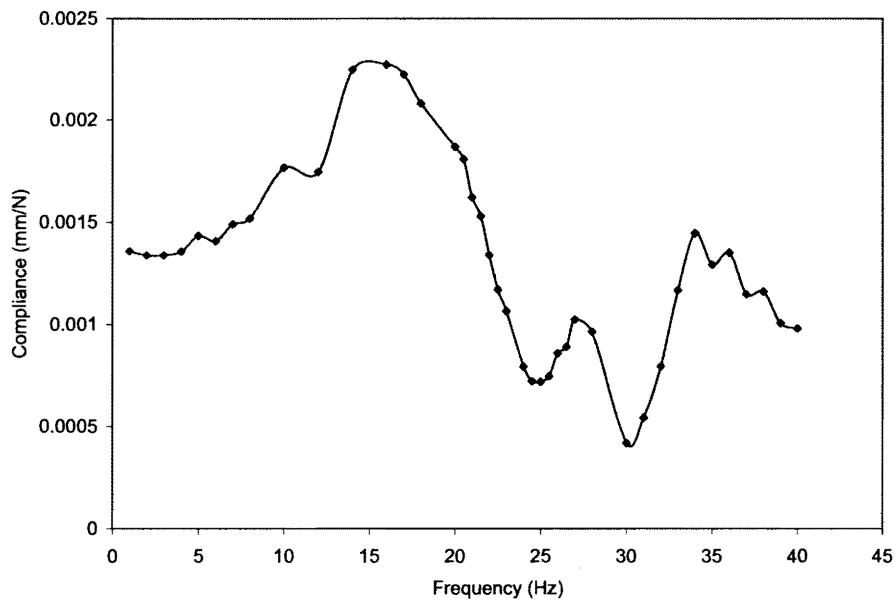


Figure A42: Specimen 4 flexion angle intact compliance graph at 400N preload, 0.04 mm amplitude

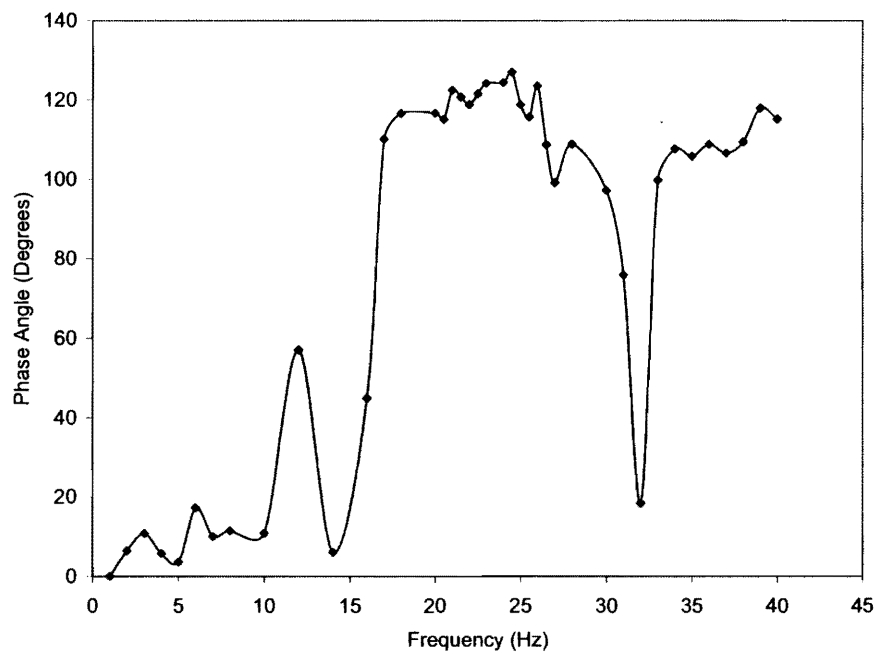


Figure A43: Specimen 4 flexion angle intact phase angle graph at 400N preload, 0.04 mm amplitude

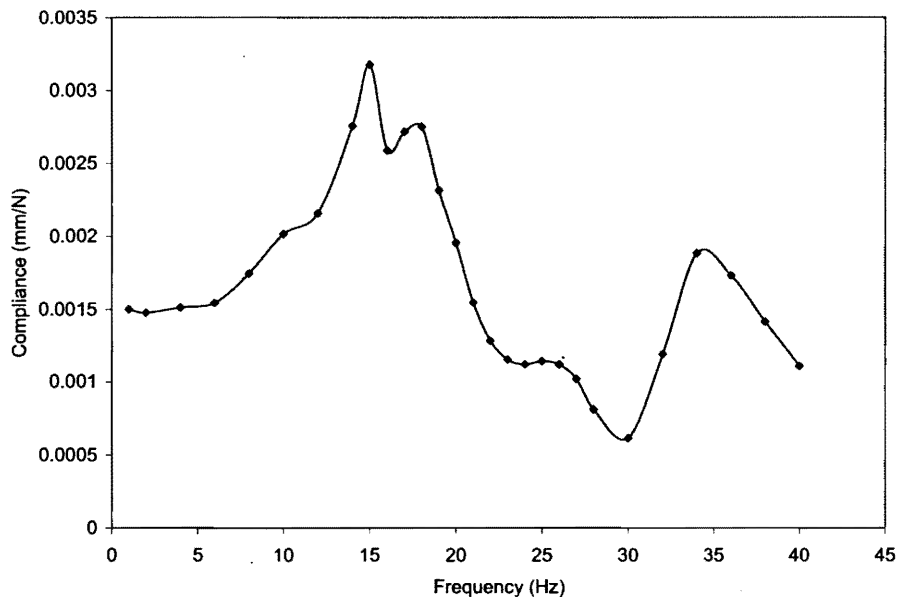


Figure A44: Specimen 4 flexion angle intact compliance graph at 400N preload, 0.08 mm amplitude

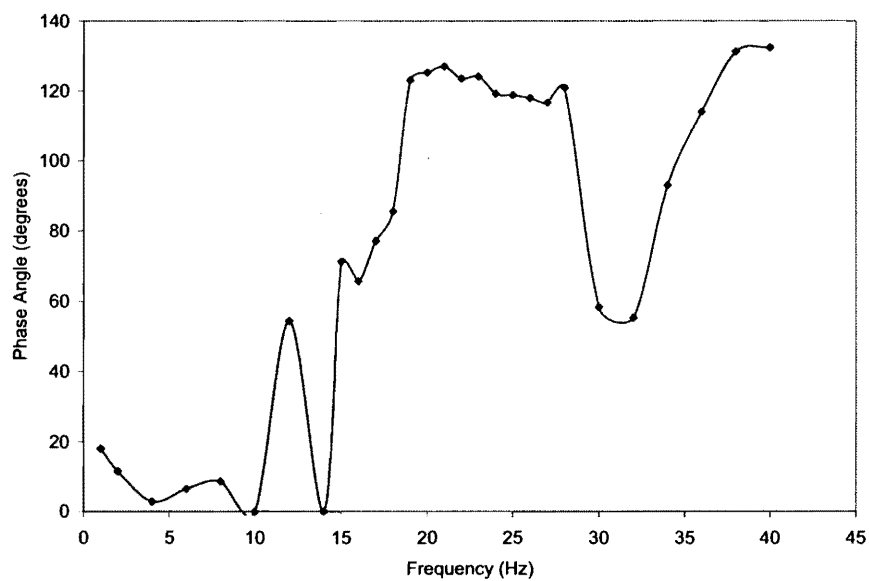


Figure A45: Specimen 4 flexion angle intact phase angle graph at 400N preload, 0.08 mm amplitude

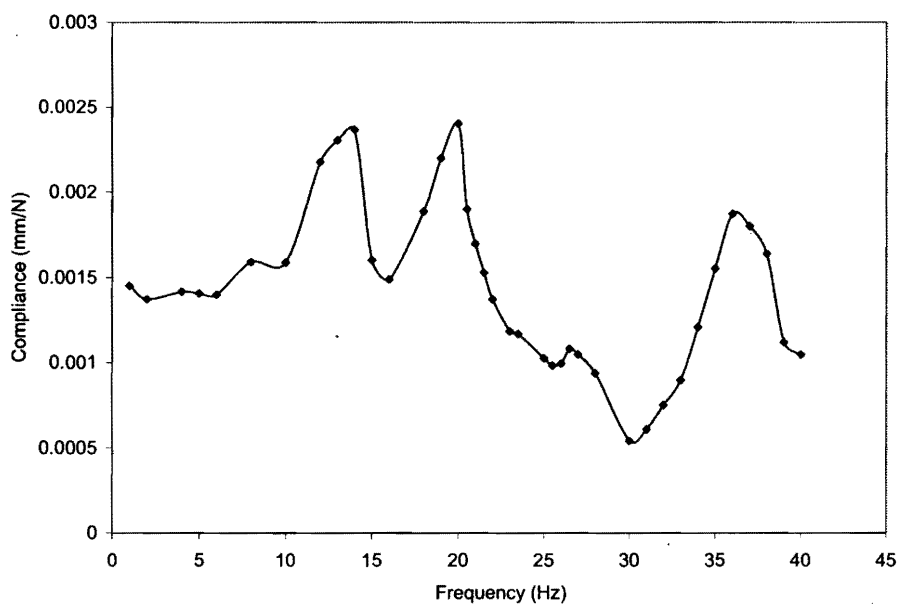


Figure A46: Specimen 4 full extension meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

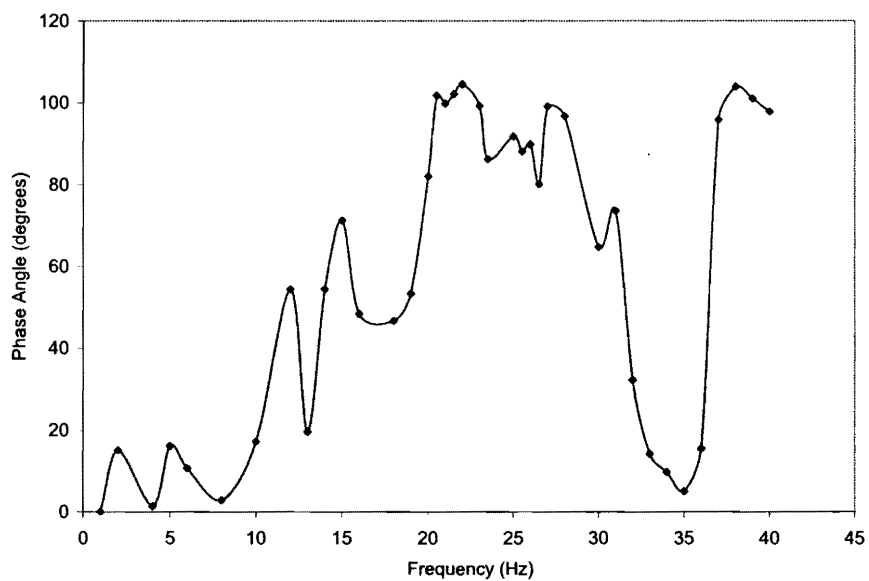


Figure A47: Specimen 4 full extension meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

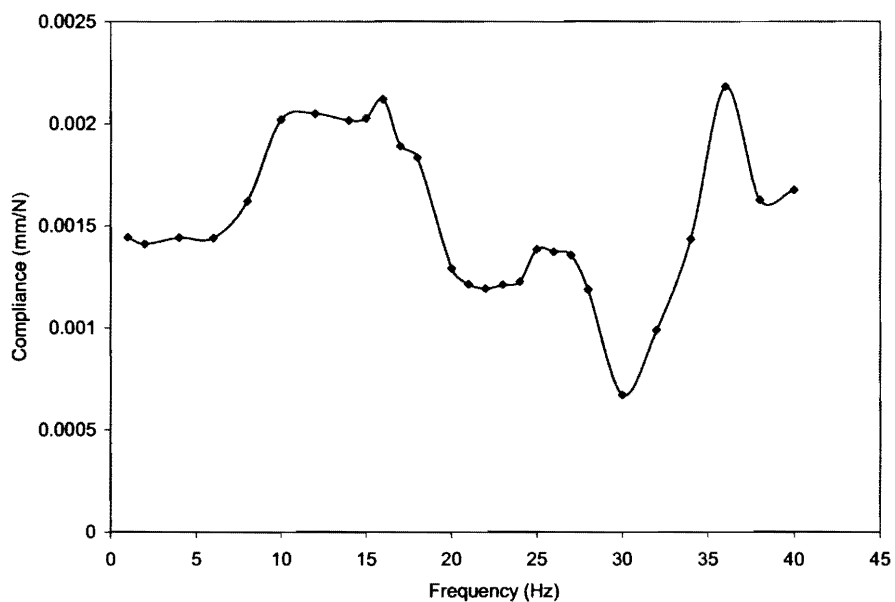


Figure A48: Specimen 4 full extension meniscectomized compliance graph at 400N preload, 0.08 mm amplitude

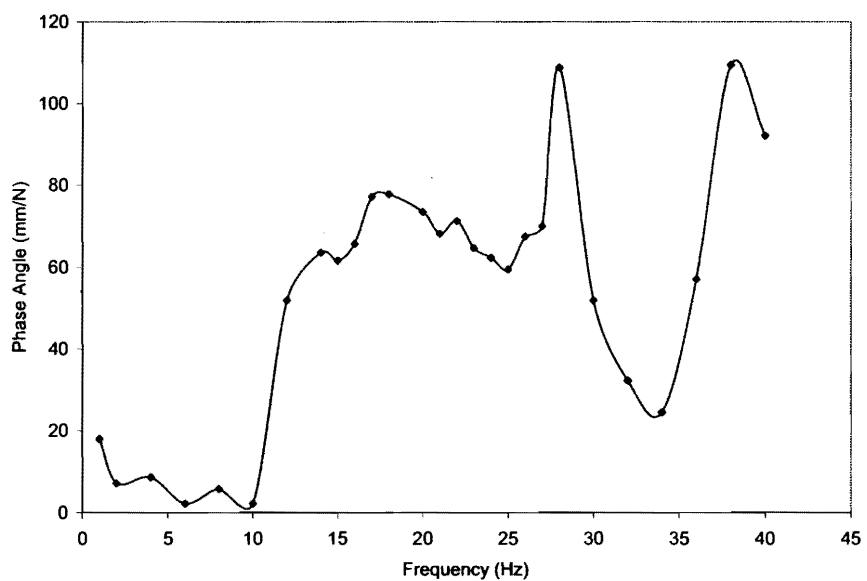


Figure A49: Specimen 4 full extension meniscectomized phase angle graph at 400N preload, 0.08 mm amplitude

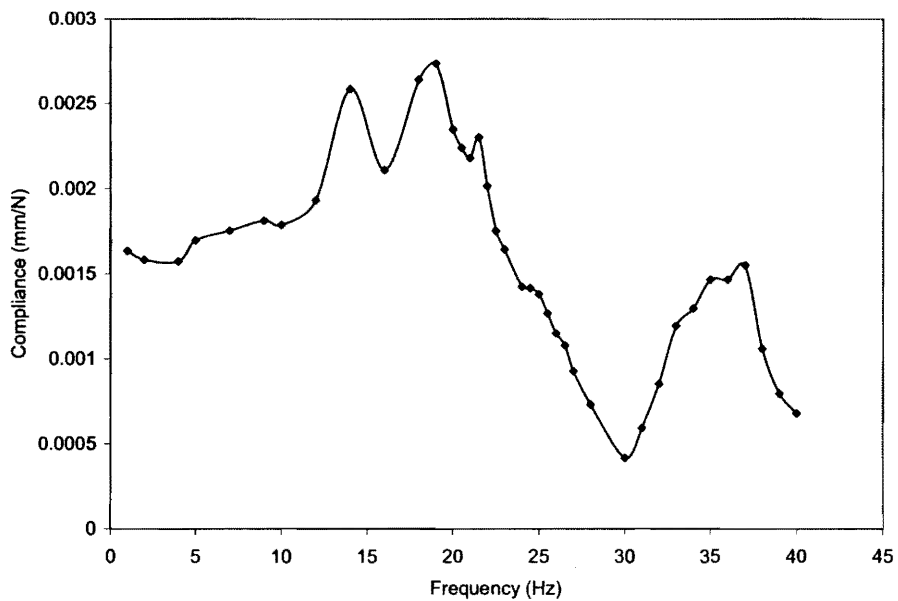


Figure A50: Specimen 4 flexion angle meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

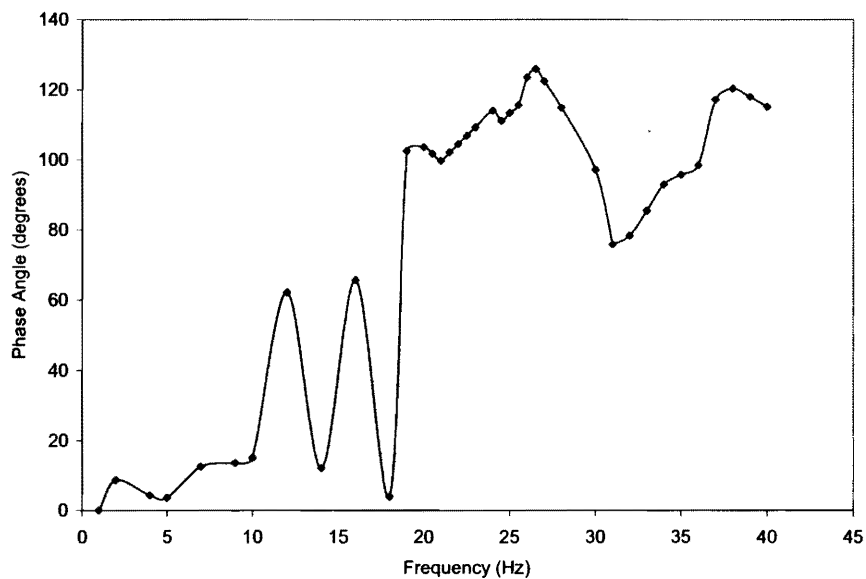


Figure A51: Specimen 4 flexion angle meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

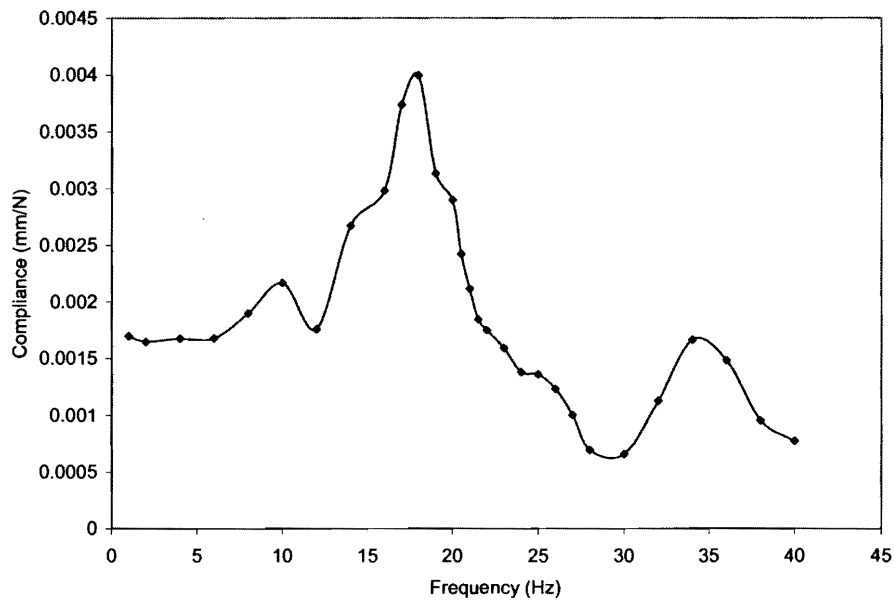


Figure A52: Specimen 4 flexion angle meniscectomized compliance graph at 400N preload, 0.08 mm amplitude

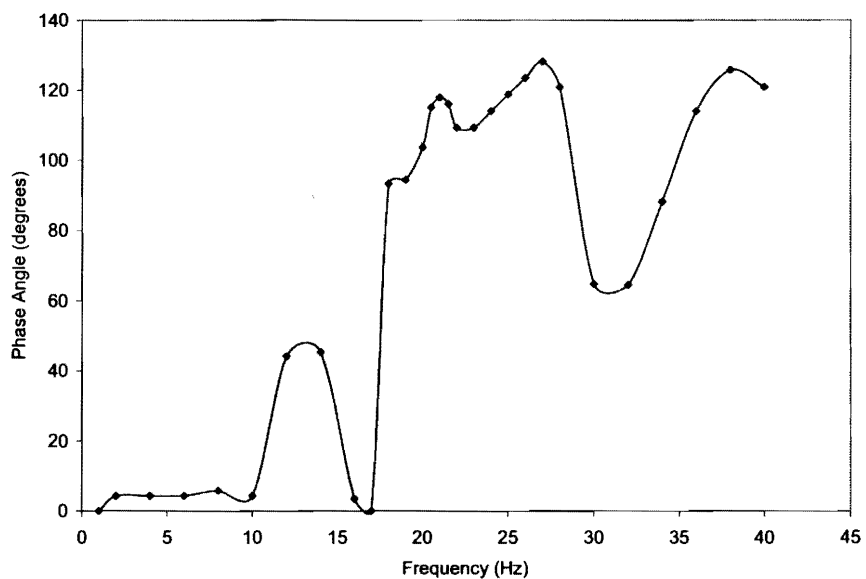


Figure A53: Specimen 4 flexion angle meniscectomized phase angle graph at 400N preload, 0.08 mm amplitude

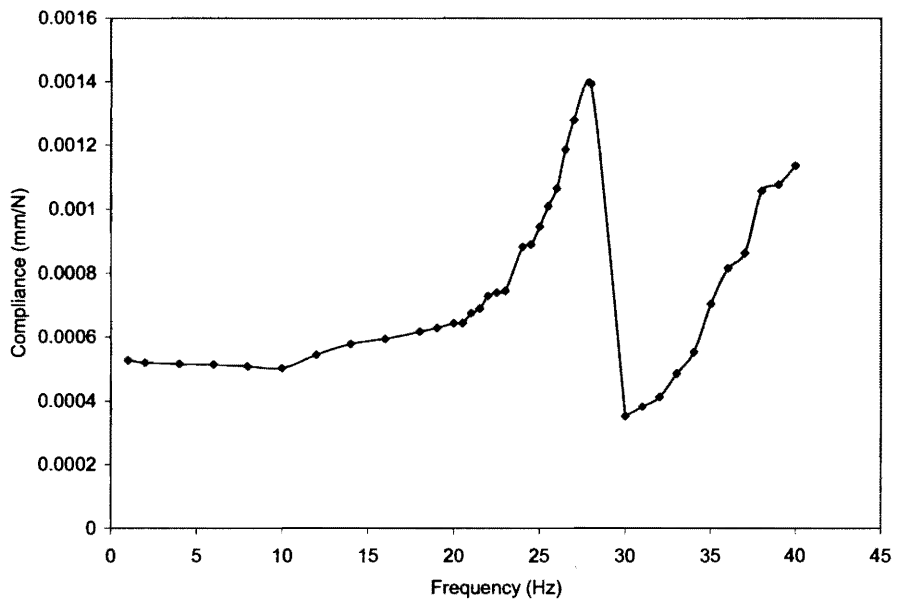


Figure A54: Specimen 5 full extension intact compliance graph at 400N preload, 0.04 mm amplitude

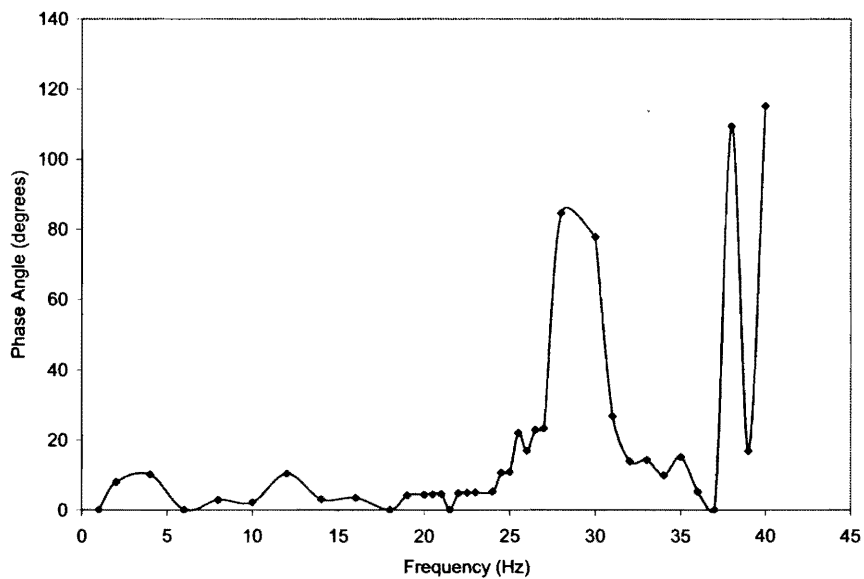


Figure A55: Specimen 5 full extension intact phase angle graph at 400N preload, 0.04 mm amplitude

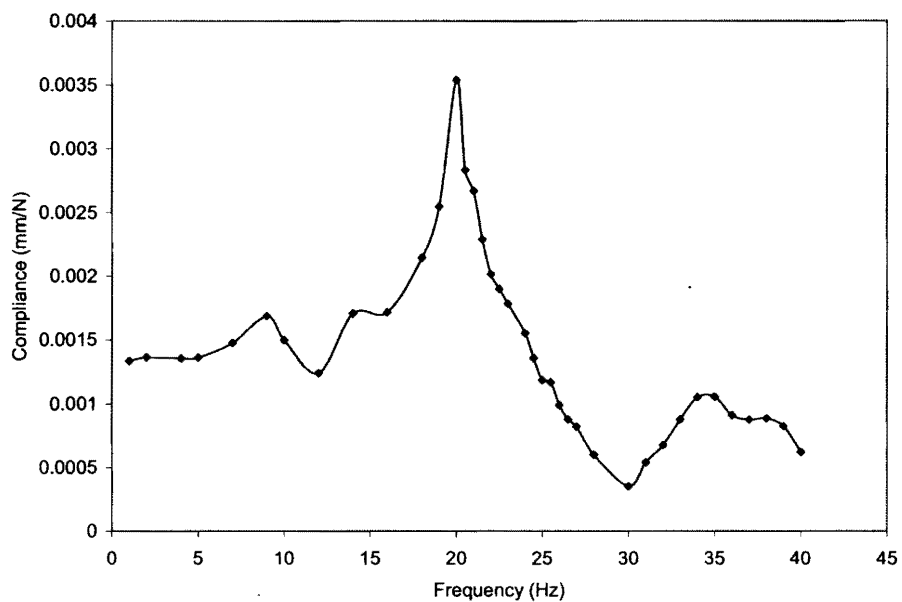


Figure A56: Specimen 5 flexion angle intact compliance graph at 400N preload, 0.04 mm amplitude

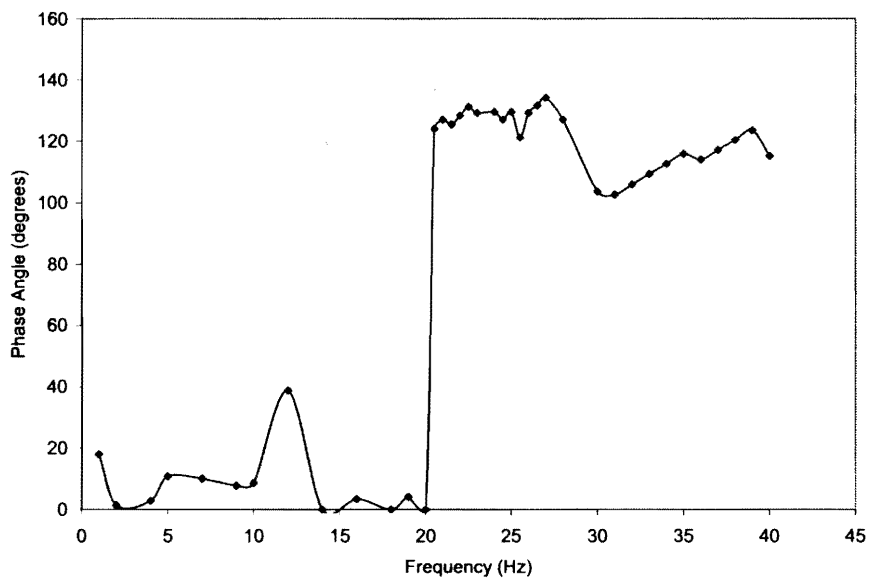


Figure A57: Specimen 5 flexion angle intact phase angle graph at 400N preload, 0.04 mm amplitude

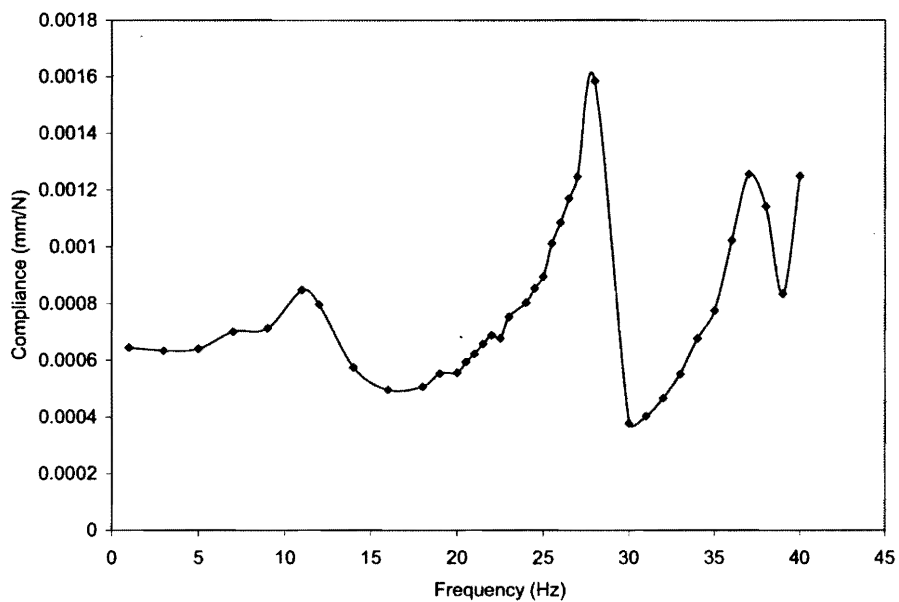


Figure A58: Specimen 5 full extension meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

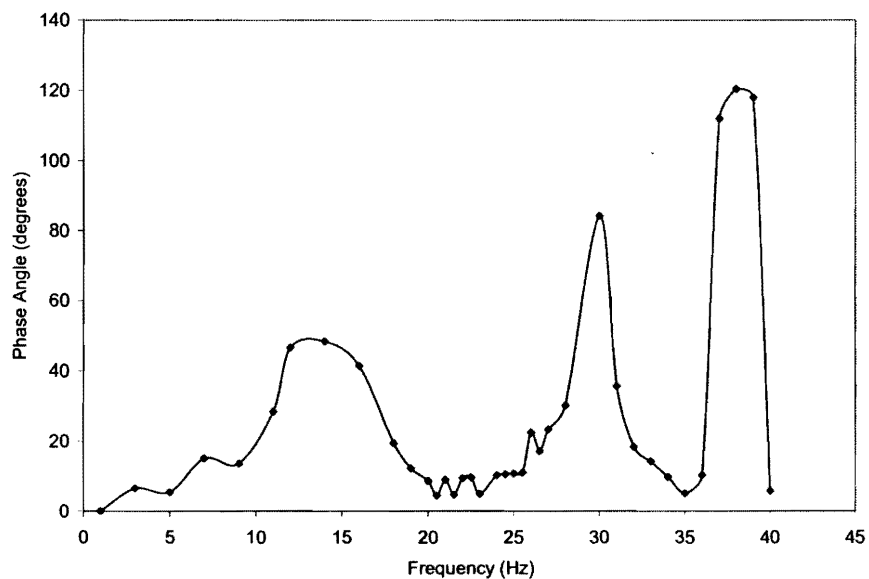


Figure A59: Specimen 5 full extension meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

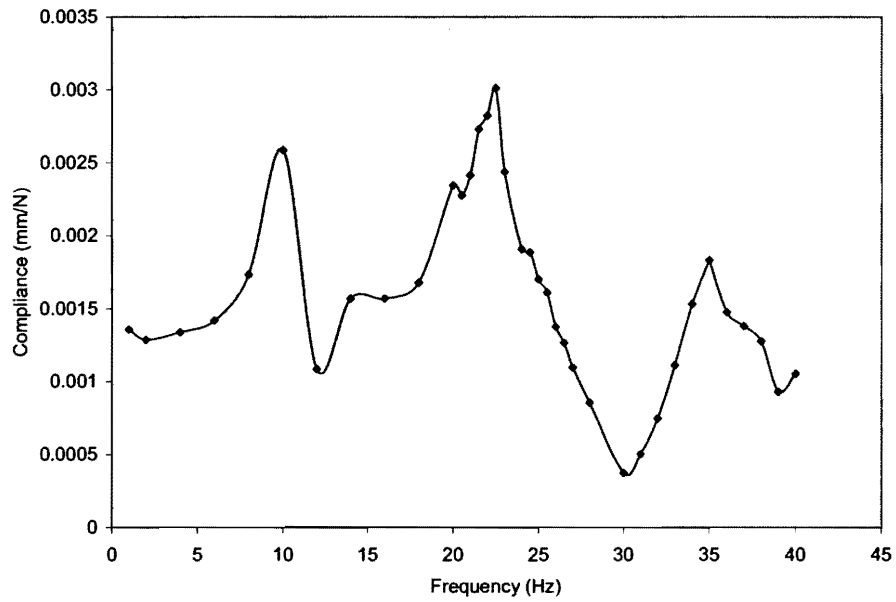


Figure A60: Specimen 5 flexion angle meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

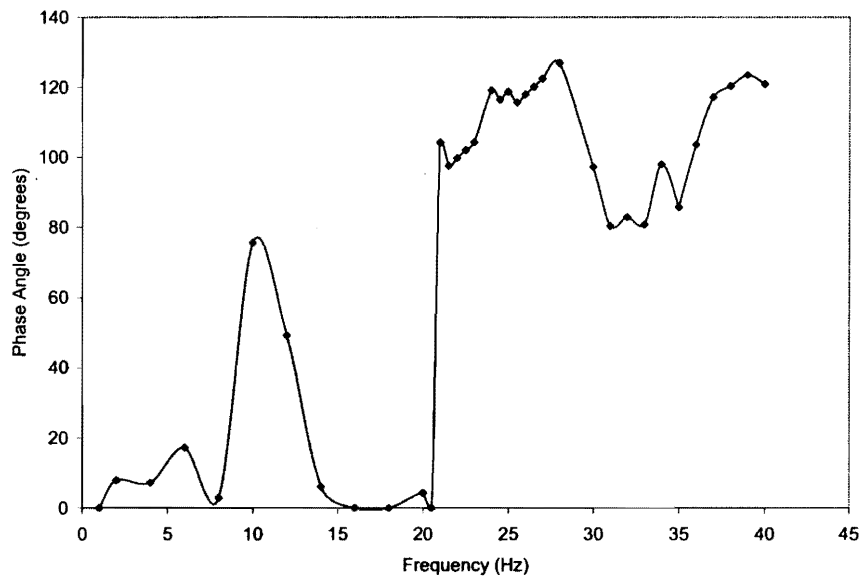


Figure A61: Specimen 5 flexion angle meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

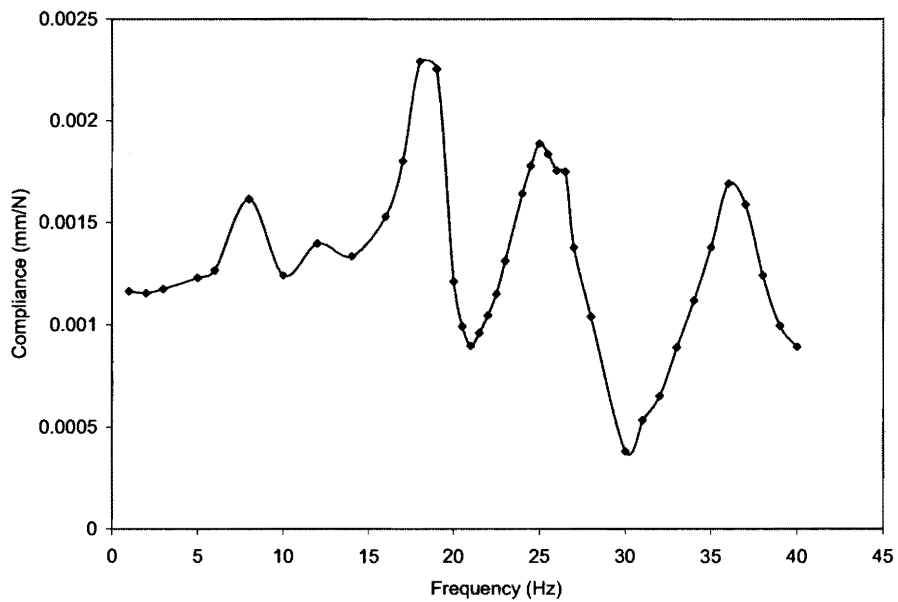


Figure A62: Specimen 6 full extension intact compliance graph at 400N preload, 0.04 mm amplitude

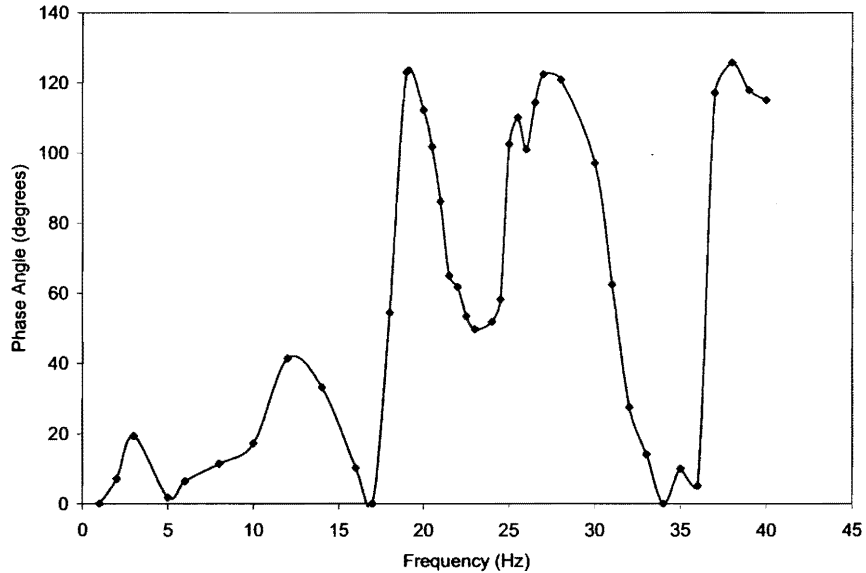


Figure A63: Specimen 6 full extension intact phase angle graph at 400N preload, 0.04 mm amplitude

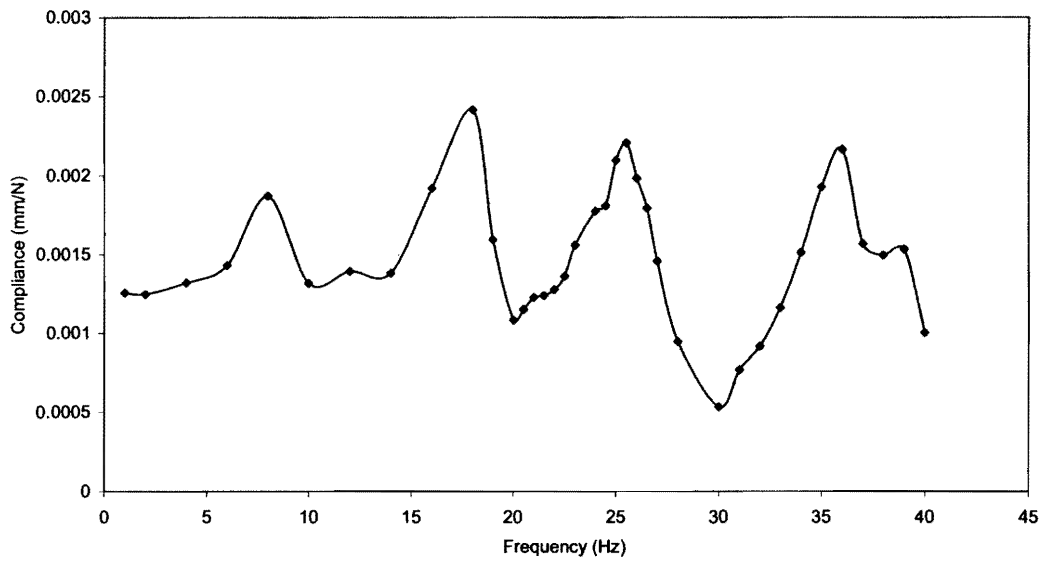


Figure A64: Specimen 6 full extension intact compliance graph at 400N preload, 0.08 mm amplitude

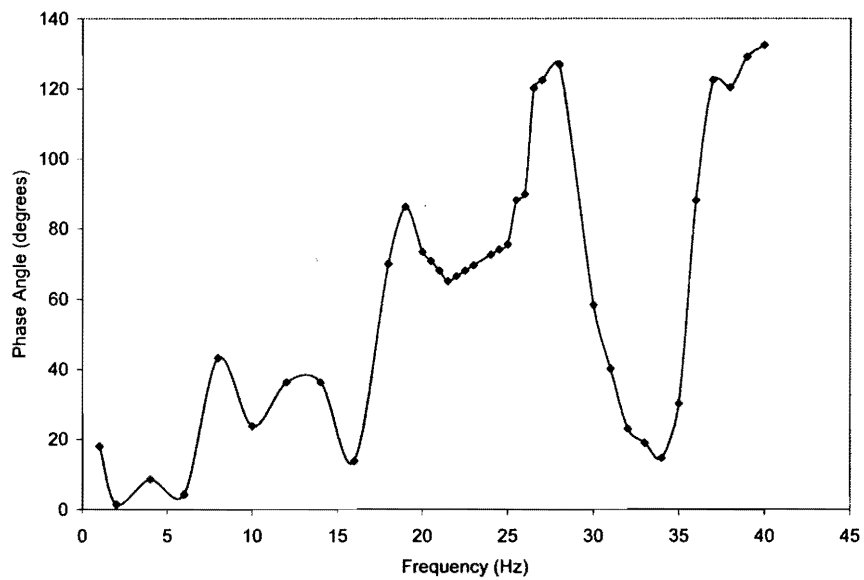


Figure A65: Specimen 6 full extension intact phase angle graph at 400N preload, 0.08 mm amplitude

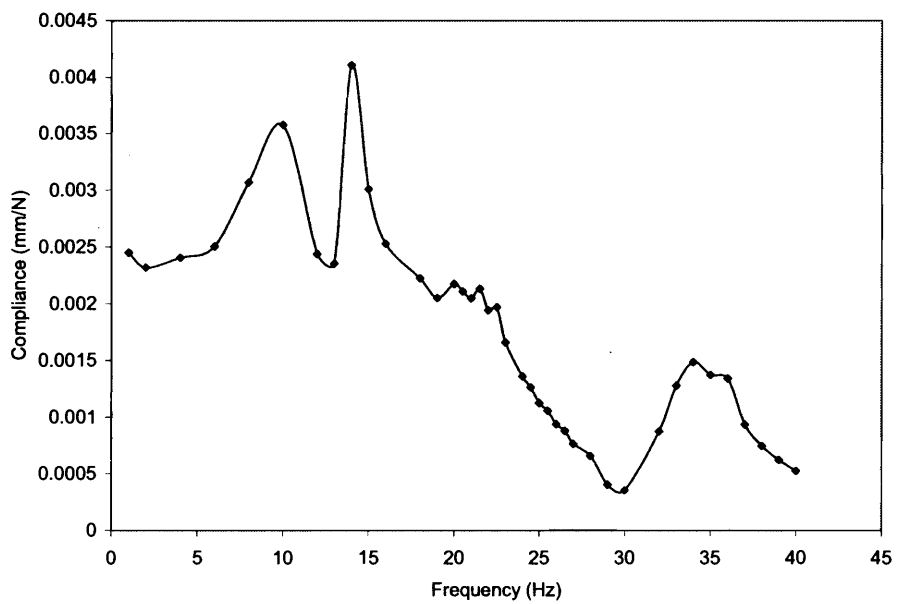


Figure A66: Specimen 6 flexion angle intact compliance graph at 400N preload, 0.04 mm amplitude

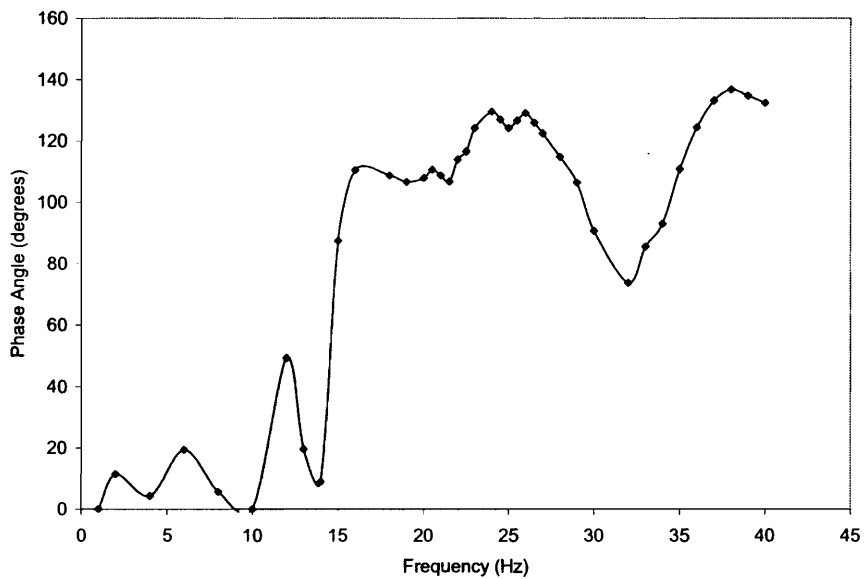


Figure A67: Specimen 6 flexion angle intact phase angle graph at 400N preload, 0.04 mm amplitude

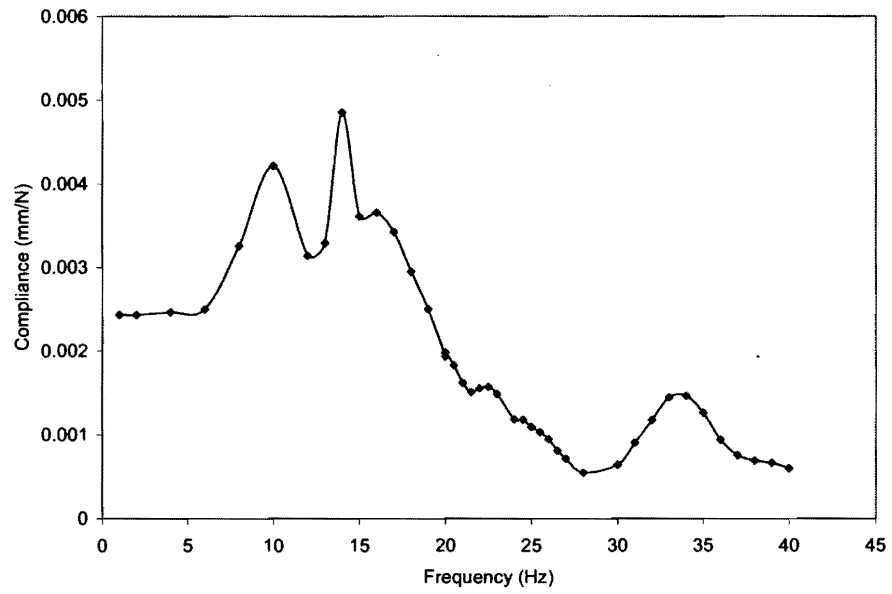


Figure A68: Specimen 6 flexion angle intact compliance graph at 400N preload, 0.08 mm amplitude

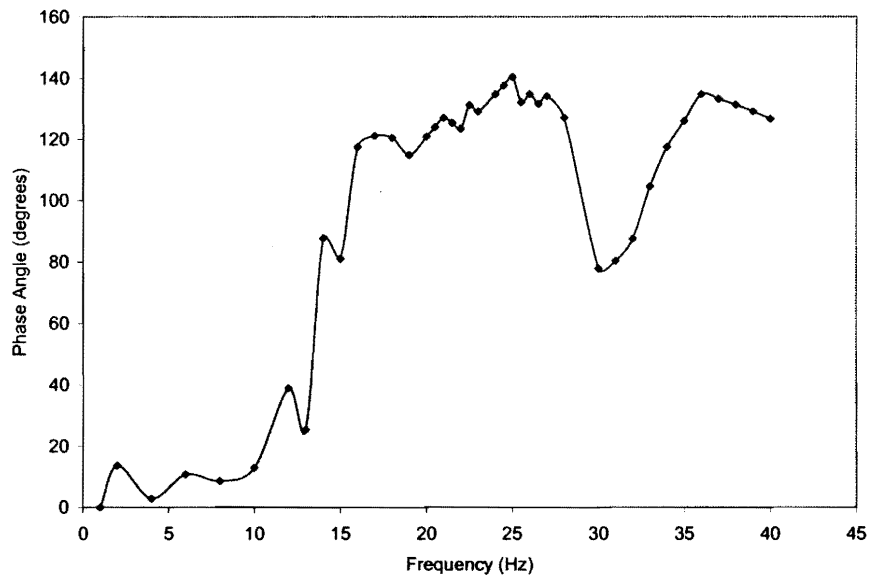


Figure A69: Specimen 6 flexion angle intact phase angle graph at 400N preload, 0.08 mm amplitude

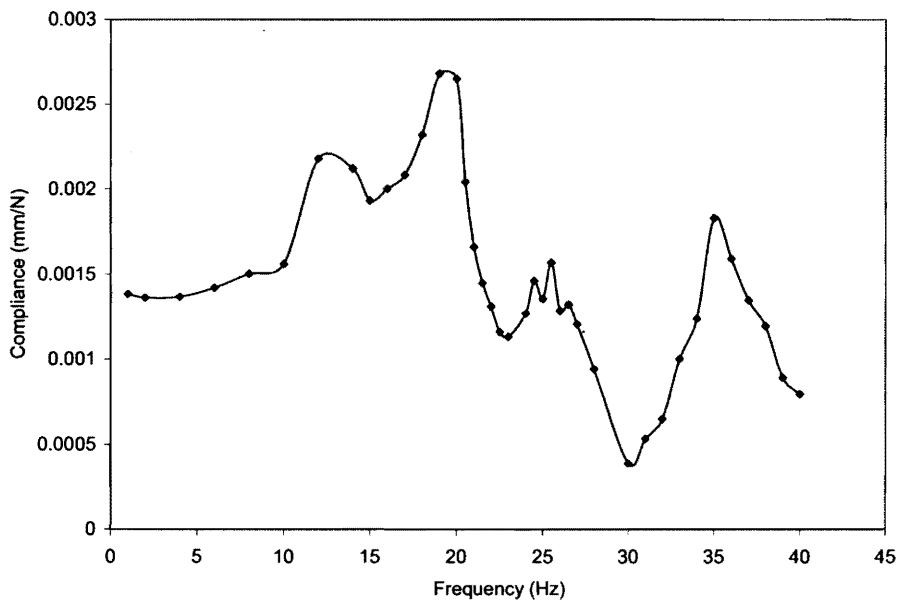


Figure A70: Specimen 6 full extension meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

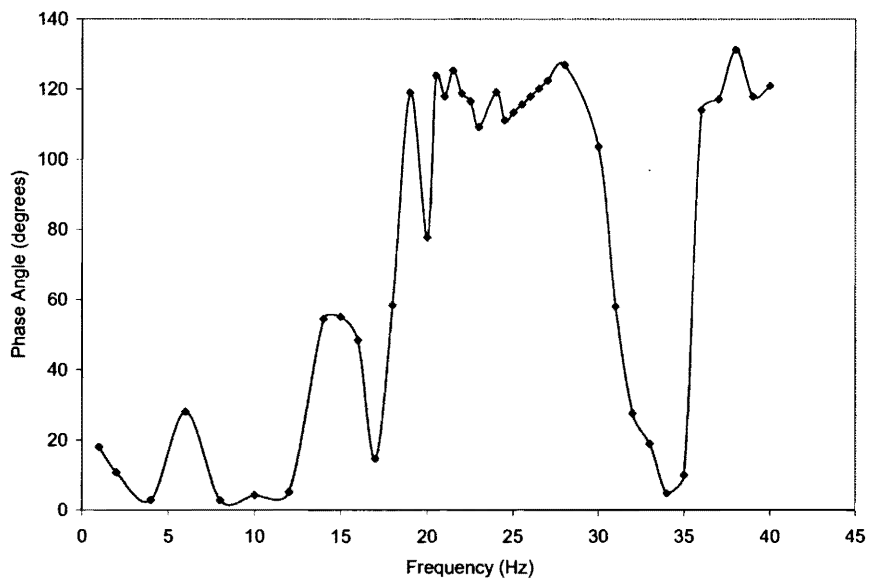


Figure A71: Specimen 6 full extension meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

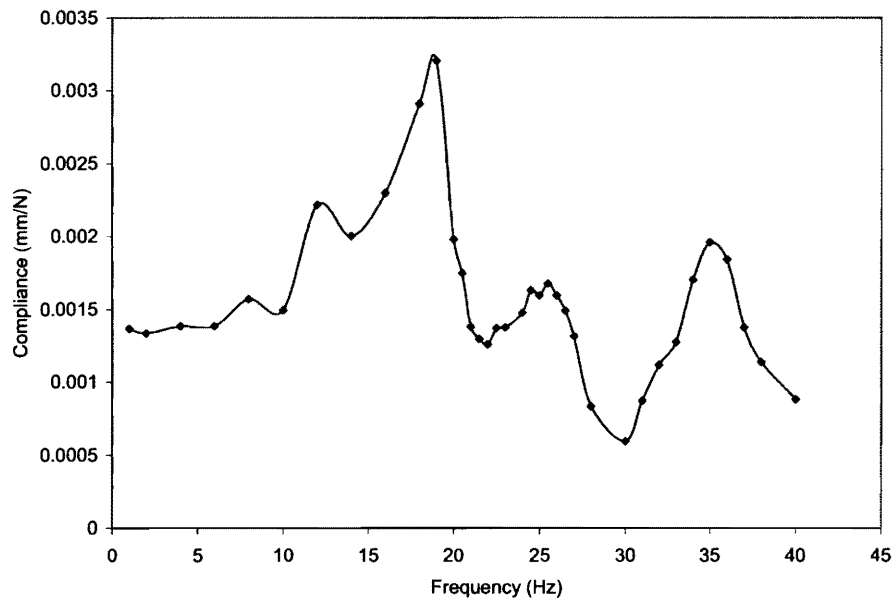


Figure A72: Specimen 6 full extension meniscectomized compliance graph at 400N preload, 0.08 mm amplitude

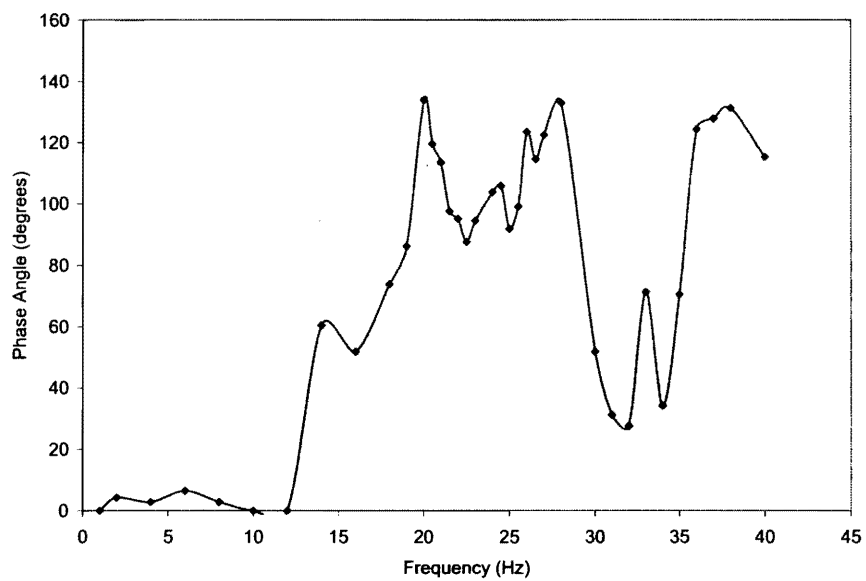


Figure A73: Specimen 6 full extension meniscectomized phase angle graph at 400N preload, 0.08 mm amplitude

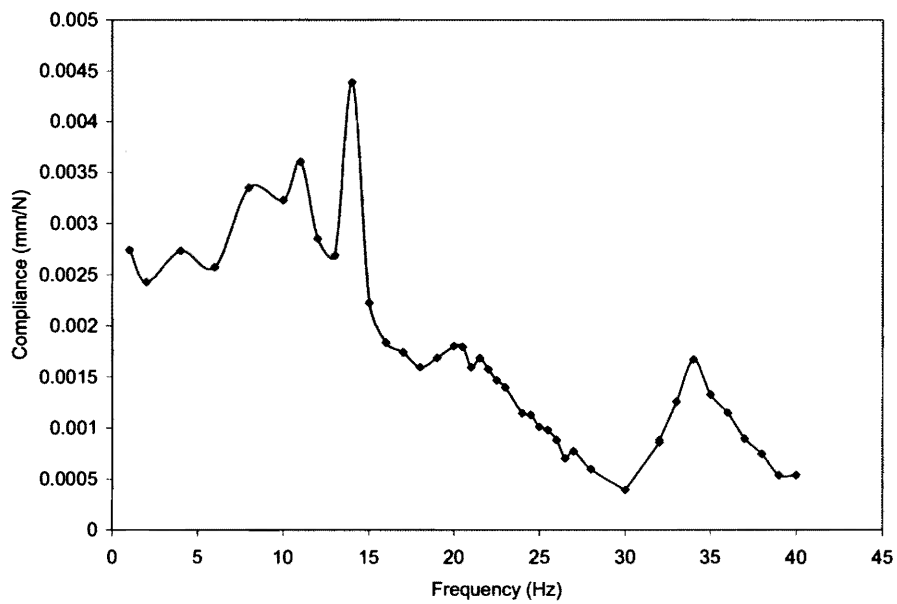


Figure A74: Specimen 6 flexion angle meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

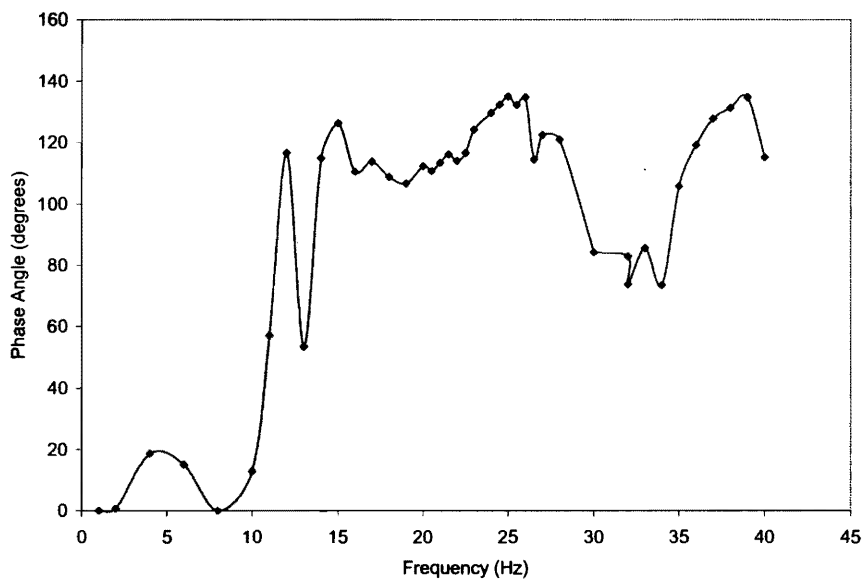


Figure A75: Specimen 6 flexion angle meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

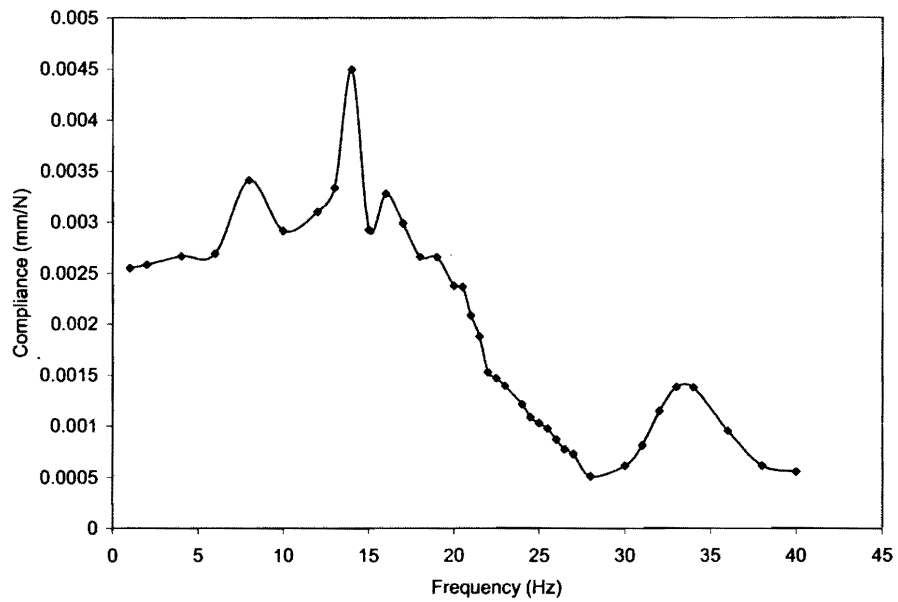


Figure A76: Specimen 6 flexion angle meniscectomized compliance graph at 400N preload, 0.08 mm amplitude

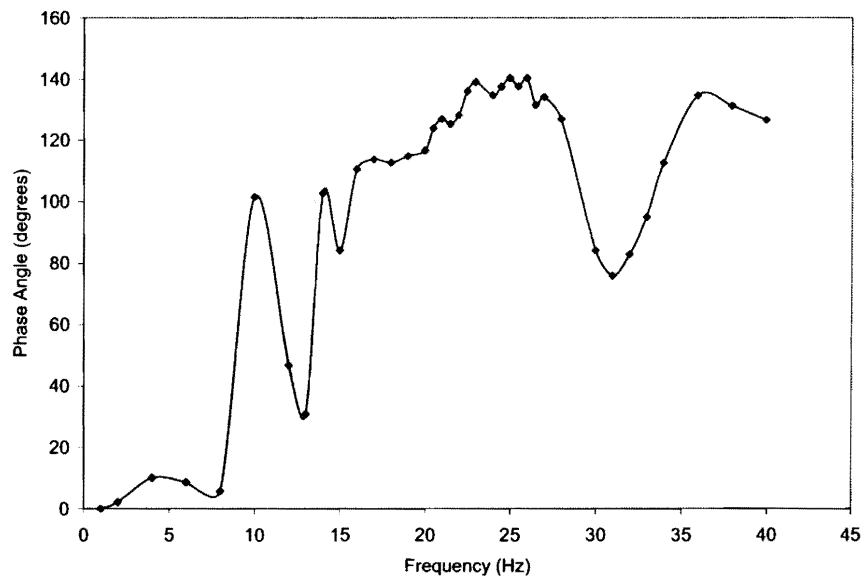


Figure A77: Specimen 6 flexion angle meniscectomized phase angle graph at 400N preload, 0.08 mm amplitude

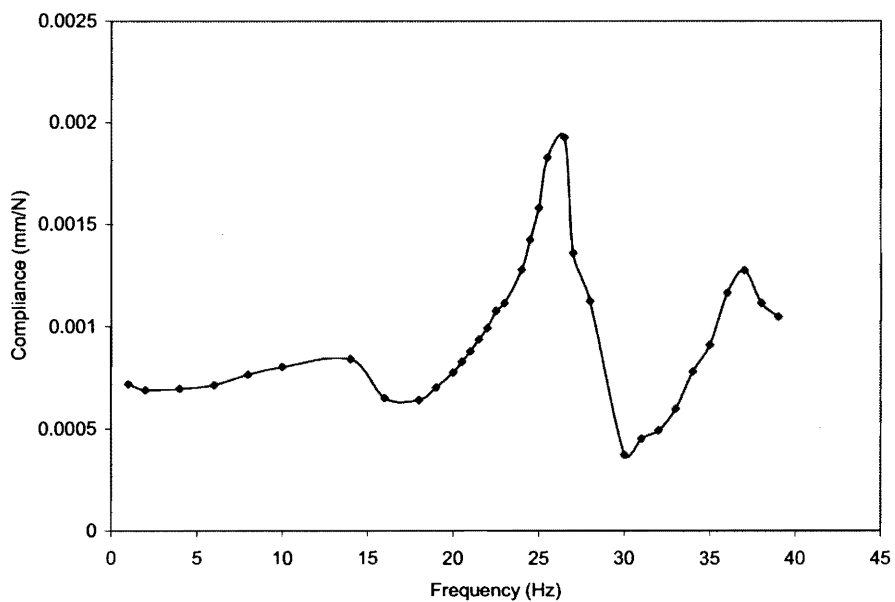


Figure A78: Specimen 7 full extension intact compliance graph at 400N preload, 0.04 mm amplitude

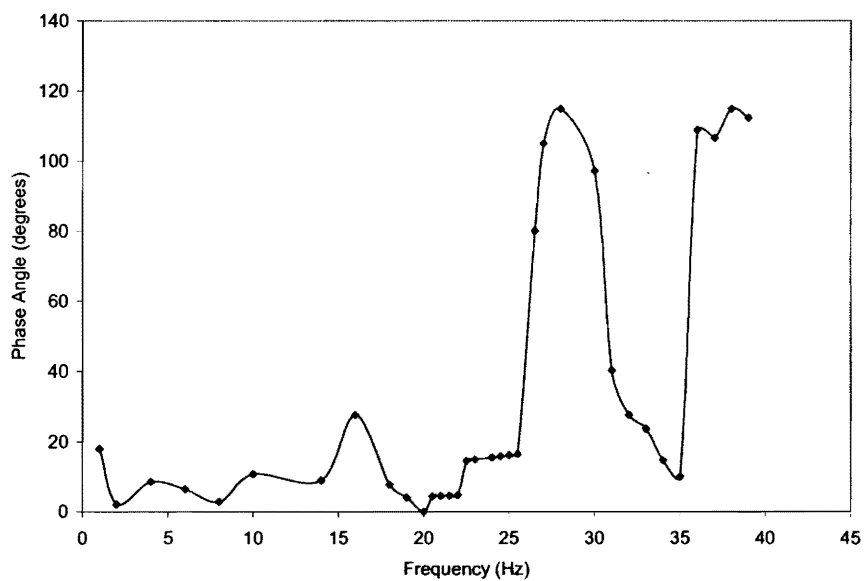


Figure A79: Specimen 7 full extension intact phase angle graph at 400N preload, 0.04 mm amplitude

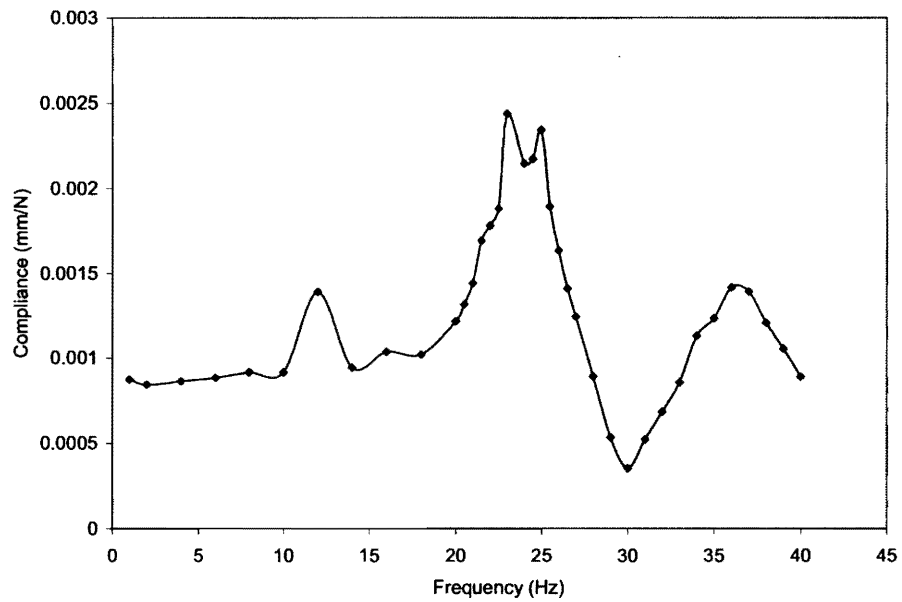


Figure 80: Specimen 7 flexion angle intact compliance graph at 400N preload, 0.04 mm amplitude

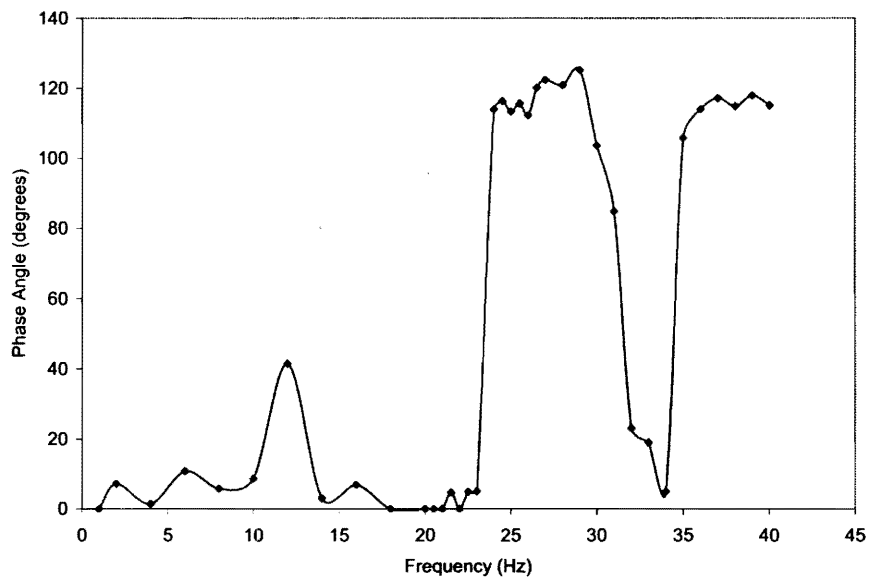


Figure A81: Specimen 7 flexion angle intact phase angle graph at 400N preload, 0.04 mm amplitude

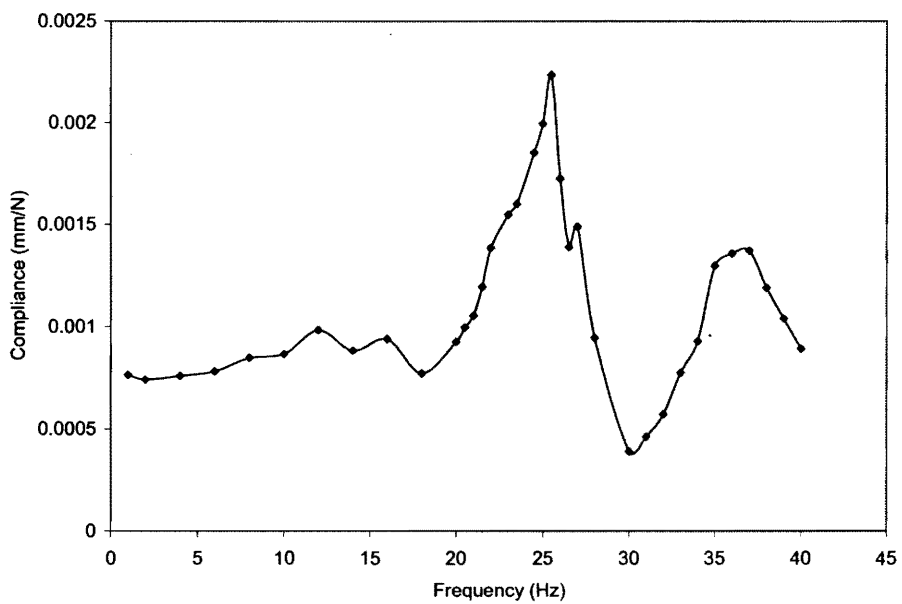


Figure A82: Specimen 7 full extension meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

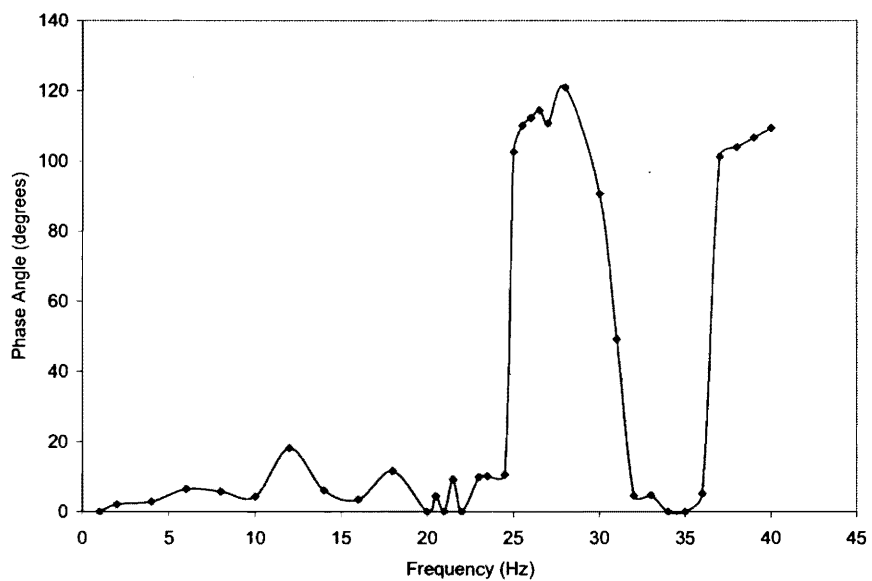


Figure A83: Specimen 7 full extension meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

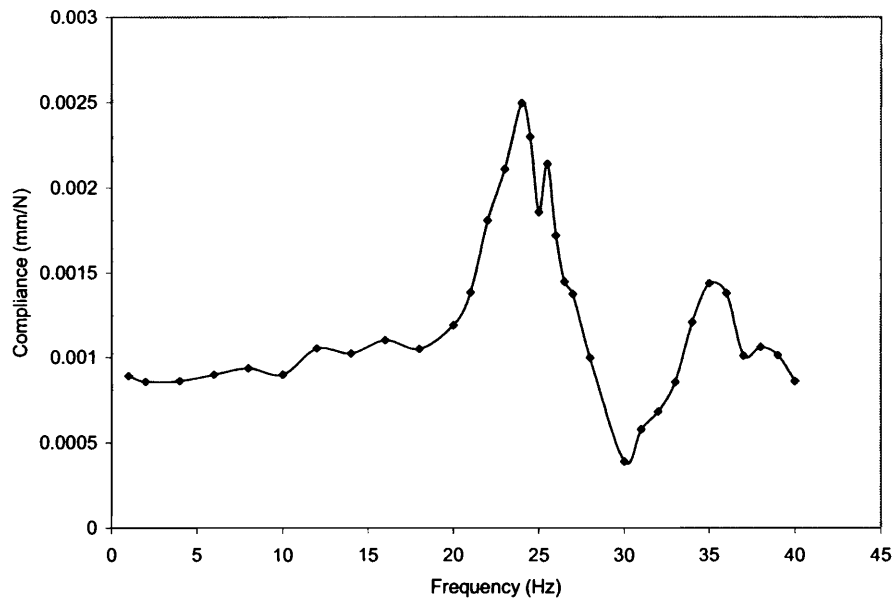


Figure A84: Specimen 7 flexion angle meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

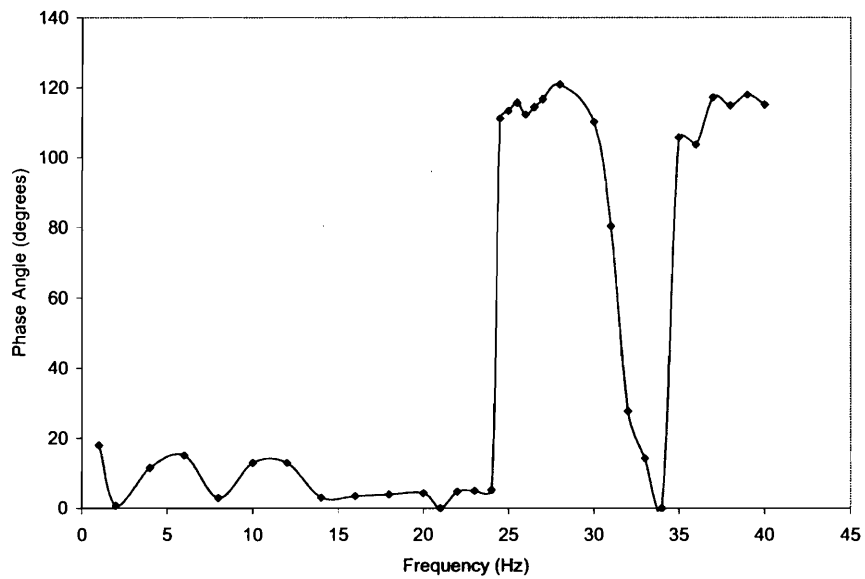


Figure A85: Specimen 7 flexion angle meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

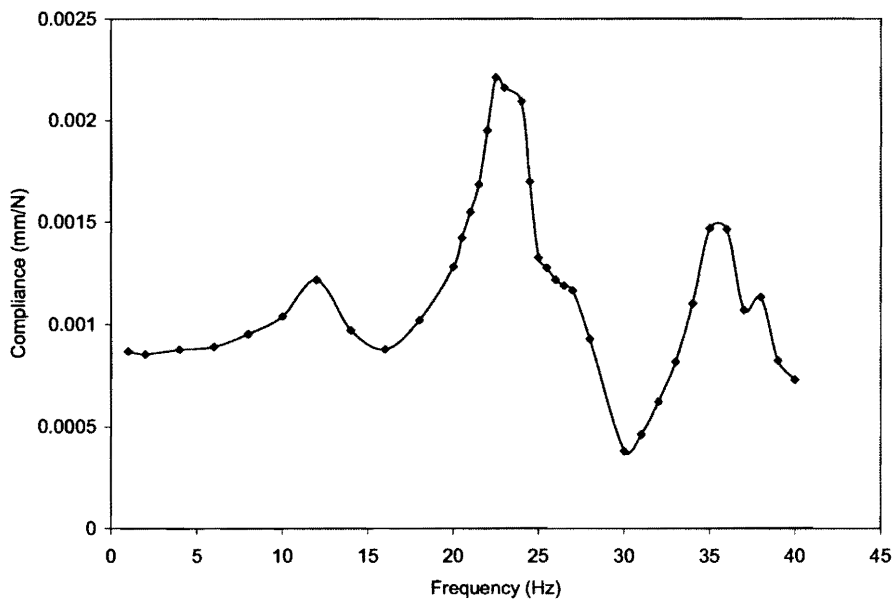


Figure A86: Specimen 8 full extension intact compliance graph at 400N preload, 0.04 mm amplitude

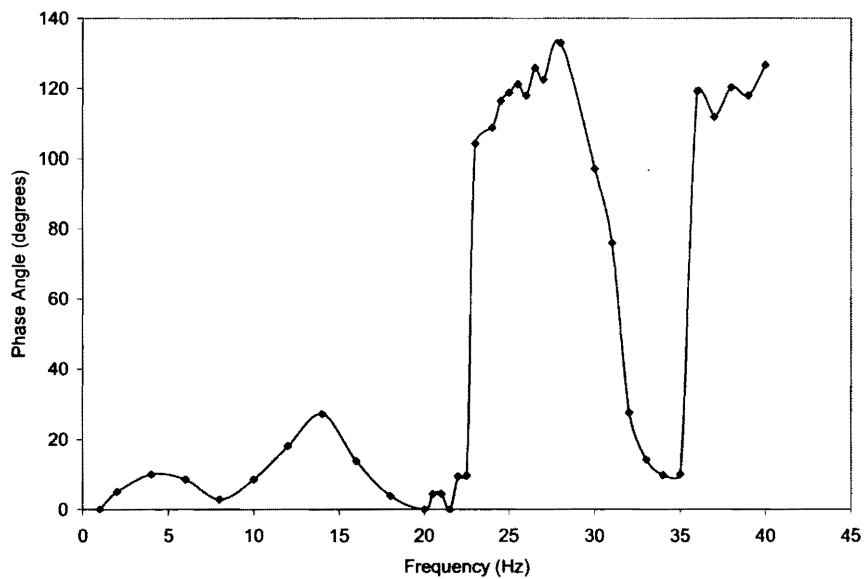


Figure A87: Specimen 8 full extension intact phase angle graph at 400N preload, 0.04 mm amplitude

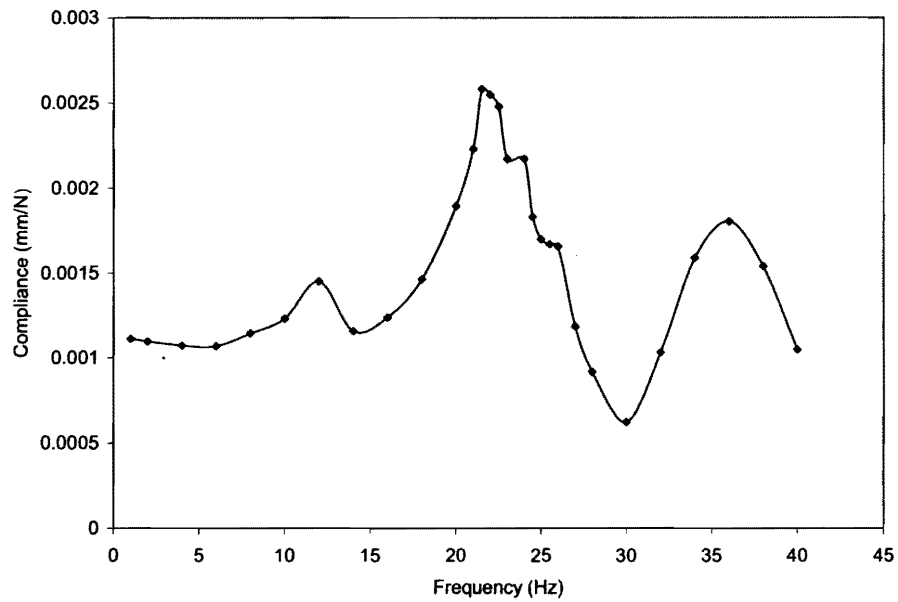


Figure A88: Specimen 8 full extension intact compliance graph at 400N preload, 0.08 mm amplitude

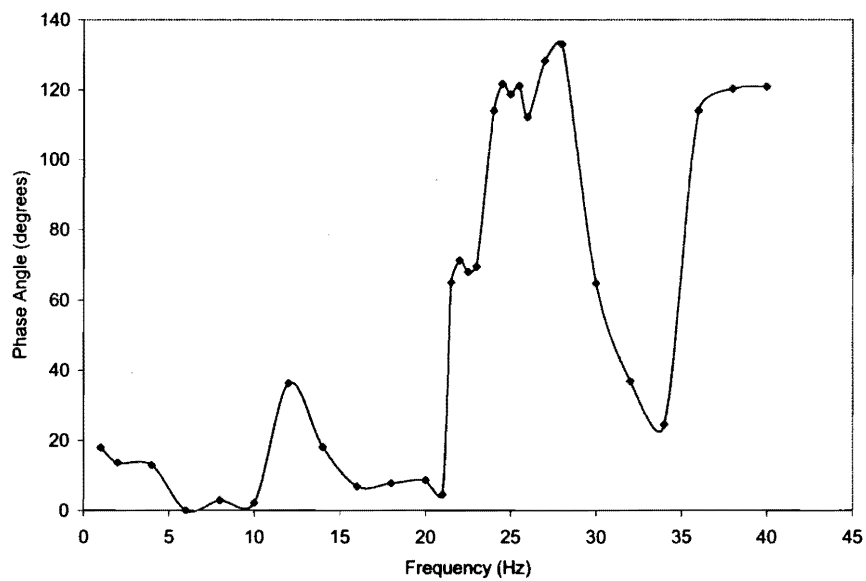


Figure A89: Specimen 8 full extension intact phase angle graph at 400N preload, 0.08 mm amplitude

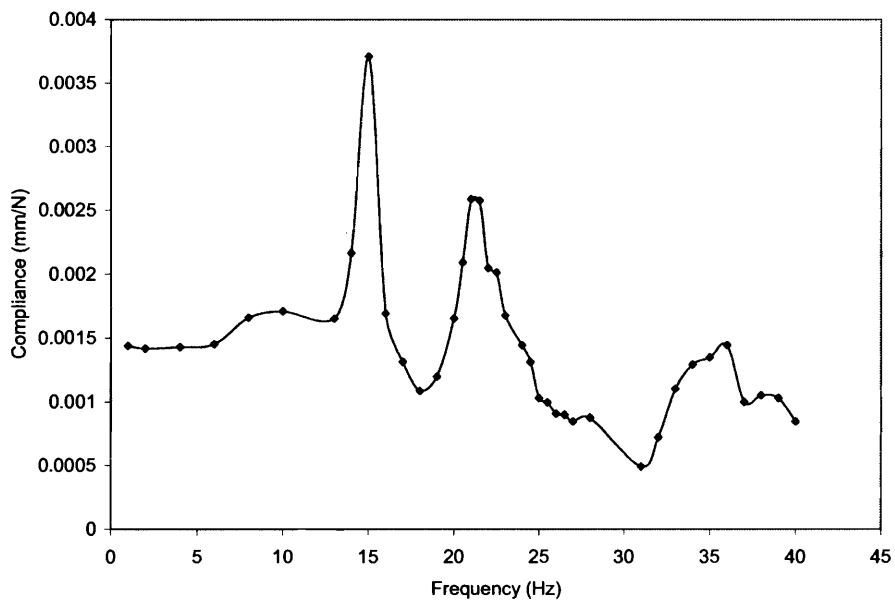


Figure A90: Specimen 8 flexion angle intact compliance graph at 400N preload, 0.04 mm amplitude

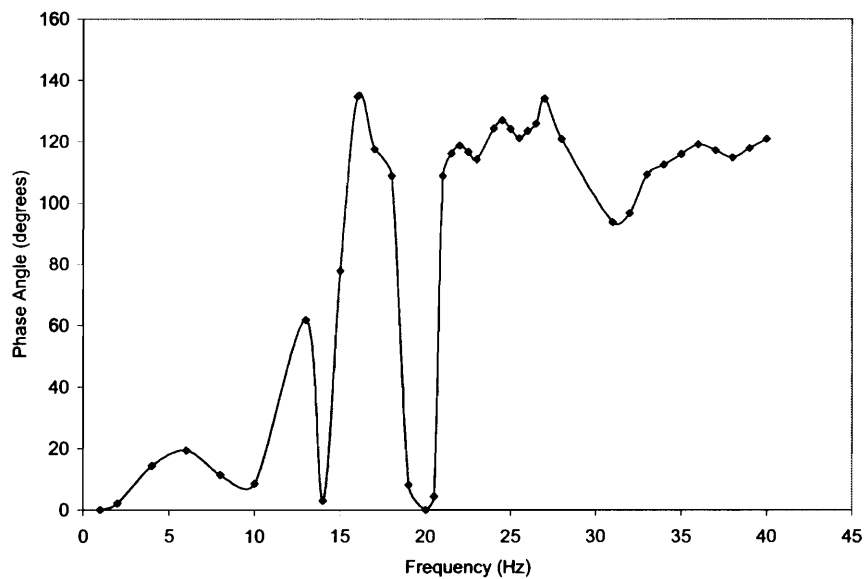


Figure A91: Specimen 8 flexion angle intact phase angle graph at 400N preload, 0.04 mm amplitude

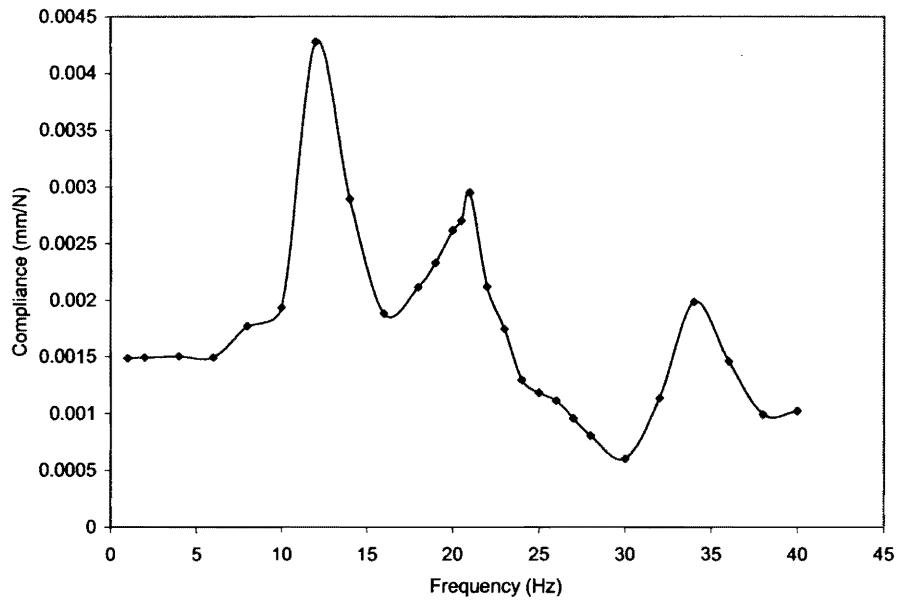


Figure A92: Specimen 8 flexion angle intact compliance graph at 400N preload, 0.08 mm amplitude

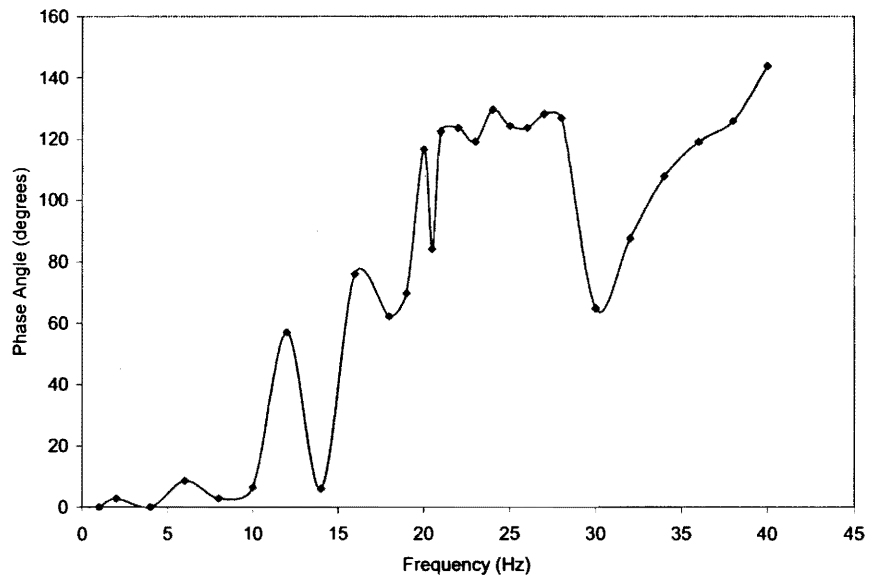


Figure A93: Specimen 8 flexion angle intact phase angle graph at 400N preload, 0.08 mm amplitude

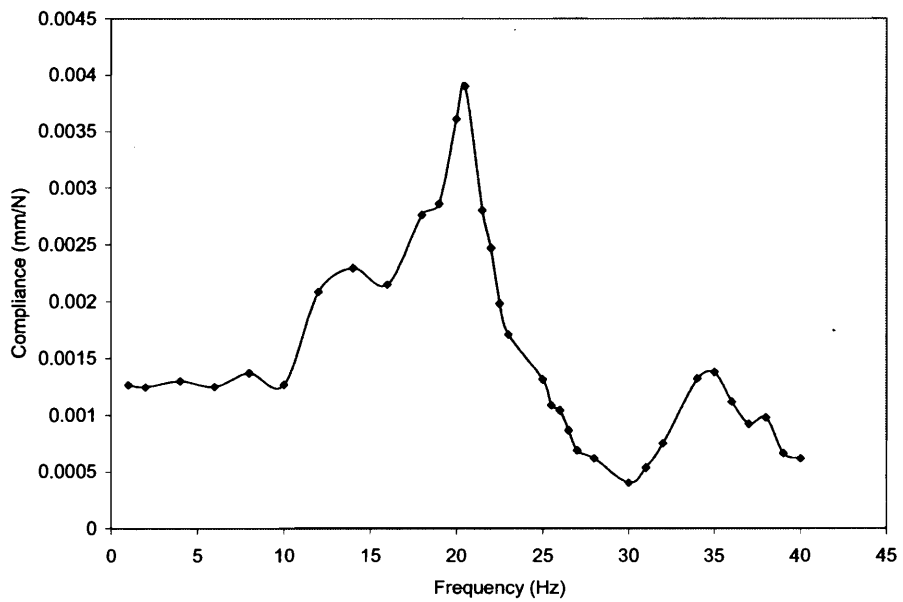


Figure A94: Specimen 8 full extension meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

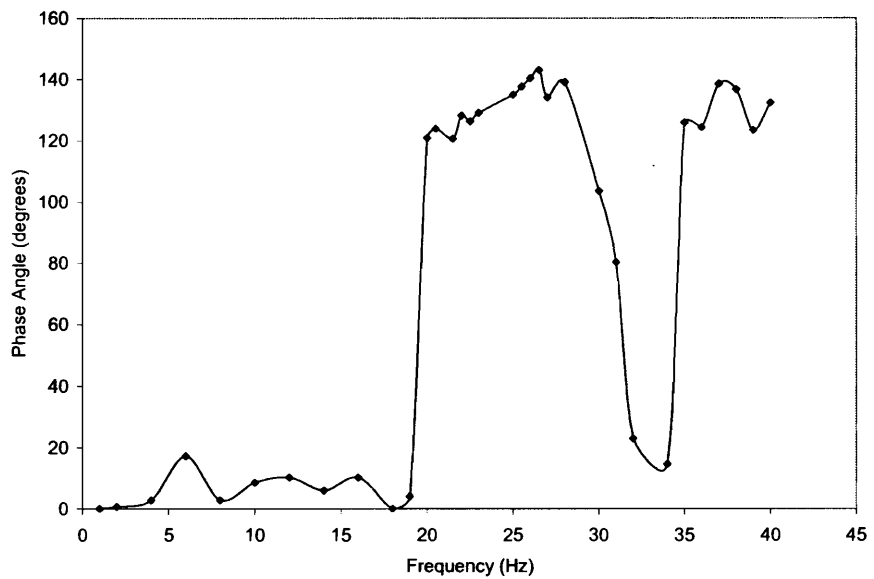


Figure A95: Specimen 8 full extension meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

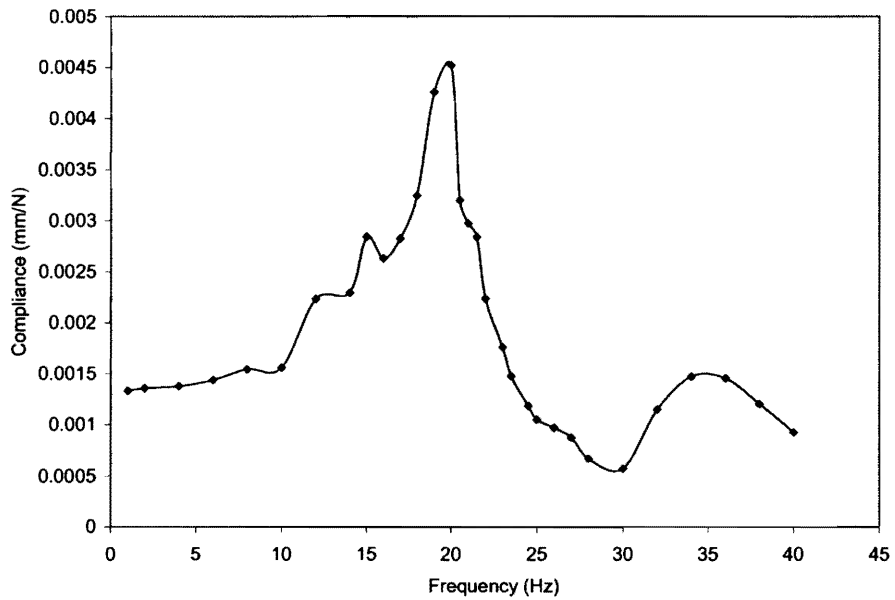


Figure A96: Specimen 8 full extension meniscectomized compliance graph at 400N preload, 0.08 mm amplitude

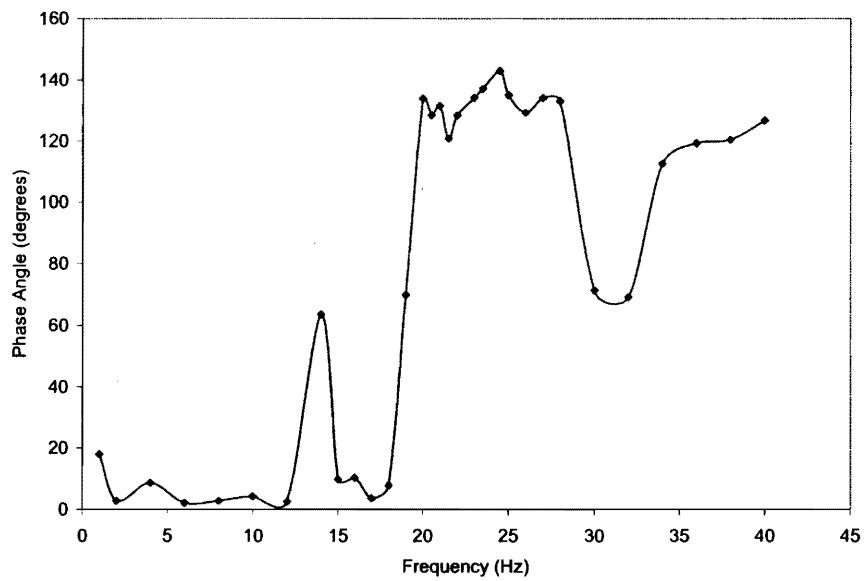


Figure A97: Specimen 8 full extension meniscectomized phase angle graph at 400N preload, 0.08 mm amplitude

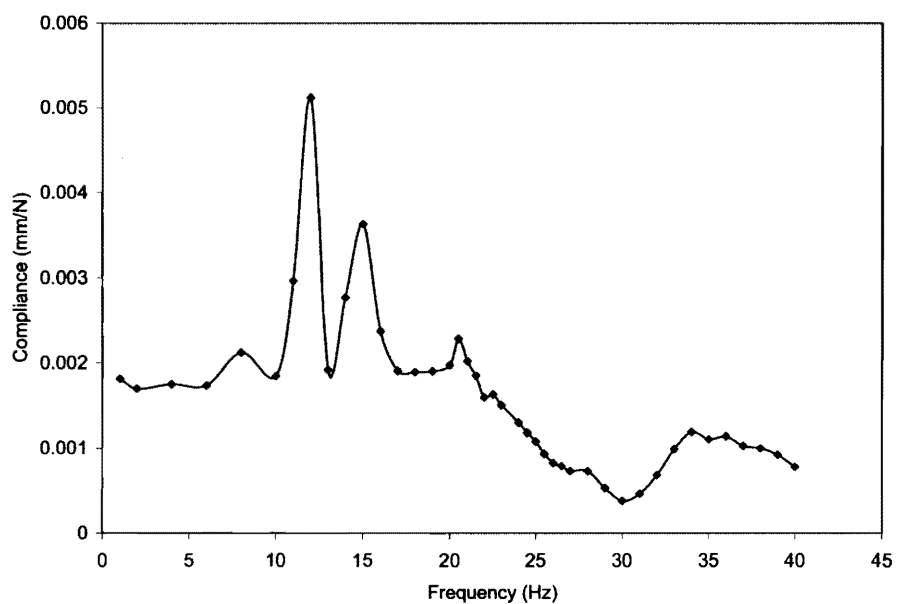


Figure A98: Specimen 8 flexion angle meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

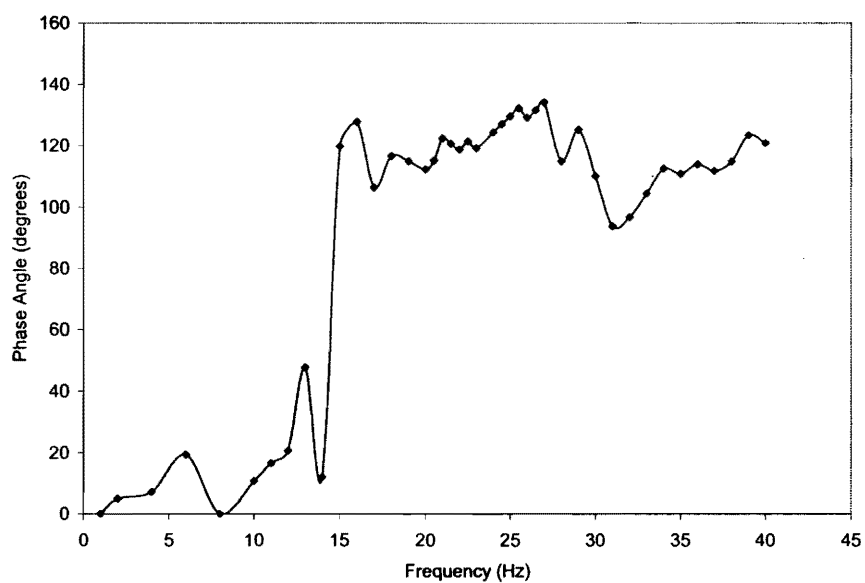


Figure A99: Specimen 8 flexion angle meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

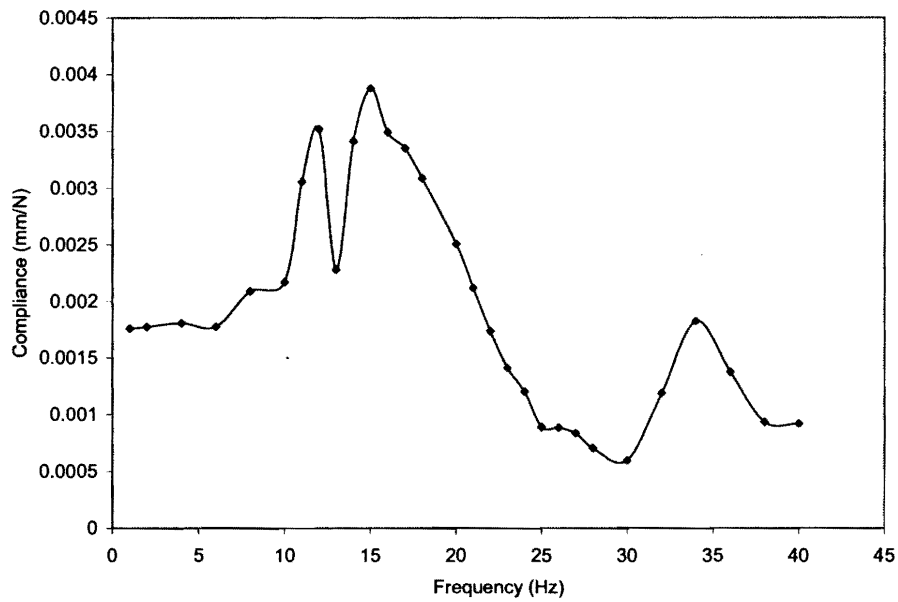


Figure A100: Specimen 8 flexion angle meniscectomized compliance graph at 400N preload, 0.08 mm amplitude

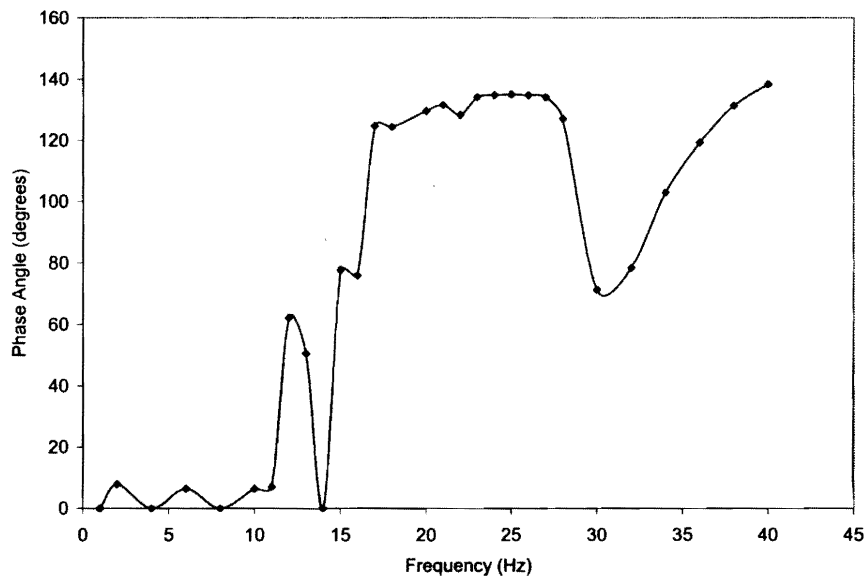


Figure A101: Specimen 8 flexion angle meniscectomized phase angle graph at 400N preload, 0.08 mm amplitude

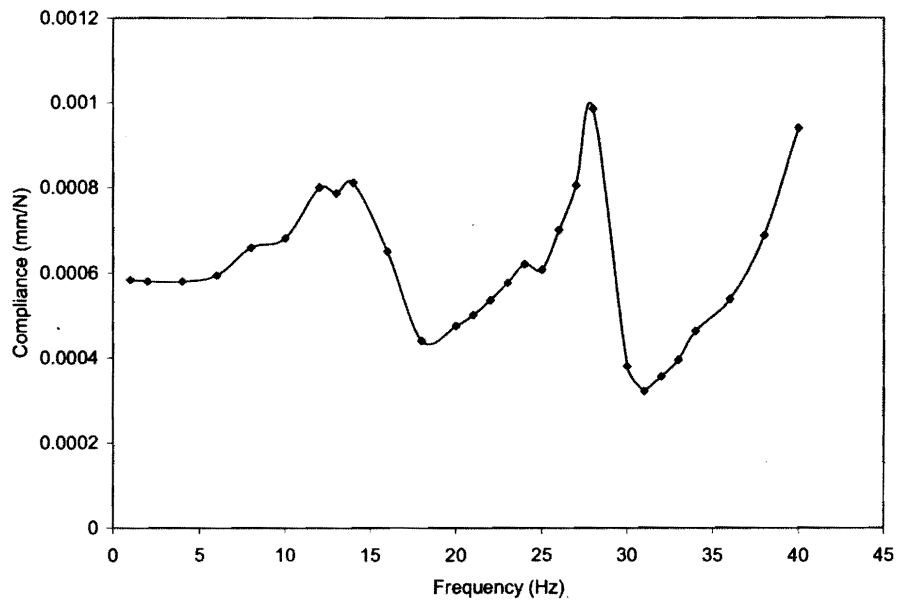


Figure A102: Specimen 9 full extension intact compliance graph at 400N preload, 0.04 mm amplitude

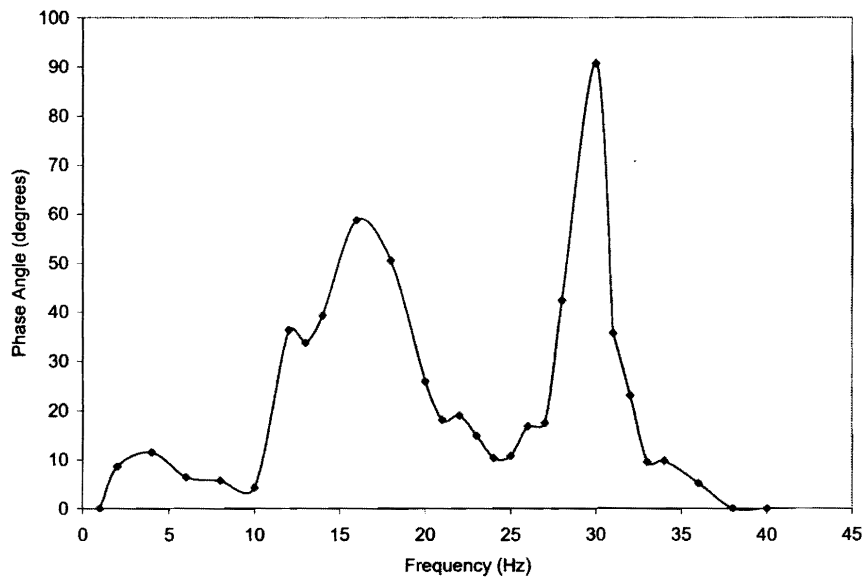


Figure A103: Specimen 9 full extension intact phase angle graph at 400N preload, 0.04 mm amplitude

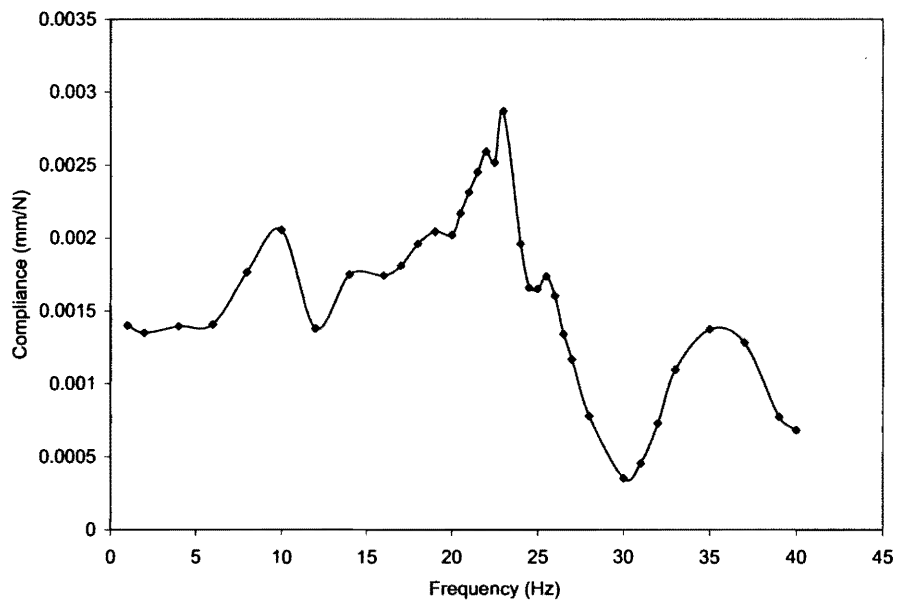


Figure A104: Specimen 9 flexion angle intact compliance graph at 400N preload, 0.04 mm amplitude

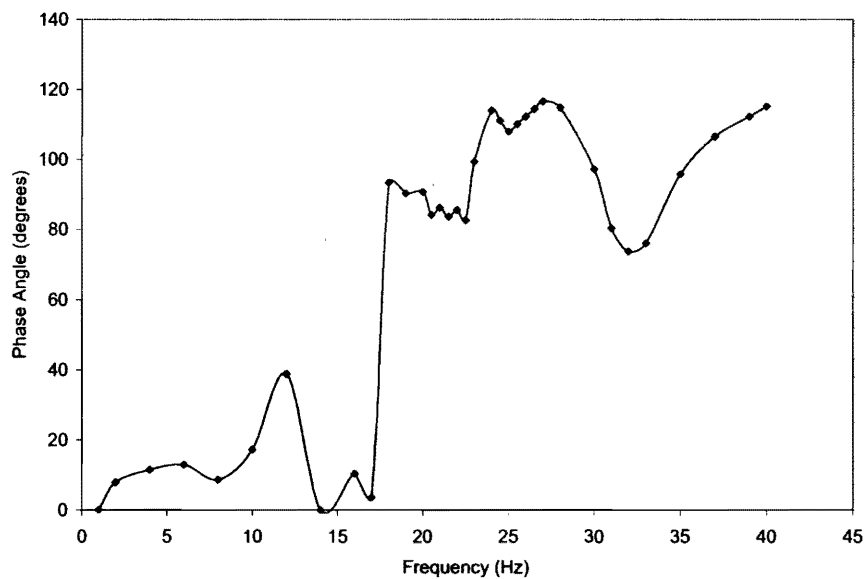


Figure A105: Specimen 9 flexion angle intact phase angle graph at 400N preload, 0.04 mm amplitude

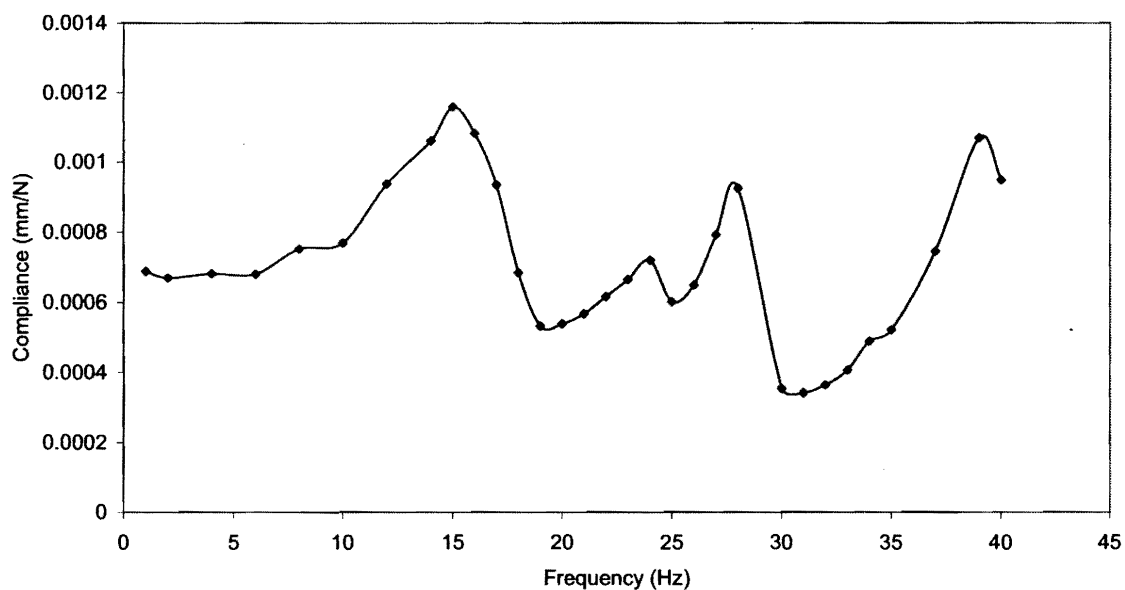


Figure A106: Specimen 9 full extension meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

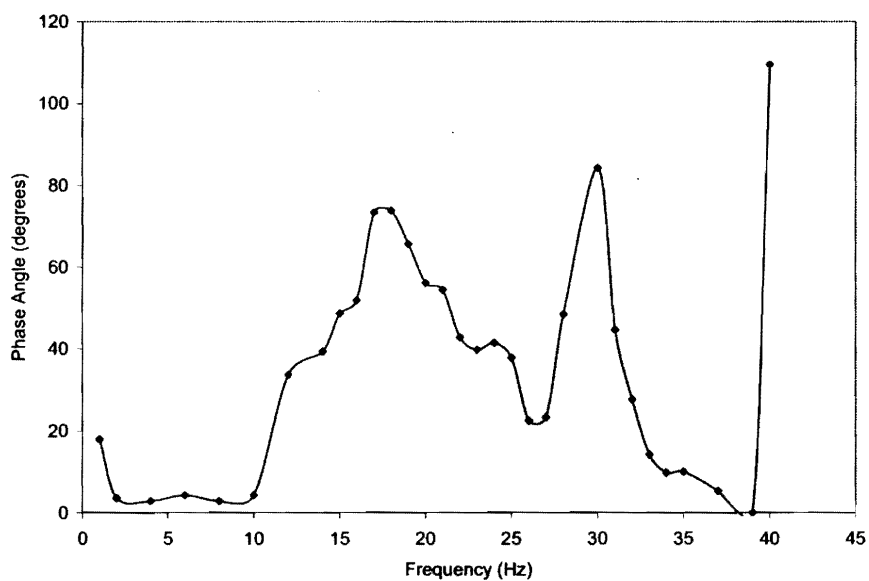


Figure A107: Specimen 9 full extension meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

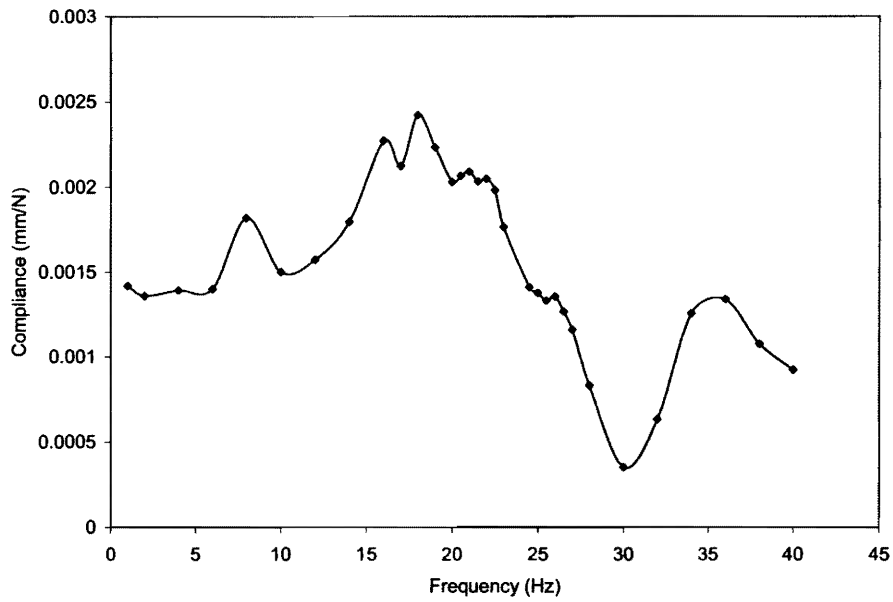


Figure A108: Specimen 9 flexion angle meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

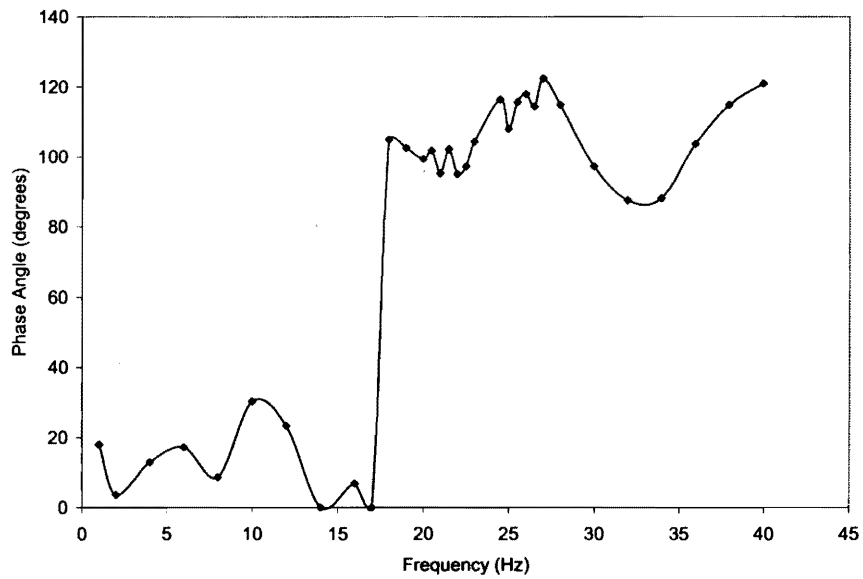


Figure A109: Specimen 9 flexion angle meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

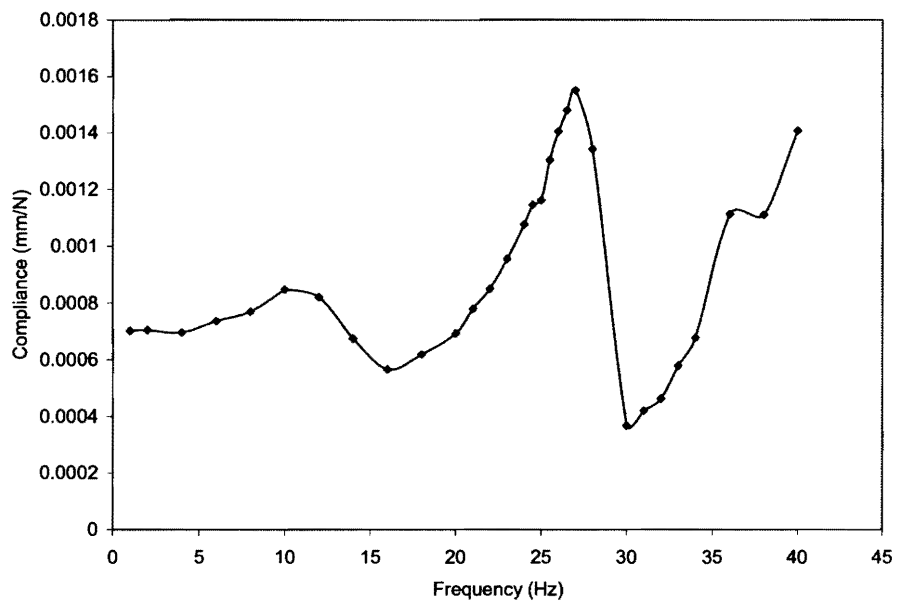


Figure A110: Specimen 10 full extension intact compliance graph at 400N preload, 0.04 mm amplitude

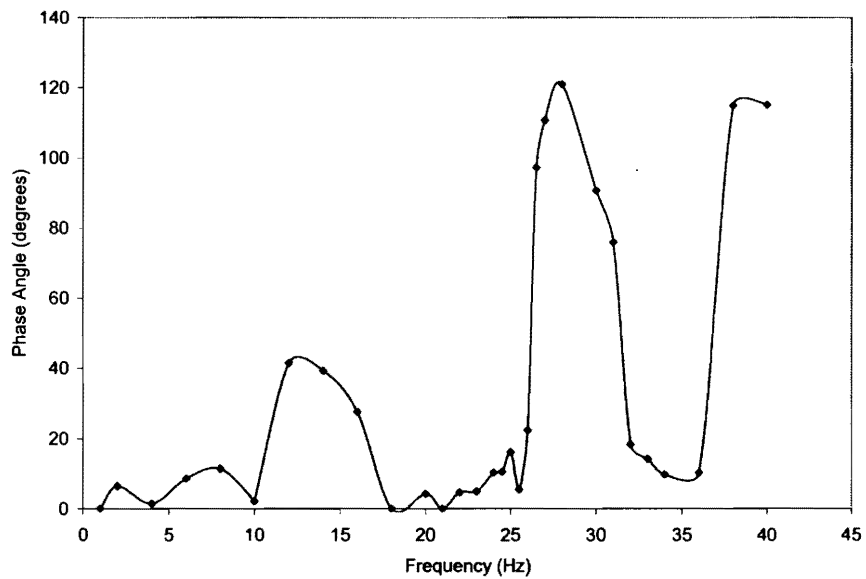


Figure A111: Specimen 10 full extension intact phase angle graph at 400N preload, 0.04 mm amplitude

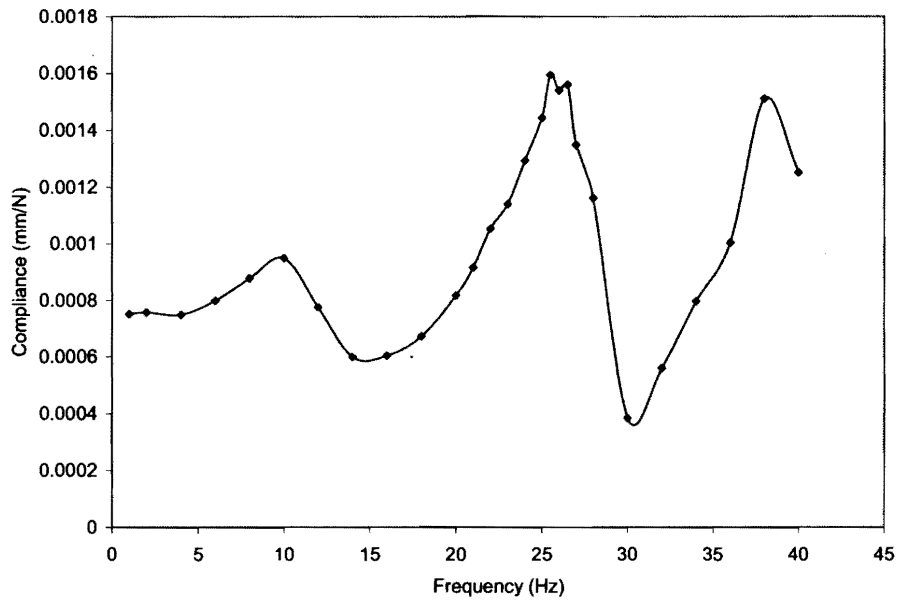


Figure A112: Specimen 10 full extension intact compliance graph at 400N preload, 0.06 mm amplitude

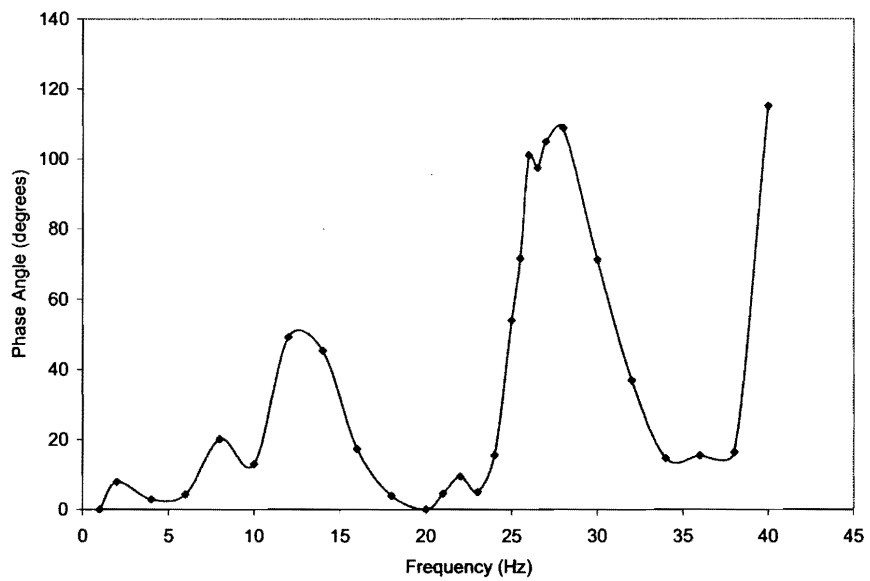


Figure A113: Specimen 10 full extension intact phase angle graph at 400N preload, 0.06 mm amplitude

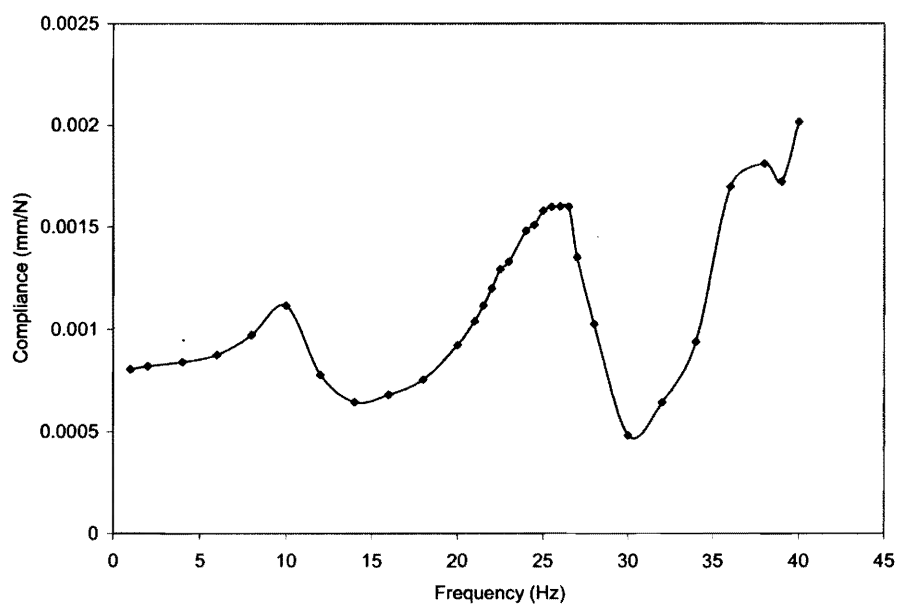


Figure A114: Specimen 10 full extension intact compliance graph at 400N preload, 0.08 mm amplitude

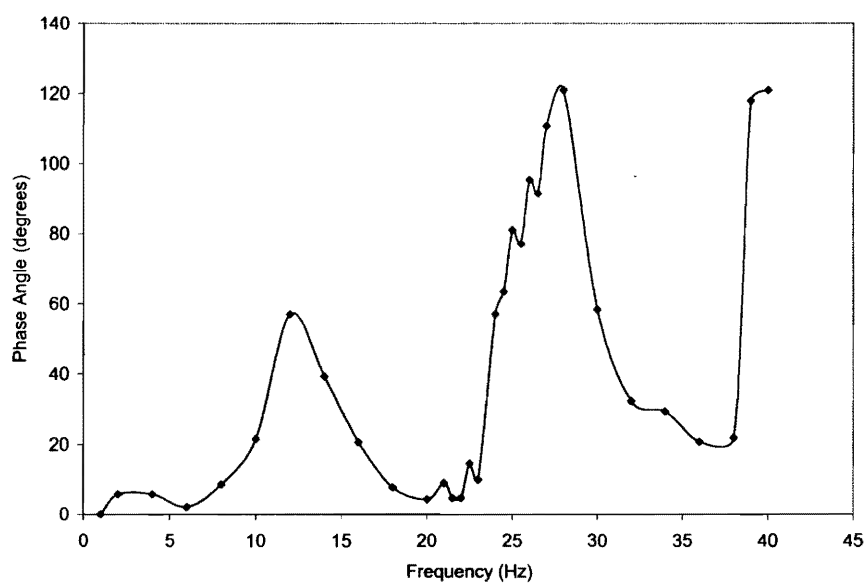


Figure A115: Specimen 10 full extension intact phase angle graph at 400N preload, 0.08 mm amplitude

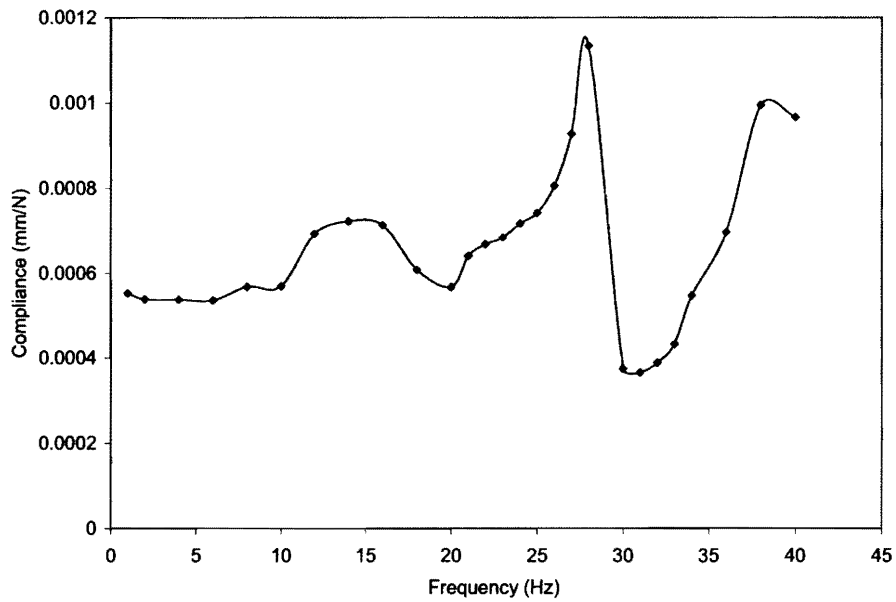


Figure A116: Specimen 10 full extension intact compliance graph at 800N preload, 0.04 mm amplitude

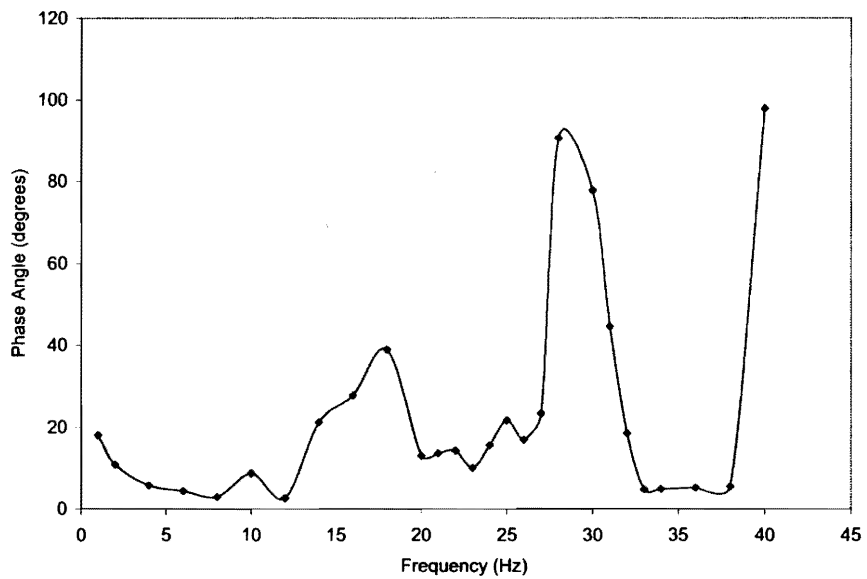


Figure A117: Specimen 10 full extension intact phase angle graph at 800N preload, 0.04 mm amplitude

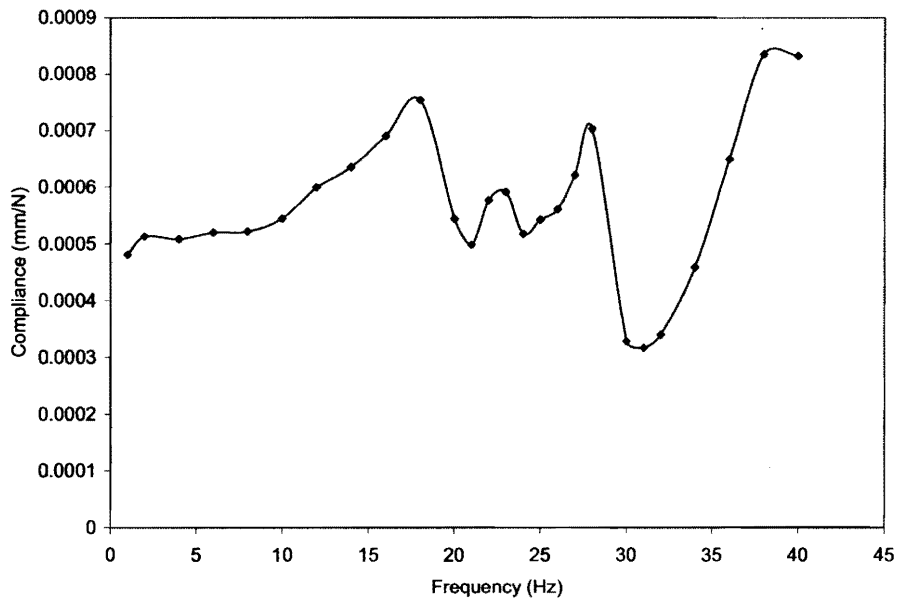


Figure A118: Specimen 10 full extension intact compliance graph at 1200N preload, 0.04 mm amplitude

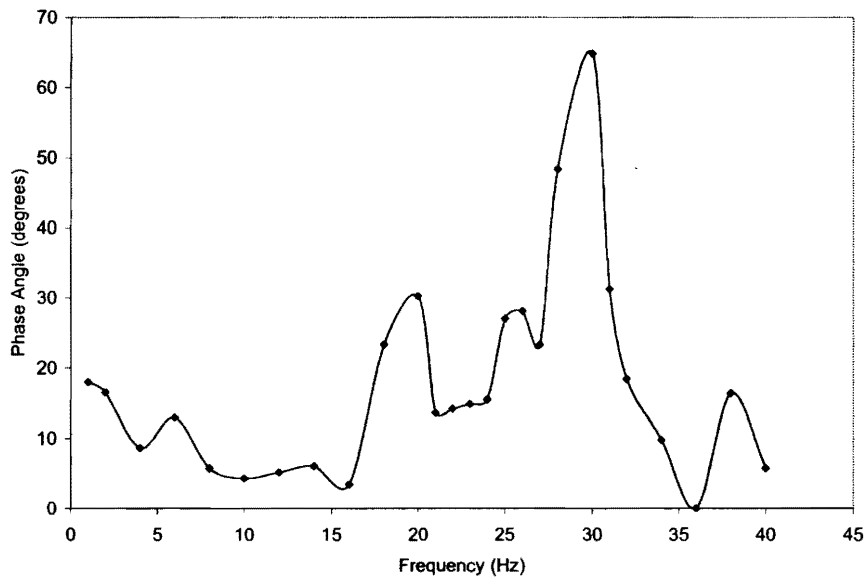


Figure A119: Specimen 10 full extension intact phase angle graph at 1200N preload, 0.04 mm amplitude

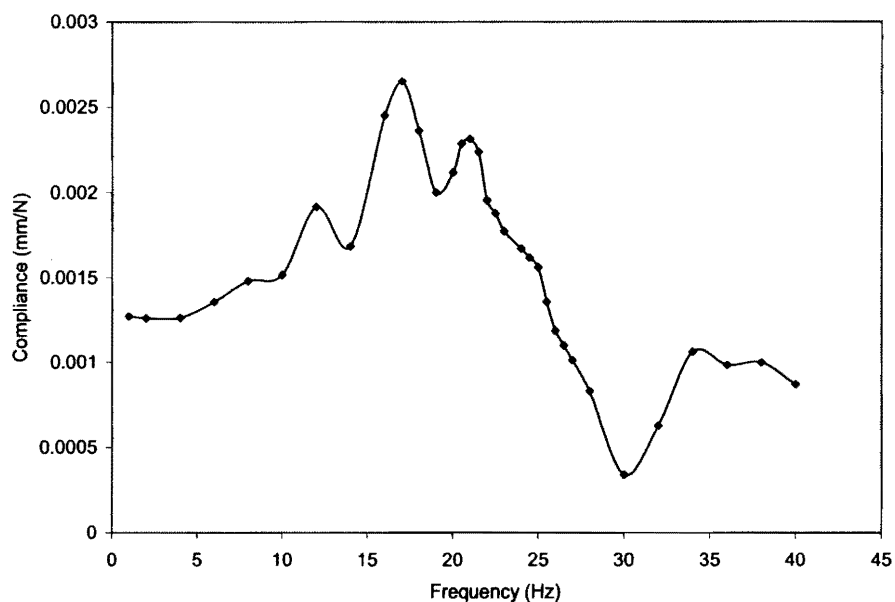


Figure A120: Specimen 10 flexion angle intact compliance graph at 400N preload, 0.04 mm amplitude

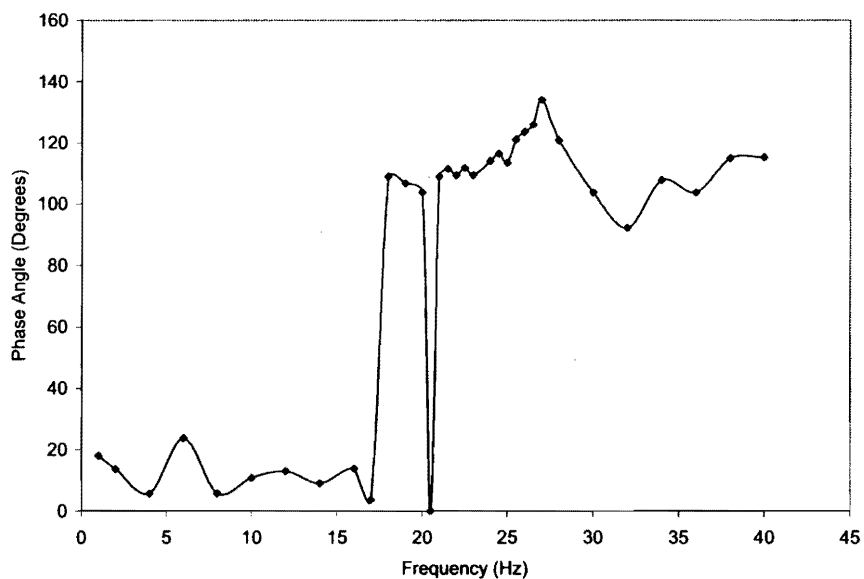


Figure A121: Specimen 10 flexion angle intact phase angle graph at 400N preload, 0.04 mm amplitude

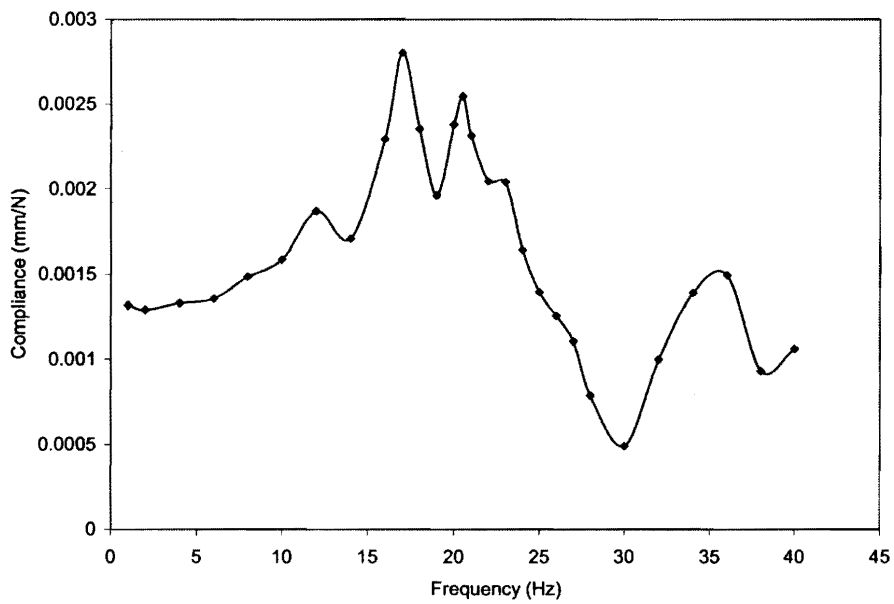


Figure A122: Specimen 10 flexion angle intact compliance graph at 400N preload, 0.06 mm amplitude

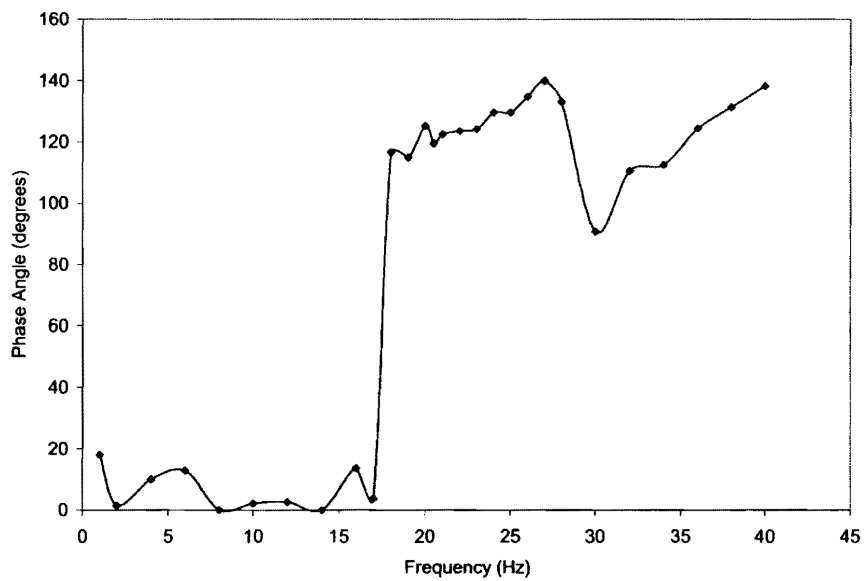


Figure A123: Specimen 10 flexion angle intact phase angle graph at 400N preload, 0.06 mm amplitude

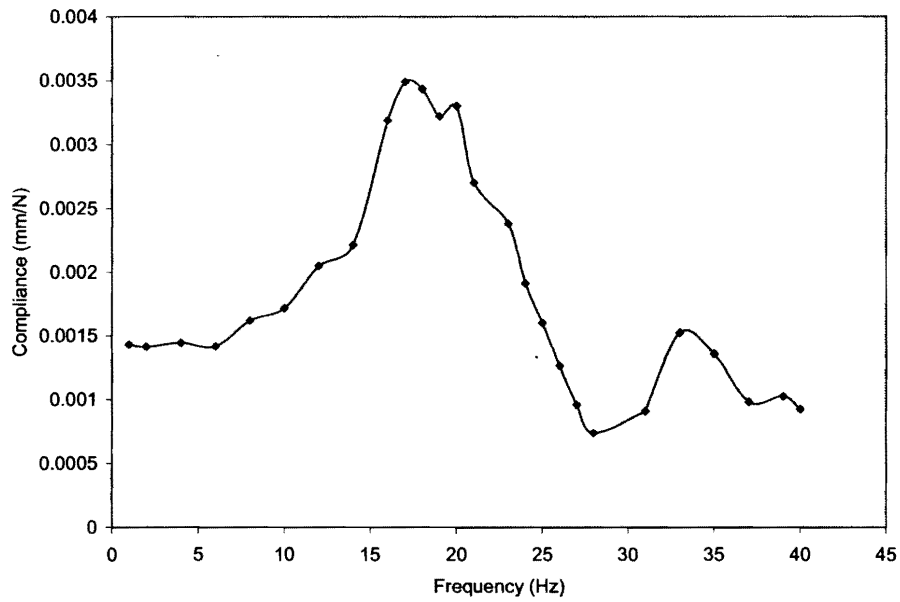


Figure A124: Specimen 10 flexion angle intact compliance graph at 400N preload, 0.08 mm amplitude

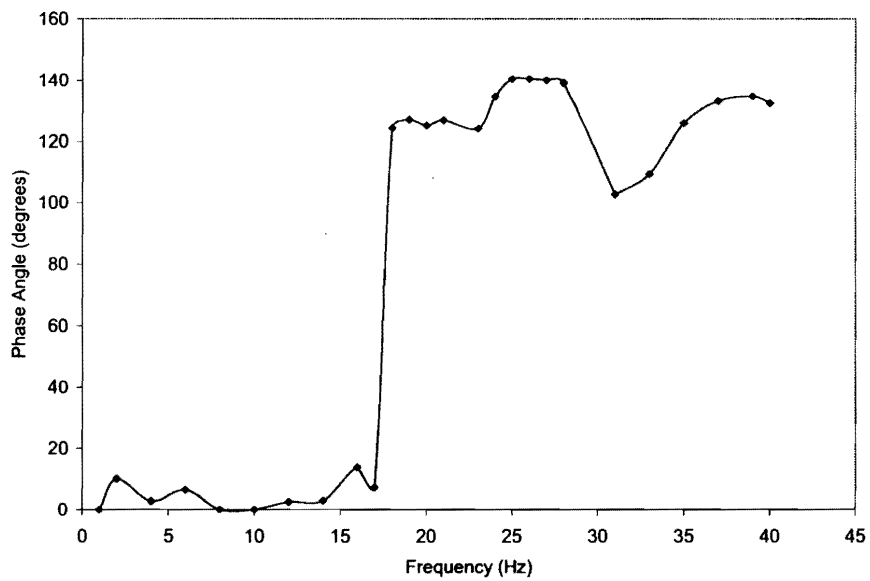


Figure A125: Specimen 10 flexion angle intact phase angle graph at 400N preload, 0.08 mm amplitude



Figure A126: Specimen 10 flexion angle intact compliance graph at 800N preload, 0.04 mm amplitude

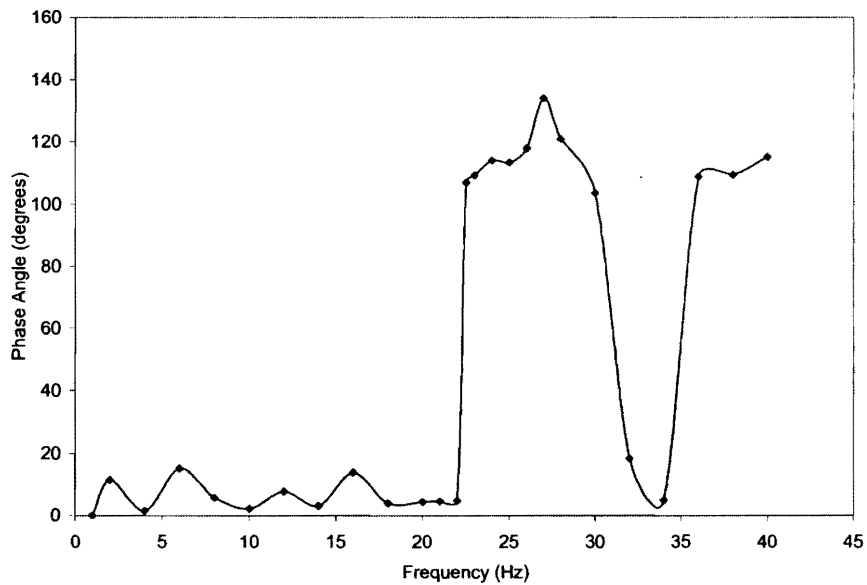


Figure A127: Specimen 10 flexion angle intact phase angle graph at 800N preload, 0.04 mm amplitude

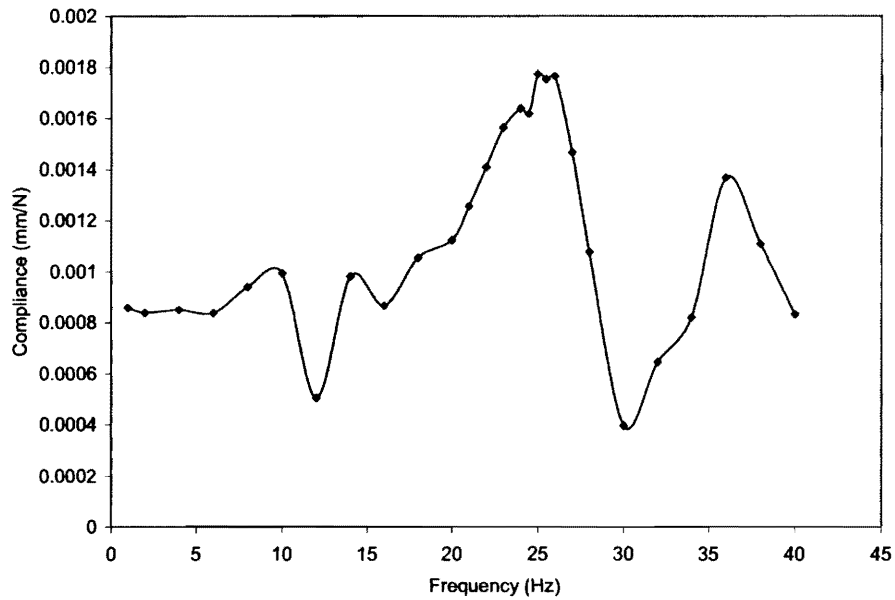


Figure A128: Specimen 10 flexion angle intact compliance graph at 1200N preload, 0.04 mm amplitude

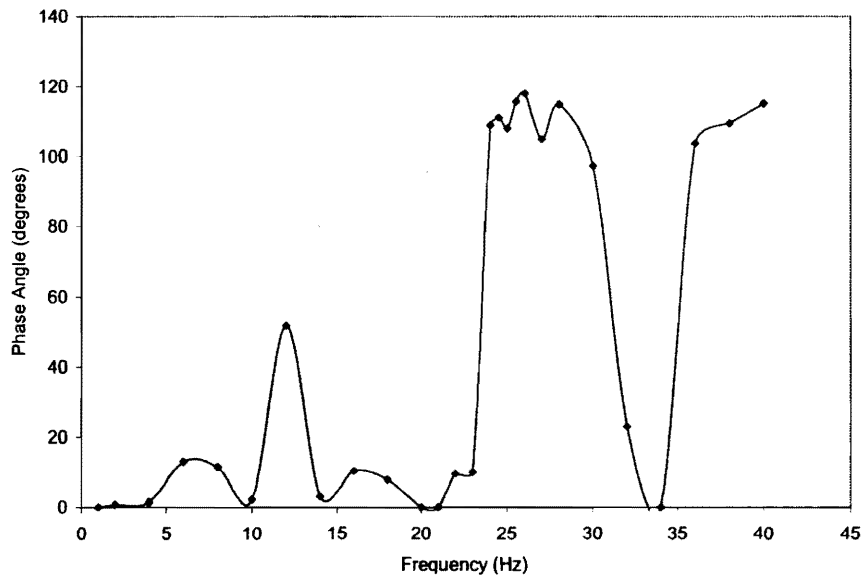


Figure A129: Specimen 10 flexion angle intact phase angle graph at 1200N preload, 0.04 mm amplitude

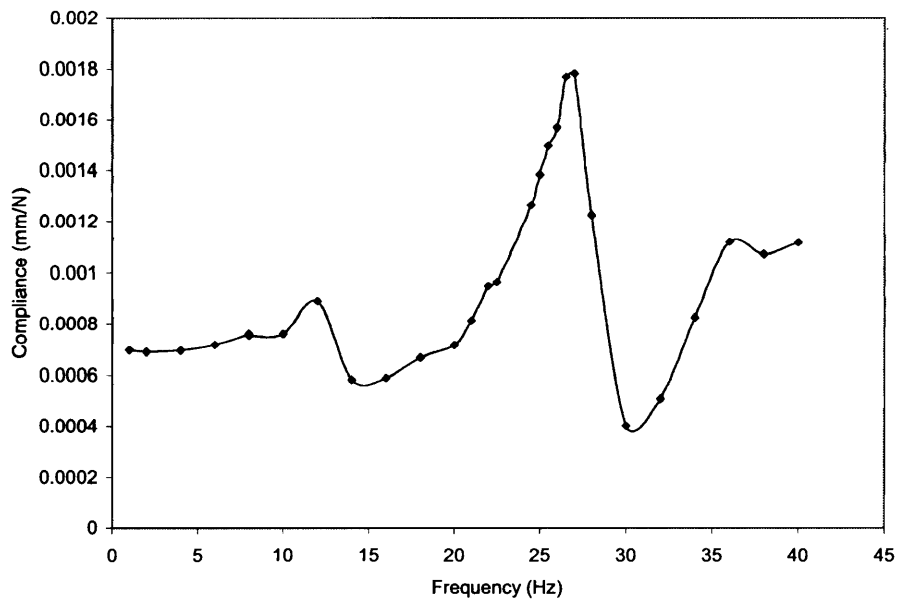


Figure A130: Specimen 10 full extension meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

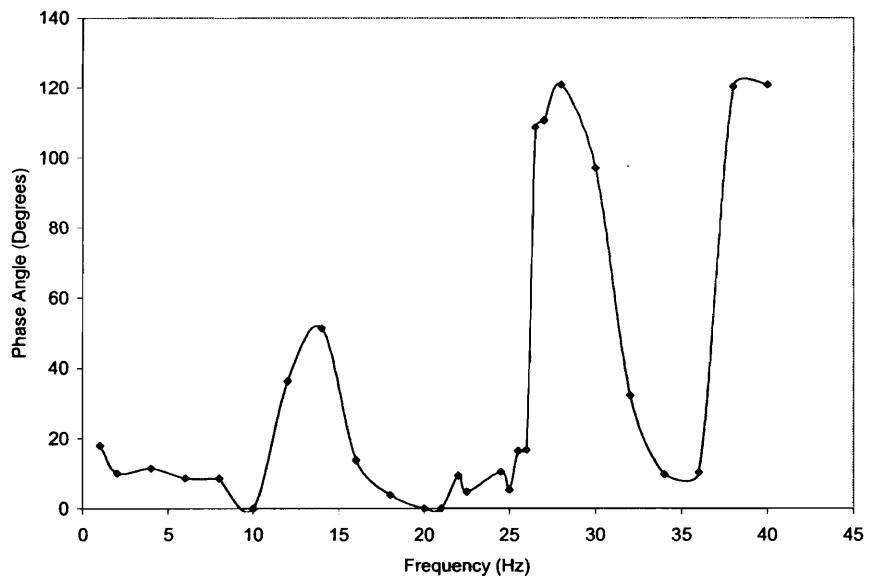


Figure A131: Specimen 10 full extension meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

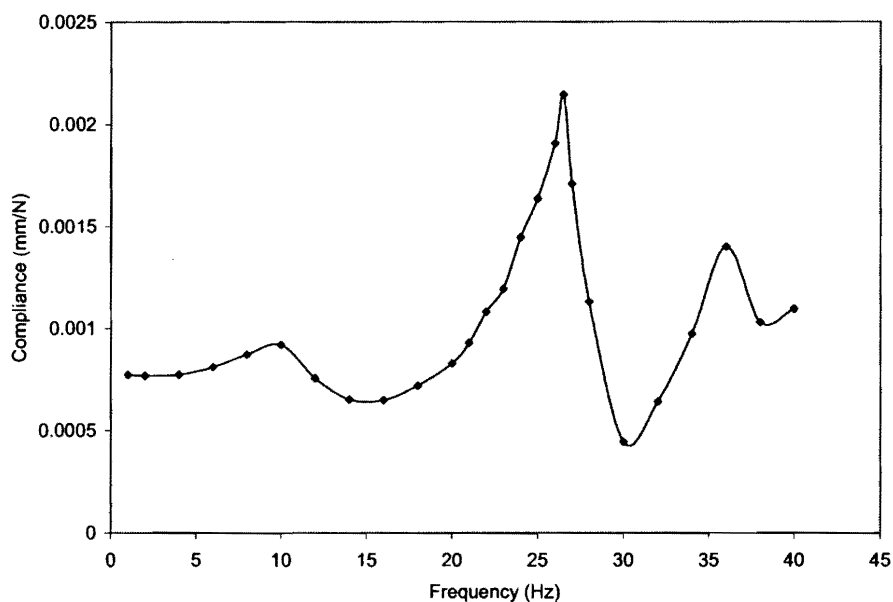


Figure A132: Specimen 10 full extension meniscectomized compliance graph at 400N preload, 0.06 mm amplitude

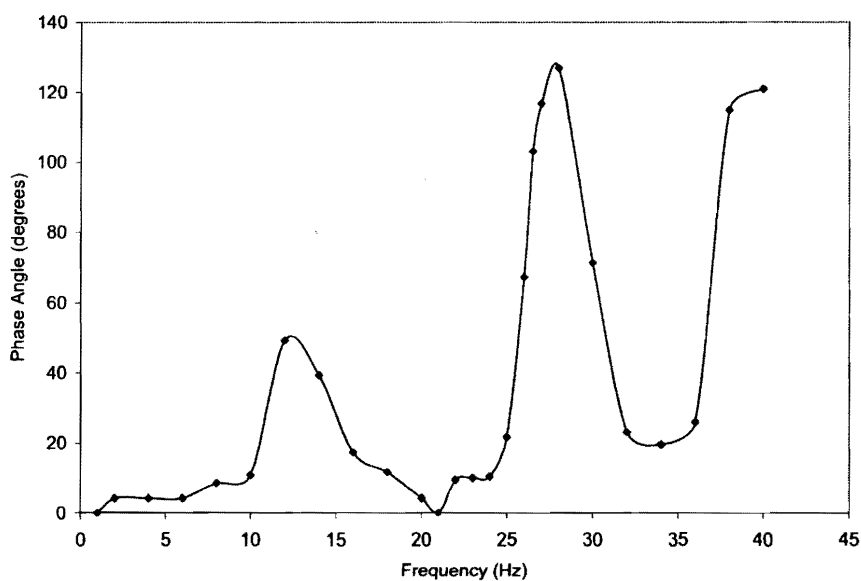


Figure A133: Specimen 10 full extension meniscectomized phase angle graph at 400N preload, 0.06 mm amplitude

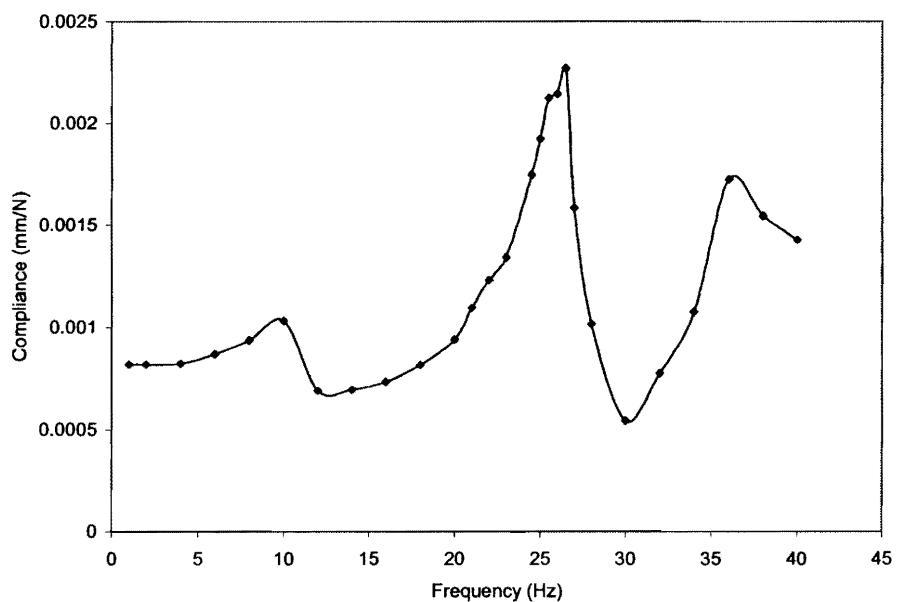


Figure A134: Specimen 10 full extension meniscectomized compliance graph at 400N preload, 0.08 mm amplitude

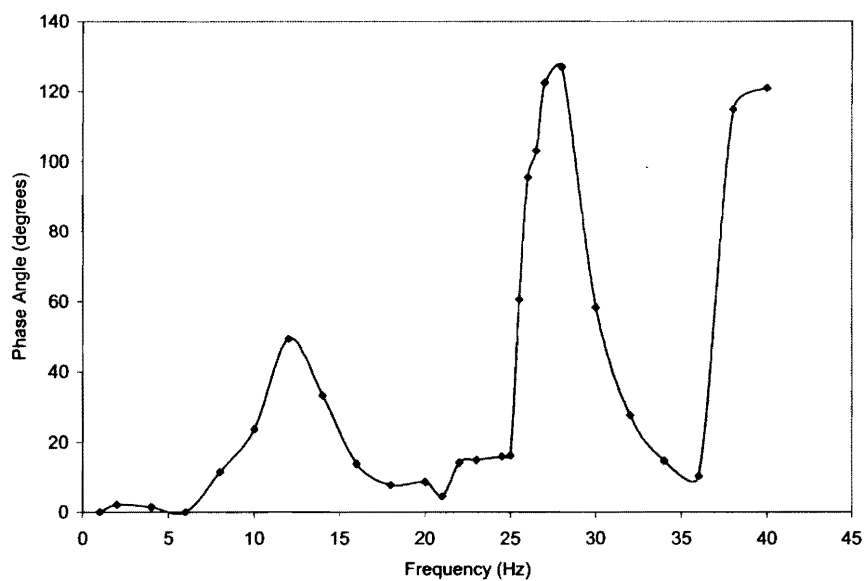


Figure A135: Specimen 10 full extension meniscectomized phase angle graph at 400N preload, 0.08 mm amplitude

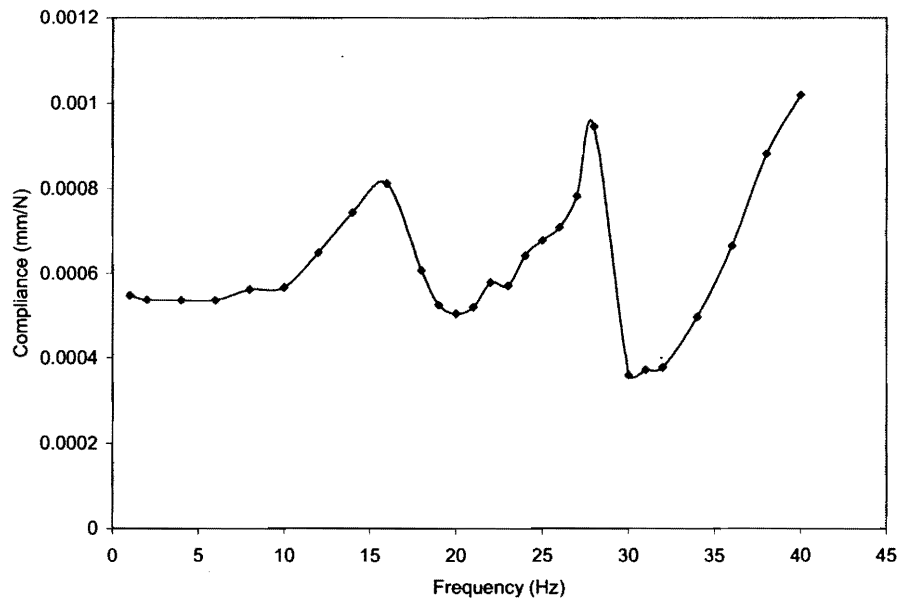


Figure A136: Specimen 10 full extension meniscectomized compliance graph at 800N preload, 0.04 mm amplitude

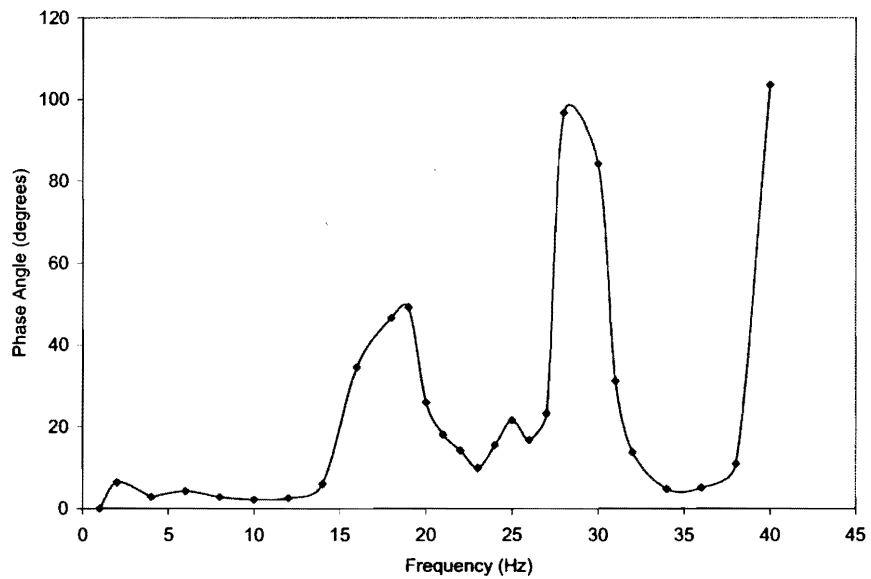


Figure A137: Specimen 10 full extension meniscectomized phase angle graph at 800N preload, 0.04 mm amplitude

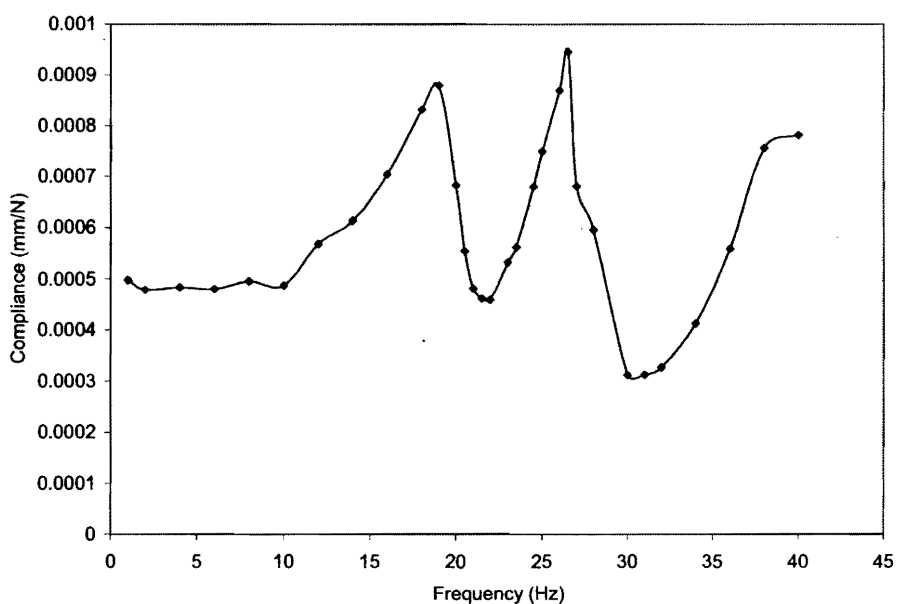


Figure A138: Specimen 10 full extension meniscectomized compliance graph at 1200N preload, 0.04 mm amplitude

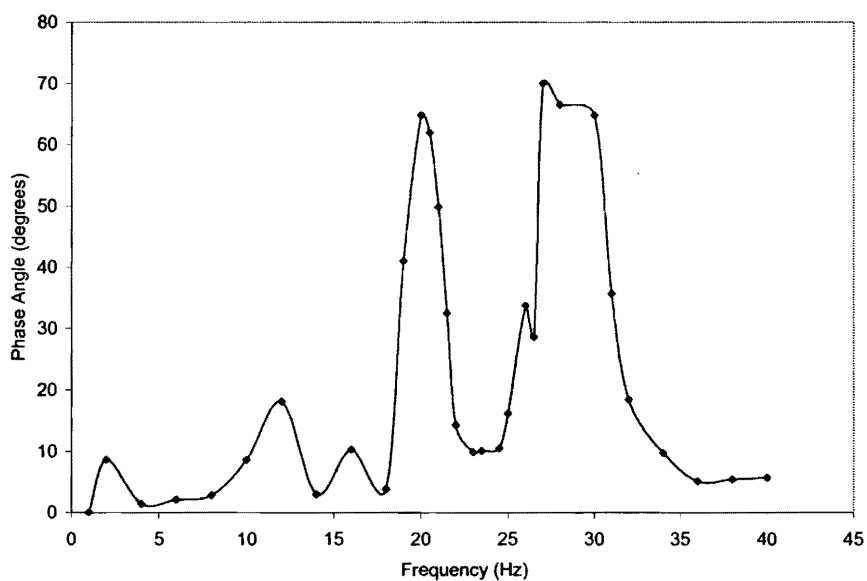


Figure 139: Specimen 10 full extension meniscectomized phase angle graph at 1200N preload, 0.04 mm amplitude

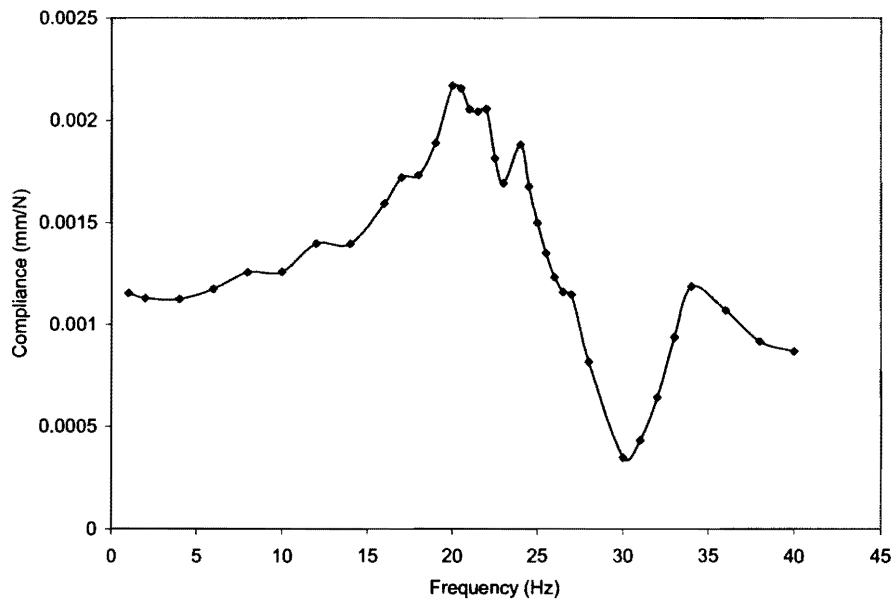


Figure A140: Specimen 10 flexion angle meniscectomized compliance graph at 400N preload, 0.04 mm amplitude

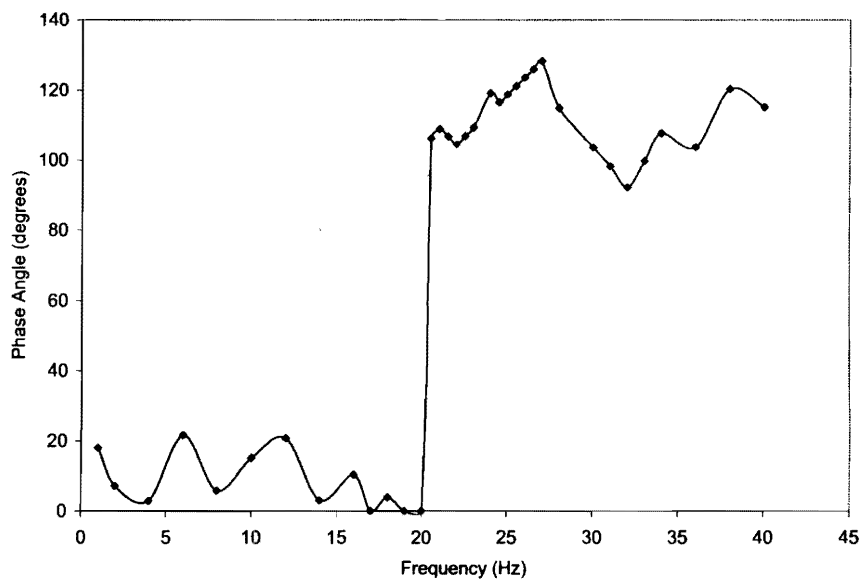


Figure A141: Specimen 10 flexion angle meniscectomized phase angle graph at 400N preload, 0.04 mm amplitude

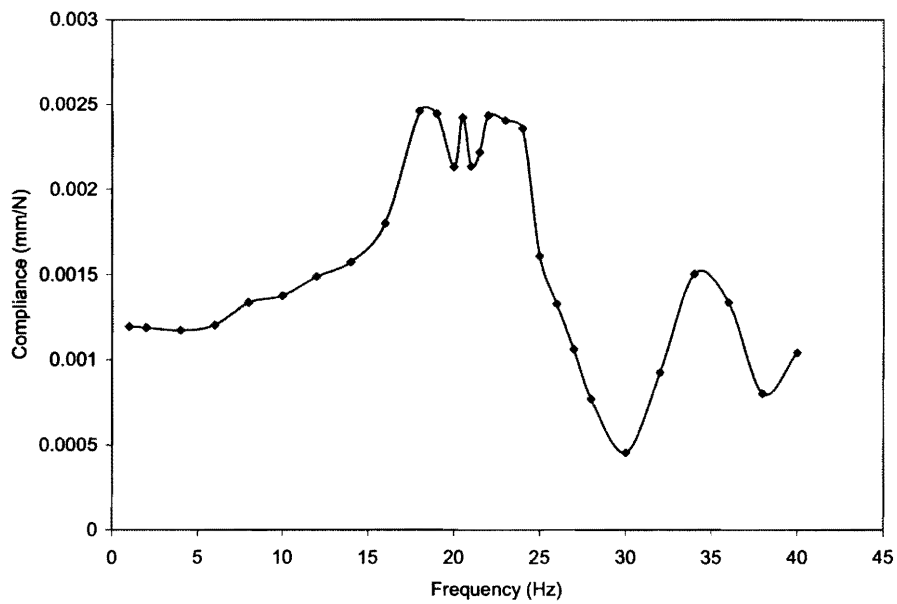


Figure A142: Specimen 10 flexion angle meniscectomized compliance graph at 400N preload, 0.06 mm amplitude

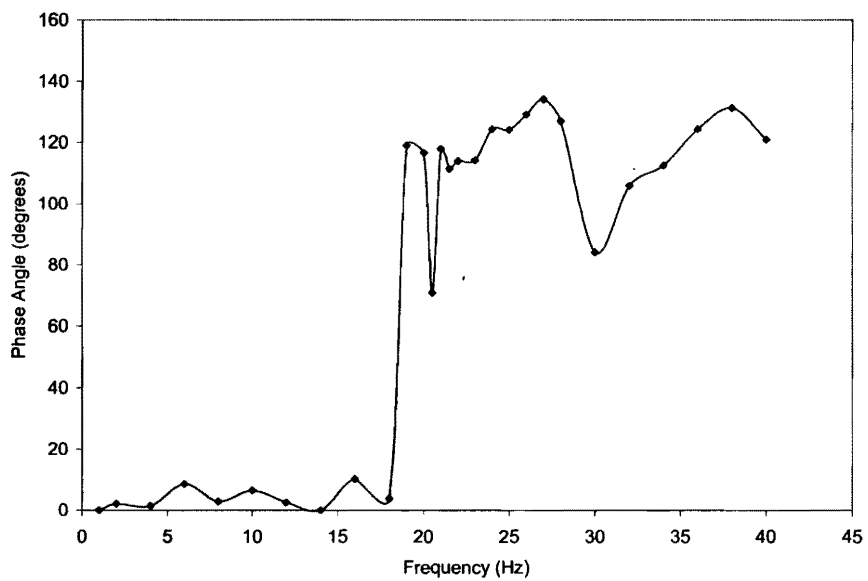


Figure A143: Specimen 10 flexion angle meniscectomized phase angle graph at 400N preload, 0.06 mm amplitude

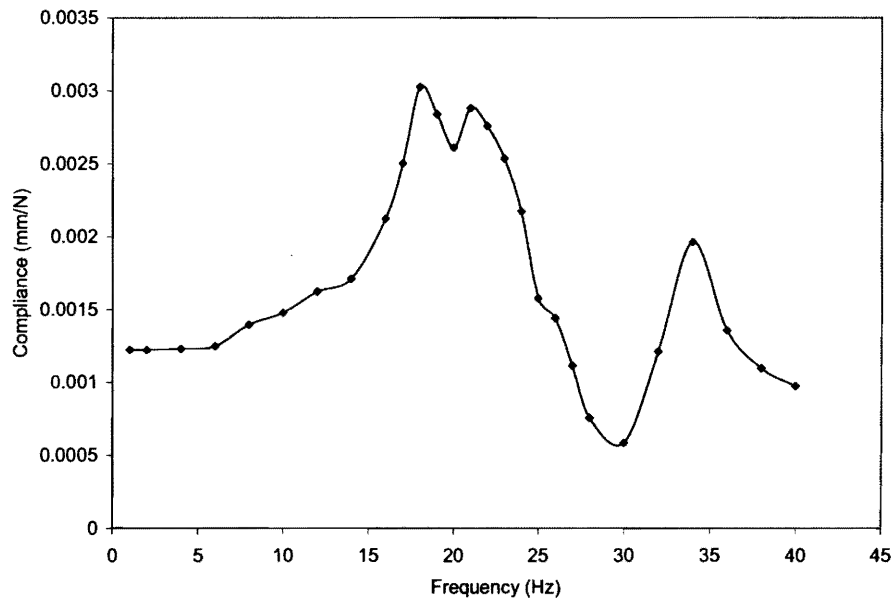


Figure A144: Specimen 10 flexion angle meniscectomized compliance graph at 400N preload, 0.08 mm amplitude

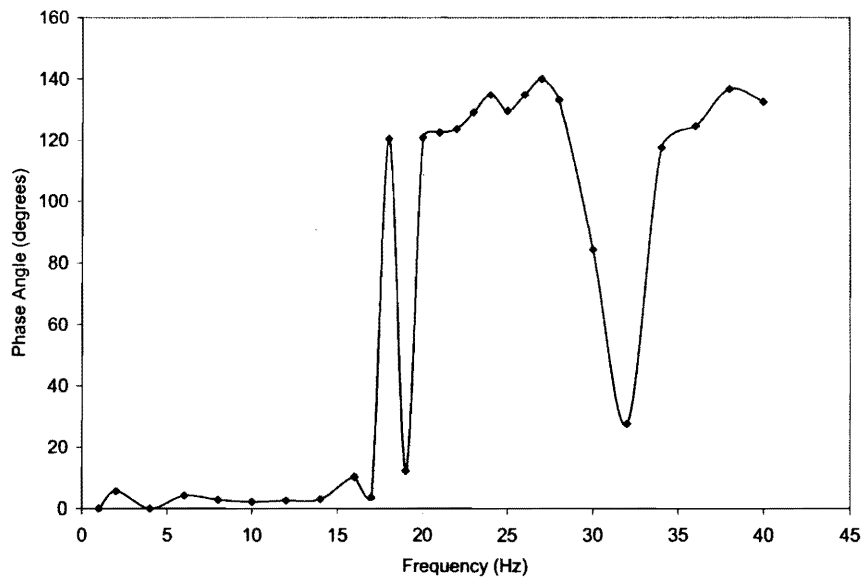


Figure A145: Specimen 10 flexion angle meniscectomized phase angle graph at 400N preload, 0.08 mm amplitude

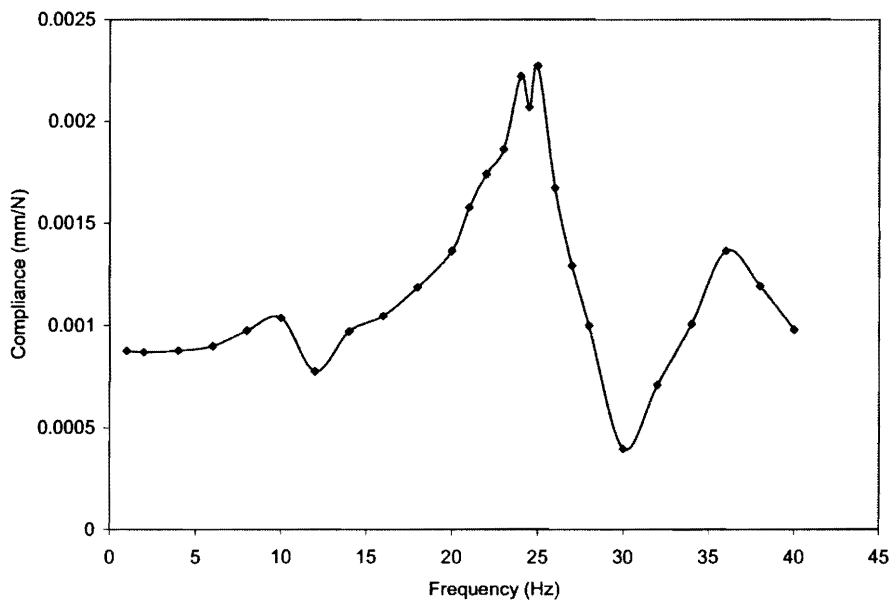


Figure A146: Specimen 10 flexion angle meniscectomized compliance graph at 800N preload, 0.04 mm amplitude

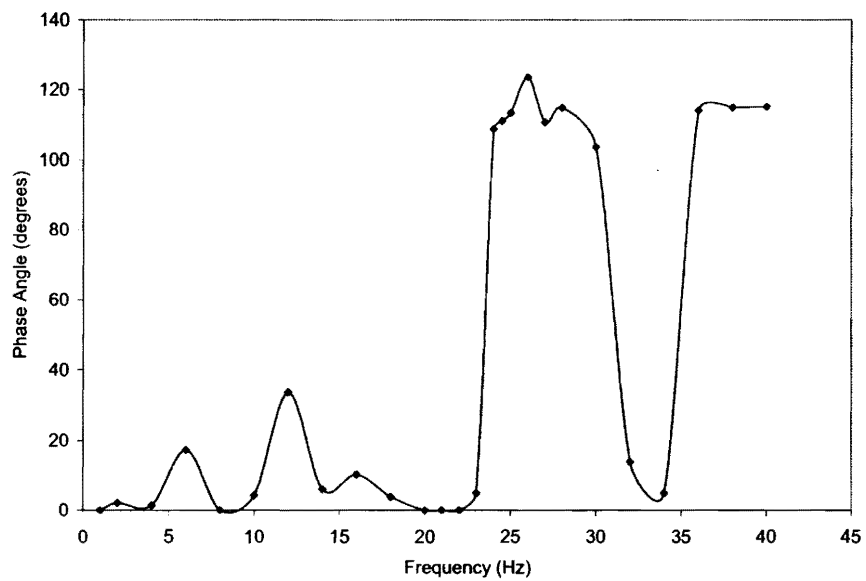


Figure A147: Specimen 10 flexion angle meniscectomized phase angle graph at 800N preload, 0.04 mm amplitude

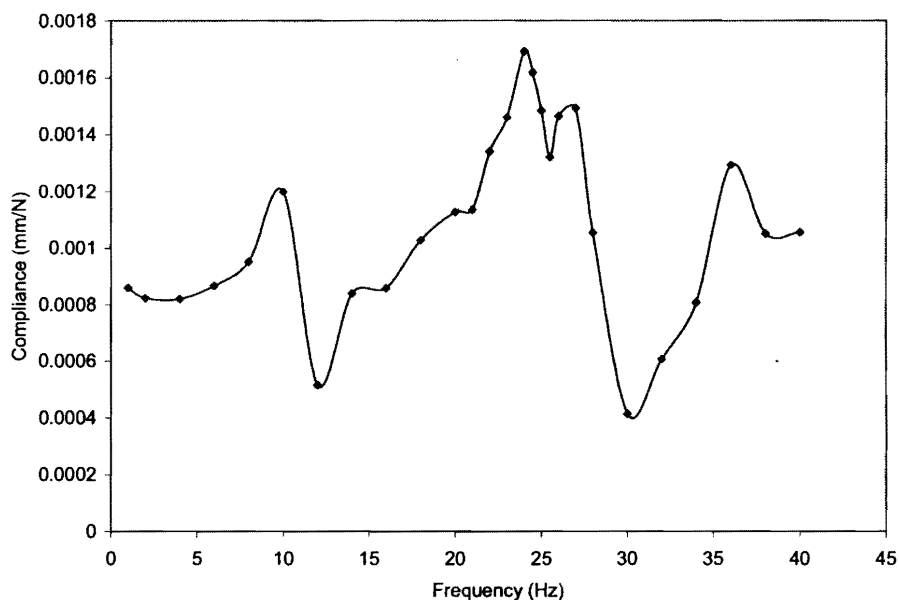


Figure A148: Specimen 10 flexion angle meniscectomized compliance graph at 1200N preload, 0.04 mm amplitude

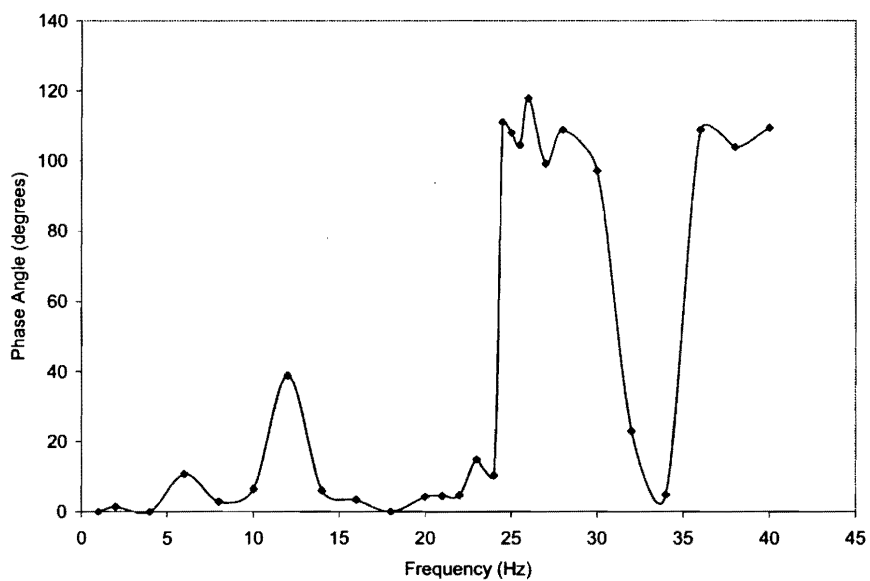


Figure A149: Specimen 10 flexion angle meniscectomized phase angle graph at 1200N preload, 0.04 mm amplitude

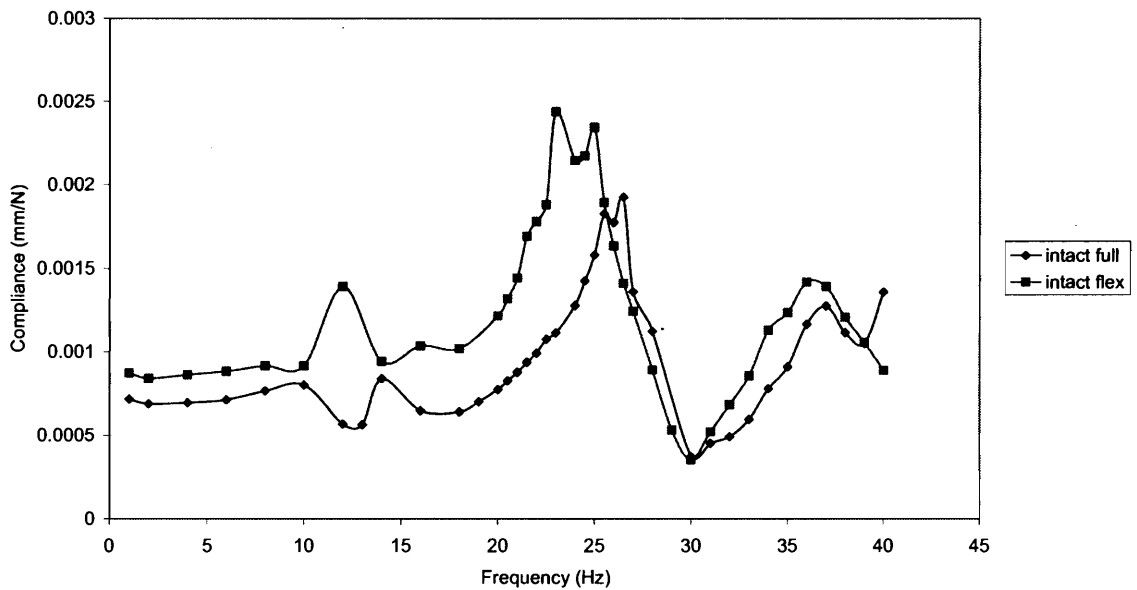


Figure A150: Specimen 7 comparison of intact full extension to flexion angle for 400 N preload, 0.04 mm amplitude

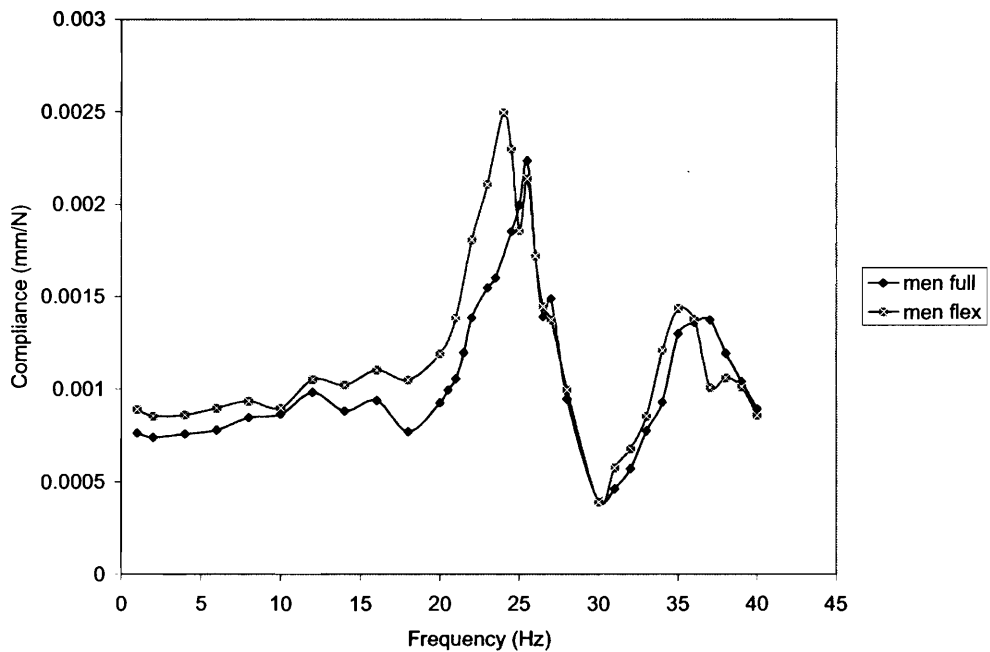


Figure A151: Specimen 7 comparison of meniscectomized full extension to flexion angle for 400 N preload, 0.04 mm amplitude

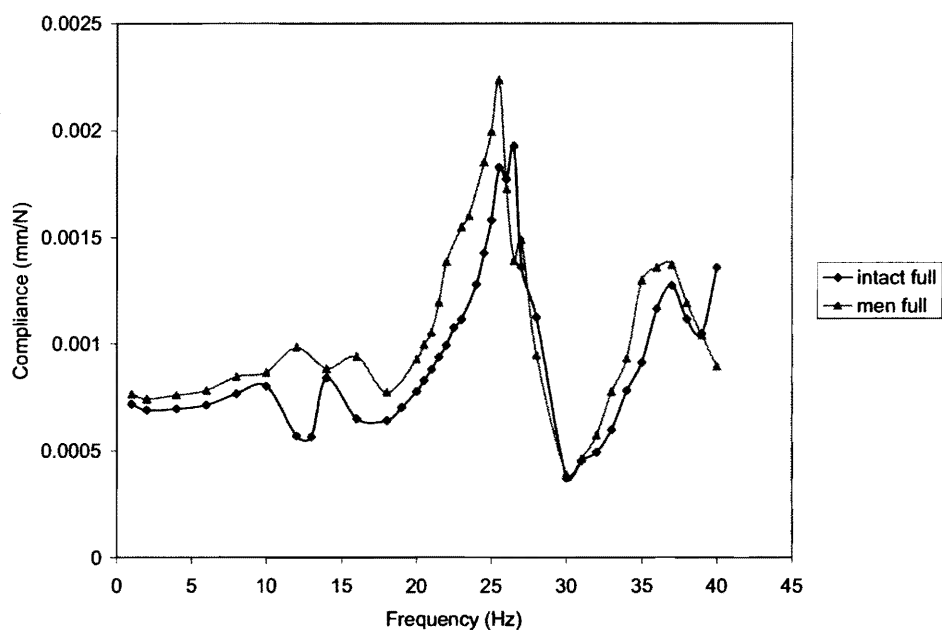


Figure A152: Specimen 7 comparison of intact to meniscectomized full extension for 400 N preload, 0.04 mm amplitude

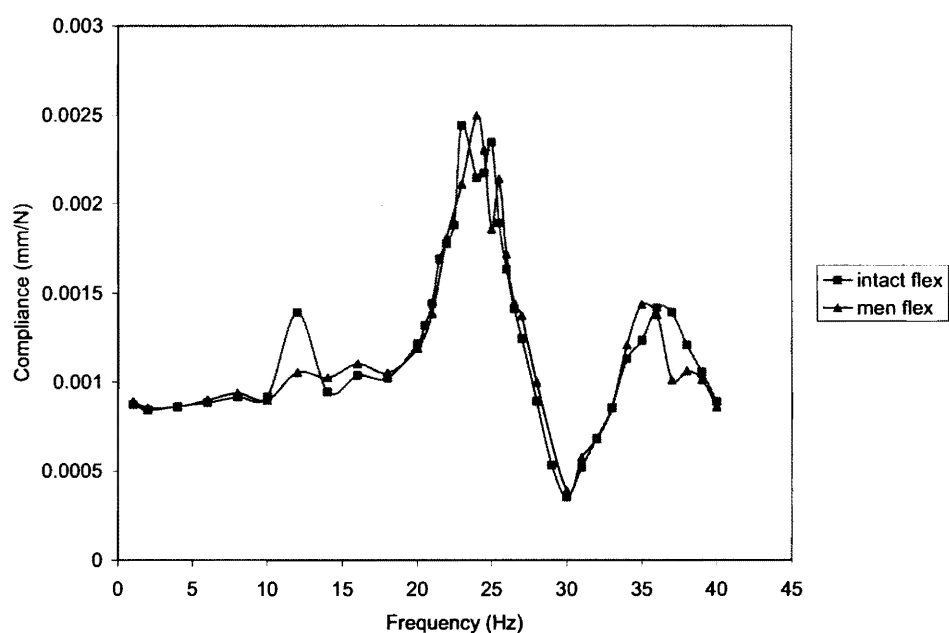


Figure A153: Specimen 7 comparison of intact to meniscectomized flexion angle for 400 N preload, 0.04 mm amplitude

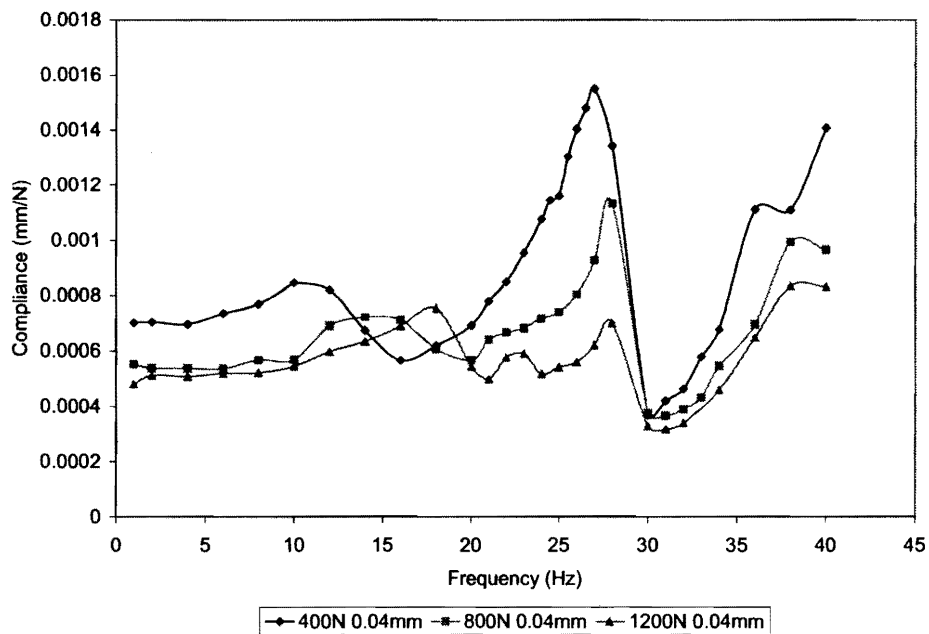


Figure A154: Specimen 10 comparison of intact full extension compliance curves for all preloads, 0.04 mm amplitude

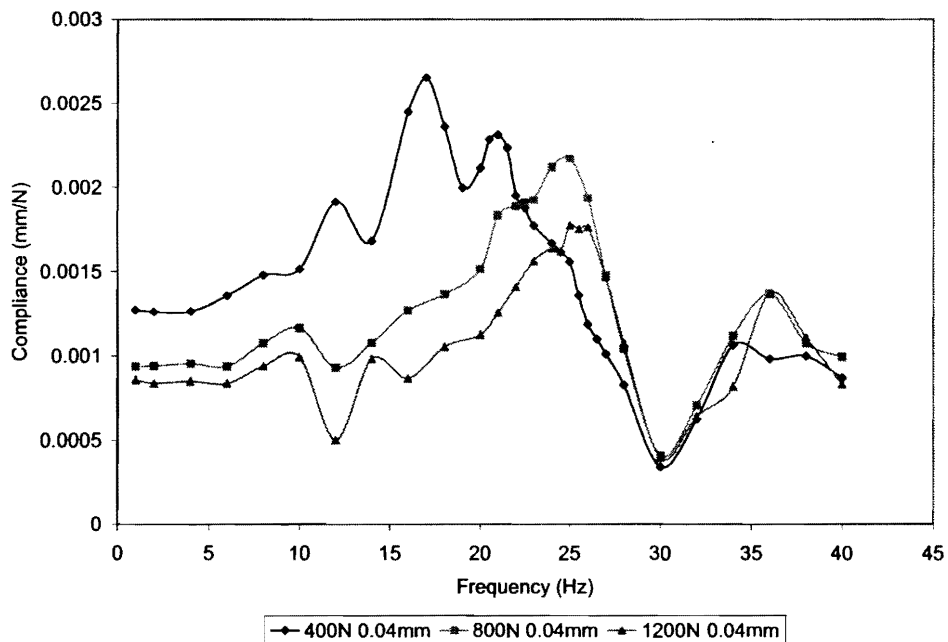


Figure A155: Specimen 10 comparison of intact flexion angle compliance curves for all preloads, 0.04 mm amplitude

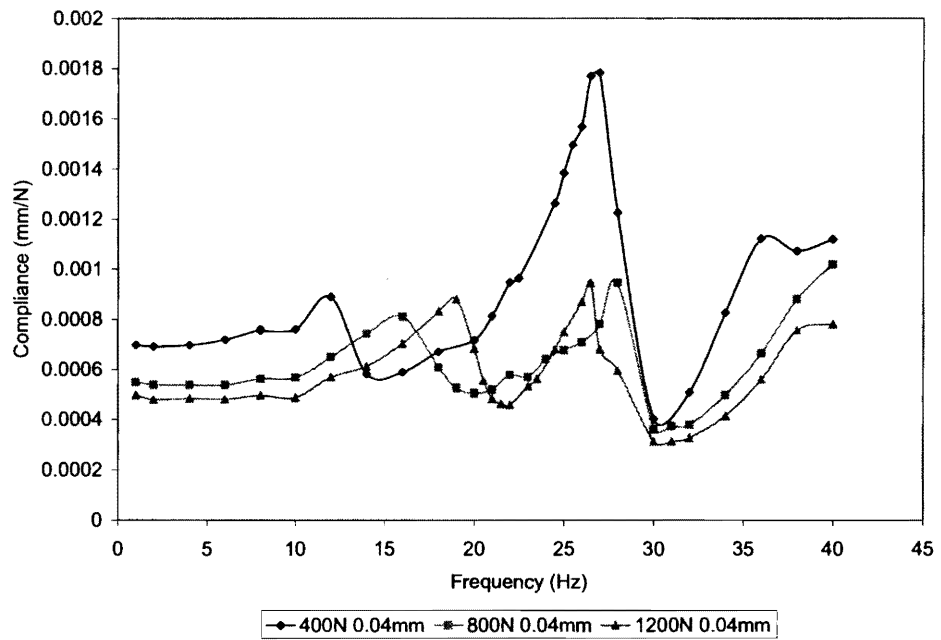


Figure A156: Specimen 10 comparison of meniscectomized full extension compliance curves for all preloads, 0.04 mm amplitude

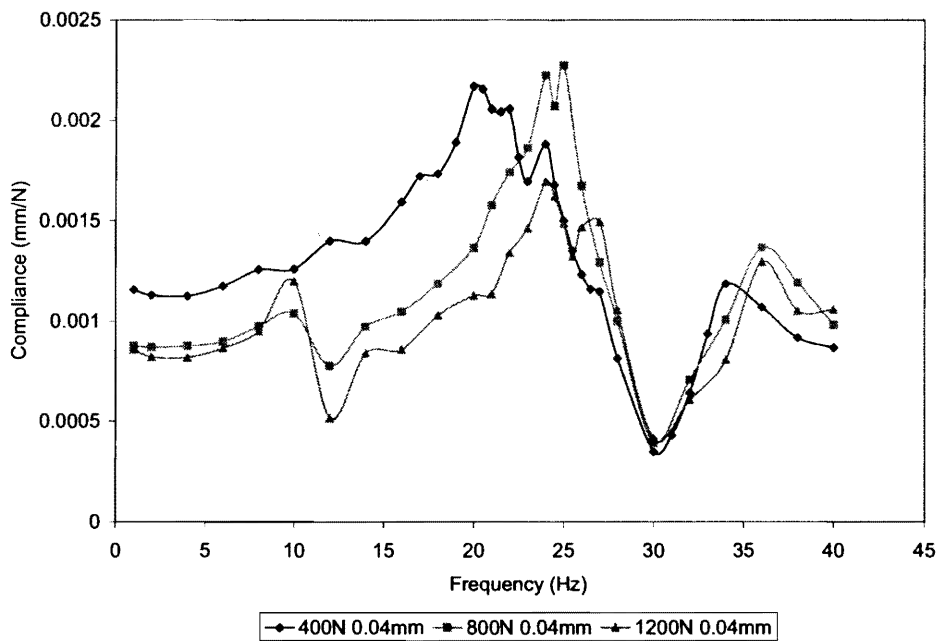


Figure A157: Specimen 10 comparison of meniscectomized flexion angle compliance curves for all preloads, 0.04 mm amplitude

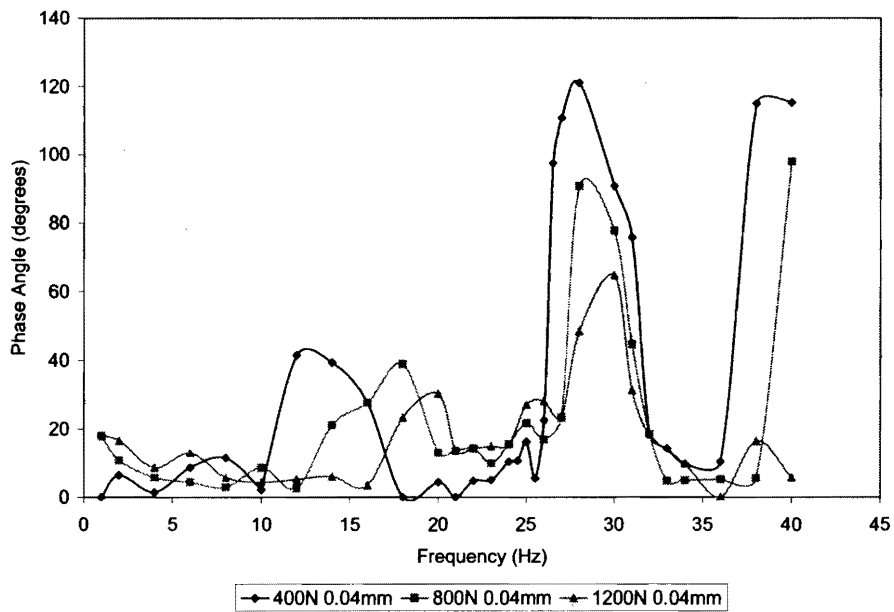


Figure A158: Specimen 10 comparison of intact full extension phase angle curves for all preloads, 0.04 mm amplitude

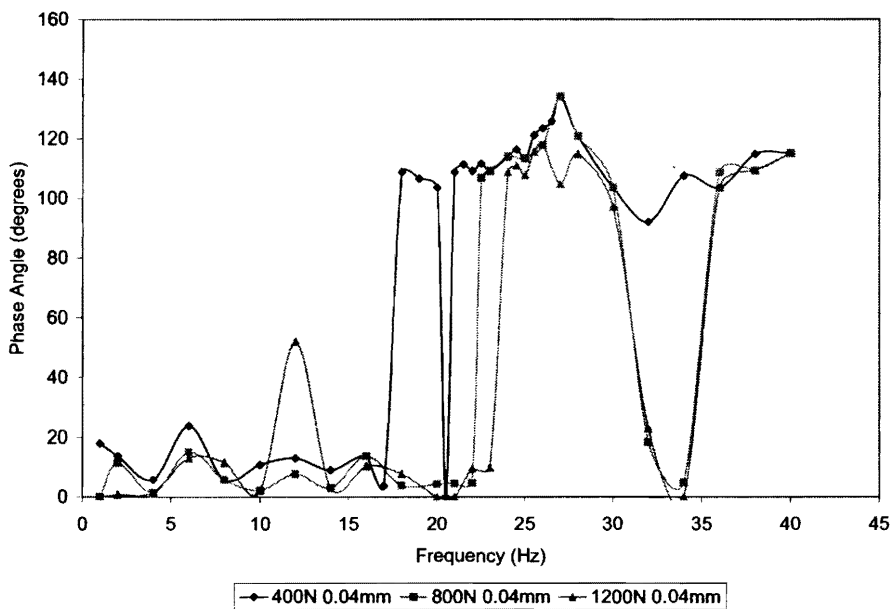


Figure A159: Specimen 10 comparison of intact flexion angle phase angle curves for all preloads, 0.04 mm amplitude

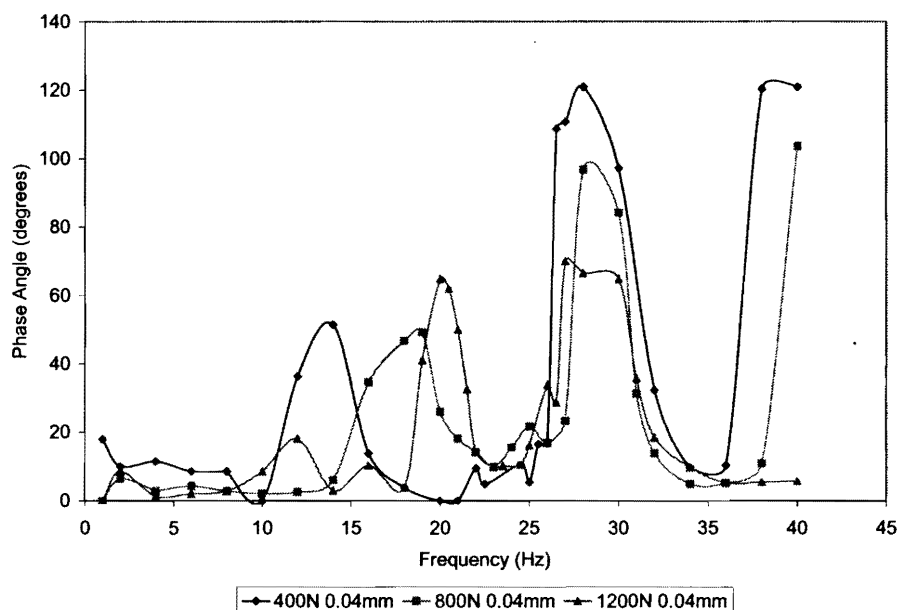


Figure A160: Specimen 10 comparison of meniscectomized full extension phase angle curves for all preloads, 0.04 mm amplitude

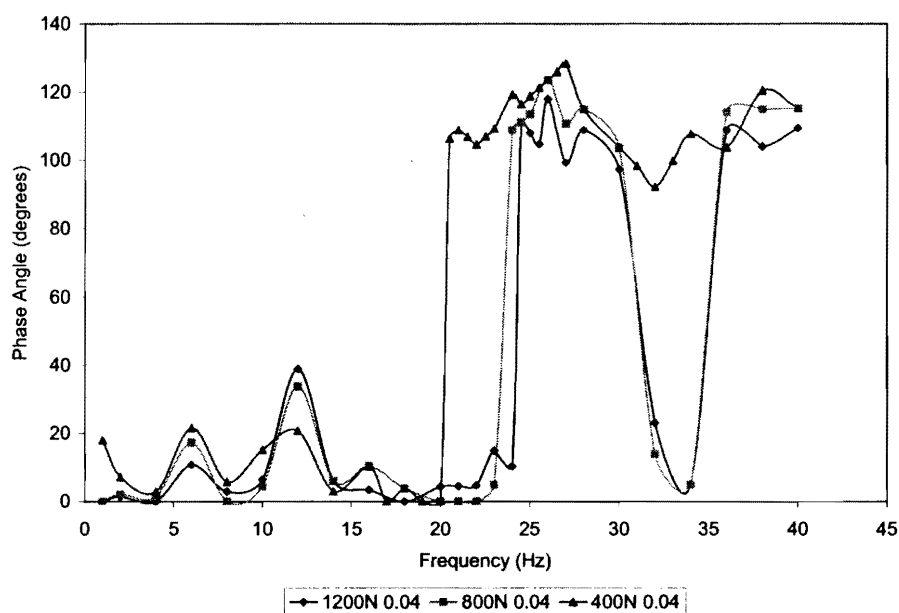


Figure A161: Specimen 10 comparison of meniscectomized flexion angle phase angle curves for all preloads, 0.04 mm amplitude

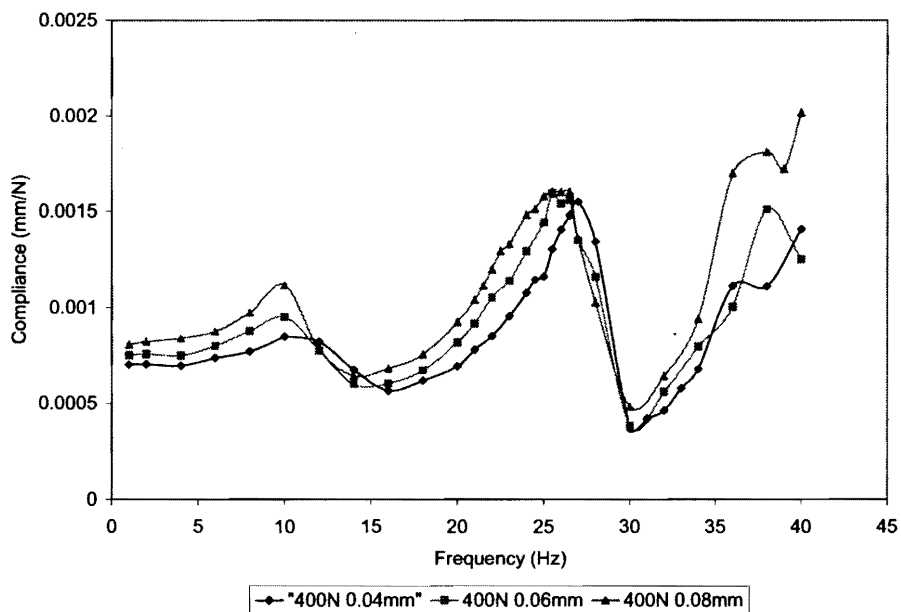


Figure A162: Specimen 10 comparison of intact full extension compliance curves for all amplitudes, 400N preload

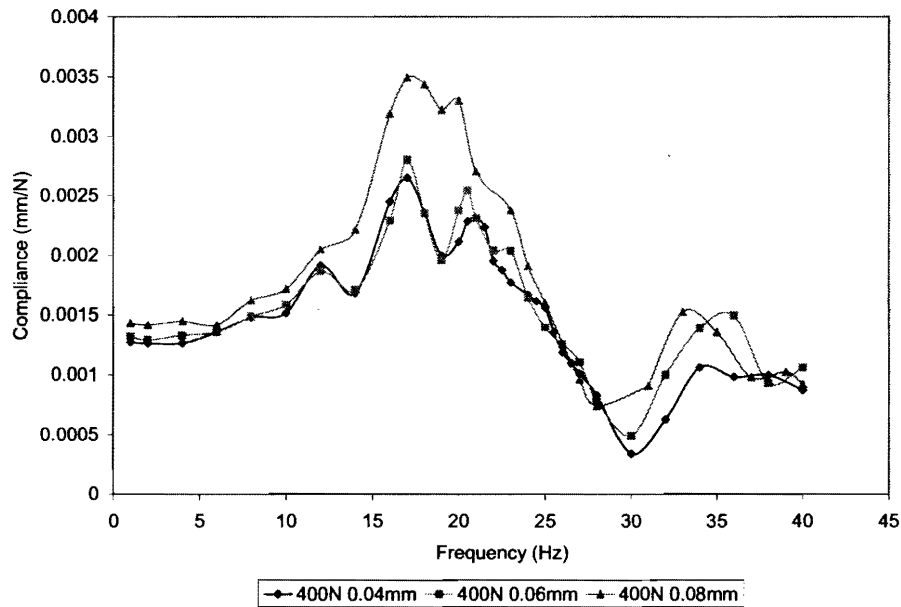


Figure A163: Specimen 10 comparison of intact flexion angle compliance curves for all amplitudes, 400N preload

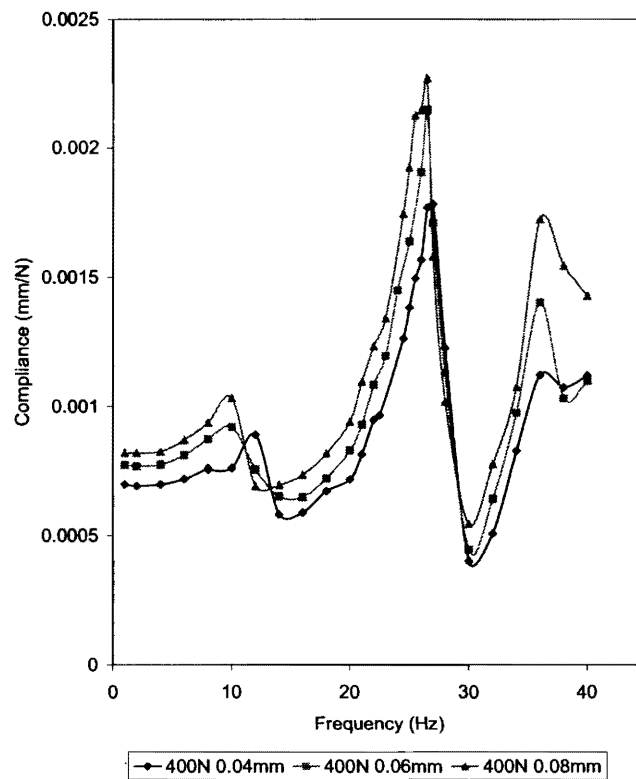


Figure A164: Specimen 10 comparison of meniscectomized full extension compliance curves for all amplitudes, 400N preload

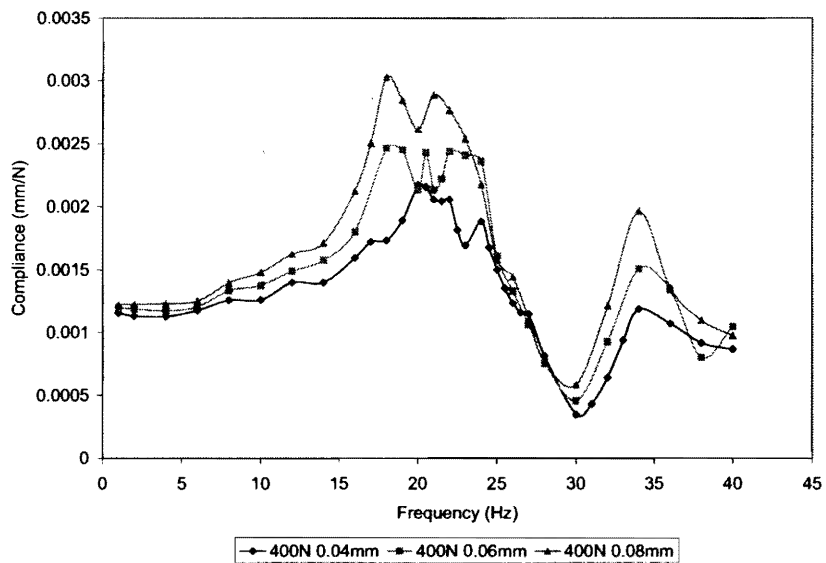


Figure A165: Specimen 10 comparison of meniscectomized flexion angle compliance curves for all amplitudes, 400N preload

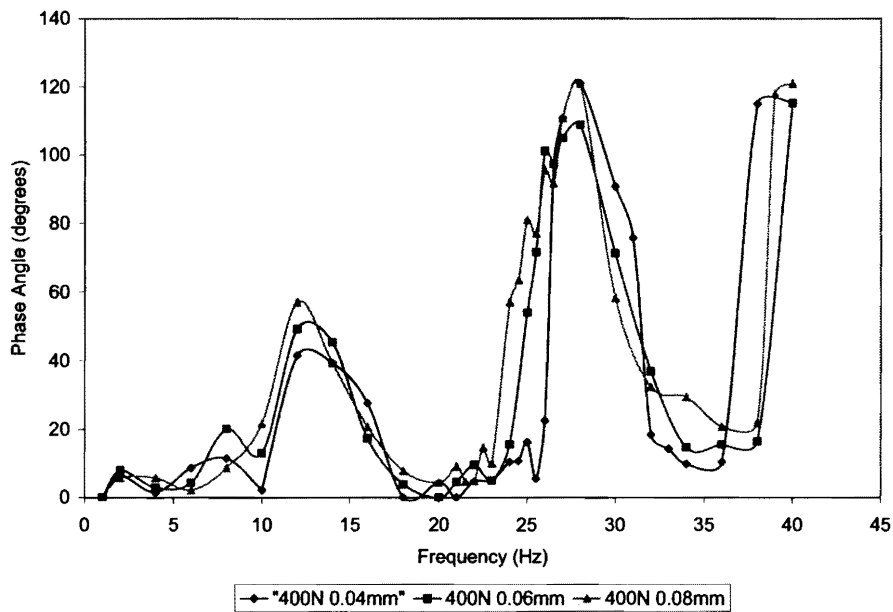


Figure A166: Specimen 10 comparison of intact full extension phase angle curves for all amplitudes, 400N preload

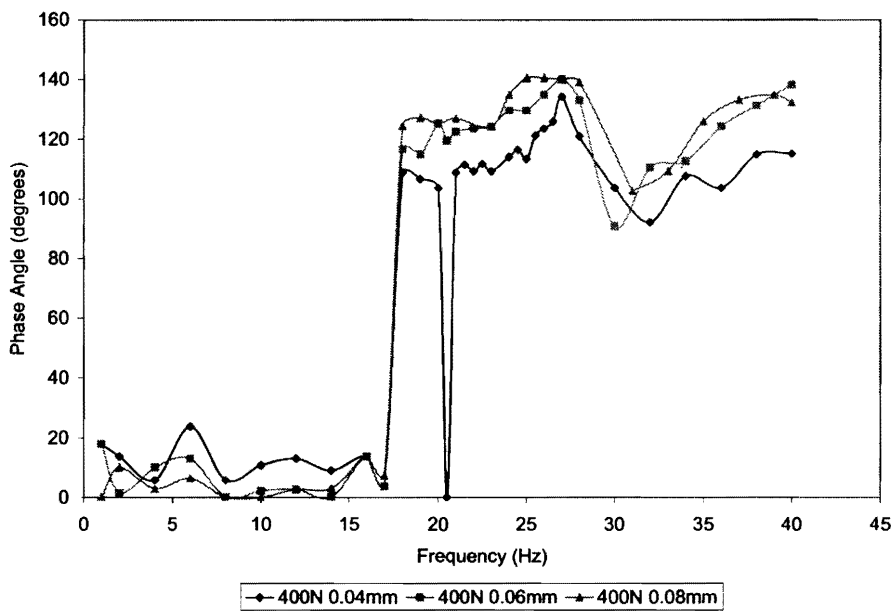


Figure A167: Specimen 10 comparison of intact flexion angle phase angle curves for all amplitudes, 400N preload

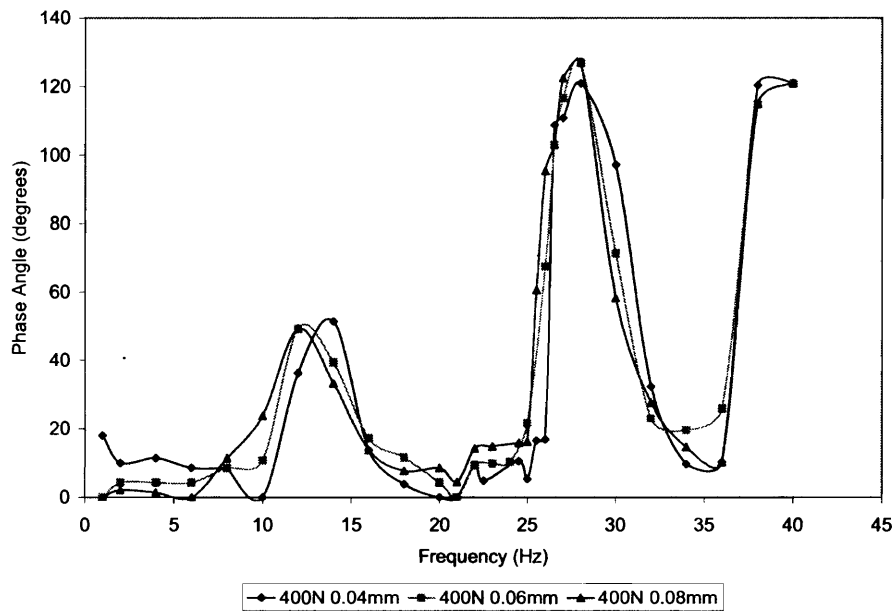


Figure A168: Specimen 10 comparison of meniscectomized full extension phase angle curves for all amplitudes, 400N preload

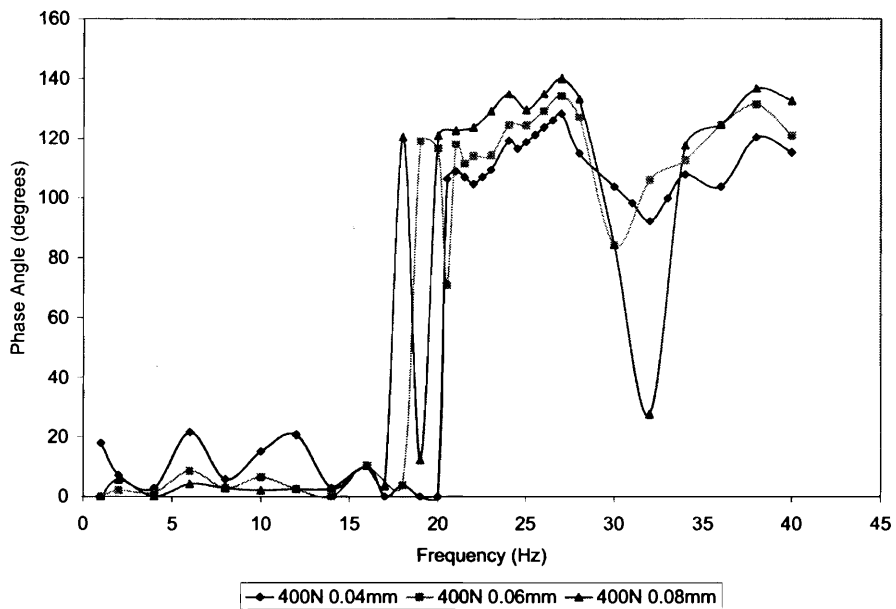


Figure A169: Specimen 10 comparison of meniscectomized flexion angle phase angle curves for all amplitudes, 400N preload

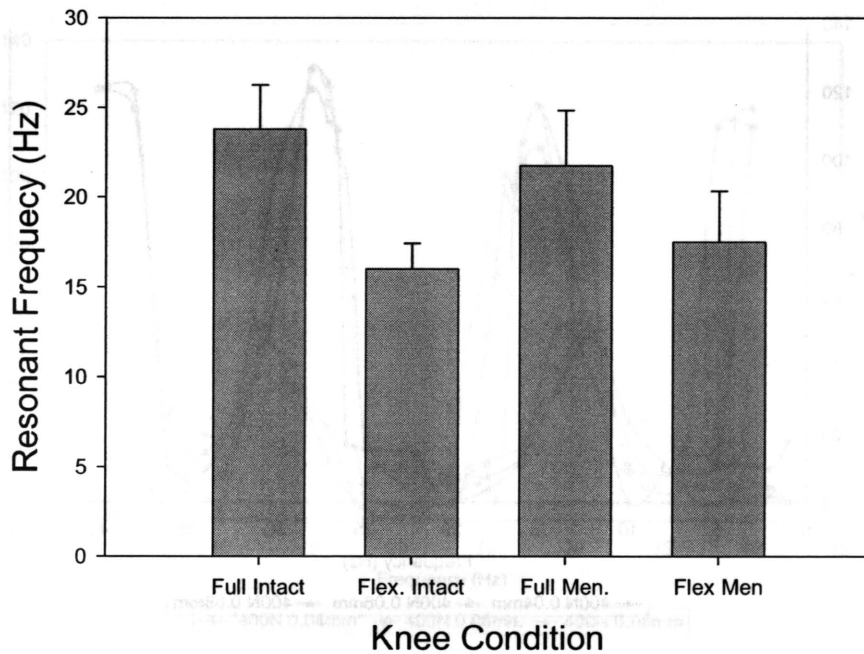


Figure A170: Average resonant frequency for female specimens with 400 N preload and 0.04 mm amplitude

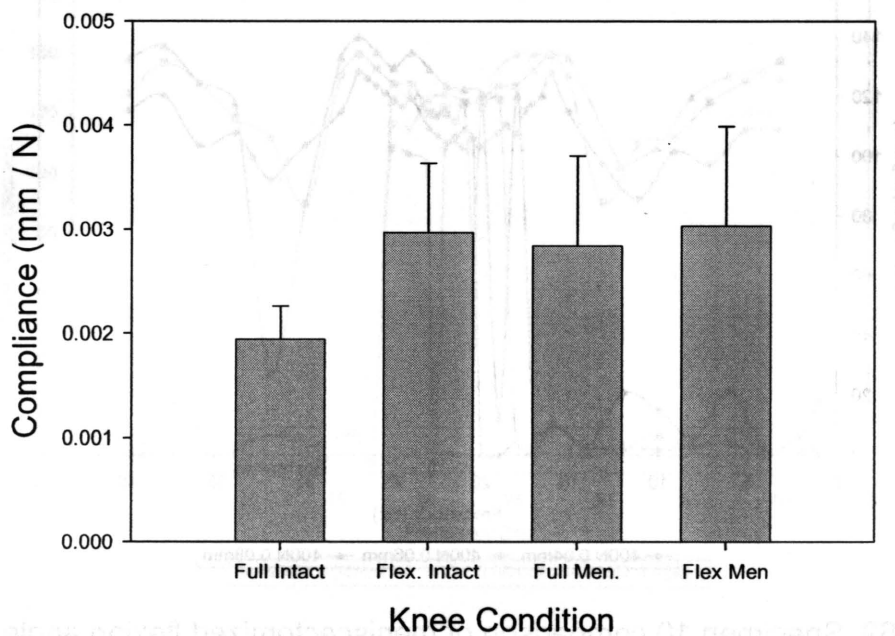


Figure A171: Average compliance at resonance for female specimens with 400 N preload and 0.04 mm amplitude

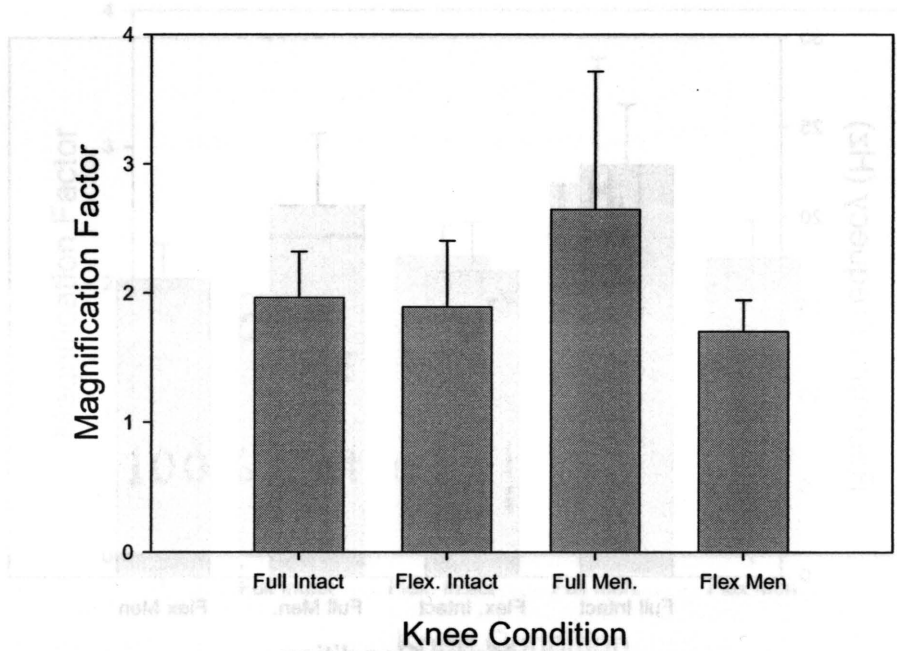


Figure A172: Average magnification factor for female specimens with 400 N preload and 0.04 mm amplitude

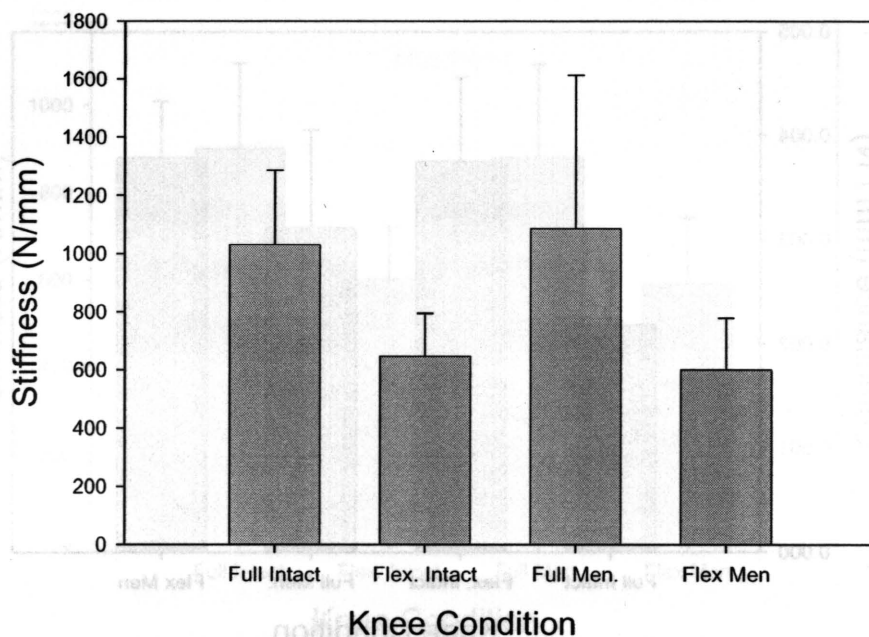


Figure A173: Average stiffness for female specimens with 400 N preload and 0.04 mm amplitude

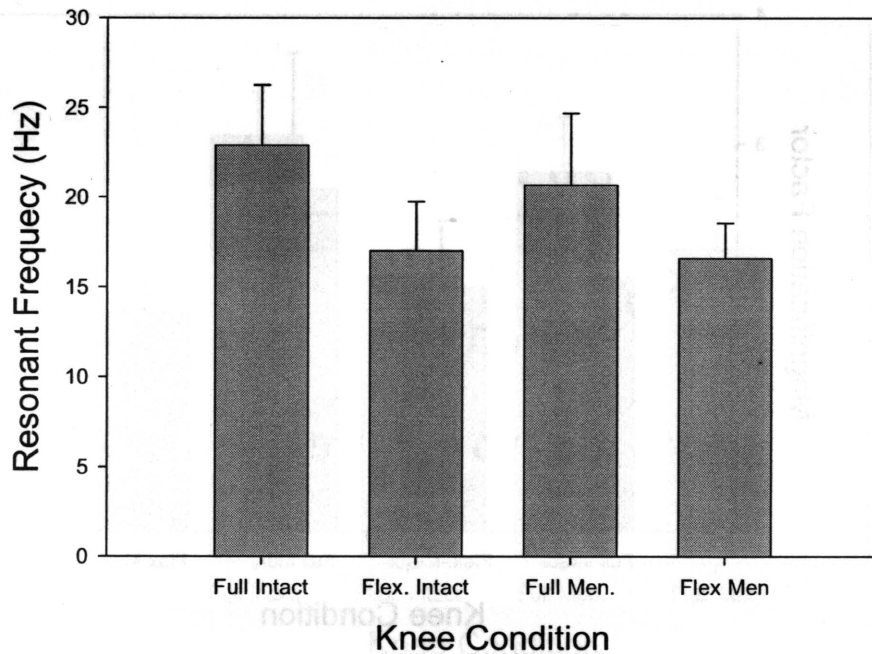


Figure A174: Average resonant frequency for female specimens with 400 N preload and 0.08 mm amplitude

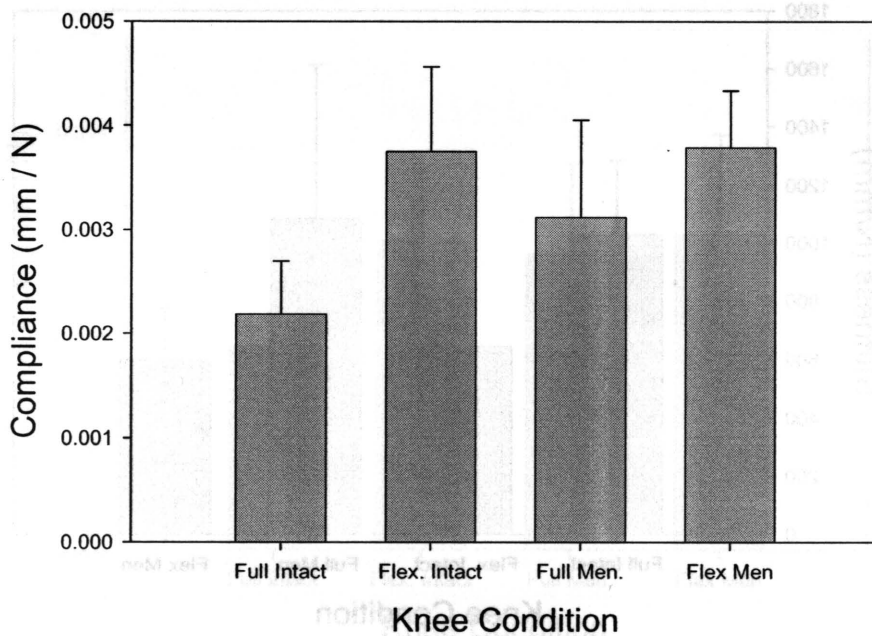


Figure A175: Average compliance at resonance for female specimens with 400 N preload and 0.08 mm amplitude

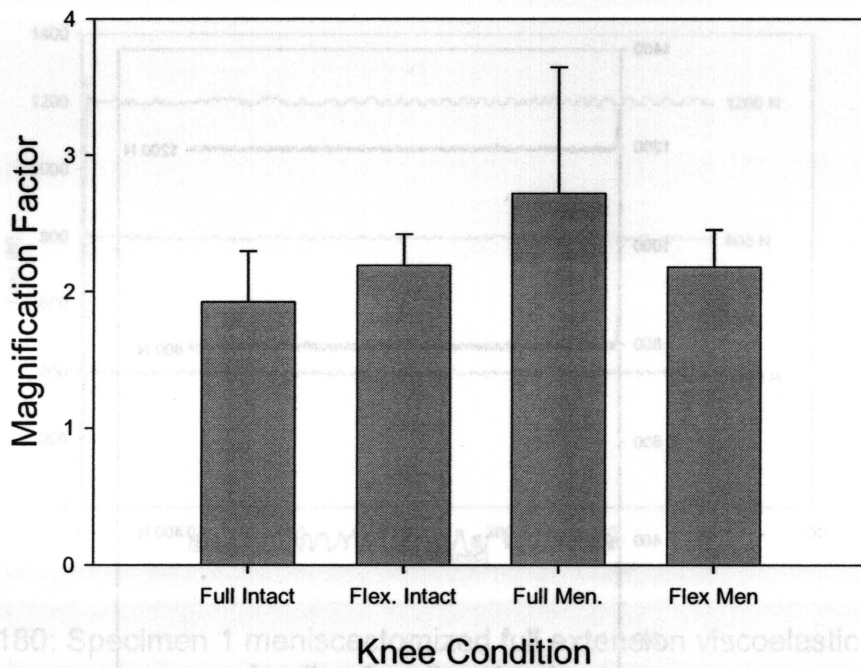


Figure A176: Average magnification factor for female specimens with 400 N preload and 0.08 mm amplitude

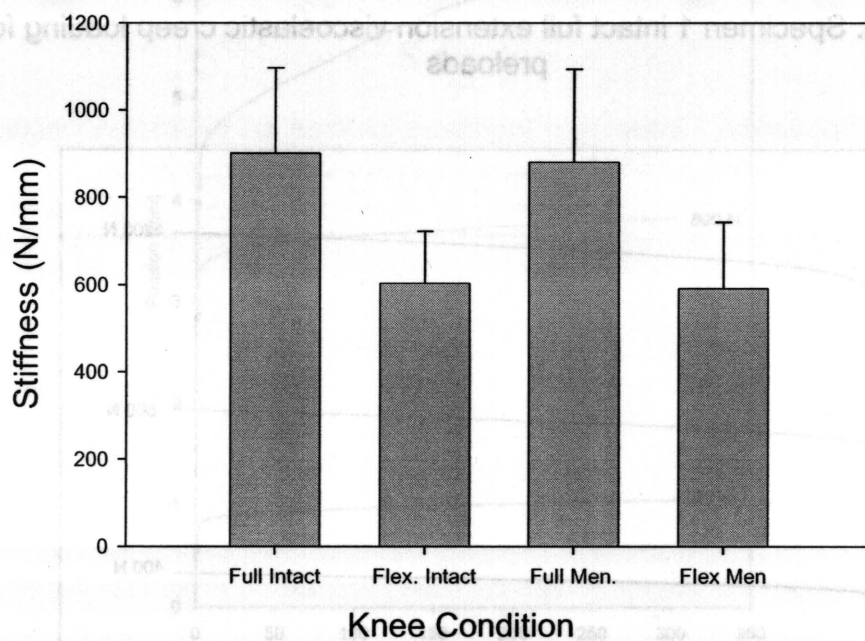


Figure A177: Average stiffness for female specimens with 400 N preload and 0.08 mm amplitude

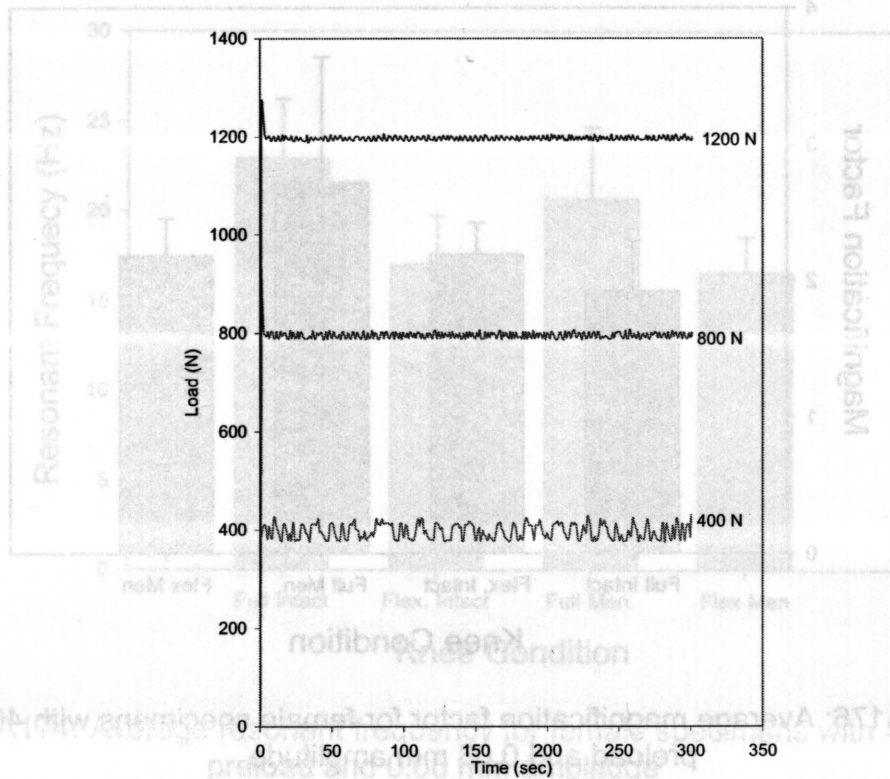


Figure A178: Specimen 1 intact full extension viscoelastic creep loading for all preloads

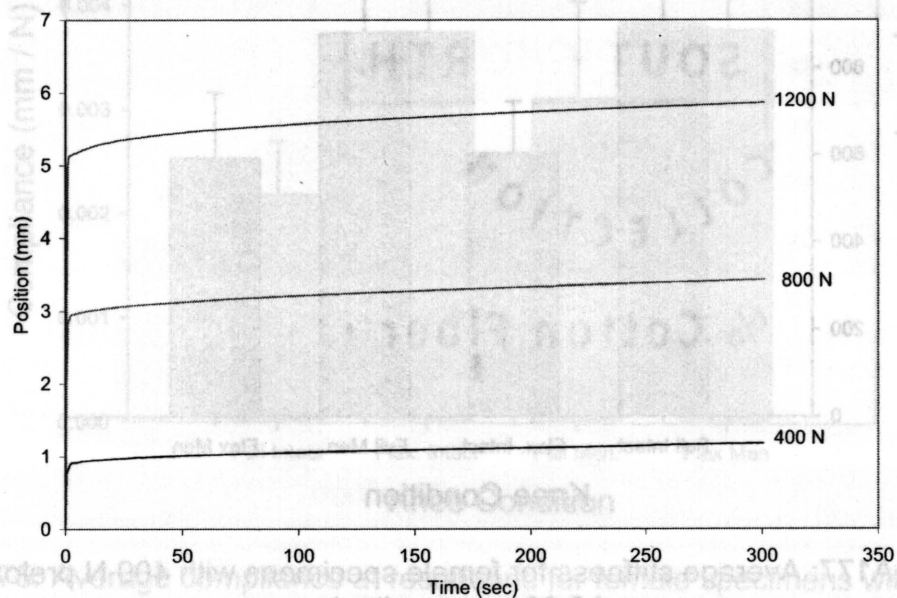


Figure A179: Specimen 1 intact full extension viscoelastic creep response for all preloads

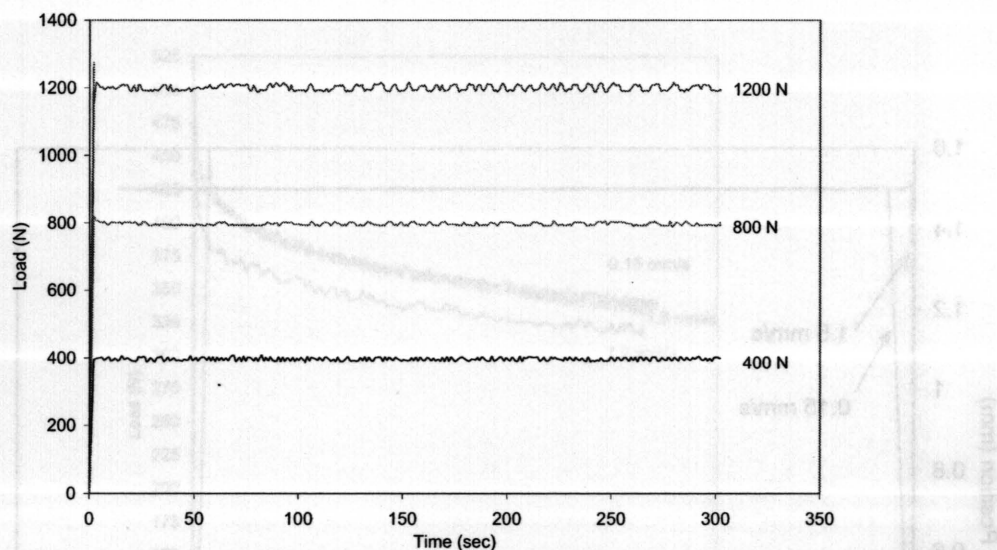


Figure A180: Specimen 1 meniscectomized full extension viscoelastic creep loading for all preloads

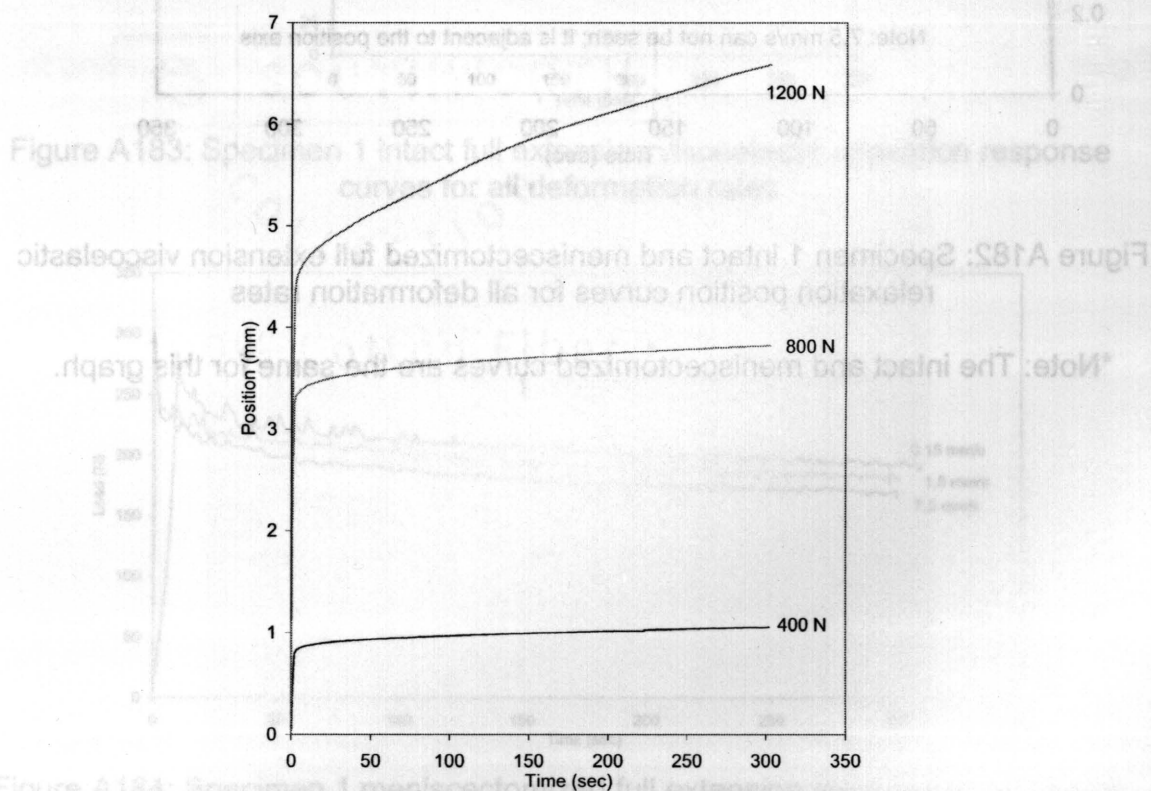


Figure A181: Specimen 1 meniscectomized full extension viscoelastic creep response for all preloads

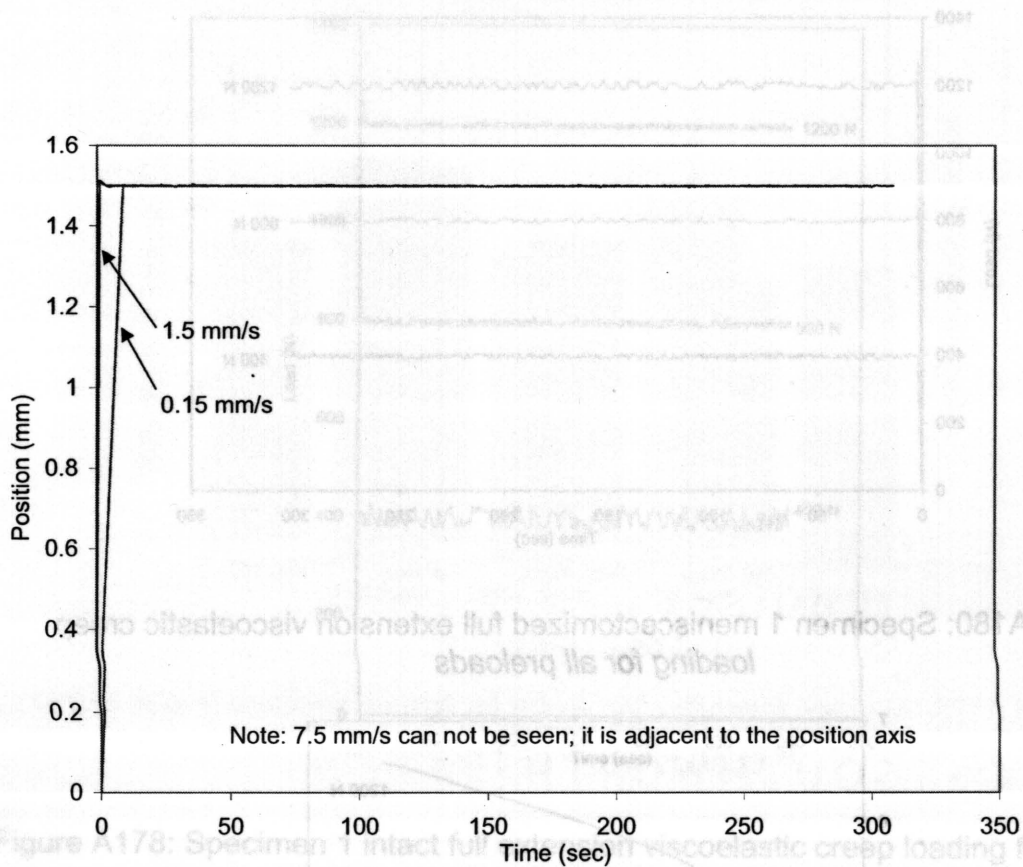


Figure A182: Specimen 1 intact and meniscectomized full extension viscoelastic relaxation position curves for all deformation rates

*Note: The intact and meniscectomized curves are the same for this graph.

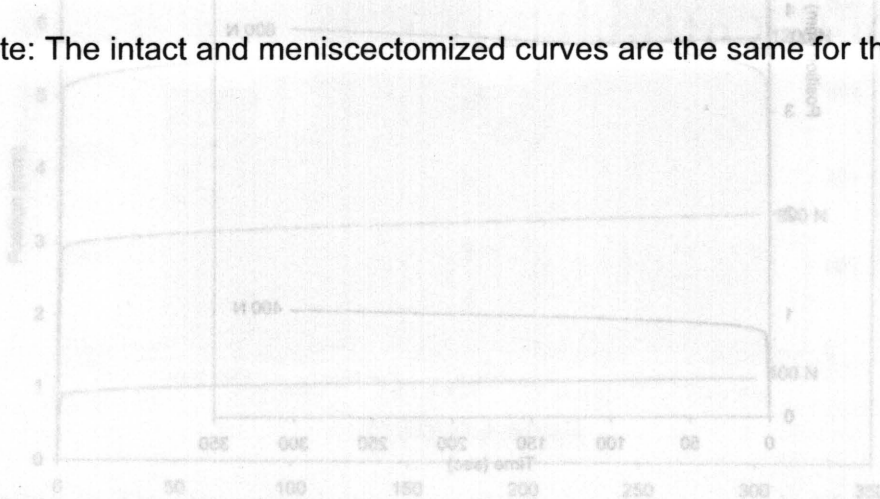


Figure A181: Specimen 1 meniscectomized full extension viscoelastic creep response for all preloads

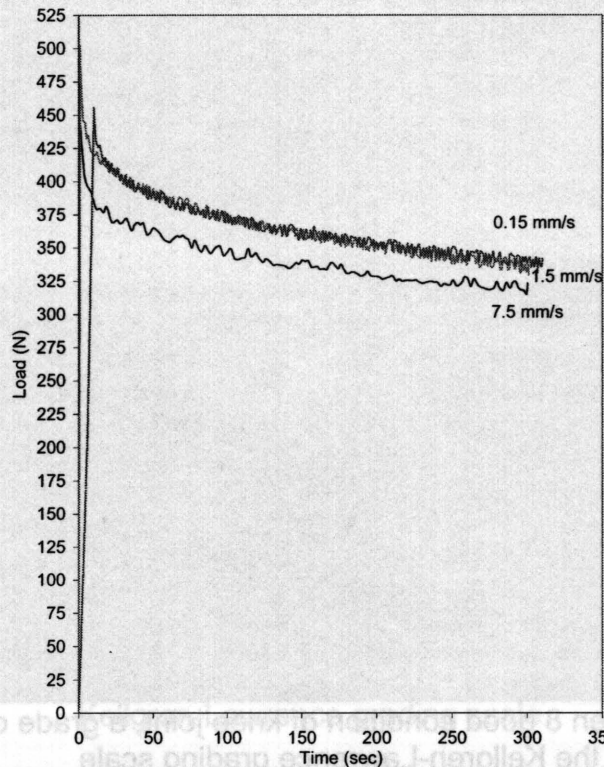


Figure A183: Specimen 1 intact full extension viscoelastic relaxation response curves for all deformation rates

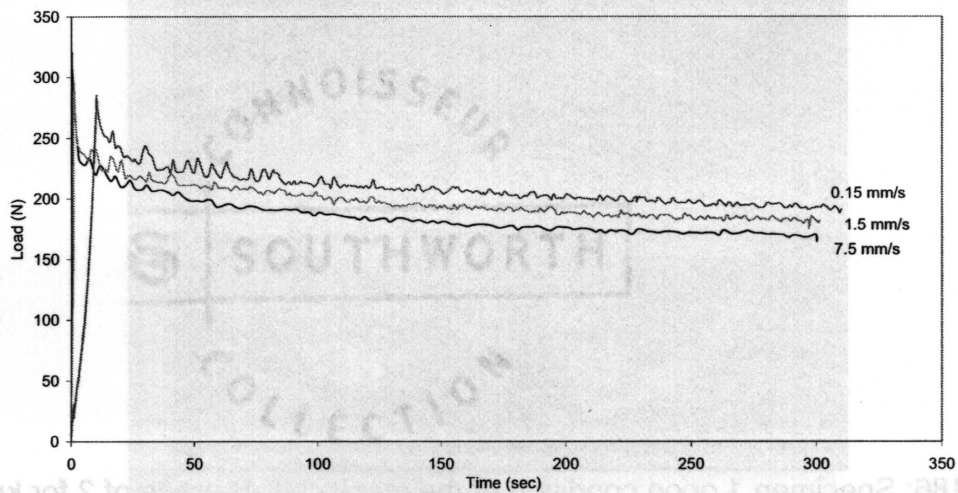


Figure A184: Specimen 1 meniscectomized full extension viscoelastic relaxation response curves for deformation rates

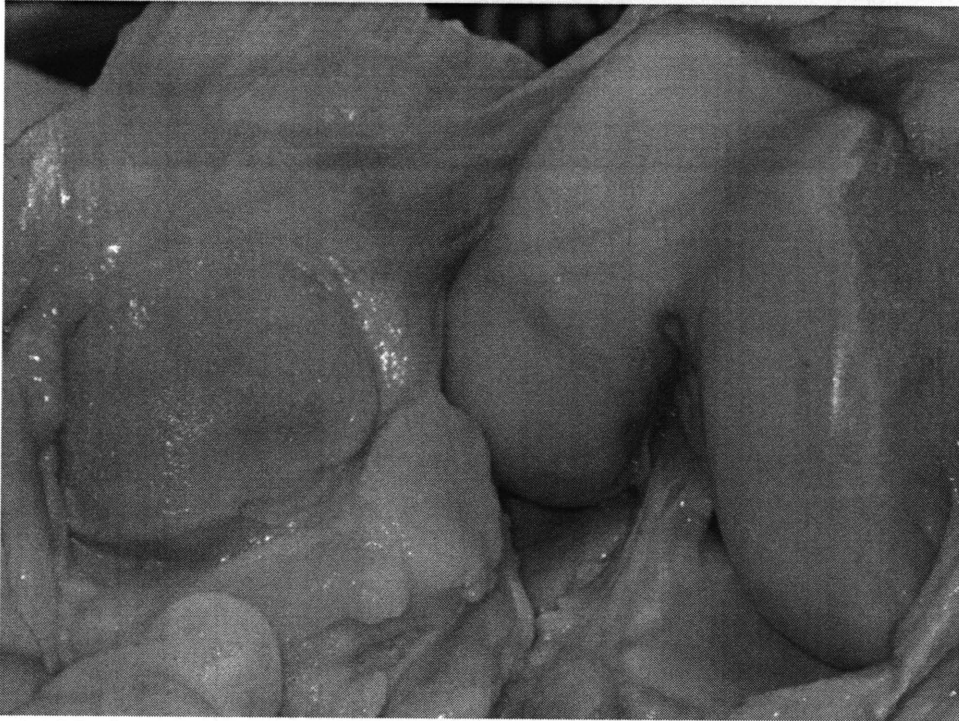


Figure A185: Specimen 8 good condition of knee joint, a grade of 2 according to the Kellgren-Lawrence grading scale

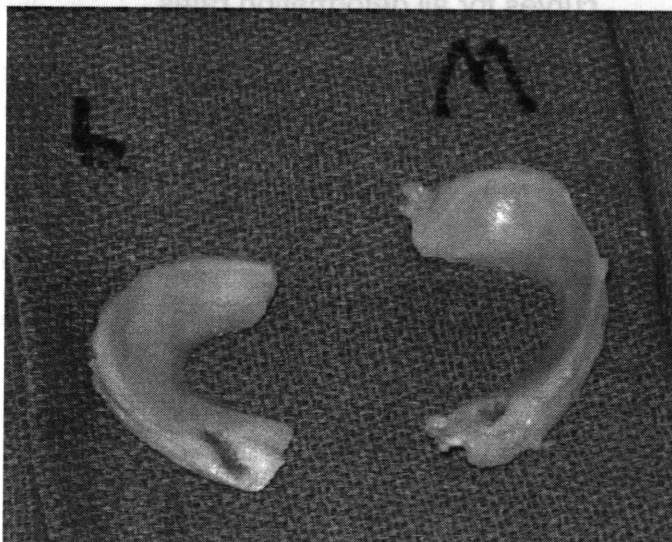


Figure A186: Specimen 1 good condition of the menisci (K-L grade of 2 for knee), medial on the right and lateral on the left



Figure 187: Specimen 7 bad condition of knee joint, a grade of 4 according to the Kellgren-Lawrence grading scale



Figure 188: Specimen 7 bad condition of the menisci (K-L grade 4 for knee), medial on the right and lateral on the left (measurement in centimeters)

Vita

Brandi Lyn Bohleber was born in Morristown, TN on March 25, 1980. She graduated from Morristown-Hamblen West High School in 1998. Next, she went to the University of Tennessee and received a Bachelor of Science in Biomedical Engineering in May 2003. She then continued her academia with a Master of Science in Engineering Science with a Biomedical Engineering concentration, and graduated in May 2005.