Study of the Loading of the Hand During Hand Tool Operation

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Abstract

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Operators who use hand held power tools are at risk of developing injuries to the hand, due to poor design and inappropriate use of hand held tools. Work with hand held power tools, such as grinders, chain saws, drills, etc., requiring high grip forces has been identified as a risk factor for hand diseases known as the Occupational Disorders (OD), such as the Vibration White Finger (VWF), and Carpal Tunnel Syndrome (CTS). Epidemiological studies conducted in several countries show that millions of workers are exposed to intense power-tool vibration and high localized grip pressures at the work place. Transmission of tool vibrations to the hand is strongly related to the grip force applied on the tool at the hand-handle interface.

Measurement and prediction of the loading of the hand is important for developing functional biomechanical models and for designing ergonomical tools, work equipment and manual handling activities. The loading of the hand was investigated in this study by focussing on the following objectives: 1) Development of a methodology to obtain hand grip pressure distribution and the forces/moments at the hand-handle interface applicable to most power tools; 2) Perform appropriate field tests using actual power tools, to study the loading of the hand in the dynamic conditions; 3) Development of mathematical models of hand-handle system.

An overall hand grip pressure distribution and the resultant forces and moments at the hand-handle interface were obtained based on the grip pressure distribution. This study provided a good understanding of the locations where there was high concentration of pressures on the hand. Under dynamic conditions, experienced operators performed field-testing with power grinders and the grip pressure distribution, postures and working environment was studied. Knowing the magnitudes of applicable hand grip pressures, and the extent to which human hand can withstand these pressures, localized and potentially dangerous grip pressures that are harmful to the human hand can be identified. Using human hand anthropometry, mathematical models were developed and analyzed to investigate the causes to the impairment of blood flow. This study revealed that the application of high grip pressures on the finger and palmar regions result in reduced or completely shutoff of blood flow to the affected segments of the hand.

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Contents

List of Figures

Chapter 1

Introduction, Literature Review and Thesis Objectives

1.1 Introduction

In industries where manpower is considered to be vital, workers who are involved in manual handling tasks may experience considerable problems, in general mentioned as occupational disorders (OD). Two common occupational disorders are 'Vibration White Finger' (VWF) and 'Carpal Tunnel Syndrome' (CTS). VWF is caused mainly due to vibration and high localized grip pressures at the hand-tool interface, and CTS is caused due to occupational overuse and awkward wrist positions.

People using hand-held power tools, such as chain saws, grinders, chisels, and drills are at risk of developing Vibration induced White Finger disease (VWF). Hand-arm and tool form a coupled system. Transmission of tool vibrations to the hand-arm is strongly related to the grip force and push/pull force applied (Radwin, R.G., Armstrong, T.J., and Chaffin, D.B., 1987). The causes of VWF may not only be due to vibration but also due to the grip pressure distribution, push/pull force and moments applied to the hand-arm. The development of VWF is thought to be directly related to high local pressures at the hand-handle interface (Radwin, R.G., Armstrong, T.J., and Chaffin, D.B., 1987). Ergonomic stresses include posture, repetitive motion, forceful exertions, contact stresses, and cold temperatures, in addition to vibration. Epidemiological studies conducted in several countries have established that millions of workers are exposed to intense hand-held power-tool vibrations regularly at the work place (Pelmear et al., 1992). The VWF disease, due to high grip pressures at the hand-handle interface is known to cause impaired blood flow in the human hand leading to the blanching of fingers. This study, made by Pelmear, 1992, is aimed at investigating the levels of grip pressure distribution applicable to the hand while an operator is gripping the power tool. Also this study investigates the finger blood flow and the results of it due to high-localized pressures, to attain significant knowledge on the mechanism of VWF disease.

Static work as when a forcefully flexed or extended posture of the hand and wrist is maintained for a prolonged time, may increase the risk for compression damage to sensitive nerve fibers (Silverstein, B.A., et. al 1987). The compression of the median nerve causes CTS, which typically leads to numbness and pain. An increased prevalence of CTS has been observed in occupational workers using vibrating tools (Silverstein, et. al, 1987). The major activity-related factors in repetitive strain injuries are rapid often repeated movements, less frequent but more forceful movements, static muscle loading, and vibration. Silverstein in 1987 suggested that high force exerted with the hand may be a causative factor by itself. Posture may be highly important. A dropped or an elevated wrist reduces the available cross-section of the carpal tunnel and hence generates a condition that may cause Carpal tunnel syndrome.

1.2 Literature Review

The severe health risks posed by prolonged exposure to hand-held power tool vibration, supported by the findings of the epidemiological studies, have prompted a strong desire to enhance a thorough understanding of the vibration response and hand grip pressure characteristics of the human hand. It was observed that vibrations and the resulting involuntary contractions in the hand and arm adversely affect the ability to release the grip. Subsequently several researchers have attempted to study the activities of various hand-arm muscles under different static and dynamic loading conditions.

Several studies on varying aspects of hand-arm vibration (HAV) syndrome have been conducted to establish an understanding of the cause-effect relationship (Stewart and Goda 1970, Ashe et al. 1962, Pearson et al. 1971). Grip force, frequency, and magnitude of the handle vibration has been identified among the most significant factors related to transmission of vibration into the hand and thus the hand arm vibration syndrome (Brammer and Taylor 1982, Pyykko et al. 1975). These studies focus on the measurement of total grip force under dynamic loads (Suggs et. al 1977, Reynolds 1977). Injuries to the hand, lower arm and shoulder are often claimed to be due to poor design and/or inappropriate use of hand tools. Also, work requiring high force has been identified as a risk factor for hand-wrist cumulative trauma disorders. (Silverstein, 1986). Work with cross-action tools often requires a substantial amount of force, and one important factor, directly influencing the grip strength for this type of tools, is the distance between the handles.

1.2.1 Occupational Disorders

a) Vibration White Finger Syndrome

Prolonged exposure to hand-transmitted vibration is known to cause a complex of vascular, neurological and musculoskeletal disorders, often referred to as hand-arm vibration syndrome, among the operators of hand-held power tools. People using vibrating hand-held power tools are at the risk of developing vibration induced white finger disease (VWF).

Hand-arm and tool form a coupled system. Shaking of hand-held objects is a common and indispensable motor act in various professions. Attenuation of hand-transmitted vibration has thus been widely recognized to reduce the health and safety risks posed by these vibrations. It was observed that vibrations and the resulting involuntary contractions in the hand and arm adversely affect the ability to release the grip (Pelmear, et. al, 1992). Several researchers have attempted to study the activities of various hand-arm muscles under different static and dynamic loading conditions. The perception of discomfort, fatigue, and loss of productivity may be related to local concentration of the contact forces at the hand-handle interface (Suggs, et. al 1974).

Transmission of tool vibrations to the hand-arm is strongly related to the grip force and push force. Operators of hand held power tools are exposed to high levels of vibration, predominant in a wide frequency range of 10-2000Hz, arising from the dynamic interactions between the tool and the work-piece. The hand and arms of the operators primarily absorb these vibrations with high amplitudes. Prolonged exposure to such high levels of hand transmitted vibrations has been related to symptoms of 'Vibration Induced White Finger (VWF)', also known as Traumatic Vasospastic disease, dead man's hand, Spastic Anemia, Raynaud's phenomenon of occupational origin, Hand-Arm Vibration Syndrome (HAVS), (Pelmear et al., 1992).

Many clinical studies defines the HAVS as a disease entity with the following peripheral components :

i) Circulatory disturbances (vasospasm with local finger blanching 'White Finger'),
ii) Sensory and motor disturbances (numbness, loss of finger co-ordination and dexterity, clumsiness and inability to perform intricate tasks),
iii) Musculo skeleto disturbances (muscle, bone & joint disorders).

The vascular symptoms of the vibration syndrome resemble the spontaneous vasoconstrictive disease first described by Raynaud. The vasoconstriction of finger vessels usually lasts from 5 to 15 minutes, during which the fingers look white and pale. Recovery is achieved by massaging or local warming. Workers using vibration tools commonly experience numbing and lacerating pains in the arms and hands. Such symptoms are annoying because they wake the worker at the night and force them to massage his hands and therefore disturb the sleep rhythm. Continued exposure to vibration in the advanced stages causes nutritional changes in the finger pulps leading to the formation of areas of skin necrosis at the finger tips. Ergonomic factors such as repetitiveness, forcefulness, contact stress, posture, low temperature, in addition to vibration can cause, precipitate or aggravate upper extremity nerve disorders such as Carpal Tunnel syndrome. Vibration may increase the risk of Cumulative Trauma Disorder, (CTD) as a result of excessive force executed when holding some vibrating hand tools (Radwin, et. al 1987). Ultimately, the impact of these effects on health is not yet known.

The pathogenic events leading to VWF are still unexplained. An increased sympathetic disorder may play a role in the development as well as in the manifestation of the disorder. The mechanism for the development of the diffuse neuropathy with sensory deficiency seen in many vibration-exposed workers remains obscure. Mechanical influence from vibration exposure possibly plays a major etiology role in this disorder. Hand tools and tool handles need to be designed for both efficient and safe use. Tool designers often work on the assumption that 'one size fits all', when in fact there is a large variation in hand anthropometry over the working population, which is a serious problem. The interaction of the handle size and the shape with the kinematics and anthropometry of the hand have a great effect on hand posture and grip strength.

b) Carpal Tunnel Syndrome

The result of compression of the median nerve in the carpal tunnel of the wrist leads to the occupational disorder, Carpal Tunnel Syndrome (CTS). This tunnel is an opening under the carpal ligament on the palmar side of the carpal bones (figure 1.1). Through this tunnel pass the median nerve, the finger flexor tendons, and blood vessels. Swelling of the tendon sheaths reduces the size of the opening of the tunnel and pinches the median nerve, and possibly blood vessels. The tunnel opening is also reduced if the wrist is flexed or extended, or ulnarly or radially pivoted, in other words if the wrist has an awkward position.

Studies say that Carpal Tunnel Syndrome is mainly caused by typical job activities such as, operating power tools, buffing, grinding, polishing, sanding, assembly work, typing, keying, cashiering, playing musical instruments, surgery, packing, housekeeping, cooking, butchering, hand washing, scrubbing, hammering (Goldoftas, B., 1991). Among the best known ODs is the Carpal Tunnel syndrome, first described 125 years ago. In 1966, Phalen published his 'classical' reviews: he described the typical gradual onset of numbness in the thumb and the first two and a half fingers of the hand (supplied by the median nerve), with the little finger and the ulnar side of the finger unaffected. In 1975, Birkbeck and Beer described the results of a survey they made of the work and hobby activities of 658 patients who suffered from Carpal Tunnel syndrome. Four of five patients were employed in work requiring highly repetitive movements of the wrists and fingers.

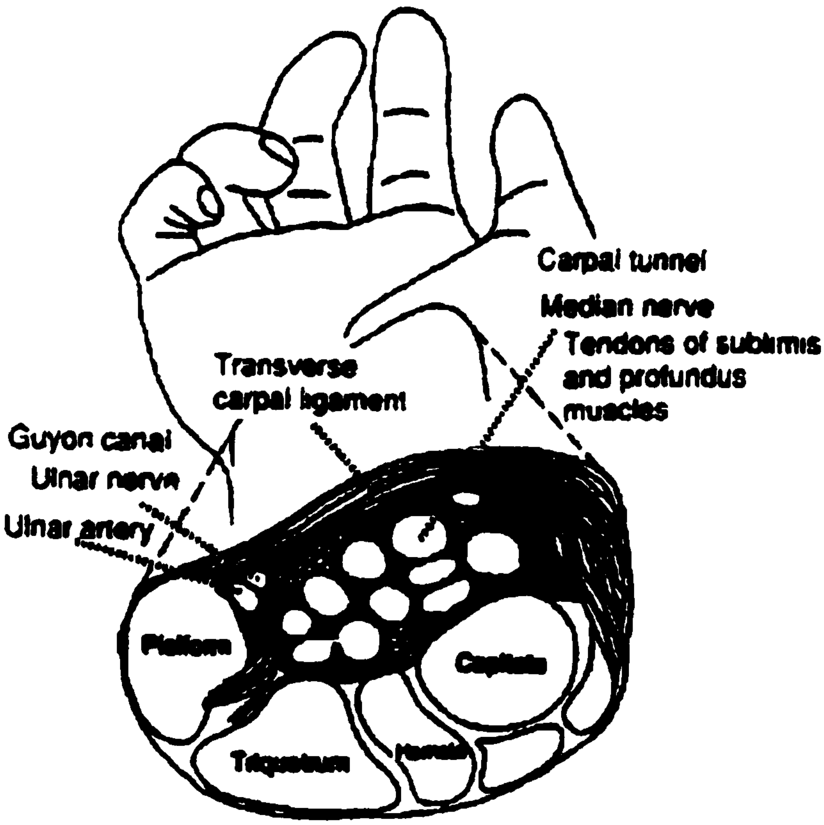


Figure 1.1. The Carpal Tunnel and associated ligaments, tendons and nerves

(Kroemer, K., 1994).

In 1959, Tanzer described several cases of Carpal Tunnel syndrome. Two of his patients had started to milk cows on a dairy farm, three worked in a shop in which objects were handled on a conveyor belt, two had done gardening with considerable hand weeding, one had been using a spray gun with a finger trigger. Two patients had been working in large kitchens with much stirring and ladled soup. These cases explain us the obvious causes of Carpal Tunnel syndrome, which probably might be due to high grip pressures on hand and fingers, unnatural wrist positions and highly repetitive movements of the wrists and the finger.

c) Relationship between Hand-Arm Vibration and Carpal Tunnel Syndrome

Scientific attention has focused primarily on vascular vibration disorders such as vibration white finger (VWF), bone and joint deformations, autonomic disturbances, perception, discomfort, and other miscellaneous abnormalities. Musculoskeletal and peripheral nerve disorders associated with HAV, however, are now gaining recognition.

Carpal tunnel syndrome, a neuropathy of the median nerve at the wrist, is a commonly cited cumulative trauma disorder associated with operating vibrating hand tools. carpal tunnel syndrome is characterized by tingling, numbness, and pain in the areas of the hand innervated by the median nerve. Separating neurological disorders, such as CTS, from vascular disorders, such a VWF, has been difficult since a number of the early symptoms for both disorders are similar. Hence, the effects of carpal tunnel syndrome (CTS) and hand-arm vibration syndrome (HAVS) are often confounded. Epidemiological studies of degenerative changes in the hand-arm system caused by vibration have proved it difficult to differentiate between the direct effects of vibration and those of heavy manual work involving forceful and repetitive movements.

Rothfleisch and Sherman in 1978, studied the factors associated with CTS for 25 hands in 16 workers at an automobile assembly plant. Each of these workers at some time used pneumatic tools, which were reported vibrating between 8 Hz and 33 Hz. They also found that awkward positioning of the hand and wrist while performing their tasks was a common factor. This study again showed that ergonomic and vibration factors occur together, and that their effects were not easily separated. Cannon et al. in 1981, performed a retrospective case controlled study on 30 workers with CTS. The most significant factor was the use of vibrating hand tools. Although performing repetitive motion tasks was less important, it can be assumed that exposure to vibration also involved intensive use of the hands. Therefore, sustained exertions, high forces, and postures may account for some or most of the apparent vibration effect.

A cross-sectional study of 652 active workers in 39 jobs in seven different industrial plants was performed in order to investigate occupational risk factors of CTS (Silverstein et al. 1986). Four of the jobs were classified as high-force involved nearly continuous exposure to vibration (buffing, grinding, cutting). The data collected suggested that the risk of CTS for low-repetitive, low-force is increased by a factor of 6 and that the risk of CTS for high-force, high-repetitive work is elevated by a factor of 2 when accompanied with nearly continuous vibration exposure. While hand and wrist tendinitis were highly associated with high-force, high-repetitive work, no association with vibration was found.

1.2.2 Stress factors pertaining to manual power tools

If physical exertions are sufficiently frequent, long, and forceful, or they occur in certain postures, they are performed in cold environments, or they result in sufficient contact stress, a worker can develop pain and impairment in the upper limb. These disorders have specific names, depending on the location and the tissues involved, but it suffices to simply refer to them collectively as cumulative trauma disorders (CTDs). The risk of incurring a CTD may be altered by congenial factors, chronic diseases, acute injuries, and physiological states. This discussion will focus on the work-related factors: 1) hand grip pressure distribution, 2) contact stress, 3) posture, 4) repetitiveness.

a) Hand grip pressure distribution at the hand-handle interface

Hand grip pressure distribution is the forcefulness or the amount of force exerted using the hands for gripping, lifting, moving, pulling or pushing something. Some investigators use surface electromyography and job analysis to estimate hand forces at work, but many of them only talk about forceful exertions without actually measuring them. Armstrong et al. in 1979 found that persons with CTS tend to exert 18% more force than age, gender, and job-matched controls. Silverstein et al. in 1987, estimated forces using electromyography, but grouped their study population into two groups with high and low-force exposure. They found that the risk of tendinitis and CTS increased 29 and 15 times, respectively, with high force and repetitiveness. Recently small, flat sensors that attach to the hands have been demonstrated as being useful for measuring finger forces produced during gripping pulling/pushing activities. Similar kind of sensors are used in this research, to investigate grip force distribution at the hand-handle interface.

b) Contact stress at the hand-handle interface

Contact stress is produced when the body comes into contact with an external object. Contact stress is related to the force and area of contact. The smaller the contact area, the greater the stress concentration for a given amount of force. Contact with lateral sides of the fingers is associated with digital neuritis and contact with the palmar sides of fingers is associated with trigger finger while contact with the base of the palm is associated with CTS.

c) Worker-Tool interface

The worker-tool interface is the path vibration energy takes between the source and the human operator. It explains the interaction between the hand tool and the operator. The worker-tool interface may involve the use of handles or other parts of the tool in contact with the hands and body. Handle location, the amount of force to be exerted on the tool handle and the type of tool can have a dramatic effect on the level of vibration transmitted to the operator.

The intensity of incentive work resulted in increased vibration transmission and therefore exposure, presumably due to increased grip exertions and the resulting improved coupling between the hand and the power tool. Daily vibration exposure is directly related to the repetitive nature of work or the number of operations per day. Radwin and Armstrong in 1987, undertook a study to investigate the contribution of pneumatic screwdrivers to CTDs, which were a major cause of lost time and workers' compensation due to the highly repetitive nature of work.

d) *Repetitiveness of a job*

Repetitiveness refers to the number of exertions repeated per unit time, and how long exertions are maintained. In many instances, it can be shown that the number of exertions is related to the number of parts produced per unit time, or the number of work cycles. The relationship between the degree of repetitiveness and the risk of a CTD is not yet known. Hammer in 1934, suggested that human tendons do not tolerate more than 1,500 to 2,000 exertions per hour. Tichauer in 1966, concluded 5,000 exertions per day were sufficient to produce injury of the median nerve. Luopajarvi et al., in 1979, concluded that the prevalence of muscle-tendon syndromes in the hands of assembly-line packers were related to operators keeping up with machine cycles of 25,000 cycles per day. Kuorinka and Koskinen in 1975, found the symptoms of muscle-tendon disorders increased as the number of parts handled per year increased from less than 200,000 to more than 300,000. Silverstein in 1986, found increases in the risk of CTS with fundamental work cycles of less than 30 seconds that were performed for more than 50 percent of the time.

1.3 Scope and Objectives of the Research

A measure of distribution of hand grip force can provide a better insight into transmission of localized forces and stresses experienced by the operators of hand-held power tools. Measurement of 'Grip Pressure Distribution' (GPD) at the hand-handle interface necessitates a large number of flexible pressure sensors to be adopted to curved surfaces, such that the hand-handle interface remains unaltered. This paves way to understand and estimate the causes of risks associated with these occupational disorders.

1.3.1 Objectives

The overall objective of this research is to measure and predict the loading of the hand during hand held tool operation. The importance of this study leads to the development of functional biomechanical models and for designing ergonomical tools, work equipment and manual handling activities. Further, this study should provide people with a healthier, safer and more comfortable work environment, to assess how people carry out certain job activities and to ensure they carry out theses activities in such a way that they are least likely to injure themselves.

Specific objectives can be listed as follows:

1) Develop methodology to obtain the loading applied by the tool handle on the hand applicable to most power tools. This part is based upon further analysis of data obtained by Gouw (1996) previously.

2) Perform appropriate field tests using actual power tools, to study the hand grip pressure distribution and the loading of the hand in the dynamic conditions.

3) Develop mathematical model of hand-handle system.

This study should provide safer work environment for operators of power tools. Although this study focuses on power tools, it can be extended to general manual material handling tasks and many other tasks involving hand/fingers with the aim to reduce incidence and risk of injury, especially 'Vibration white finger disease', and 'Carpal tunnel Syndrome'. The results of this study could lend greater objectivity to the evaluation of functional losses, and could also have important implications of industrial design. The constant relationship of forces among the fingers should contribute to the functional design of hand tools and instruments that will contribute to greater comfort and efficiency in job performance.

1.3.2 Overview of the Thesis

The measurement methodology of the loading of the hand and the results of hand grip pressure distribution are described in Chapter 2. The grip pressure distribution at the hand-handle interface was measured for various subjects using capacitive pressure sensors. These sensors as they were placed at discrete points on the handle, measured the forces only at those discrete points. To obtain the overall grip pressure distribution between the hand-handle interface, these discrete points are interpolated using the spline interpolation technique. The results described in Chapter 2 include the overall grip pressure distribution on the palmar side, and the fingers' side, the individual grip force contributed by each finger, and the resultant forces and moments applied to the hand or parts of the hand (e.g., fingers).

The testing and analysis pertaining to various hand-held power tools are described in Chapter 3. For the field testing, particular attention was given to grinders as operators of these tools are known to develop VWF disease after prolonged exposure. Subjects tested various power tools under static and dynamic conditions and GPD, and posture are studied and analyzed. It is postulated that a subject grips a vibrating tool more tightly and that there are highly peak pressures when the tool is poorly balanced. In addition, the influence of posture during tool operation was studied. Key parameters that contribute to high local pressures were identified.

The development and analysis of the mathematical models of hand-handle system are described in detail in Chapter 4. Several mathematical models are developed and analyzed for various forces applicable on the hand-handle systems using ANSYS finite element analysis package. The models use relevant anthropometric data of the hand as well as the results obtained from the grip pressure distribution measurement done as described in the second chapter. The deformations, intensity, stress and strain levels pertaining to the human hand are studied in detail.

Chapter 2

Study of the Loading of the Hand

2.1 Introduction

Measurement and prediction of hand grip pressure distribution as well as individual finger forces during grip exertions are important for developing functional biomechanical models and for designing ergonomical tools, work equipment and manual handling activities. The functions of the hand and digits are widely studied in the fields of orthopedic surgery, physical medicine and rehabilitation where the major concern has been to relate the kinematic characteristics of individual digits with the electrical activity of muscle or muscle components.

Injuries to the hand, lower arm and shoulder are often claimed to be due to poor design and/or appropriate use of hand tools. Also, work requiring high force has been identified as a risk factor for hand-wrist cumulative trauma disorders (Silverstein, 1986). Work with cross-action tools often requires a substantial amount of force, and one important factor, directly influencing the grip strength for this type of tools, is the distance between the handles.

Although much neurophysiological research into the functional organization of the hand's motor has been done, little attention has been paid to individual digits. Also, there were no studies which concluded with a precise, definite and more appropriate solution in overcoming the occupational disorders related to hand functions like gripping, pushing, pulling, lifting etc. 'Grip strength' has long been used as one of the most convenient and reliable indices of muscular strength, but kinematic and physiological features of individual digits have been neglected.

Numerous authors (Bechtol 1954, Hertzberg 1955, Montoye and Faulkner 1965, Cotten and Bonnell 1969, Cotten and Johnson 1971) have investigated an isometric grip, performed with parallel handles. Most of the studies describe an optimal handle separation, giving maximal force output. The fingers differ in strength, the middle finger being the strongest and the little finger the weakest. Hence, the force output from fingers index-plus middle finger is larger than from fingers ring-plus little finger (Hazelton et al. 1975, Ohtsuki 1981).

Napier in 1956 and Landsmeer in 1962 divided the essential activities of the hand into power grasp and precision handling (pinch). Power grasp is a forceful act performed with the finger flexed at all three joints so that the object is held between the fingers and palm, with the thumb acting as an additional stabilizing element. Precision handling concerns the manipulation of small objects in a finely controlled manner between the finger and the thumb. These two isometric functions with multiple variations are extremely important to the performance of daily activities. Smith et al. in 1964, initiated the mathematical analysis of the forces involved in fingers during pinch. The tendon forces and joint-contact forces were calculated, based on the pinch force exerted on the pulp of the finger. Flatt and associates performed a series of biomechanical analysis of finger functions pertaining to the pathomechanics of ulnar drift in rheumatoid arthritis (Flatt 1966, Flatt and Fischer, 1969). These well-executed studies provide the present limits of the biomechanical knowledge of finger functions. However, such analyscs were again confined within the plane flexion-extension, which prevent the determination of the three-dimensional bony and soft-tissue constraints. These constraint forces are essential in governing the stability of the finger joints in forceful actions.

'Grip Strength' has long been used as one of the most convenient and reliable indices of muscular strength, but kinetic and physiological features of individual digits have long been neglected. The strength share of each digit during grip strength exertion and the maximum voluntary strengths of single digits, and the relation of these strengths to the physiological cross-sectional areas of finger flexors were determined in experiments conducted by Ohtsuki 1981. The functions of the hand and digits are widely studied in the fields of orthopedic surgery, physical medicine and rehabilitation where the major concern has been to relate the kinematic characteristics of individual digits with electrical activity of muscles or muscle components.

The analysis and experiments in this chapter were made for an attempt to determine not only the total grip pressure distribution but also the strength share of each finger during grip strength exertion. Before describing the study and analysis made to determine the hand grip pressure distribution (GPD), an in-depth study of the human hand anatomy, its strength and use are discussed. This study gives a good background to proceed with analyzing the problems that lead to several occupational disorders in the human hand-arm system.

2.2 The hand - its anatomy, strength and use

The human hand is an outstanding apparatus with two major features; a mechanical aid to exert force to the environment and a sensory organ retrieving information about the world external to the body. These two features are interrelated and cannot operate isolated from each other. The hand, its structure and function, represents a fertile field of study that is largely untapped, but the complexities of the function and anatomy of the human hand have long been recognized.

2.2.1 *Anatomy of the hand*

The hands are amazing instruments, but they are also quite delicate and susceptible to injury if used inappropriately. To understand what kinds of injuries can occur, and what kinds of usage may create those injuries, we first need to understand something about the anatomy of the hand and wrist. The complexities of the function and anatomy of human hand have long been recognized. The human hand is a three-dimensional structure.

From a biomechanical standpoint, the human hand can be considered as a linkage of intercalated bony segments. Ligaments, tendons and muscles span the joints between each phalanx. With the contraction of muscles, these joints can be moved in a characteristic manner constrained by the interposing soft tissues and the bony articulation. If the motion is resisted, functional strength in the forms of pinch and grasp can result. In the hand most of the tendons span the joint and continue their course over one or more joints, thus forming a bi-articular or poly-articular system (Bunnell, 1948; Landsmeer, 1963; Smith, 1974). Landsmeer in 1955, has extensively studied the functional anatomy of the spatial relationships between these tendons and muscles and their associated joints.

The metacarpo-phalangeal (MP) joint forms the articulation at the base of each finger (figure 2.1). The joint surfaces are classified as ellipsoid or condyloid with the metacarpal heads fitting into shallow cavities at the base of the proximal phalanges. The joint normally has active flexion-extension of 90-100 degrees and abduction-adduction of 60 degrees (Berme et al. 1977). The musculature bringing about these movements falls into two groups: The extrinsic muscles, the flexors and extensors which pass from the upper forearm to the hand and the intrinsic muscles the interosseus and lumbricals which are situated close to the metacarpal bones of the hand. Figure 2.2. shows the carpal tunnel and the associated ligaments, tendons, bones, nerves and arteries.

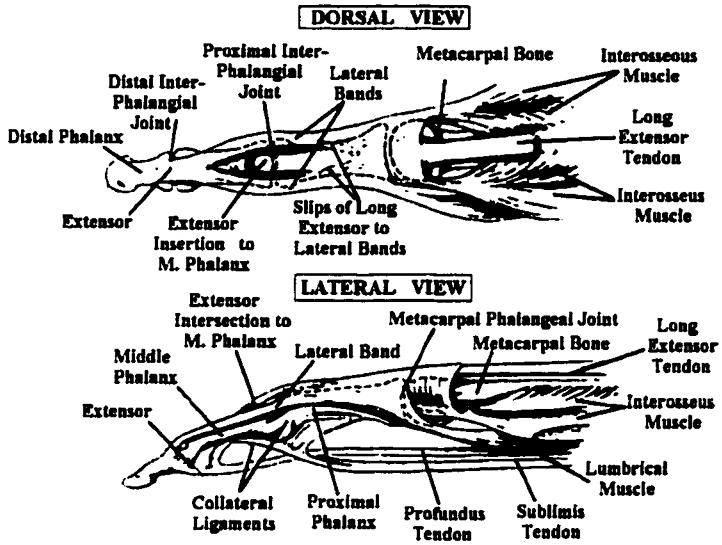


Figure 2.1 Musculotendinous structure of a long finger. (Chao, E.Y., Opgrande, J.D., and Axmear, F.E., 1976).

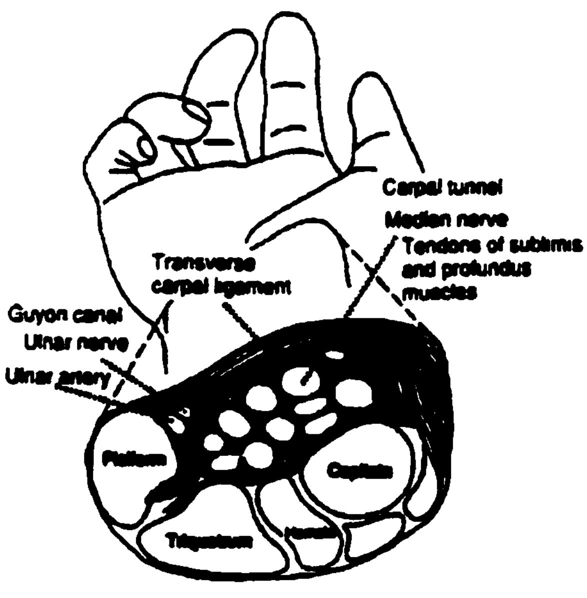


Figure 2.2 Carpal tunnel and associated nerves and arteries (Kroemer., K., 1994).

The index or second finger has the largest dorsal interosseus muscle on its radial side. This occupies the space between the thumb and the index finger and is inserted into the radial side of the proximal phalanx of the index finger. On the ulnar side the second palmar interosseus arises from the full length of the metacarpal bone and is inserted into the digital expansion on that side. The muscles that provide the force for flexion of the interphalangeal joints of the fingers are located in the forearm., and their tendons pass through the carpal tunnel (Silverstein et al. 1987), anterior to the wrist joint before they fan out in their approach to individual fingers.

The flexor tendons leave the palmar bursa at the middle of the palm and pass into synovial sheaths at the metacarpo phalangeal joints. These sheaths bind down the flexor tendons to the three joint surfaces over which they pass. The extensor tendons do not have such a complex structure, they are free to slip over the knuckles before they divide into three bands and blend into the extensor hood. The extensor hood joins onto the palmar ligament, which is loosely attached to the metacarpal phalanx at the MP joint. The palmar ligaments of the fingers are attached to the deep transverse metacarpal ligaments which prevent the metacarpal bones from spreading (Kroemer et al. 1994). Finally, the collateral ligaments pass obliquely, distally forward on each side of the joint. Because of the eccentric attachments to the sides of the metacarpal heads the collateral ligaments are slack in extension and taut in flexion.

2.2.2 *Basic functions and grip characteristics of the hand*

If we are to profess the knowledge and ability to adequately cope with problems presented by the disabled we must look at the total scope of the hand functions. In order to develop meaningful standards for exposure of the hand to vibration, both the vibration of hand tools and the response of the hand-arm system when coupled to a tool must be better understood. Several investigators (Brammer 1984, Pyykko 1975, Taylor 1982) have identified a relationship between various muscular disorders and vibration induced into the hands of power tool operators. Only a little solid evidence is available which states the exact nature of this relationship, which exists between vibration directed into the hands and any of deficiencies associated with the vibration syndrome, although there is increasingly more information available on this subject.

Several writers have suggested that hand function is divided into power and precision grip functions. The thumb, index and long fingers form a tripod of prehension that is used in precision activity such as holding a pencil. In this function, the ring and little fingers are used for support and control. In the power grip, the ring and little fingers, assisted by the long and index fingers as necessary, form a mobile jaw to squeeze objects against the palm of the hand and the thenar eminence, with the thumb and index finger providing any necessary precision in the grip. Napier (1956) and others have described these functions in a similar manner. It is interesting to note that the innervation pattern of flexor functions in the hand roughly follows this division of function with the ulnar nerve distribution supplying the power grip functions, and the median nerve distribution supplying the precision grip functions. The hand and arm form a very complex, continuous , non-homogeneous system consisting of skin, muscle, bone, etc., and an accurate model must contain all these components. Past investigators like Reynolds, Soedel, Jokel, Griffin, Abrams have shown that the hand-arm system can be modeled as a lumped parameter, mass-excited vibration system. To be more precise it can be said that the model can be represented by a number of discrete masses, linear springs, and viscous dampers.

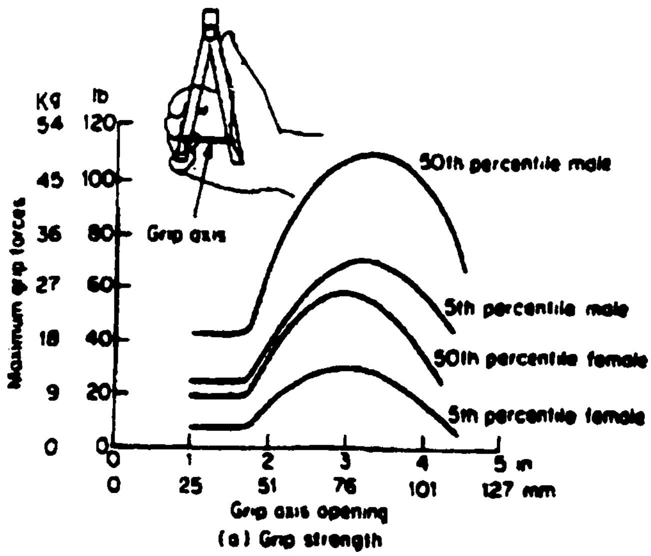


Figure 2.3 Maximum grip strength for various handle openings

(Mark S. Sanders, 1987).

Figure 2.3 shows a plot for maximum grip strength for various handle openings. The fingers differ in strength, the middle finger being the strongest and the little finger the weakest (Fransson and Winkel, 1991). Hence, the force output from fingers II+III (index-plus middle finger) is larger than that from fingers IV+V (ring-plus little finger) (Hazelton, 1975; Ohtsuki 1981).

The finger force of a specific finger at a given finger grip span differs between the traditional and the reversed grip types. This seems to be due to the relative positions of the fingers. Thus, the results indicate that the finger force of a finger depends upon the position of the remaining fingers, i.e., there is an interaction between the fingers. One probable reason for this is that some of the finger flexors, e.g., flexor digitorium profundis and flexor digitorium superficialis, contribute to flexion of several fingers, but are united at the origin (Fransson and Winkel, 1991). Also, the fingers are, to some extent, linked together via the juncture tendinum. Therefore, the fingers should not be considered as separate units, but as intimately cooperative parts of the hand.

The finger/hand grip span effects the pre-contractile length in the flexor muscles of the forearm. Accordingly, the number of cross-bridges that can be formed differs, which affects the muscle force correspondingly (Huxely, 1973). The force-loss at wide handgrip spans may also be due to a change in lever arms; as the hand grip span increases, the handle moves from the proximal to the distal part of the fingers. Thus, the lever arm of the extension moment, which opposes the finger flexion, increases correspondingly. As a consequence, the force output of a wide handgrip span is lower than that of a narrow handgrip span. For wide handgrip spans, all fingers cannot grip properly around the handle of the tool, implying a corresponding loss of force.

Gloves were recommended at the starting times of hand-arm vibration investigations to decrease the percent of vibration induced to human hand-arm system. But, later investigations proved that gloves are not at all recommended as the percent of grip strength decreases. In other words, the human hand looses sensation of the grip strength it is providing to the handle, and as a result it tries to grip much more firmly. Figure 2.4 shows the maximum voluntary grip strength while wearing rubber, cotton, or insulated gloves. The plot clearly shows the tremendous drop in the percent bare-handed grip strength for all the above mentioned glove material types.

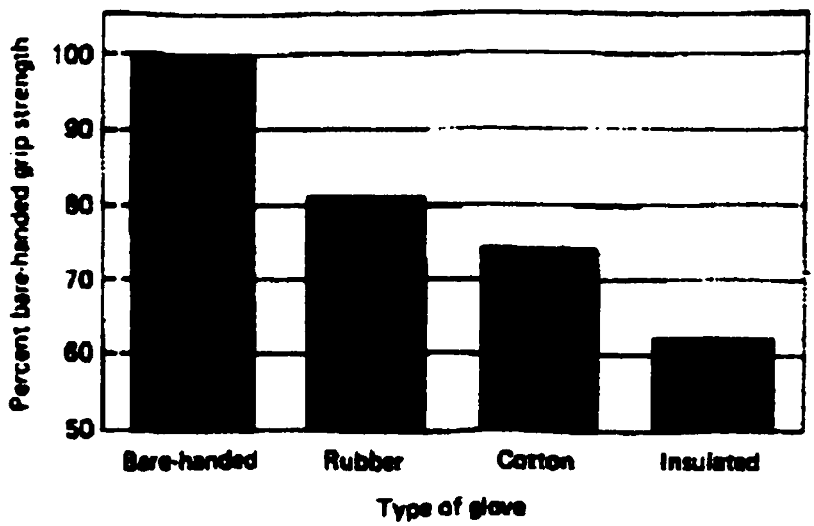


Figure 2.4 Maximum voluntary grip strength while wearing rubber, cotton or insulated gloves (Sanders., M.S., 1987).

The maximal force of a muscle is proportional to its cross-sectional area, muscular force is proportional to the square of the body length, $F \propto L^2$ (Astrand and Rodahl, 1986). Accordingly, the hand size measurements were squared when correlated to the resultant force between the jaws of the tool. A large hand is able to exert a higher grip force than a small hand. There exists about 35% of force difference between females and males (Fransson and Winkel, 1991). The difference in hand size may also explain the narrower optimal hand and finger grip for females compared to males. A non-linear profiling of the handle according to optimal finger grip spans would be advantageous.

2.3 Experimental setup and procedure

A major difficulty in accurately predicting internal hand forces for biomechanical models is the determination of external finger forces for different joint configurations and grasping functions. This is probably because force sensors needed for measuring individual finger forces during grasping activities have not been available precisely for that purpose. Even, the available sensors are not able to measure the whole grip pressure distribution over the entire surface area of the human hand. However, several researchers, to predict the external and internal finger and hand grip forces were extensively conducting a lot of studies. These are studied to some extent in this section.

Hand biomechanical models have been limited in their ability to accurately predict internal hand forces because adequate force transducers have not been able for measuring individual finger and hand forces during grasping activities, and for determining actual external forces applied during different grip configurations and hand functions (Chao, et al., 1985). Hand force sensors are also needed for evaluating the results of surgical procedures such as joint replacement and tendon transfers (Dickson, 1972), for force feed back in functional neuromuscular stimulation and for sensory substitution rehabilitation devices that compensate for loss of sensation in the hand.

An isometric grip, performed with parallel handles, has been investigated by numerous authors, e.g., Bechtol (1954), Hertzberg (1955), Montoye and Faulkner (1965). Most of the studies describe an optimal handle separation giving maximal force output. Fitzhugh in 1973, studied a dynamic grip, performed with angulated handles. At a closing speed of 29 cm/s, the highest force was developed when using an initial handle separation of 83-89 cm. An isometric grip, performed with angulated handles, was of greatest interest to cross-action tool work, because many tasks are performed with such a grip.

Conventional methods for measuring finger forces and grip exertions include subjective magnitude estimation (Stevens, 1962) integrated electromyography (Armstrong, 1979) and installation of transducers, such as strain gauges and force sensors on tools and objects handled. Magnitude estimation is however low in resolution and depends on the objectivity of the participant. Surface electromyography is limited to static exertions, is not specific to individual fingers or locations on the hand, and is not practical for measuring the forces during complex manual work activities. Force transducers attached to handles must be installed on all objects handled and measurements are limited to the locations on the hand.

There exist several sensor systems, which can be used to measure the static or dynamic pressure distribution between visco-elastic surfaces. It is essential that the sensors are thin and flexible, so as to not affect the pressure measurement by changing the interface. Such systems include sensor arrays to measure the pressure distribution at the interface of a hand and an object being handled (e.g. a tool or a container). The sensor technologies can be broken down into,

a) Capacitive sensors, comprising two electrodes with an elastometer in between, whose capacitance changes due to applied pressure, which can be measured electrically (Gurram, 1993).

b) Resistive sensors, comprising two electrodes with a conductive material (e.g. a graphite glue mixture) in between, whose conductivity changes with an applied pressure, or strain gauges, resulting in a change of resistance which can be measured electrically.

Studies on these sensor types have shown the capacitive sensors to have less hysterisis, greater repeatability, no deterioration with time, and superior flexibility (Gurram, 1993).

To study the hand grip pressure distribution a pressure measurement system comprising flexible variable capacitance sensors, a conditioning circuit and data-acquisition software, referred to as the EMED system, was used (*Novel gmbh*, 1989). EMED is an electronic measurement system for recording and evaluating pressure distributions on flat and curved surfaces. The EMED sensor consisted of a pressure-sensing element sandwiched by an elastic synthetic mat. These sensors are flexible and are capable of obtaining pressure measurements even on curved surfaces. The measurement system provided digital voltage (AD) values proportional to the variations in sensor capacitance with the applied load (Gurram, 1993).

In order to be able to measure pressures at the interface of a hand and a handle Gouw in 1996, designed two mats of 10cm × 4cm each with the variable capacitive pressure sensors described above. Each mat had 12 sensors of 1cm × 1cm. One mat covers the complete palmar surface of the hand. Another mat covers the four fingers: index, middle, ring and little. These mats are used with the hardware and software previously obtained. Obviously, the mat that covers the fingers part of the hand, would not record pressure in the gaps between the fingers while gripping the tool. The mat configuration is shown in the figure 2.5 below.

Gouw (1996) used a split cylindrical handle for this study (figure 2.7), as large varieties of hand tools have a cylindrical shaped handle. The radius of the cylinder with the mounted sensors was 12.7 mm and its length is 100 mm. To facilitate exertion of force and hand movement, the two half cylinders were separated by a gap of 25 mm. The surface area of the handle is considered to span the total area of a normal human hand including the palmar (proximal) and fingers (distal) portion.

Gouw asked the subjects to grip the fixed handle made of two half cylinders in various wrist positions such as neutral position, dorsal flexion, palmar flexion, radial deflection and ulnar deviation. Figure 2.6 shows various wrist positions, as to how a subject can grip the handle. The pressures measured by the sensors on both halves of the cylindrical are recorded. Figure 2.7 shows the split cylindrical handle with the sensors mounted on it and figure 2.8 shows a subject's hand gripping the cylindrical handle in the neutral position of the hand.

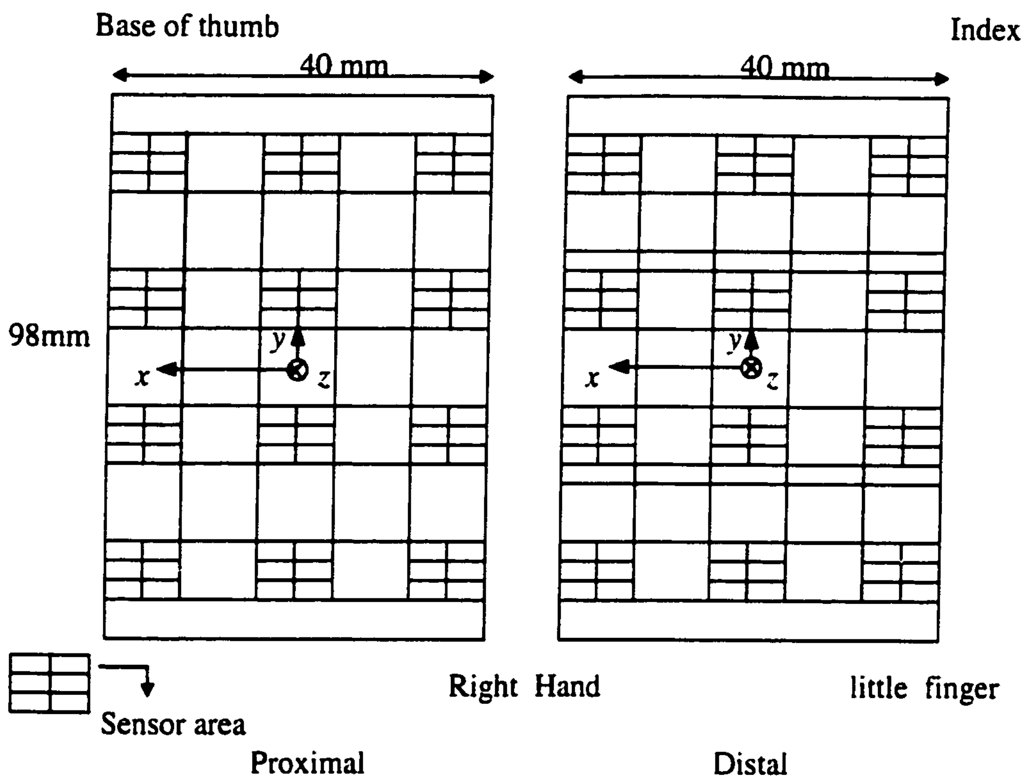


Figure 2.5 Schematic diagram of the configuration of the sensor mats on each half.

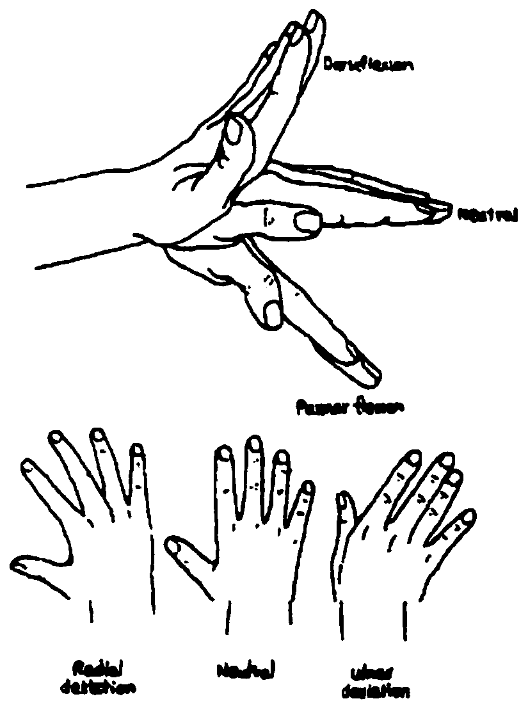


Figure 2.6 Movements of the wrist joint about two axis (Sanders., M.S., 1987).

Figure 2.7. The split cylindrical handle with sensors mounted on it.

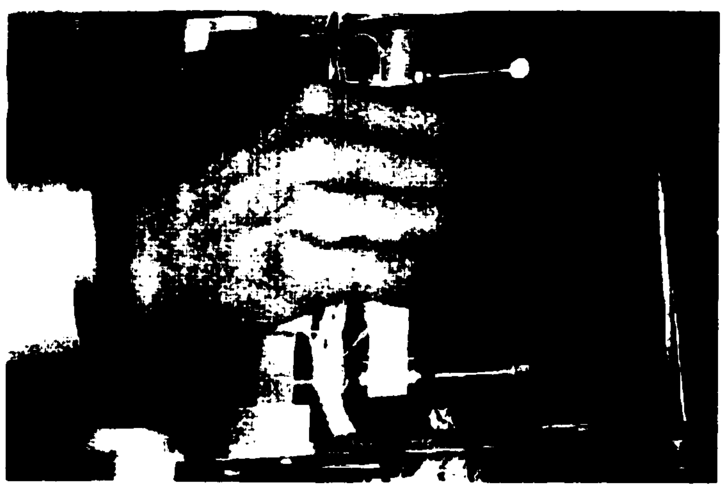


Figure 2.8. A subject's hand gripping the handle in neutral position.

The above experiments provided a discrete set/array of grip pressures (3×4 on each side) that are distributed on the proximal (palmar) and distal (fingers) side of the hand, of each subject. This discrete array of pressure values doesn't obviously give the whole pressure distribution on the entire surface area of the hand. So, to find this complete pressure distribution, there is a requirement for interpolating these points. As a first step, a discrete linear interpolation technique was used, to obtain a rough idea of the total forces and moments on the hand. As a next step '*SPLINE*' interpolation technique was used to obtain a finer and more precise array that resembled the overall grip pressure distribution of the hand. This gave better and more accurate data. The 3×4 points that are discrete were interpolated three dimensionally in X, Y and Z axes, using 'cubic spline interpolation'. Cubic spline interpolation is explained in the next section. This resulted in a 99×41 point mesh of the overall grip pressure distribution. It can be visualized that this array of pressures is obtained by placing sensors at each mm of the cylindrical handle, which may not be possible conventionally.

2.4 Spline data interpolation

To ruin or to break something is much simpler than to carefully accrue and glue together the fragments, and to do it in such a way that the creation is meaningful, clear and a pleasure for the eye. In this section, the way the arbitrary data of the grip pressure distribution obtained from the experiments, was interpolated using the most efficient and effective interpolation technique - *splines*, is explained.

In the cubic spline interpolation a curve or surface is constructed by the points through the choice of necessary fragments after a description of the desired curve or surface by the array of the support points is chosen correspondingly (Skikin, E.I., Plis, E.I., 1995). Solving the problem of the construction of the curve or surface is divided into the following steps: 1) Determination of a suitable set of support points, 2) development of a universal and relatively simple method for constructing the elementary fragments of the curve or surface, 3) search for an effective mechanism for a smooth joining of the elementary fragments, and 4) analysis of the results.

It is clear that the solution of the problem is not unique, since the smoothing curve or surface in a number of ways may approximate the given array of points. At the same time, when solving specific problems, it is necessary, as a rule, to find only one approximating, sufficiently well behaved object. For this reason it would be prudent to first understand clearly what object plays the role of a needle in a haystack of possibilities. Due to this reason several combinations were being interpolated and the best result was selected for the analysis. The interpolation was made from one edge to another along the circumference, and from one end to another end along the cylindrical handle. The data points were chosen to be zero at the ends of the handle. The advantage of spline interpolation is a graph of the constructed function passes through every point of the given array. The constructed function is uniquely determined by the given array. The constructed function possesses good approximation properties. To obtain an overall hand grip pressure distribution, the discrete pressure data points were interpolated using MATLAB spline toolbox software.

2.5 Results and Discussion

The subjects were asked to grip the cylindrical handle in various wrist positions such as medial position, lateral position, extended position and flexed position. The pressure readings measured by the sensors on both halves of the cylindrical handle are recorded in the computer. These pressure recordings provided a discrete set/array of grip pressures (3×4 on each side) that are distributed on the proximal (palmar) and distal (fingers) side of the hand, of each subject. In order to obtain the overall pressure distribution of a subject's hand, it is required to interpolate these points over the surface area of the hand. Figure 2.9 shows sensor locations of discreet distribution of recorded pressure values.

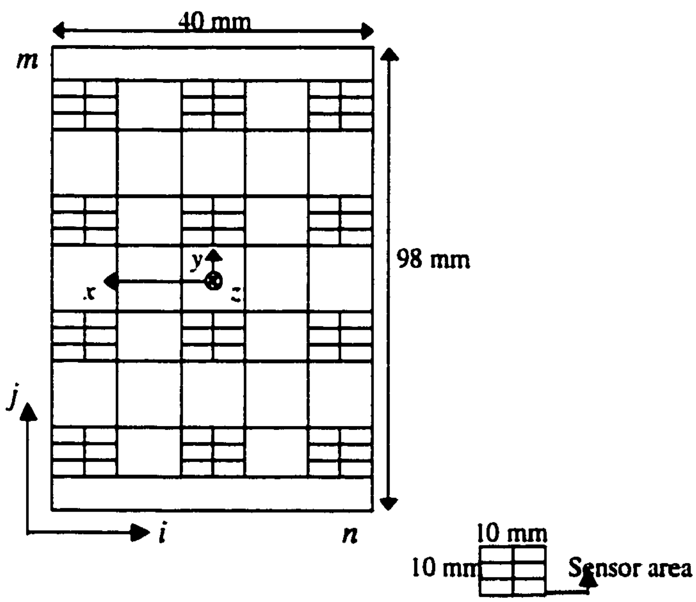


Figure 2.9 Sensor locations showing regions of discrete pressure recordings.

Firstly, a discrete linear interpolation technique was used, to obtain a rough idea of the total forces and moments on the hand. The linear interpolation was not a perfect measure of the overall grip pressure distribution as it was a coarse interpolation. As a next step the discreet points (grip pressure values) were interpolated using cubic spline interpolation, to obtain a finer and more precise array that resembled the overall grip pressure distribution of the hand.

The 3×4 points that are discrete were interpolated three dimensionally in X, Y and Z axes, using 'cubic spline interpolation'. This resulted in a 99×41 point mesh of the overall grip pressure distribution. In the analysis of obtaining a precise overall GPD, another vital point that was noted down and taken into consideration was the area of region each sensor covered. Each sensor covered one cm^2, whereas the resulting spline interpolated GPD gives values at each mm^2 of the overall span of grip. Care was taken to ensure that the average pressure over a region covered by a sensor calculated using the interpolated GPD was equal to the pressure measured by that same sensor.

The discrete values of recorded pressure for all the four subjects and the corresponding overall hand surface grip pressure distribution plots on the palmar as well as fingers side, for all the four subjects in the neutral grip position is shown in the figures 2.10 a, b, c, d, and figures 2.11. The contour plots obtained for the hand grip pressure distribution were also shown in the figures.

Subject One

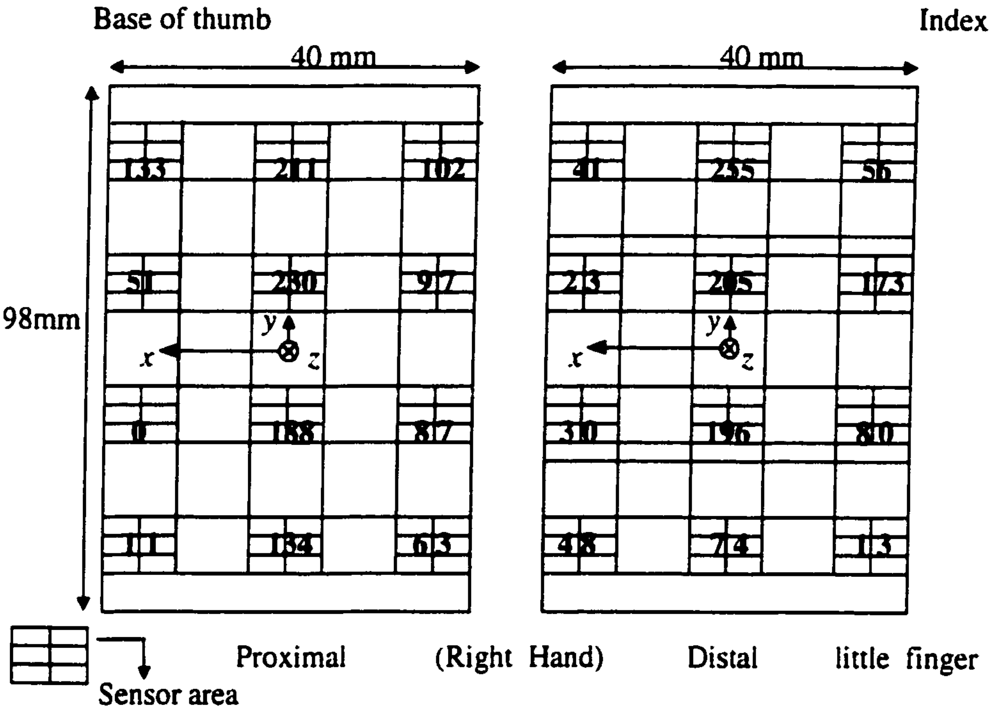


Figure 2.10a Data values obtained for subject one.

Subject Two

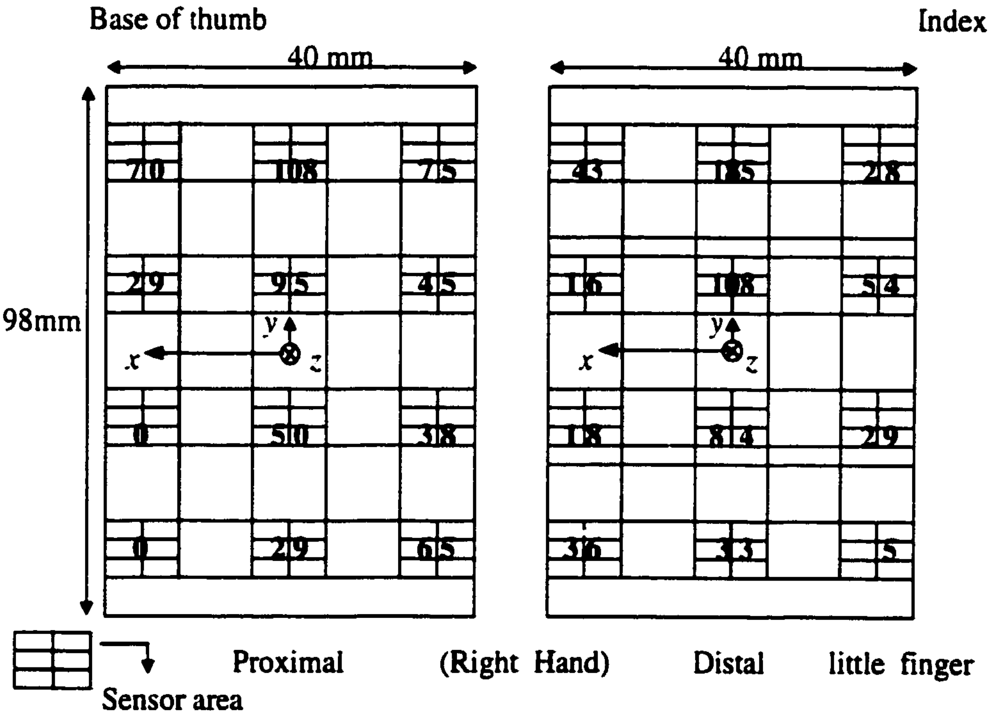


Figure 2.10b Data values obtained for subject two.

Subject Three

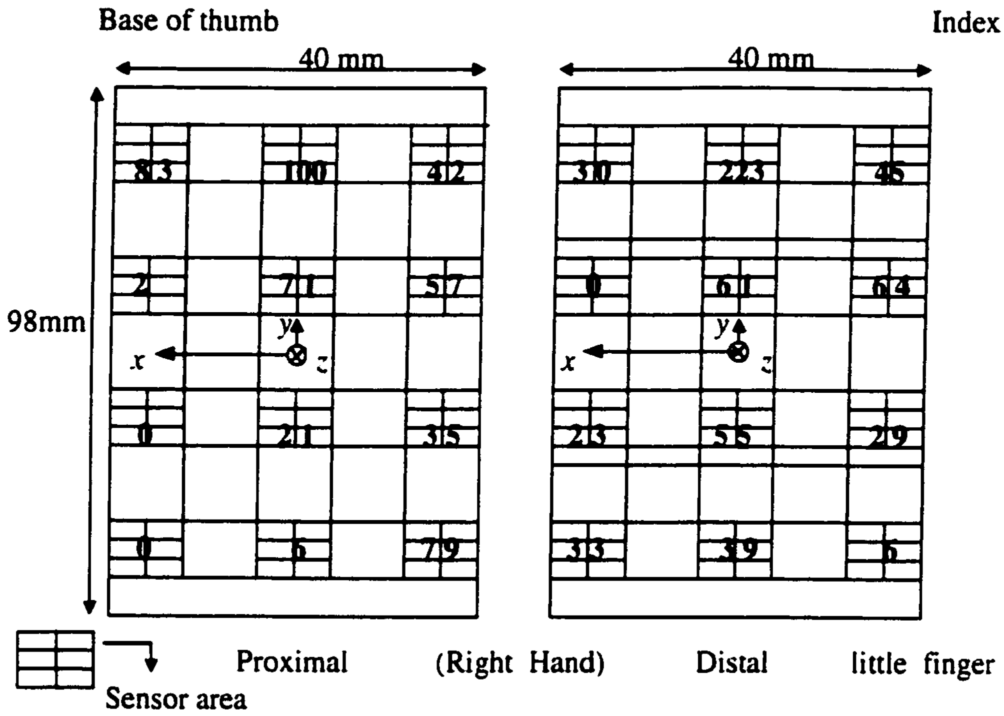


Figure 2.10c Data values obtained for subject three.

Subject Four

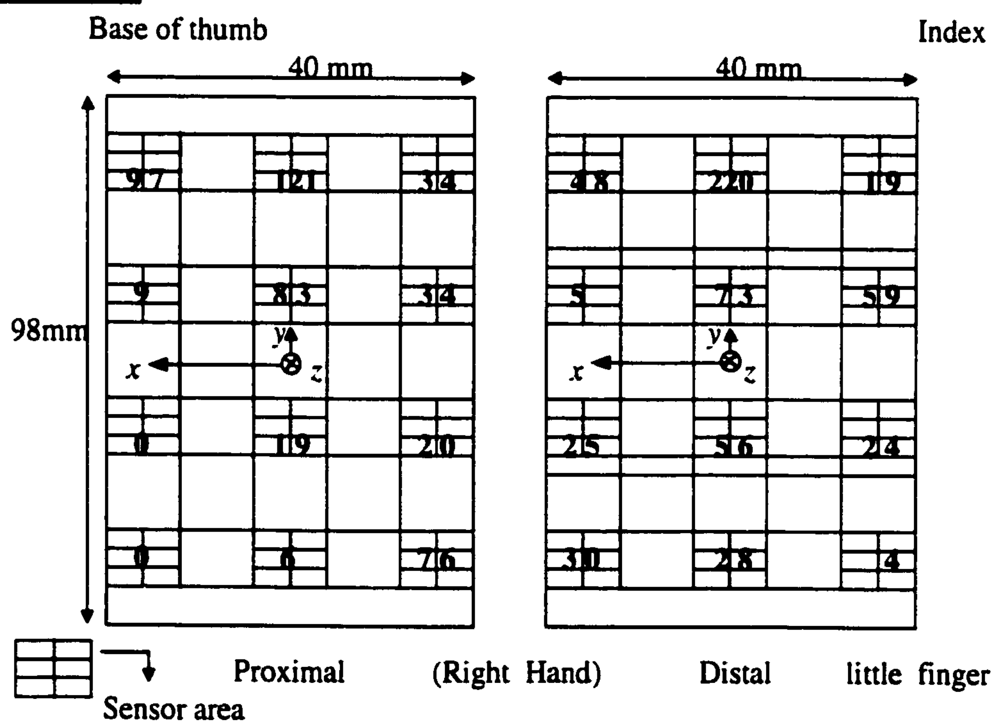


Figure 2.10d Data values obtained for subject four.

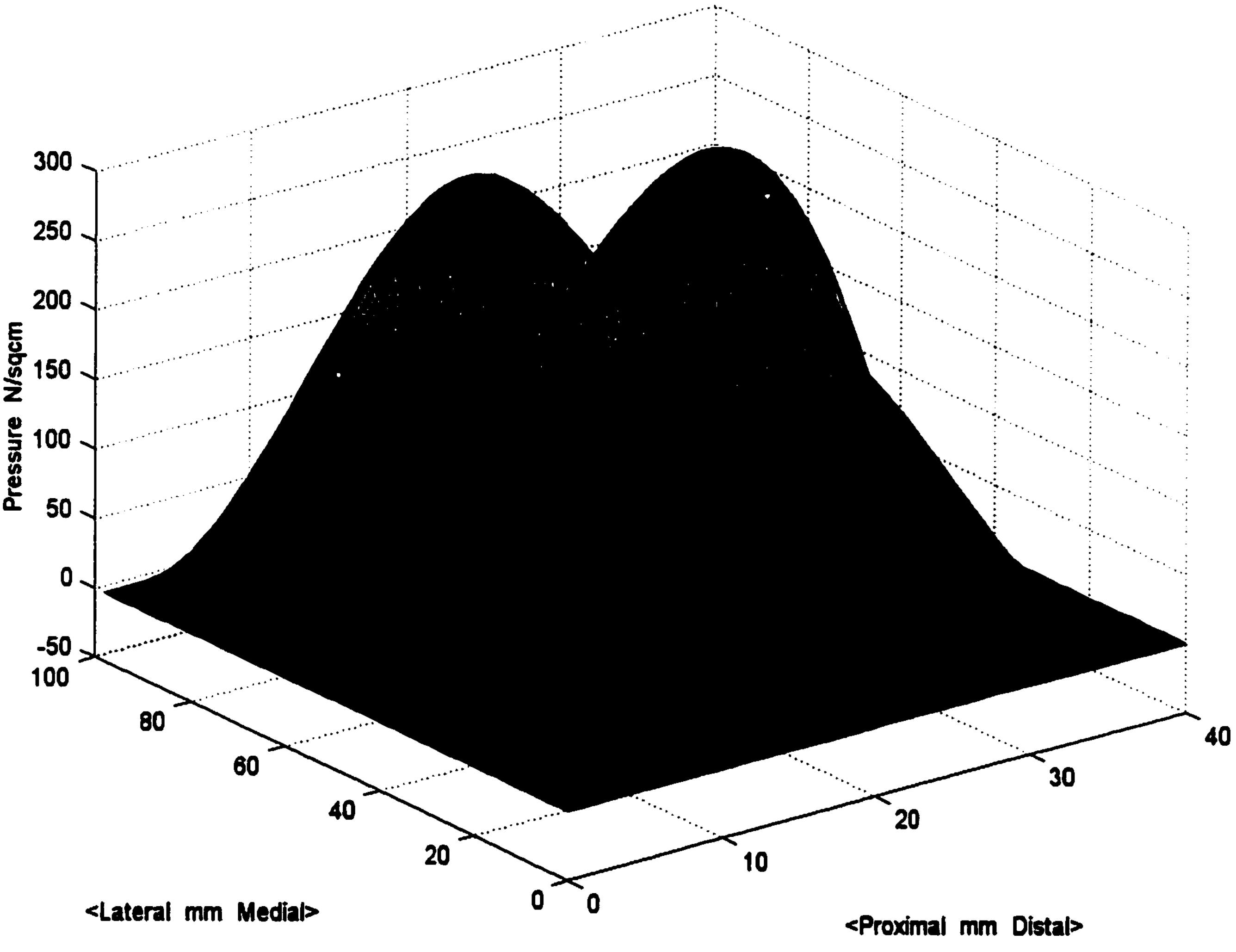


Figure 2.11a. Grip Pressure Distribution on fingers side of right hand of subject one.

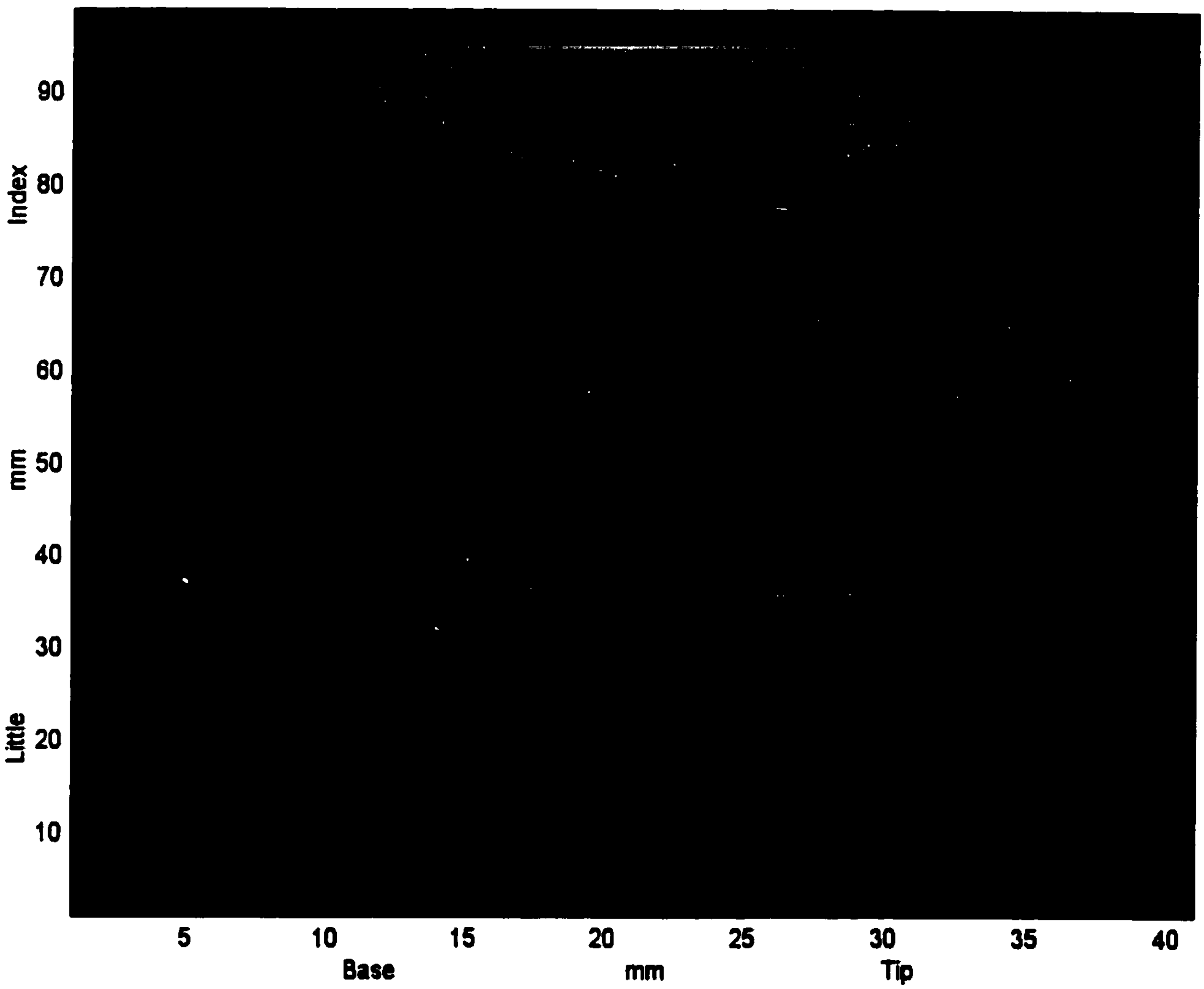


Figure 2.11b. Contour plot of Grip Pressure Distribution on fingers side of right hand of subject one.

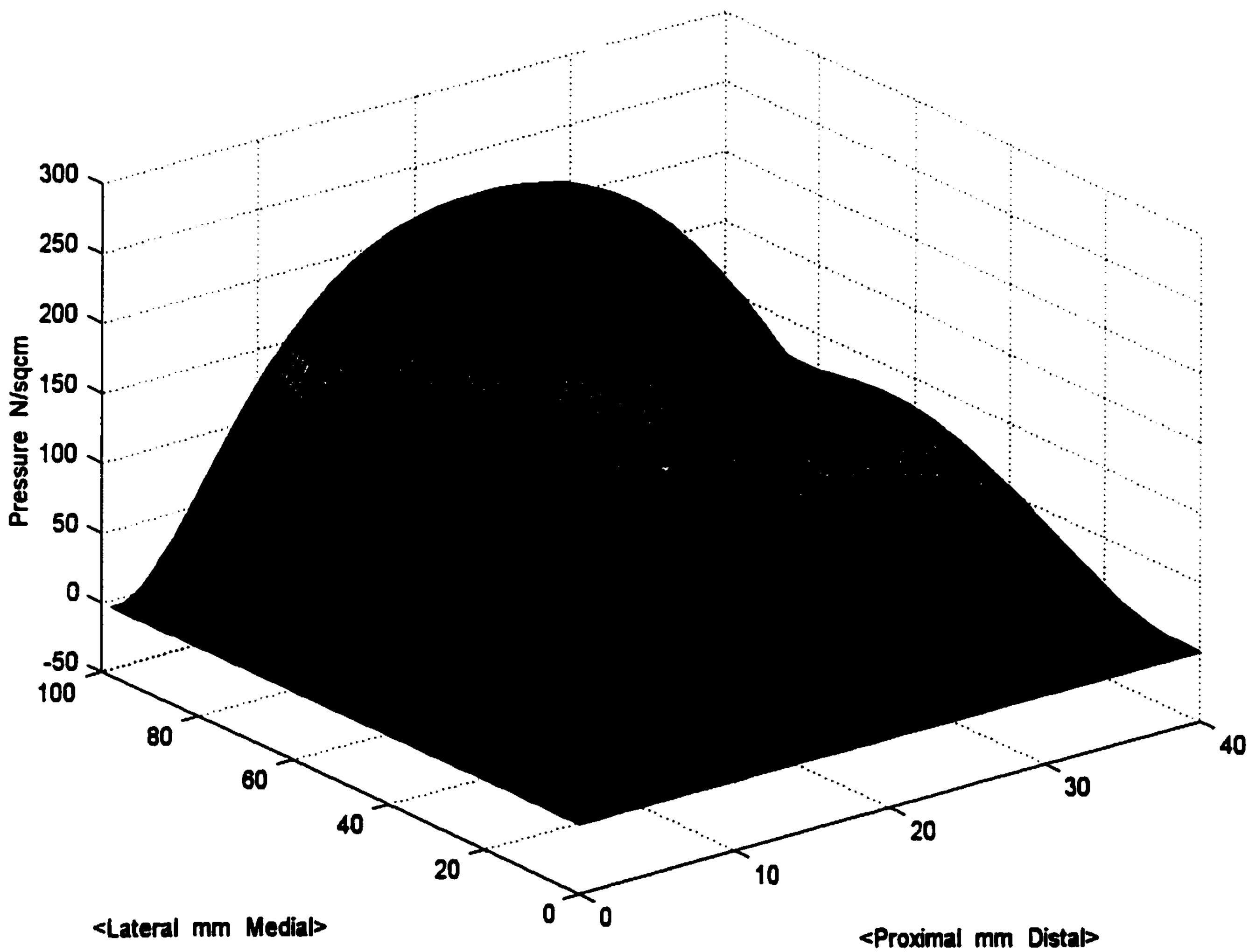


Figure 2.11c. Grip Pressure Distribution on palmar side of right hand of subject one.

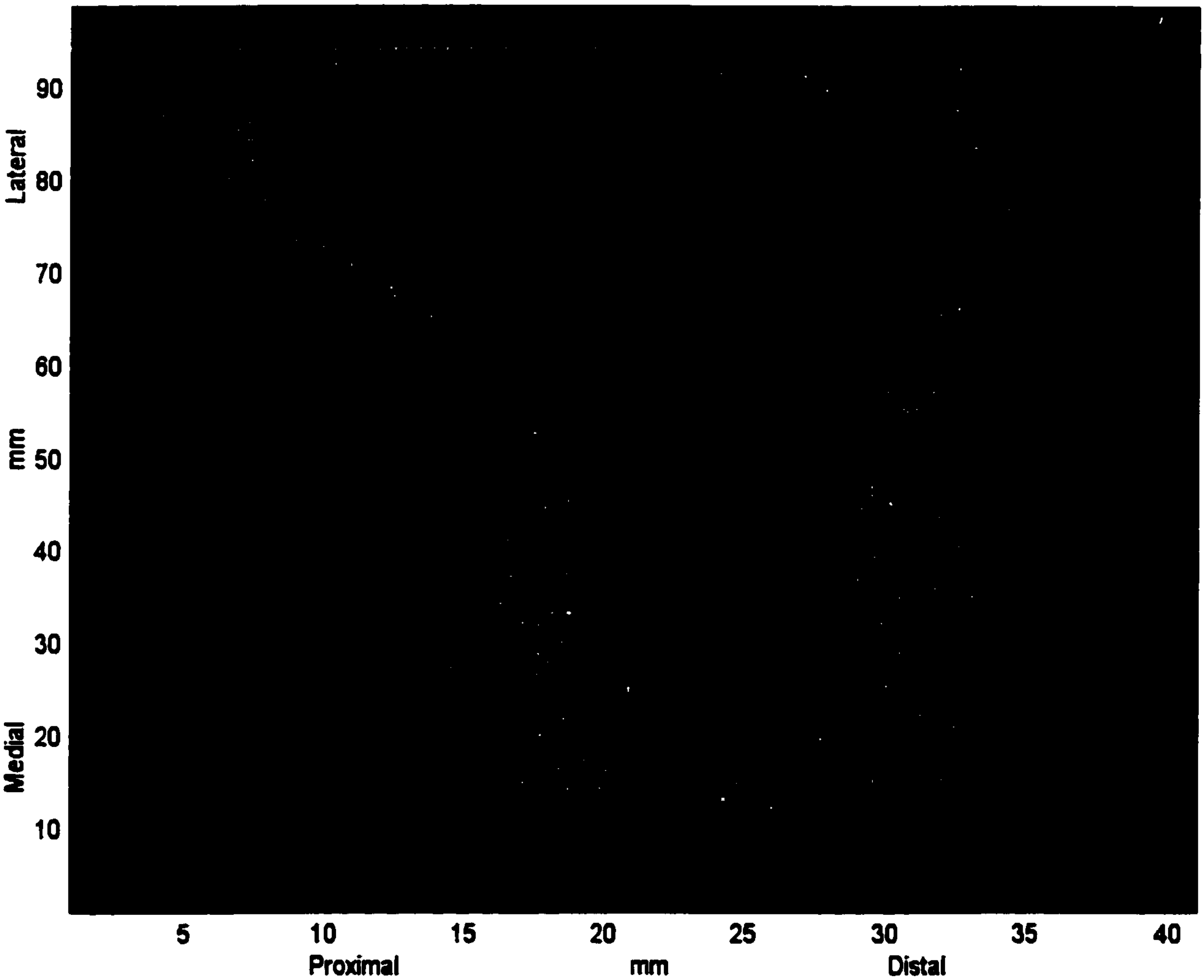


Figure 2.11d. Contour plot of Grip Pressure Distribution on palmar side of right hand of subject one.

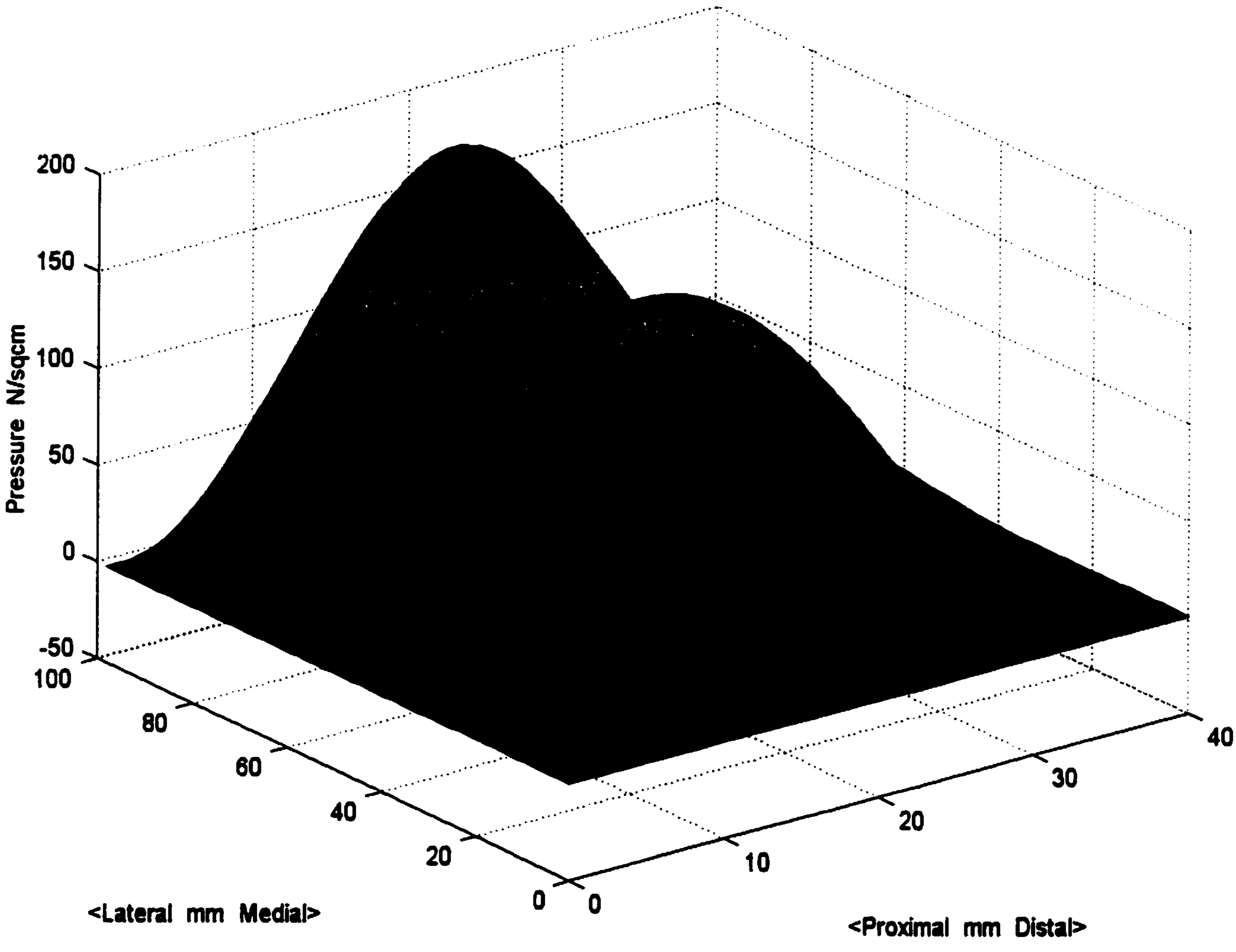


Figure 2.11e. Grip Pressure Distribution on fingers side of right hand of subject two.

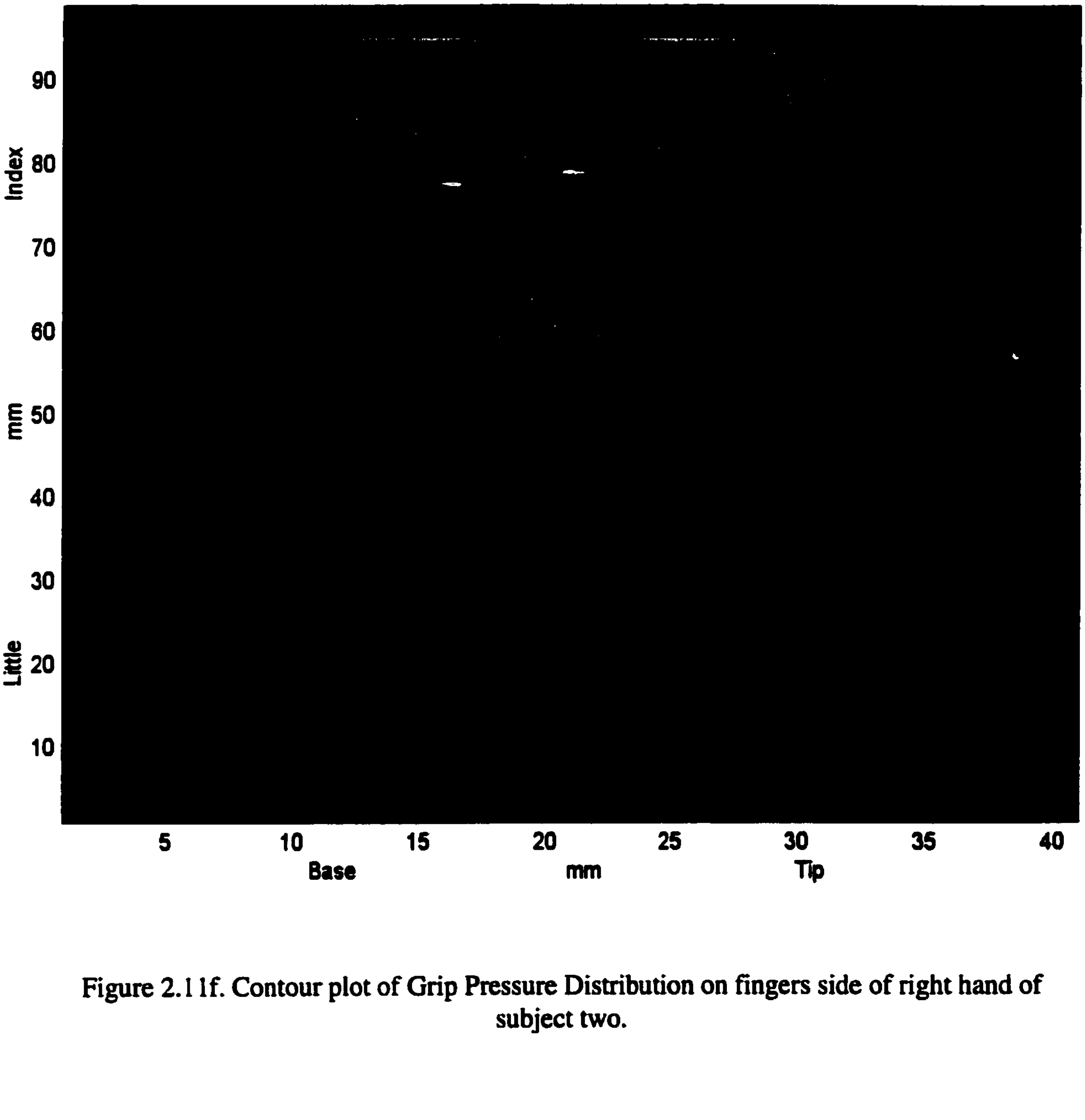


Figure 2.11f. Contour plot of Grip Pressure Distribution on fingers side of right hand of subject two.

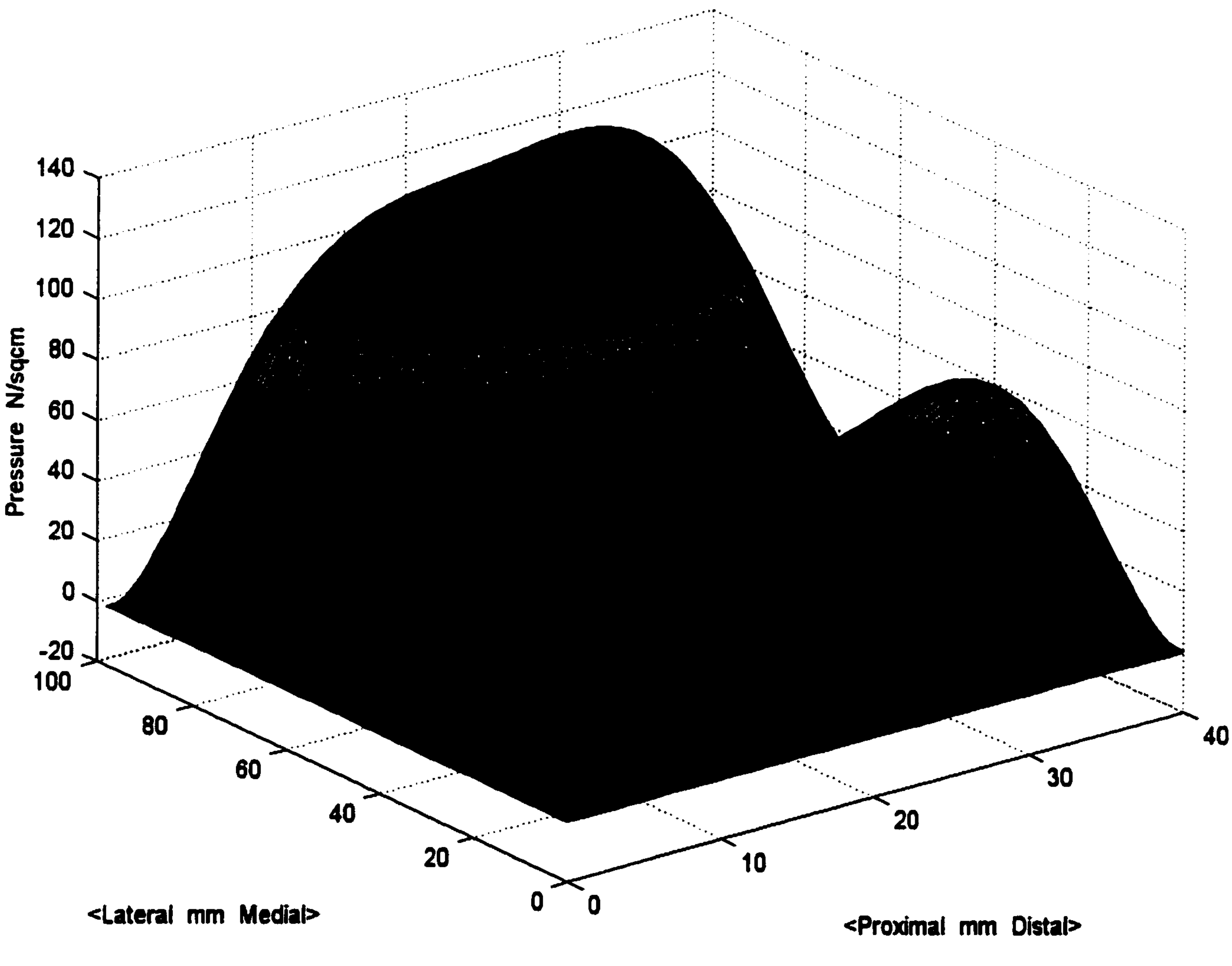


Figure 2.11g. Grip Pressure Distribution on palmar side of right hand of subject two.

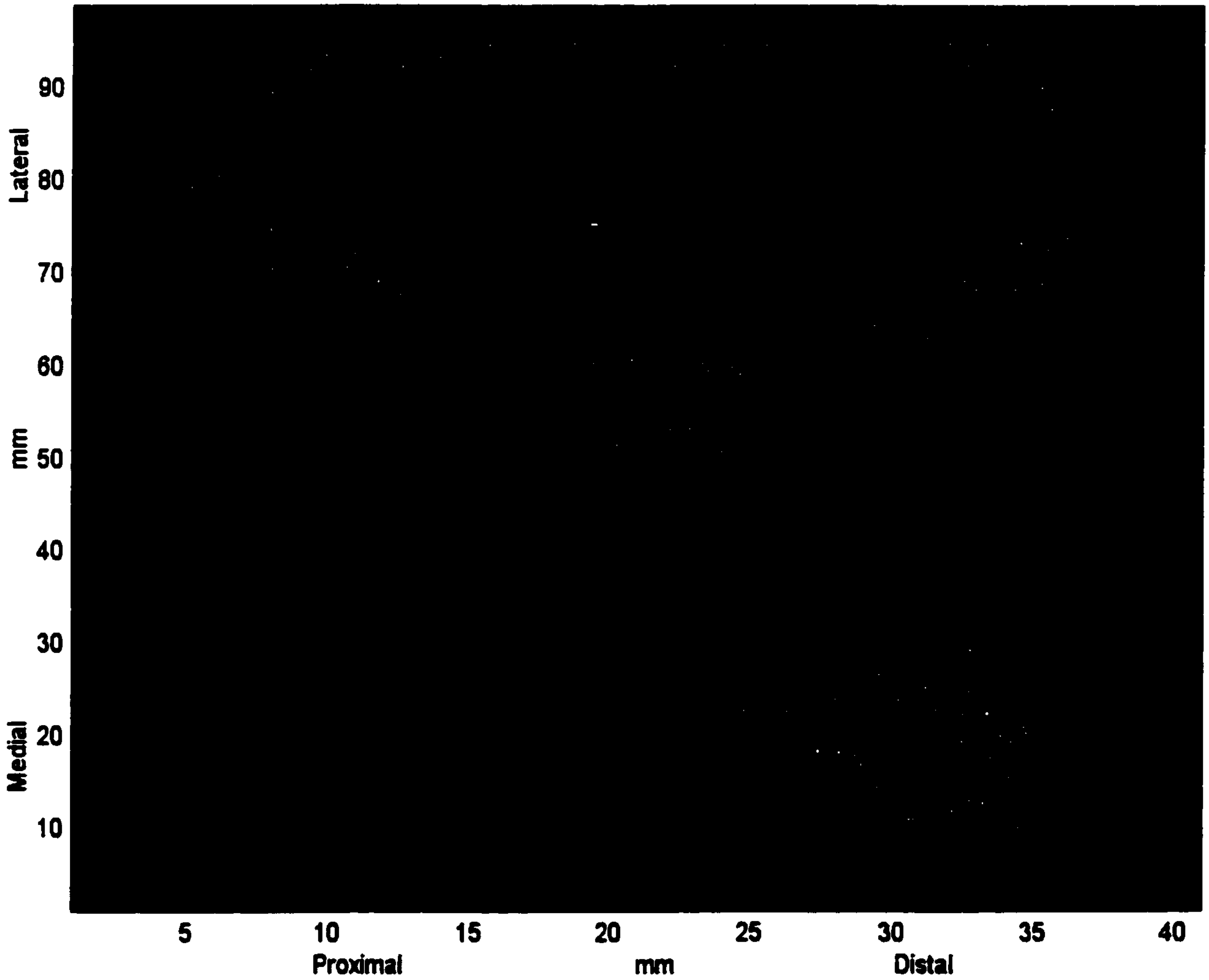


Figure 2.11h. Contour plot of Grip Pressure Distribution on palmar side of right hand of subject two.

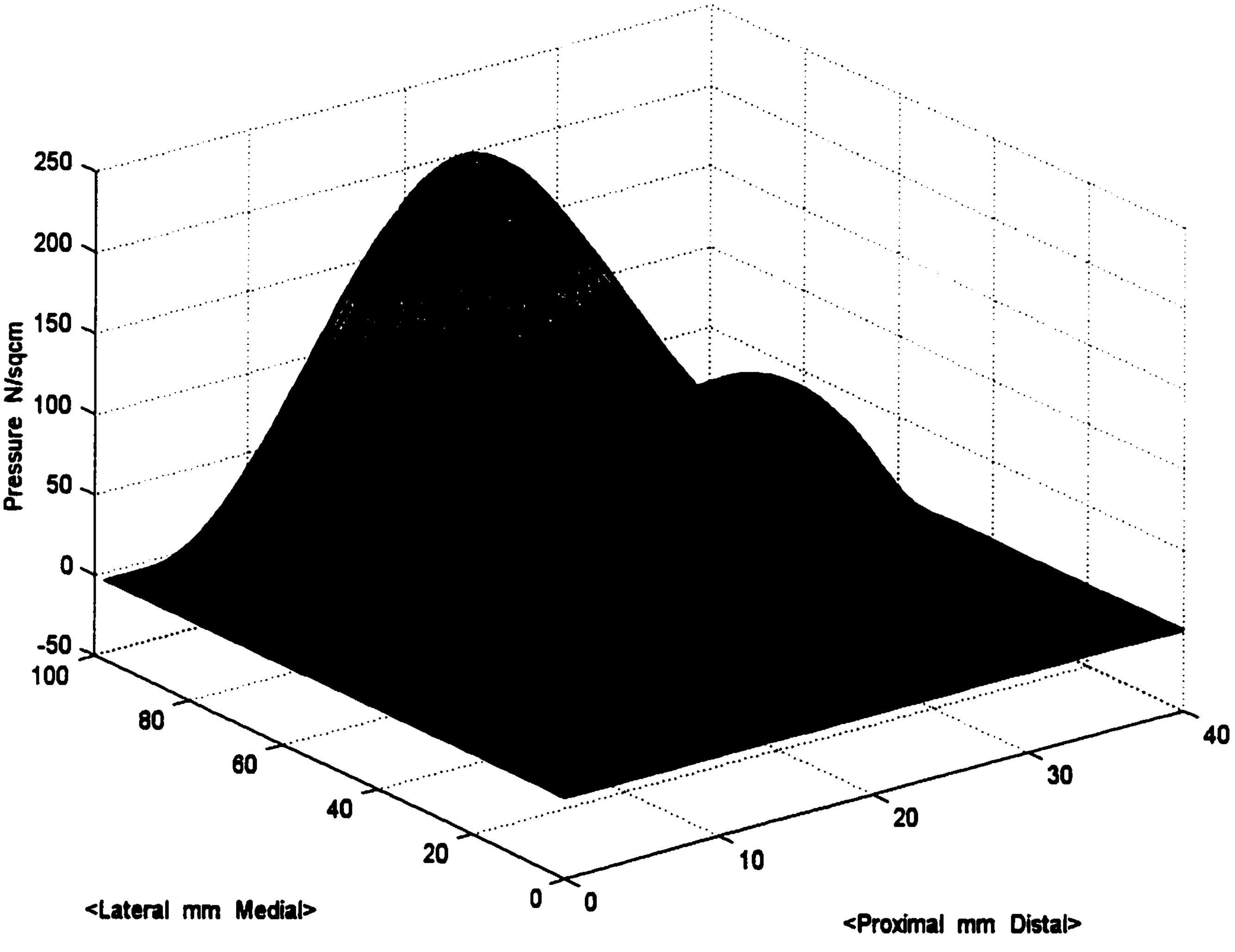


Figure 2.11i. Grip Pressure Distribution on fingers side of right hand of subject three.

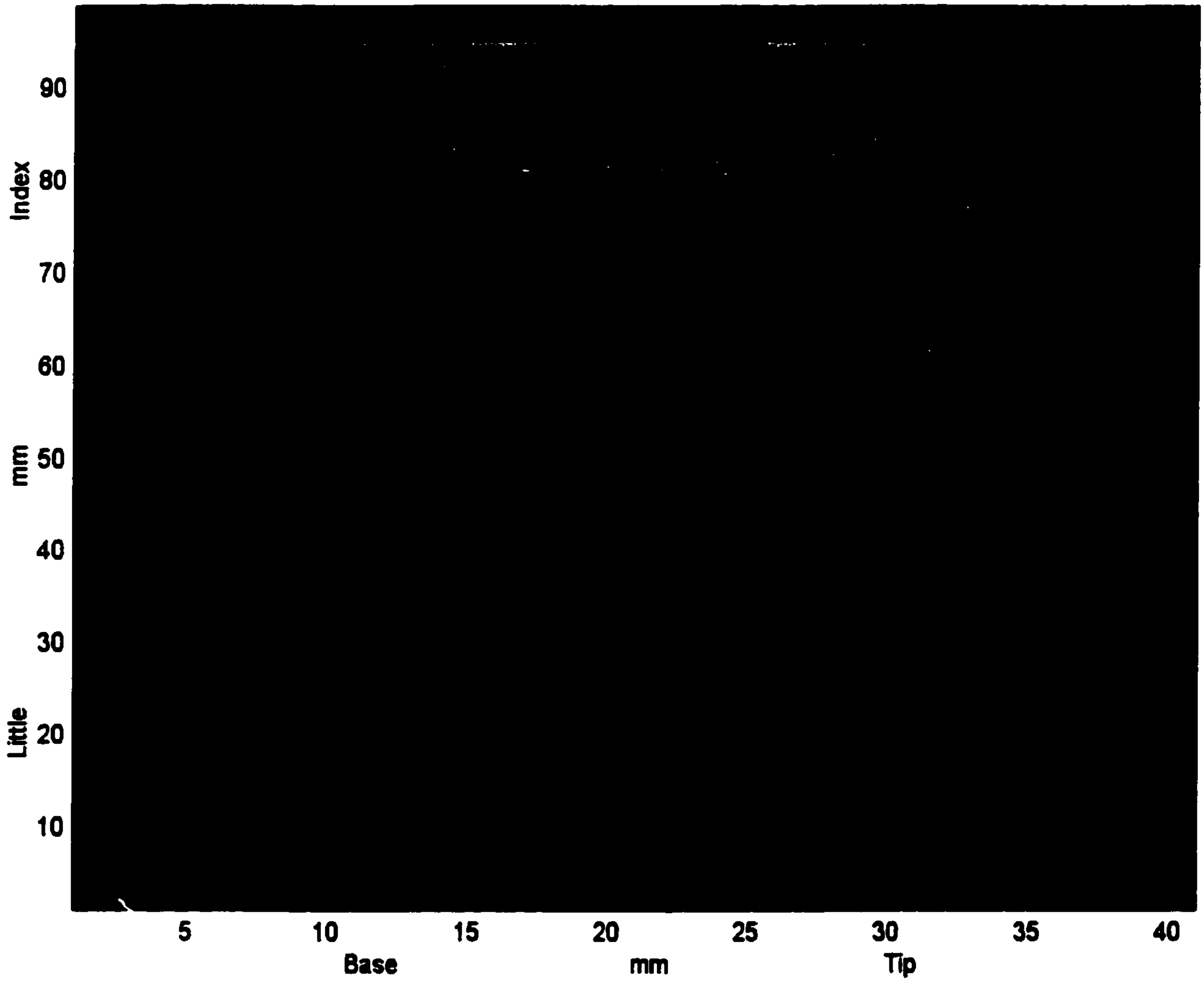


Figure 2.11j. Contour plot of Grip Pressure Distribution on fingers side of right hand of subject three.

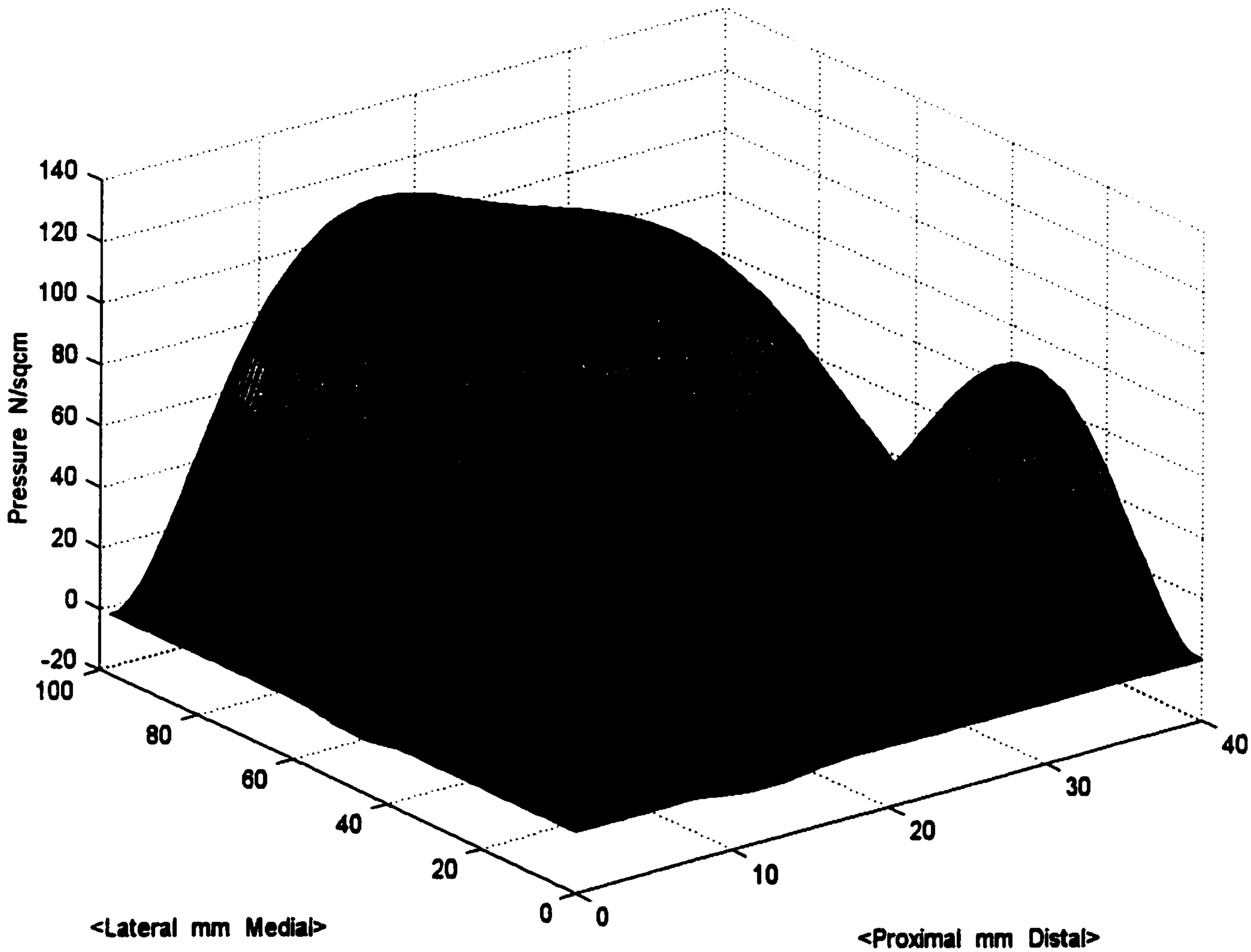


Figure 2.11k. Grip Pressure Distribution on palmar side of right hand of subject three.

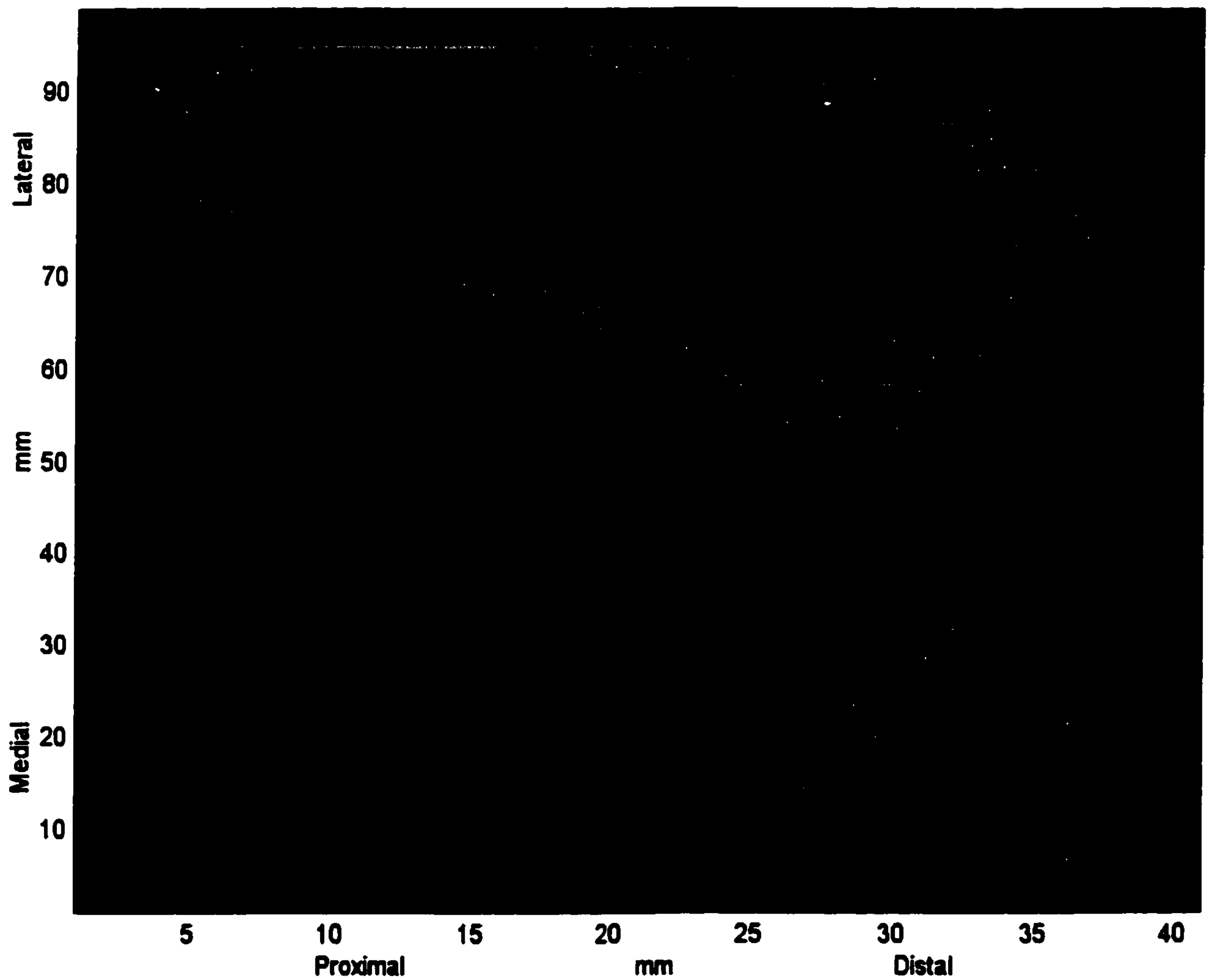


Figure 2.1 11. Contour plot of Grip Pressure Distribution on palmar side of right hand of subject three.

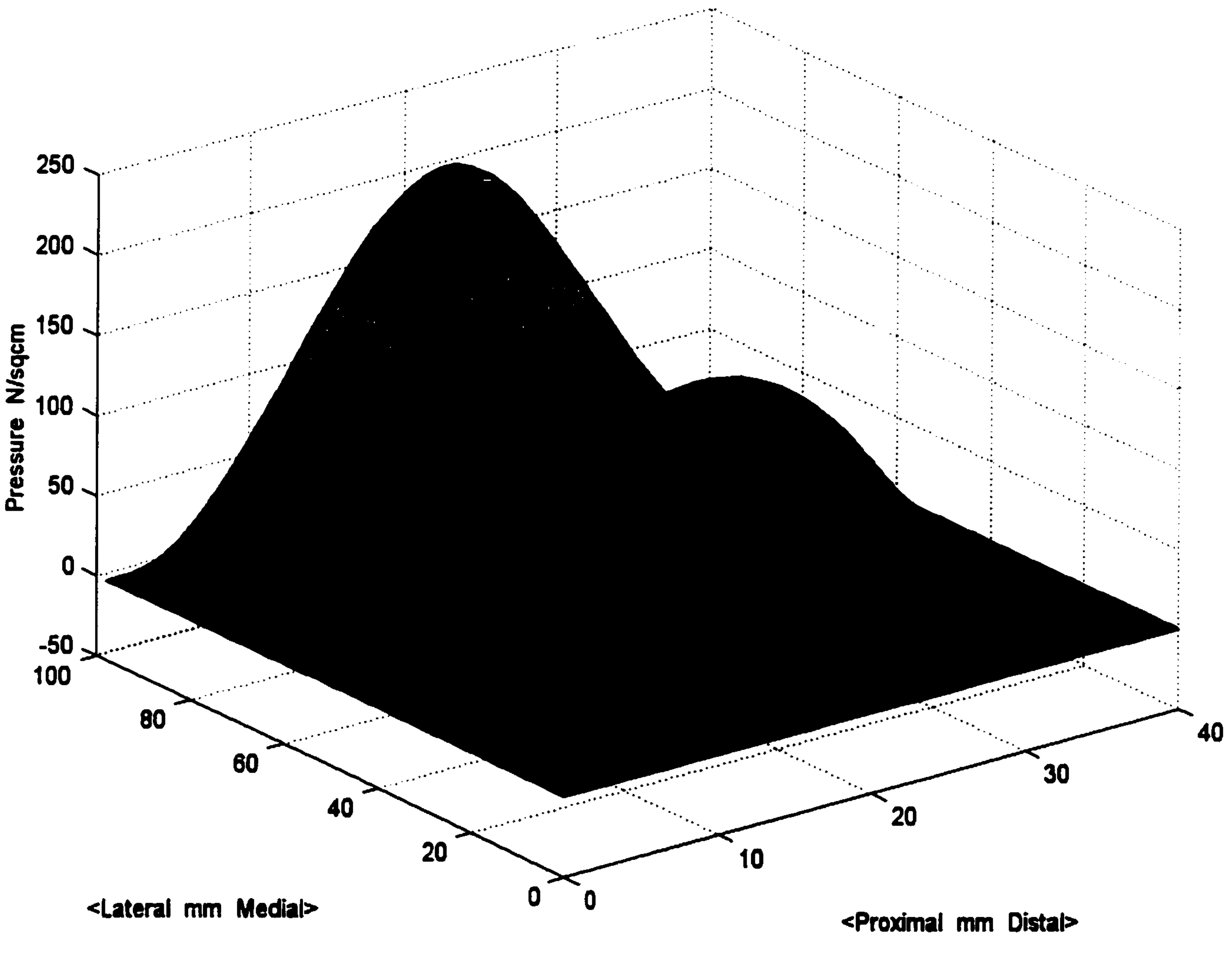


Figure 2.11m. Grip Pressure Distribution on fingers side of right hand of subject four.

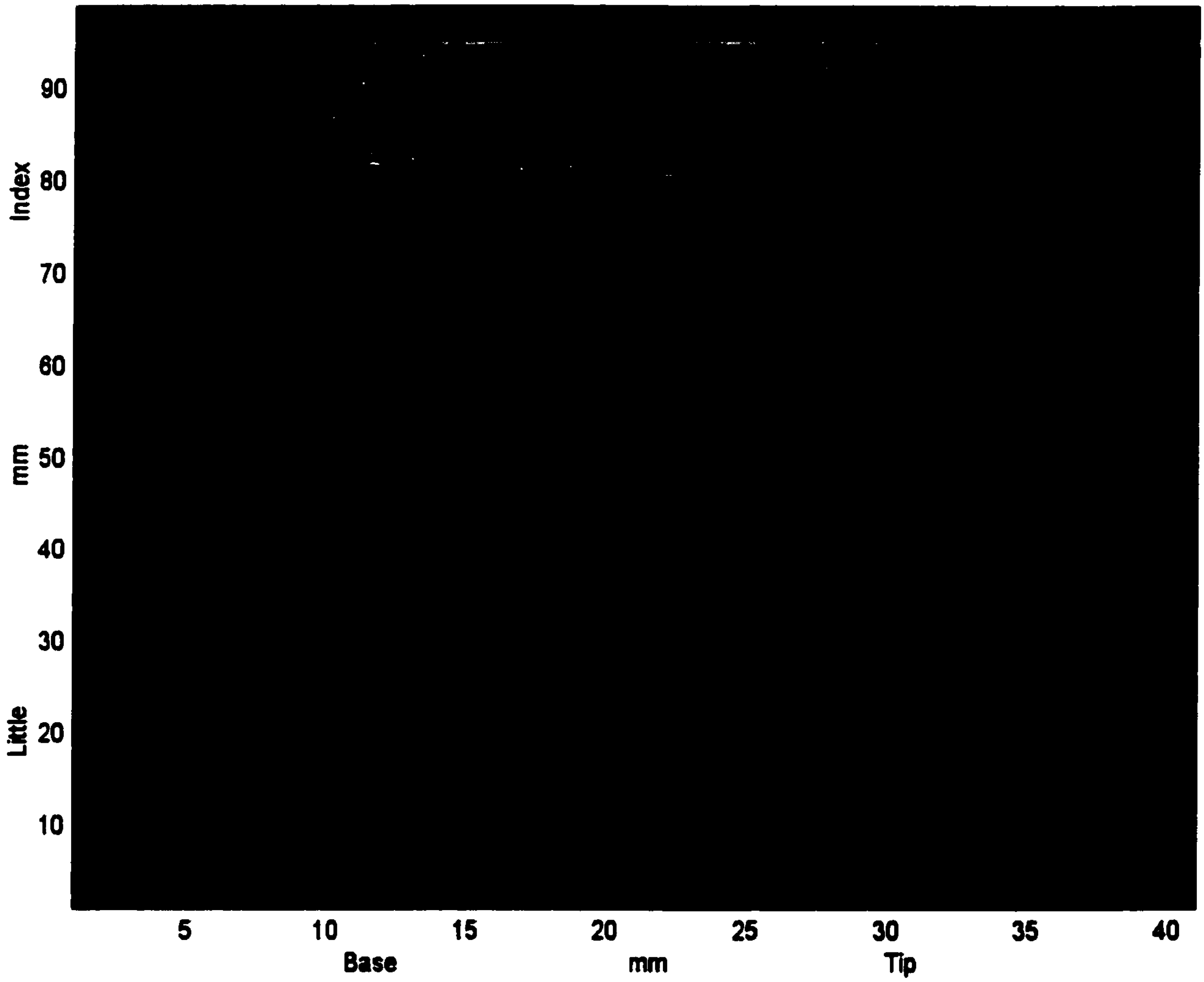


Figure 2.11n. Contour plot of Grip Pressure Distribution on fingers side of right hand of subject four.

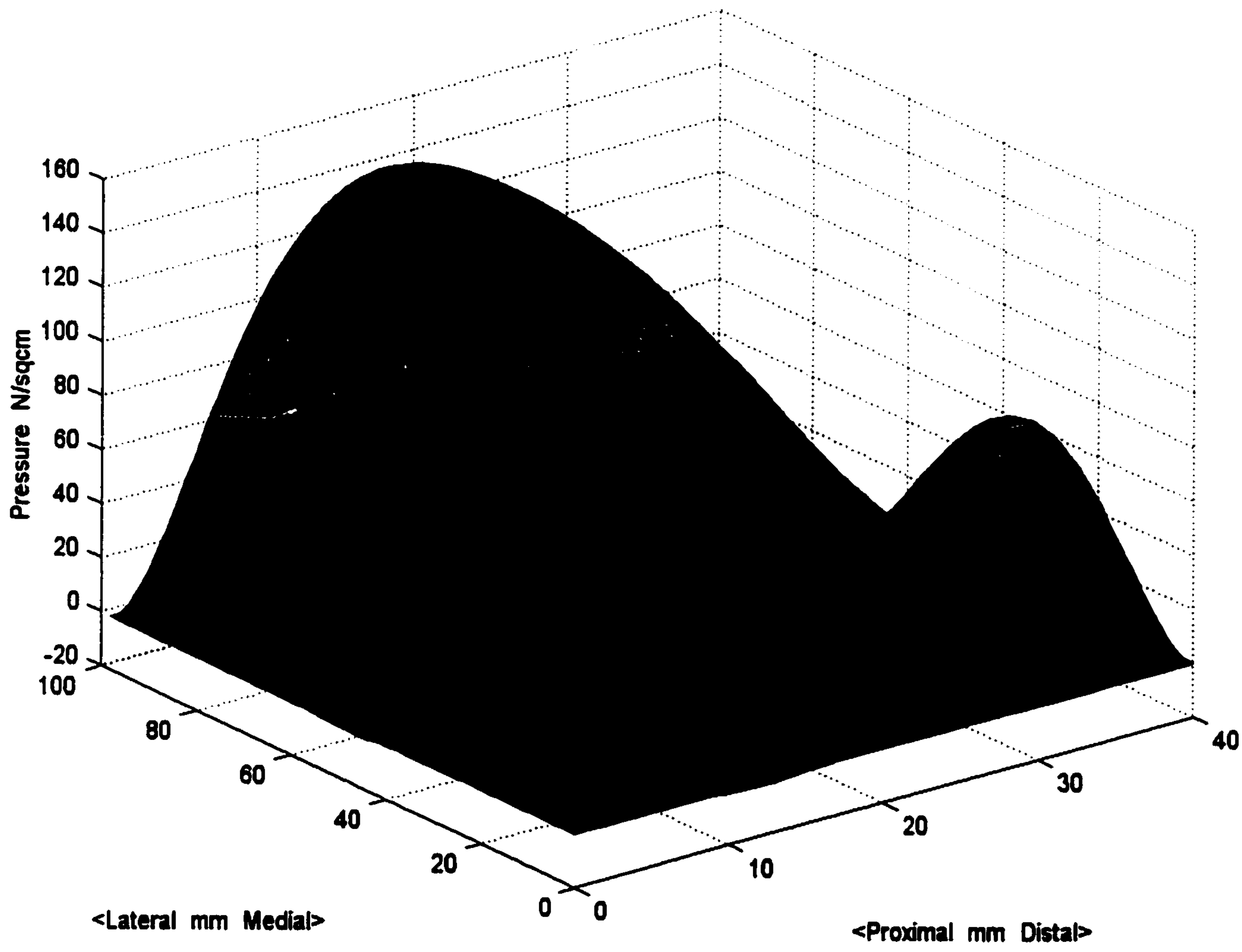


Figure 2.11o. Grip Pressure Distribution on palmar side of right hand of subject four.

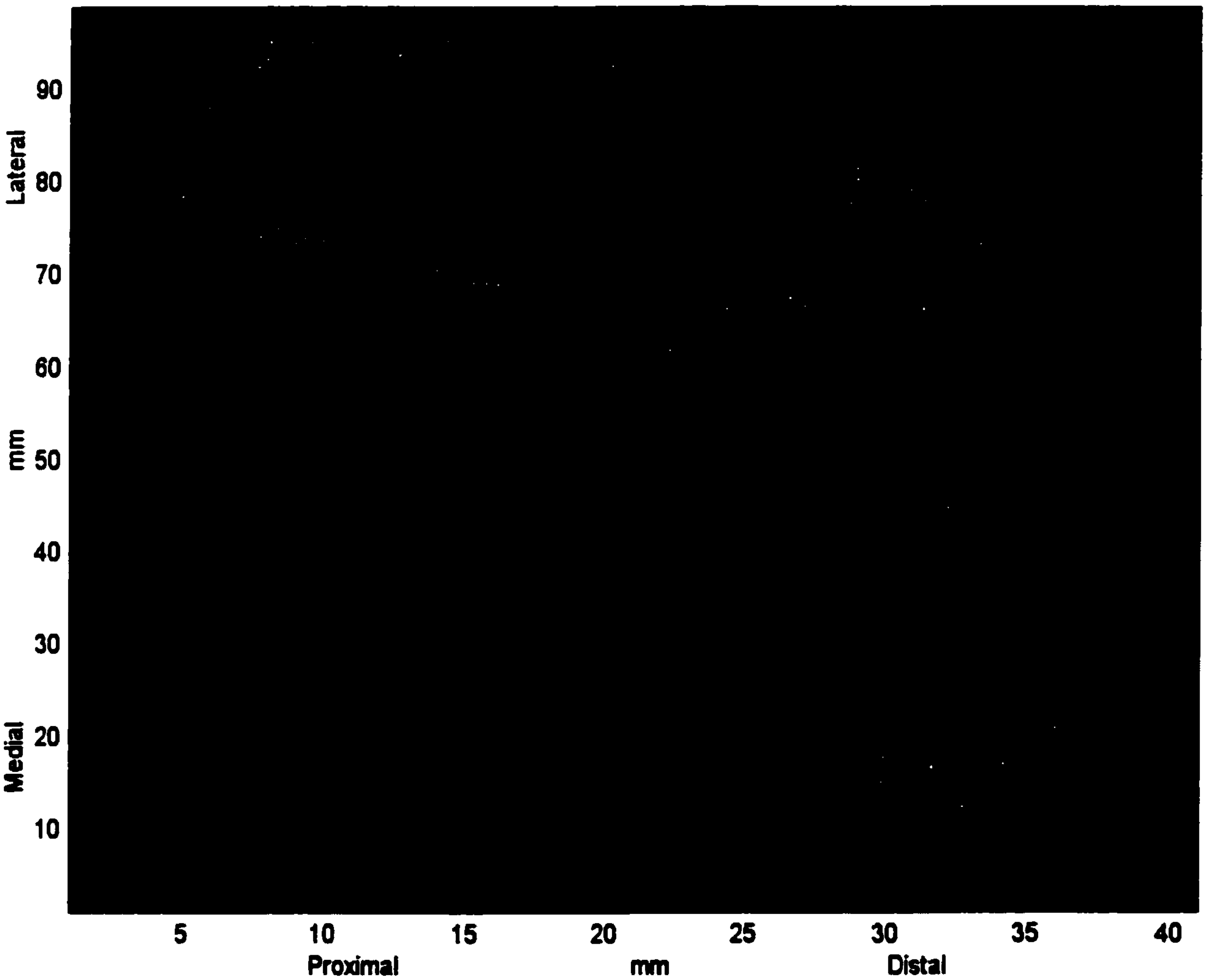


Figure 2.11p. Contour plot of Grip Pressure Distribution on palmar side of right hand of subject four.

This study was made using a cylindrical handle, which was gripped by several subjects. The grip pressure distribution (GPD) is closely related to the force applied on the handle, since pressure equals force per unit area. The grip pressure distribution is dependent on the diameter of the cylinder as well as the amount of force applied. During grasping around a cylindrical object, the finger phalanges are exposed to the largest pressure, while only negligible pressure is applied to the palmar area. In these experiments under static gripping of the cylindrical handle, the finger phalanges are exposed to the largest localized pressures, while comparatively lesser localized pressures are applied to the palmar region (comparing figures 2.11 a and c and figures 2.11 e and g). Moreover, high grip pressures are present at the tips of the index and middle fingers (figures 2.11 a, e, i, and m). When the overall hand is taken into consideration, higher grip pressures are present on the lateral half of the hand than that on the medial half.

On the fingers region, the lowest pressures were recorded at the distal phalanx of the little finger (figure 2.11a), and the highest pressures were recorded at the distal and the middle phalanges of the index and the middle fingers. On the palmar region, lowest pressures were recorded at the proximal and medial regions of the palm, and the highest pressures were recorded at the distal and lateral regions of the palm (figure 2.11c). This was observed in all the subjects. According to the above inferences, the lowest pressure on the finger side is recorded as 2 dN/cm^2 (0.3 Psi) and the highest pressure is recorded as 255 dN/cm^2 (35 Psi). On the palmar side the lowest pressure is recorded as 5 dN/cm^2 (0.7 Psi) and the highest pressure is recorded as 220 dN/cm^2 (32 Psi).

A study was made to analyze the forces and moments acting on the operator's hand, who uses typical hand held power tools. The significance of this study is to know the magnitude and direction in which the operator's hand tends to move or rotate. Figure 2.12. shows the coordinate system of the hand related to the split cylindrical handle and the way a subject grips the handle. It is important to know whether the operator's hand is exerting a push or a pull force (in Z direction); pronation or supination moment (about Z); sideways force in the medial or lateral direction (in X direction); ulnar deviation or medial deviation moment (about X direction); flexion or extension moment (about Y direction). The calculation of the net forces and moments reveals the resultant direction in which the hand tends to move, and the direction in which it produces the reaction forces. This study also explains whether the hand is in equilibrium position or not, and whether the posture would be comfortable or not.

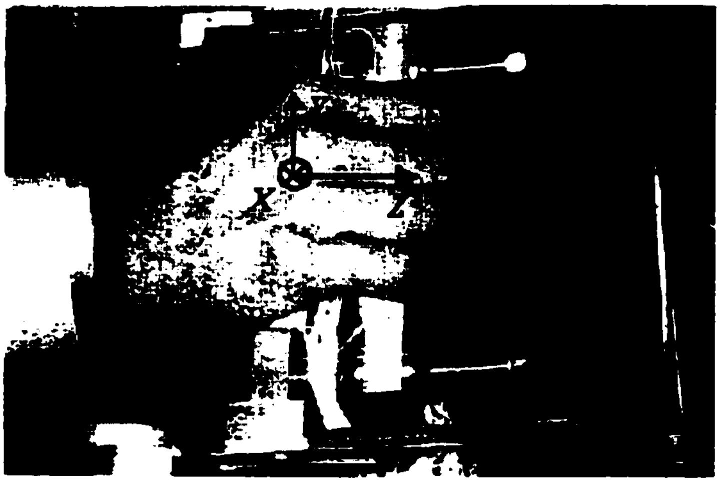
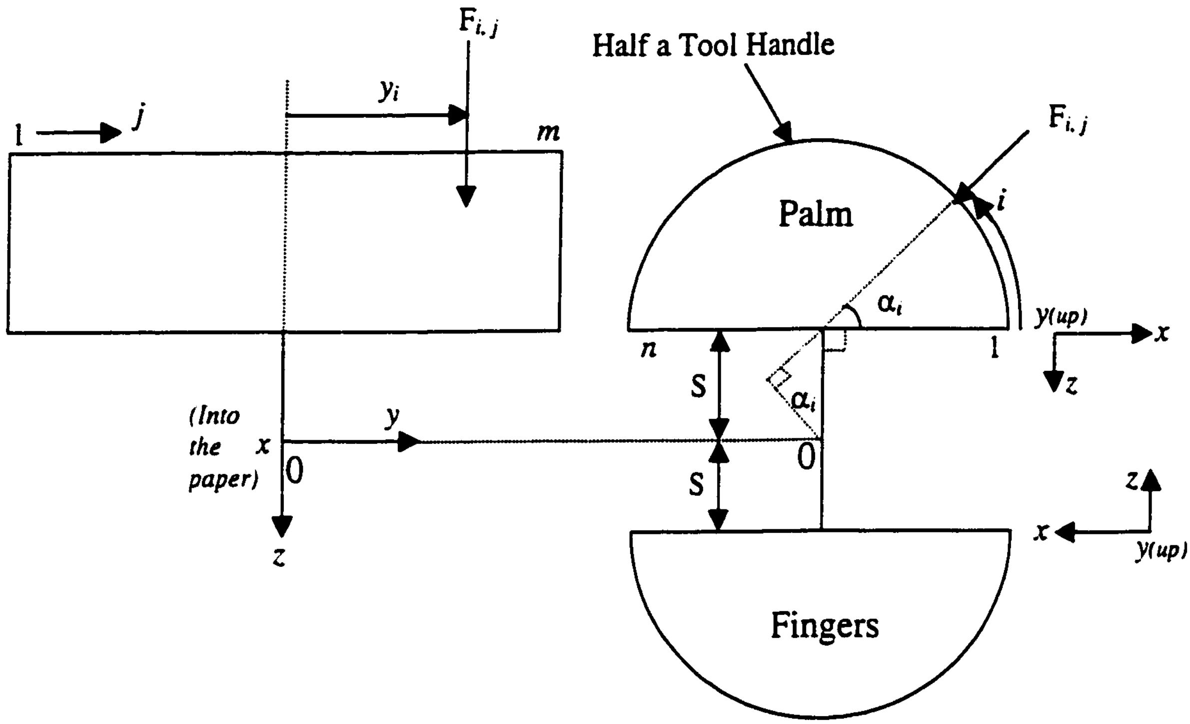


Figure 2.12. The right-handed coordinate system of the hand used for the study.

Assuming the axis of the cylinder to be Y-axis, the forces – F_X, F_Z and the moments – M_X, M_Z were identified to be acting at the interface of the hand and handle of the designed cylindrical handle. The above said forces and moments at the hand handle interface describe the magnitude and direction of the stresses acting on the operator's hand. In general the handle of a typical hand tool would be close to cylindrical shape. Given the shape of the tool handle one can define the shape function of the surface and find the direction of the normal at any point on the surface of the tool handle in the XYZ coordinate system and find out the forces. Assuming the tool handle to be cylindrical the forces and moments can be calculated using the figure 2.13 and the following equations.

The forces and moments acting on the fingers and palm portions of each subject were calculated using the resulting grip pressure distribution (GPD). The force (F_X, F_Z) and moment components (M_X, M_Z) were calculated, for both the fingers and palm side, and tabulated for all the subjects. Also, the individual force components (F_X, F_Z) are calculated for the individual fingers of all the subjects. To do this an assumption was made where the spaces between the fingers were located. In these spaces the pressures were set to zero. One important point to be noted here is, one of the four subjects (# 1) was asked to grip the handle with 100% (i.e., maximum) force and all the others were asked to grip the handle with 20% of the maximum force. The 20% force is the force that is applicable, in general, to the workers using power tools.



$$F_z = \sum_i \left(\sum_j F_{i,j} \right) Sin\alpha_i \qquad M_z = \sum_j \left(\sum_i F_{i,j} Cos\alpha_i \right) y_j$$

$$F_x = -\sum_i \left(\sum_j F_{i,j} \right) Cos\alpha_i \qquad M_x = \sum_j \left(\sum_i F_{i,j} Sin\alpha_i \right) y_j$$

$$M_y = S\sum_i \left(\sum_j F_{i,j} \right) Cos\alpha_i = -SF_x$$

Figure 2.13. Definition of handle coordinate systems and calculations of forces and moments acting on half a tool handle (0 is the origin of the coordinate systems).

Figure 2.14 shows the tabulated values of total force (F_Z, F_X) and moment (M_Z, M_X and M_Y) component values on the fingers and palm side of the four subjects. Figure 2.15 shows the tabulated values of individual finger force (F_Z, F_X) components of the four subjects. By clearly studying the forces and moments in these figures one can draw several inferences about the overall grip pressure distribution (GPD) at various grip conditions. The figure 2.16 shows the net forces and moments applied to the hand. All subjects exhibit a net push force (F_Z), in addition to the grip force. The hand of all the subjects tends to move sideways because of the force (F_X) in the medial direction. All the subjects exhibit a net positive moment (M_Z) which causes their hand to supinate. Subjects 1, 2 and 4 exhibit a net positive moment (M_X) which causes the hand to deviate in the radial direction. Subject 3 exhibits a net negative moment (M_X) which causes the hand to deviate in the ulnar direction. All the four subjects exhibit a net negative moment (M_Y) which causes their hand to extend at the wrist. These results give a good knowledge of the kind of forces and moments acting on the hand and the tendency of the hand to move in a direction.

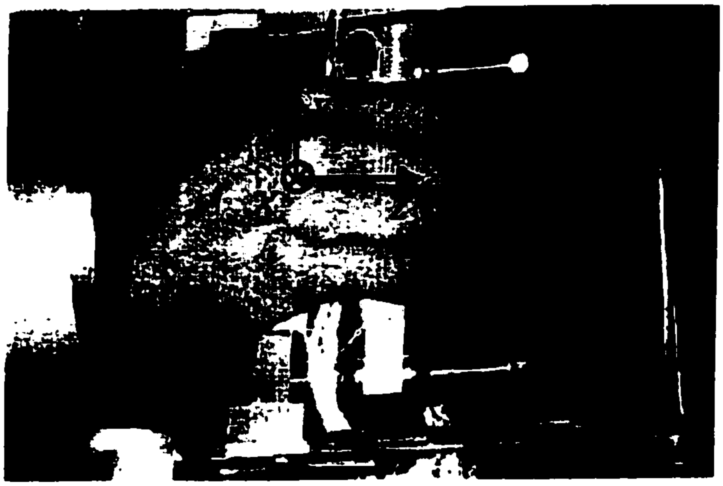
Hence, it is vital to quantify externally applied pressure at the hand, since it is associated to subjective perception of pressure and discomfort, since pressure with high amplitude or long duration in an awkward position may cause injury to the tissues. And the distribution of pressure may be used to reflect which regions of the hand that apply force. The net forces may be used to reveal the direction of forces that are applicable to the hand, and to know which kind of force (e.g., push, pull) is applicable to the hand.

Subject	Palm (Proximal) side					Fingers (Distal) side				
	Forces (N)		Moments (Ncm)			Forces (N)		Moments (Ncm)		
	F_Z	F_X	M_Z	M_X	M_Y	F_Z	F_X	M_Z	M_X	M_Y
1	356.74	42.74	81.57	203.95	-53.43	192.80	23.32	-47.30	184.03	-29.16
2	147.85	30.46	56.23	161.85	-38.07	107.68	-1.13	-14.34	153.25	1.41
3	114.75	32.07	83.24	157.10	-40.08	103.90	7.27	-35.56	178.80	-9.08
4	119.40	14.03	104.52	192.77	-17.54	101.46	-2.10	-6.75	187.36	2.62

Figure 2.14. Total forces (F_Z, F_X) and moments (M_Z, M_X, M_Y) applied by the fingers and the palm on the handle.

Subject	Individual Finger Forces (N)							
	Index		Middle		Ring		Little	
	F_Z	F_X	F_Z	F_X	F_Z	F_X	F_Z	F_X
1	73.96	4.20	49.55	18.01	41.90	6.40	27.37	-5.28
2	52.58	-2.07	23.53	4.56	18.00	1.42	13.57	-5.04
3	61.05	3.22	15.17	7.58	13.35	0.904	14.34	-4.44
4	59.71	-4.22	17.15	6.43	13.34	-0.042	11.25	-4.34

Figure 2.15. Individual finger forces (F_Z, F_X) applied by the fingers on the hand.



Subject	Net Forces (N)		Net Moments (Ncm)			Comments
	F_Z	F_X	M_Z	M_X	M_Y	
1	163.94	19.42	128.87	19.92	-82.59	Push, medial movement, supination, medial deviation, extension.
2	40.17	31.59	70.57	8.60	-36.66	Push, medial movement, supination, medial deviation, extension.
3	10.85	24.80	118.80	-21.70	-49.16	Push, medial movement, supination, ulnar deviation, extension.
4	17.94	16.13	111.27	5.41	-14.92	Push, medial movement, supination, medial deviation, extension.

Figure 2.16. Net Forces and Moments applied by the hand on the handle expressed in terms of the coordinate system given above.

A considerable amount of difference was observed between the grip pressure distribution of the palm and the fingers. This does not allow the handle to be in equilibrium. In other words, comparatively larger amounts of forces were acting on one half of the handle than the other. This can be observed from the results of force and moment components. With the increase in the percentage applied force, the middle finger phalanges suffered higher pressures than the index finger phalanges at the hand-handle interface whereas, during the application of lower percentage of forces, higher pressures shifted towards the index finger phalanges.

The patterns of force on individual fingers indicate that the fingers exhibiting higher amount of forces are the index finger with approximately 38.36% of the total force on the distal half of the hand, the middle finger with approximately 27.64% of the total force. The fingers exhibiting lower amount of forces are the ring and the little fingers with the rest of 34% of the total force on the distal half of the hand. This variation occurs even on the proximal half of the hand, one half (the thumb side) exerting much higher amount of force than the other half. This shows that the grip pressures are not evenly distributed on the overall surface area of the hand. In other words, the grip pressure distribution is not at all even on the overall surface area of the hand. This resulted in large concentrated forces acting at some parts of the hand, which might contribute to the causation of the occupation disorders.

Chapter 3

Hand Grip Pressure Distribution Under Static and Dynamic Conditions Using Typical Power Tools

3.1 Introduction

Operators of hand-held power tools, such as grinders, chain saws, chisels, jigs, and drills, are exposed to comprehensive levels of vibration arising from the tool-workpiece interactions. These high amplitude vibrations predominate in a wide frequency range, 10-2000 Hz, and are often limited to the hand-arm of the operators (Wasserman et al., 1974). Prolonged exposure to such vibration has been related to several occupational health disorders, specifically tingling, numbness, and blanching of fingers, resulting in a common disease called 'Vibration White Finger' (VWF).

The first symptoms of VWF disease are related to intermittent tingling and numbness of the fingers. With continued exposure, the tingling is followed by an attack of finger blanching confined, in the first instance, to a fingertip, which subsequently propagates to the base of the finger (Pyykko, 1975). While cold acts as the provocative agent, factors such as central body temperature, metabolic rate, and emotional state, etc.

are also involved (Pyykko, 1986; Taylor et al., 1982). An attack usually lasts 15-60 minutes but in advanced cases it may extend from 1 to 12 hours. The recovery phase is signaled by the appearance of a red flush, usually seen in the palm. With further vibration exposure nutritional changes take place in the finger pulps leading to the formation of small areas of skin necrosis at the fingertips.

Injuries to the hand, lower arm and shoulder are often claimed to be due to poor design and/or appropriate use of hand tools. Also, work requiring high force has been identified as a risk factor for hand-wrist cumulative trauma disorders (Silverstein, et al. 1986). Work with cross-action tools often requires a substantial amount of force, and one important factor, directly influencing the grip strength for this type of tools, is the distance between the handles. Measurement and prediction of hand grip pressure distribution as well as individual finger forces during grip exertions are important for developing functional biomechanical models and for designing tools, work equipment and manual handling activities. The functions of the hand and digits are widely studied in the fields of orthopedic surgery, physical medicine and rehabilitation where the major concern has been to relate the kinematic characteristics of individual digits with the electrical activity of muscle or muscle components.

There were no studies which concluded with a precise, definite and more appropriate solution in overcoming the occupational disorders related to hand functions like gripping, pushing, pulling, lifting etc., with the actual use of hand-held power tools. Although, much neurophysiological research into the functional organization of the hand's motor has been done, and 'Grip Strength' has long been used as one of the most convenient and reliable indices of muscular strength, only little attention was paid to the kinetic and physiological features of individual digits. The strength share of each digit during grip strength exertion and the maximum voluntary strengths of single digits, and the relation of these strengths to the physiological cross-sectional areas of finger flexors were determined in experiments conducted by Ohtsuki, T., 1981. The functions of the hand and digits are widely studied in the fields of orthopedic surgery, physical medicine and rehabilitation where the major concern has been to relate the kinematic characteristics of individual digits with electrical activity of muscles or muscle components. The actual testing, and use of hand-held power tools was not done in the recent years to investigate the causes of the occupational disorders.

Hand-arm and tool form a coupled system. Transmission of tool vibrations to the hand-arm is strongly related to the grip force applied. The causes of VWF may not only be due to vibration but also due to the static grip pressure distribution, push/pull force and moments applied to the hand-arm. Due to the application of high grip force the human hand seems to appear as a rigid connection to the handle of the tool. These grip forces are the cause to make vibrations induced to the hand and arm of the operator. The development of VWF is directly related to high local pressures at the hand-handle interface. Epidemiological studies conducted in several countries have established that millions of workers are exposed to intense hand-held power-tool vibrations regularly at the work place (Palmear et al., 1992). Some studies have concluded that the tips of index, middle and ring fingers are the first of the hand that are affected the most by the VWF disease (Brubaker et al., 1983; Hellstrom et al., 1972).

The operator hand-tool interface is the path vibration energy takes between the source and the human operator. It explains the interaction between the hand tool and the operator. The operator-tool interface may involve the use of handles or other parts of the tool in contact with the hands and body. The operator posture, handle location, the amount of force to be exerted on the tool handle and the type of tool can have a dramatic effect on the level of vibration transmitted to the operator. Knowledge of the overall distribution of contact grip forces of the hand is thus extremely vital to identify the location of concentration of high forces that may cause reduced blood flow to the finger tips, and thus the VWF disease. Measurement of overall grip pressure distribution at the hand-handle interface, however, is complex due to the requirements of a large number of thin and flexible sensors, and a signal analysis system with capabilities to acquire and analyze many channels of data.

The testing and analysis pertaining to various hand-held power tools are described in this Chapter. For the field testing, particular attention was given to grinders, as operators of these tools are known to develop VWF disease after prolonged exposure. Subjects tested various power tools under static and dynamic conditions and GPD, and postures were measured and studied. It is postulated that a subject grips a vibrating tool more tightly and that there are highly peak pressures when the tool is poorly balanced, as compared to a well-balanced tool. Key parameters that contribute to high local pressures were identified.

3.2 Measurement of Grip Pressure Distribution (GPD)

The procedure for the measurement of the overall grip pressure distribution was related to the way it was explained in the second chapter of this thesis. In the second chapter emphasis was made in investigating the overall grip pressure distribution, forces and moments in different axes at different percentages of grip force that a human hand can apply to a cylindrical handle. But, in this chapter and work, emphasis was made to investigate the overall grip pressure distribution in static and dynamic typical conditions with several subjects, tools and postures.

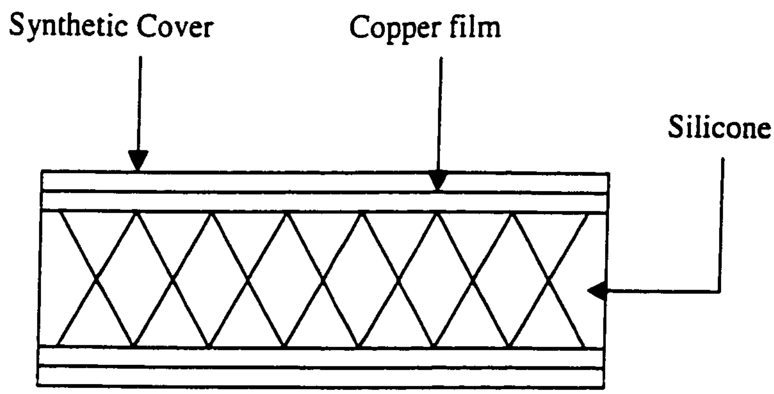
3.2.1 Capacitive Pressure Sensors

Measurement of grip pressure distribution at a human-machine interface requires a comprehensive grid of thin and flexible sensors, such that the visco-elastic properties of the interface remain unaltered during static and dynamic conditions. In the recent years, a number of interface pressure measuring systems have been developed. In this chapter, flexible capacitive sensors, which offer the potential to acquire static as well as dynamic pressures, were investigated to acquire the grip pressure distribution at the hand-handle interface.

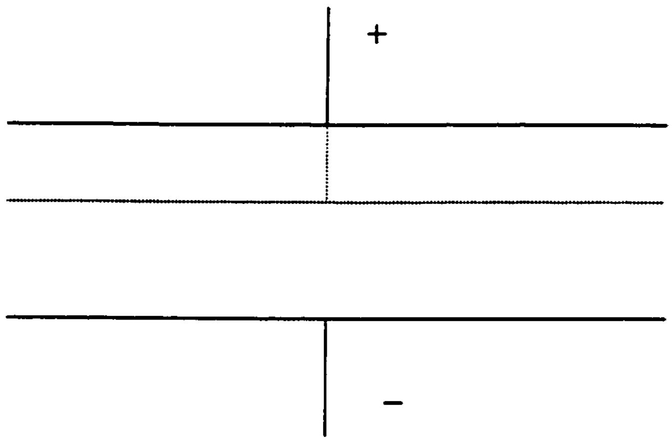
A pressure measurement system comprising flexible variable capacitance sensors, a signal conditioning circuit and data-acquisition software referred to as the EMED system (NOVEL gmbh, 1989), was employed to acquire the overall grip pressure distribution (GPD) at the hand-handle interface. The EMED sensor consisted of a pressure-sensing element sandwiched by an elastic synthetic mat. Pressure applied on the sensor deflects the elastic synthetic mat there by decreasing the distance between the plates, causing an increase in the capacitance of one plate and vice versa. This increase in capacitance is proportional to the amount of pressure applied. The sensors and associated software were designed for a maximum output of 255. Figure 3.1 shows the schematic of variable capacitance pressure sensing element and its equivalent electrical circuit. The measurement system provided digital voltage (AD) values proportional to the variations in sensor capacitance with the applied load.

3.2.2 Calibration of the pressure capacitive sensors

The pressure measured by a sensor apparently was not the actual pressure applied on the sensor. So, there was a need to calibrate the sensors. The mat was inserted in a pneumatic calibrating device, and loaded in several steps of pressure. The calibration curves for each of the sensors were obtained with the help of Table Curve 3D software. Although, the experiments described in chapter 2 used a total of 24 sensors, preliminary investigation showed that some were no longer functional. During this preliminary investigation known pressures were applied to each sensor and the sensor output was recorded as a function of the applied pressure. Of all the sensors tested, the best 12 sensors were chosen depending on sensor properties like accuarcy, repeatability and hysterisis. These sensors were arranged in a mat of 3X4 sensors.



a) Schematic of a capacitance sensor



b) Equivalent electrical circuit

Figure 3.1 Schematic of an EMED capacitive sensor and its equivalent electrical circuit.

Each sensor was calibrated by applying known pressures using a pneumatic actuator in the pressure range of 0 – 400 dN/cm^2 in steps of 50 dN/cm^2. The process was carried out in two stages, the first one from 0 – 400 dN/cm^2, and the second from 400 – 0 dN/cm^2 there by obtaining the hysterisis curve of all the sensors. The schematic of the sensor calibrating on a fixture is shown in figure 3.2. The sensor signals were then digitized to obtain the corresponding pressure values. The property of hysterisis of each sensor was clearly observed and an average curve for each sensor was selected for calibration. It was observed that the sensors produced a maximum of 5% error of hysterisis, which is considered to be negligible for further analysis (figure 3.3). With the help of Table Curve 3D software, the best fit of calibration curve of each sensor was found to be a rational function. The calibration curves and the corresponding rational equations are shown in the Appendix. The software fit most of the curves by rational functions of the following type:

$$z = \left(a + bx + cx^2 + dx^3 + ey\right)/\left(1 + fx + gx^2 + hx^3 + iy\right),$$

where $y = 0$

Figure 3.3. shows hysteresis loop and average values of a sensor. Figure 3.4 shows the calibration curve for the sensor shown in figure 3.3. Calibration curves for other sensors can be found in Appendix – I.

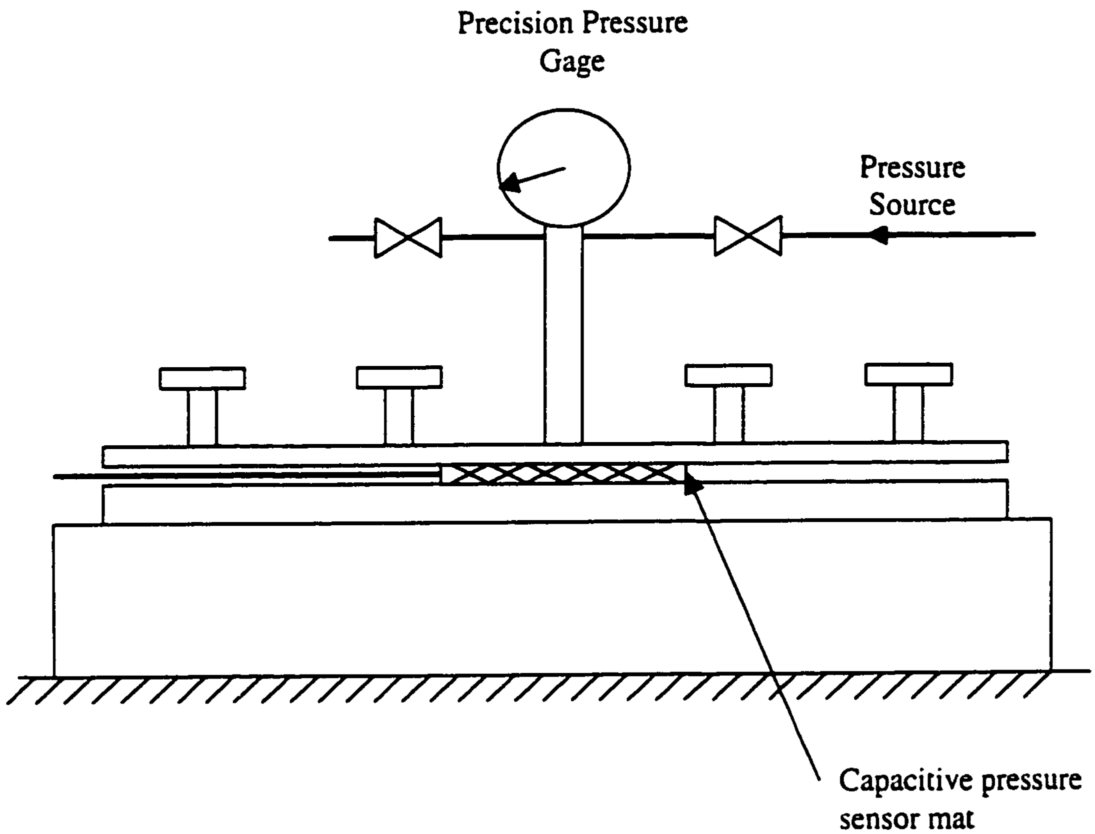


Figure 3.2 Schematic of the capacitive pressure sensor calibration setup.

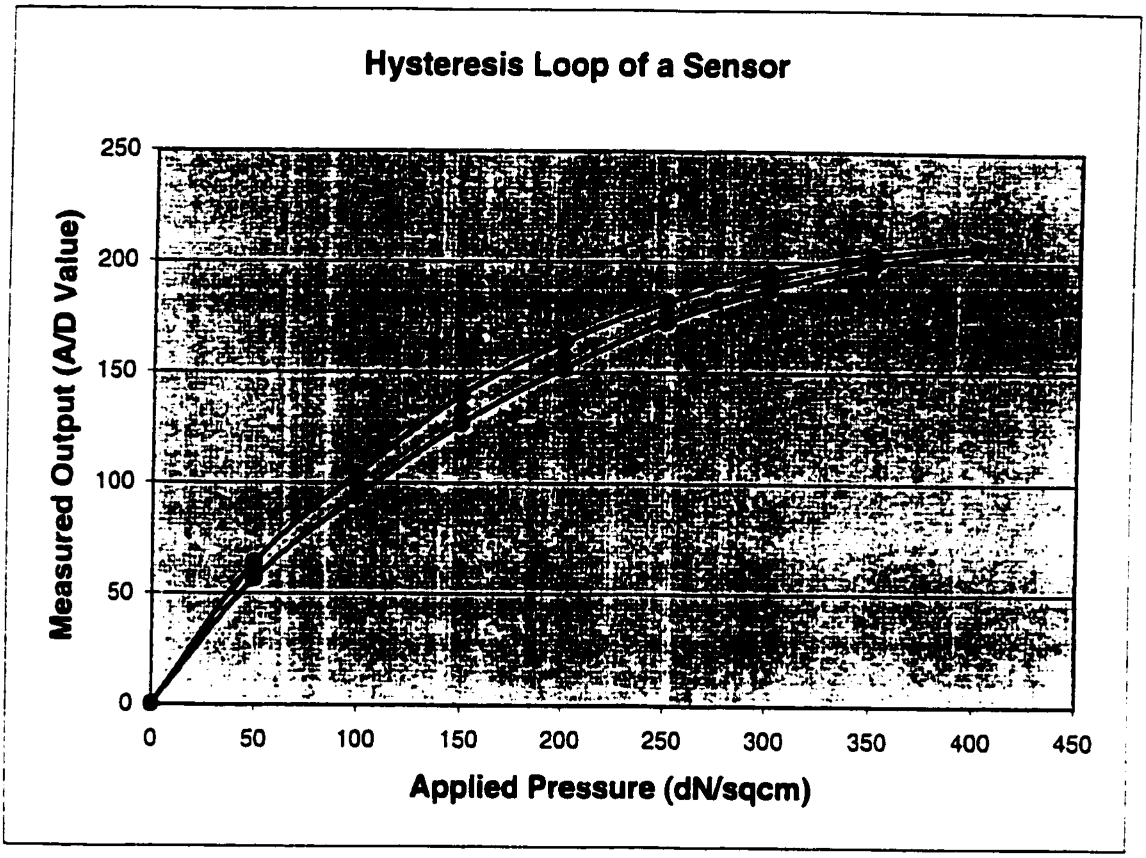


Figure 3.3. Hysteresis loop and average values of a sensor.

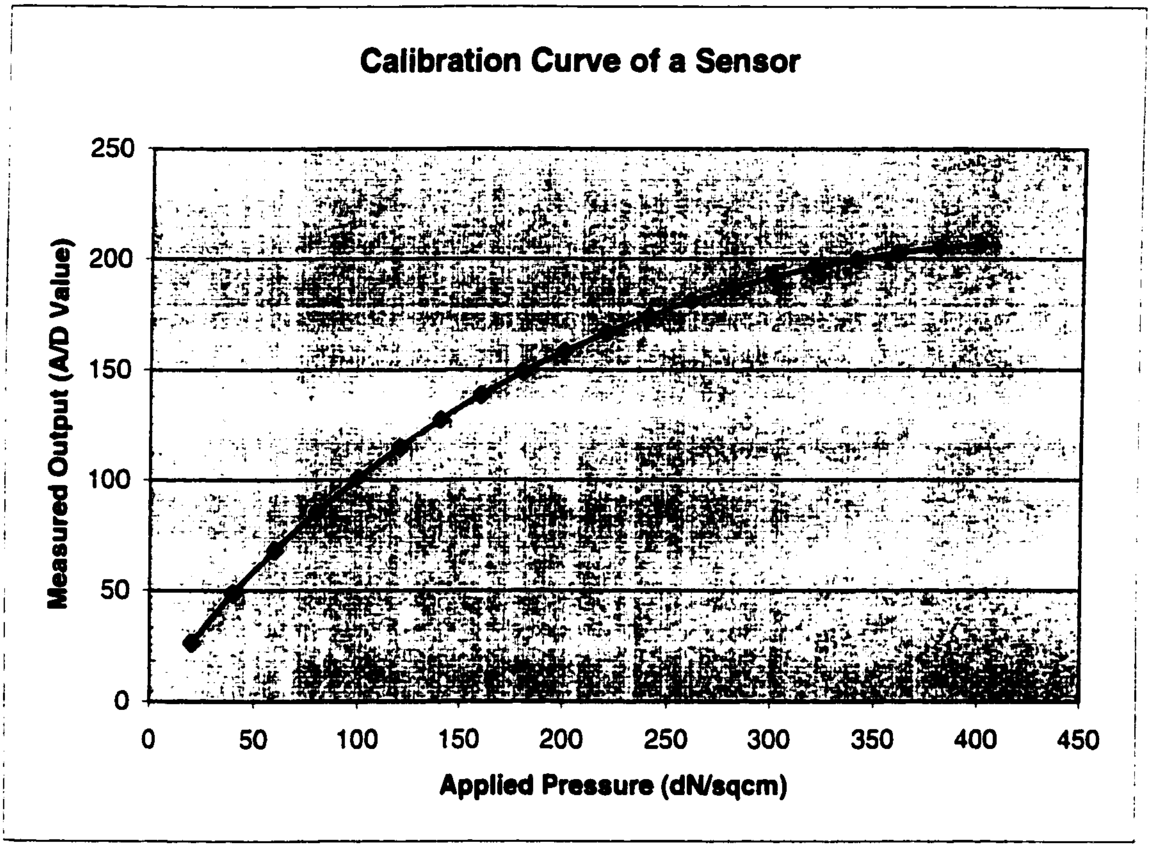


Figure 3.4. Calibration curve (from Table Curve 3D) for the sensor in figure 3.3.

3.2.3 Procedure of Measurement

Figure 3.5 shows the location of the sensors on the fingers and the palmar region of a stretched hand. The mat of sensors would measure the grip pressures at some discrete points from the distal to proximal and from the medial to lateral portions of the fingers and the palm regions. Because only a single mat of 12 sensors was available, four consecutive measurements needed to be taken to obtain the grip pressures on the fingers region and the palmar portion of the left and right hand separately. Although it was a disadvantage that the measurements could not be taken simultaneously, care and precautions were taken to maintain the same working conditions during the experiment. The subjects in these experiments were skilled machine shop workers who were experienced in using hand held power tools such as the grinding machines used in this study.

A series of experiments was carried out with various important factors described as follows. Two power tools were used to work at typical working conditions. For the static measurements one subject held the non running power tools either horizontally or vertically to study the effect of tool weight. For the dynamic conditions four subjects used the power tools to actually grind a work piece on its horizontal and vertical faces in three different postures. The data acquisition and analysis system of the sensors sampled the sensors consecutively such that each sensor was read every 0.862 seconds, or at a rate of 1.12 Hz. Before taking the measurements, each subject worked with the grinding tools for about a minute, after which measurements were taken for a period of about 26 seconds.

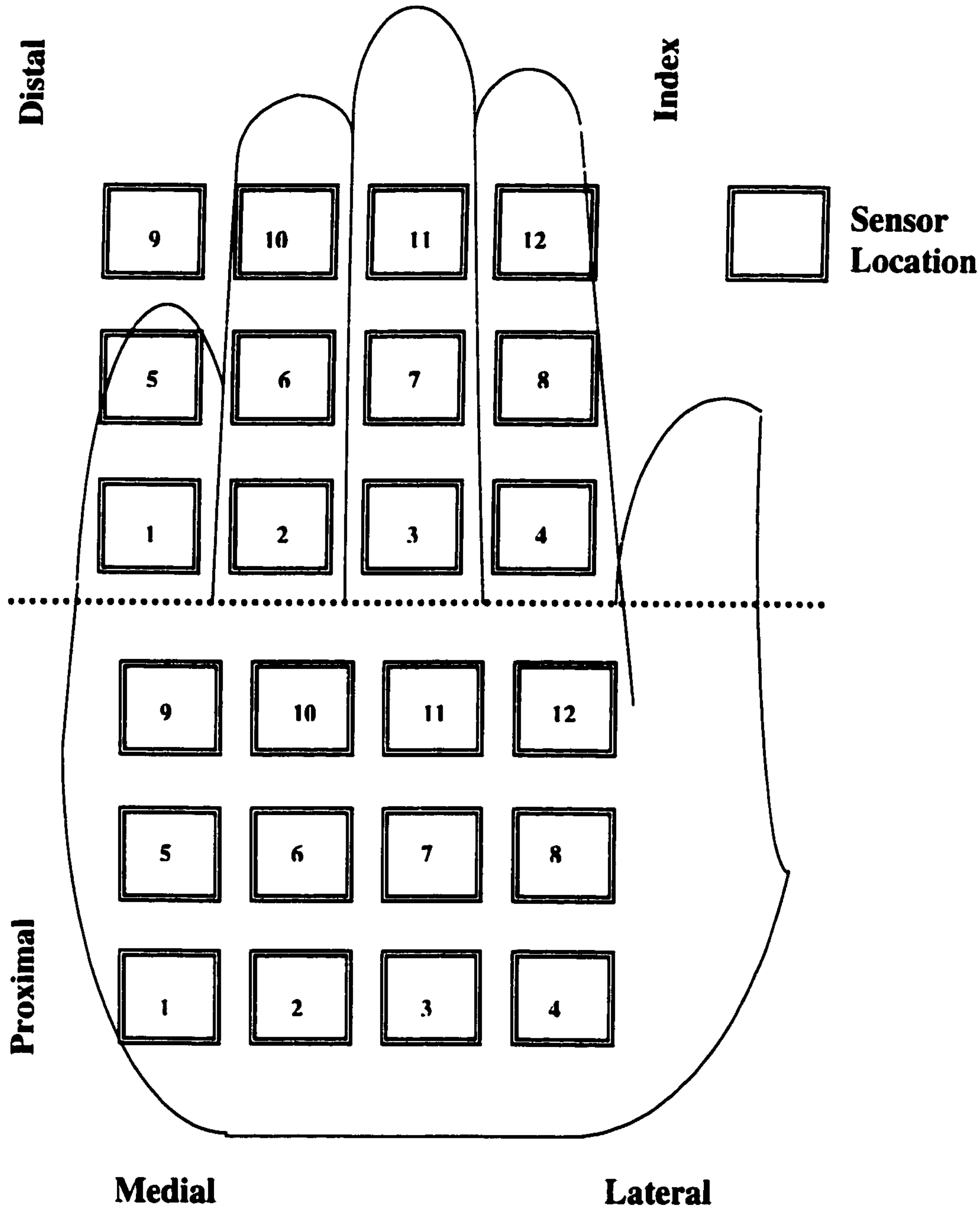


Figure 3.5 Location of capacitive pressure sensors on a stretched hand.

Keeping in mind the high rpms at which these tools run, the sampling rate of 1.12 Hz is too low to study the effect of vibration. Therefore, average grip pressures were calculated based upon a 9 seconds window in the middle of the 26 seconds measurement period, when the subject maintained near constant conditions. For each subject, measurements were taken once for each tool and posture.

Power Tools

Two kinds of hand-held power driven grinding tools were used for all the experiments. The basic differences of the two tools were their weight, size of the handles, and the diameter of the grinding wheel. The tools were chosen from a range of commonly used hand-held tools manufactured by different makers. The weights of the commonly used hand-held grinders range from 3 pounds to 15 pounds. Of the two chosen grinders, the smaller tool weighs 3.5 pounds and the larger tool weighs 13.5 pounds. These tools were used for the experiments to study the influence of their weight and the size at different working conditions. The larger tool is the one typically used in industries for grinding. The difference in diameter of their cylindrical handles changed the span of grip pressure distribution.

Subjects

Four male subjects who belong to different percentiles volunteered to take part in the experiments. A fifth subject worked in the static conditions to study the influence of the weight and balance of the tool. The subjects were selected to have different heights. Height of the subject is an important parameter effecting the posture (as thus also the GPD) when the workpiece is at a fixed height. Subject-1 was 6' 2" (188 cm), subject-2 was 5'6" (168 cm), subject-3 was 5'8" (173 cm), and subject-4 was 5'11" (180 cm) tall. These subjects were experienced machine shop workers, who all had extensive experience using grinding machines.

Working Conditions

The experiments were carried out both in the static and dynamic working conditions. Static working conditions were considered as the first set of experiments to study the proper positioning of the sensor mat on the tool and the kind of forces and pressures acting just by the weight of the tool itself. These conditions also reveal whether the tools are completely balanced and equal forces and moments were acting on both the hands of the subject or not. The static experiments were carried out with only one subject. The reason for this is the comparison between the subjects was neglected and the aspects of the balance of the tools were stressed. Moreover, the static experiments are not the typical working conditions in industries where operators use hand-held power tools. In the dynamic conditions four subjects used the power tools to grind a work piece on its horizontal and vertical faces in three different postures. The height of the workpiece was 37" (94 cm) above the floor. These experiments are the typical working conditions in industries, as all the four subjects had experiences using hand-held power tools in a machine shop. Feedback was obtained from all the subjects, by discussing about the tools, postures and their experiences.

Postures

After a series of discussions with the subjects who were experienced in using the hand-held power tools, three different postures were identified to be typical in industries for several types of work piece orientations. All the postures are clearly shown in the figures 3.6, 3.7, 3.8, and 3.9. Posture – I (figure 3.6 and 3.7) was the horizontal posture where the horizontal surface of the work piece was ground. Posture – II (figure 3.8) and Posture – III (figure 3.9) were the vertical postures where the vertical surface of the work piece was ground. The difference between Posture – II and Posture – III was that the left hand holds the handle of the tool in two different positions while the right hand holds the tool in the same position in both the postures.

Figure 3.6. The experimental setup and the working environment.

Figure 3.7. One of the subjects working with the smaller tool in posture – I.

Figure 3.8. One of the subjects working with the larger tool in posture – II.

Figure 3.9. One of the subjects working with the larger tool in posture – III.

3.3 Results and Discussion

The postures are shown in figures 3.6-3.9. Posture-I is the best posture of all the three (figure 3.7). Both the hands were in neutral position. The waist was in the neutral position. But, there was a need to change the posture depending on the work piece, and the kind of job. Posture-II (figure 3.8) and posture-III (figure 3.9) are almost the same with a few differences. In posture-II the worker has to bend at the waist and twist his hand as shown in figure 3.8. So, apparently there are problems at the left wrist and the waist as they were not neutral. This second posture due to gradual use of the tool would produce inconvenient and highly irritating problems like fatigue, pain and stress. But, the left hand would help in producing forces that oppose the reactions well. In posture-III the worker has to hold the tool with both hands and waist in neutral position. This would not help the left hand to oppose the reaction forces at the tool-work piece interface.

Posture-I is the most typical type of using the tools when working with a horizontal face of the work-piece. But, the posture-II and posture-III are two similar ways of using the tools when working on the vertical face of the work-piece. When discussed the postures with the four subjects only one of them said he was more comfortable with the posture-III than the posture-II. One other subject said he would use only posture-I for any work piece by just rearranging the work piece. The operator, if he is short, has to bend at the waist to work. But, a taller operator would work more comfortably at normal body posture. Hence, depending on the height of the worker it is recommended that the table's height is adjustable in the vertical plane. Instead of an adjustable table, the subject can also use an adjustable platform that can move in the vertical plane, to comfortably hold the power tool.

The pressures at the hand handle interface at specific discrete points were obtained by the twelve-sensor mat and the data acquisition software in all the experiments. These pressure data were carefully recorded, processed and analyzed. The discrete pressure points were interpolated using cubic spline interpolation, to obtain the overall grip pressure distribution of the fingers and palmar portions of the left and the right hands for both the tools. The overall grip pressure distribution for all the combinations of tools, subjects, postures and other working conditions provided good insight to investigate the causes of the occupational disorders. The figures 3.10-3.15 show the grip pressure distribution obtained from the experiments with two subjects (one tall and the other shorter), two tools (lighter and heavier), and two postures (I and II). All the rest of the results are listed in Appendix – II.

The diameter of the right handle of each tool is much larger than the left handle, and provided a better span of grip. The trip switch that activates the tool is located at the bottom of the right handle of the tool, which is in general gripped by the right hand. Almost all the subjects switch the tool on with either the ring or the little finger. This causes the occurrence of high local grip pressures at the distal phalanxes of the ring and the little fingers of the right hand (this can be observed from the GPD in figures 3.10c-3.16c). In most cases comparatively higher grip pressures are observed on the proximal phalanges of the left hand and the distal phalanges of the right hand (this can be observed

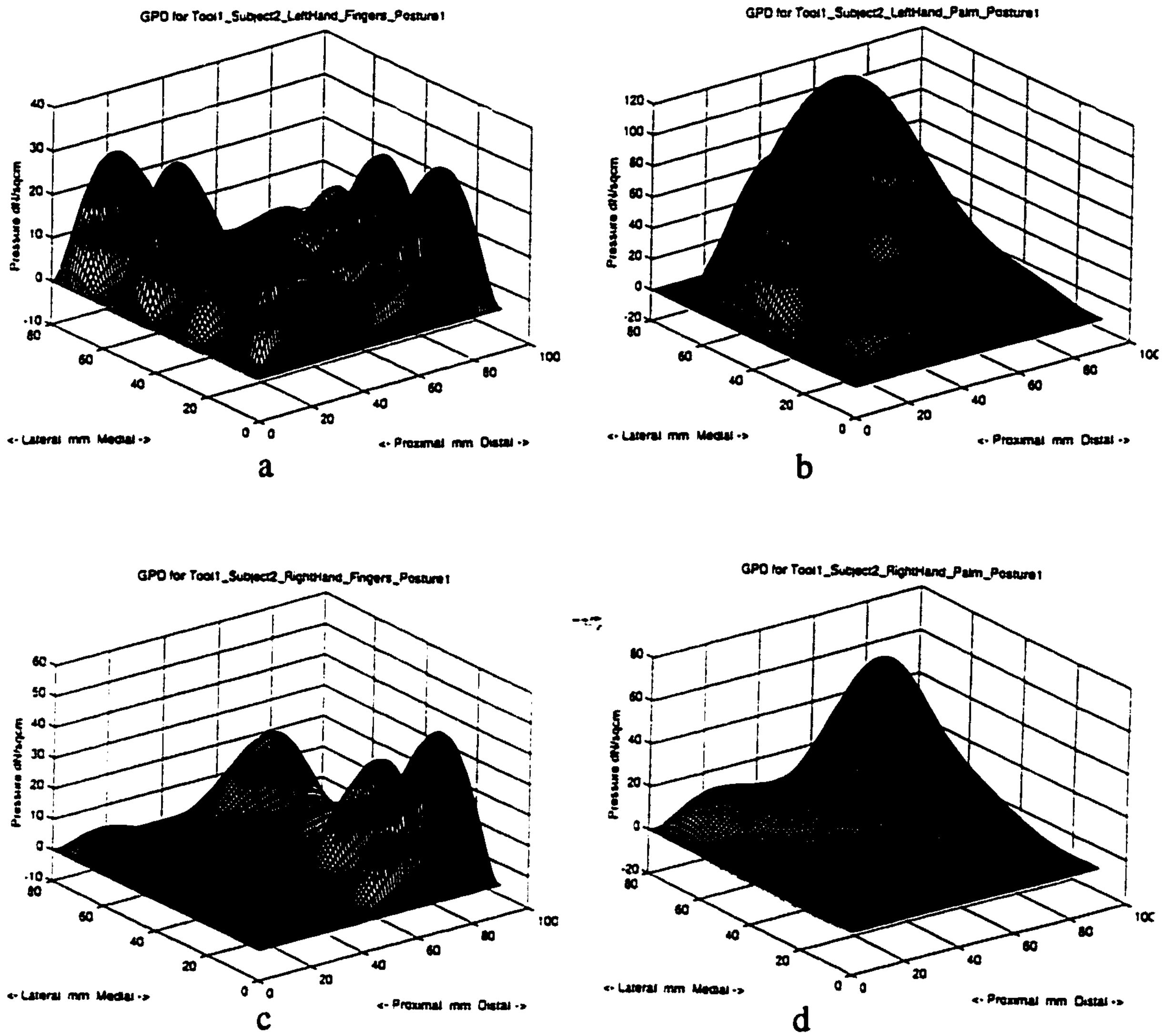


Figure 3.10. Grip Pressure Distribution (GPD) on both the hands of subject 2 working with tool 1, in the posture 1.

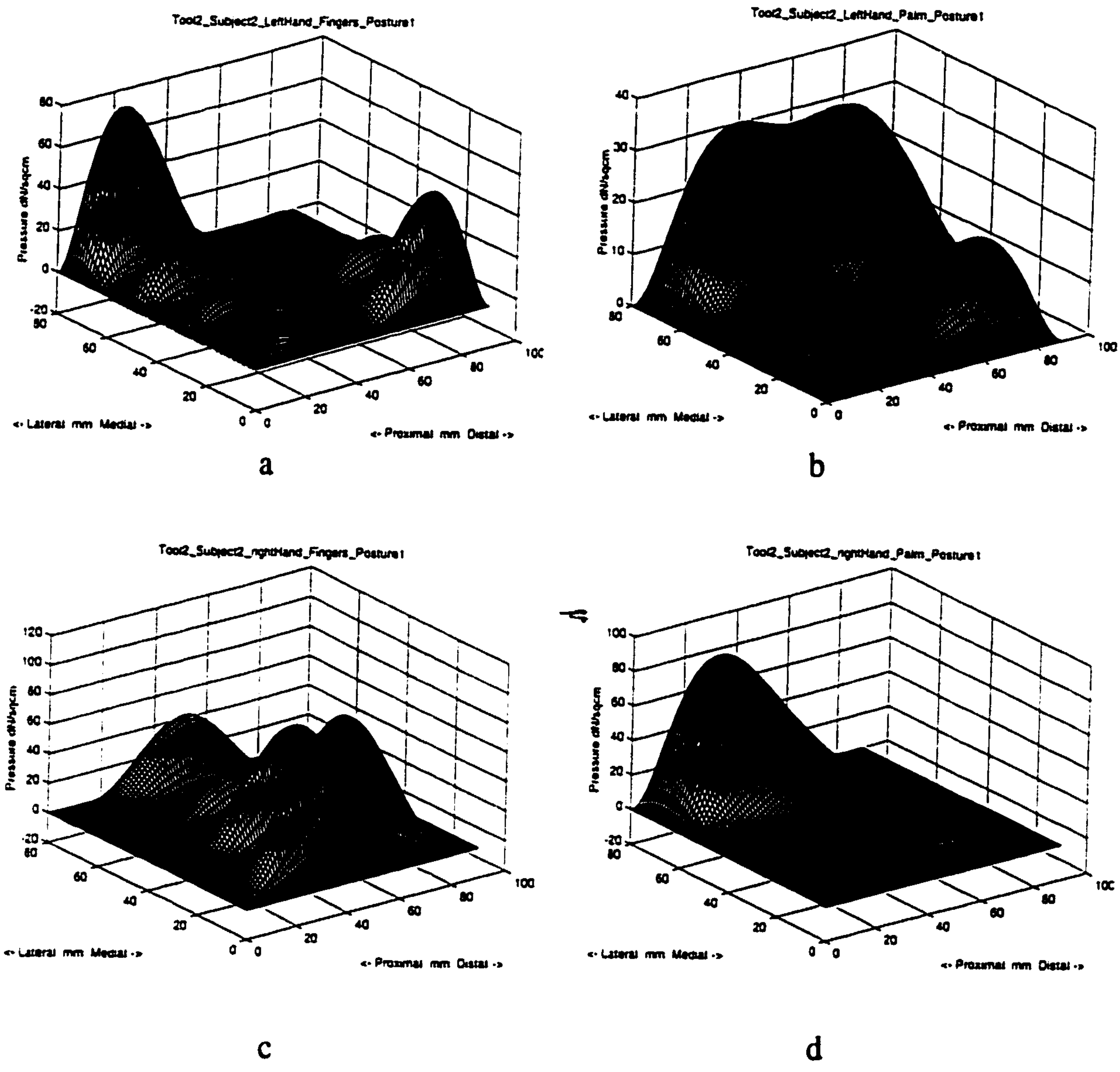


Figure 3.11. Grip Pressure Distribution (GPD) on both the hands of subject 2 working with tool 2, in the posture 1.

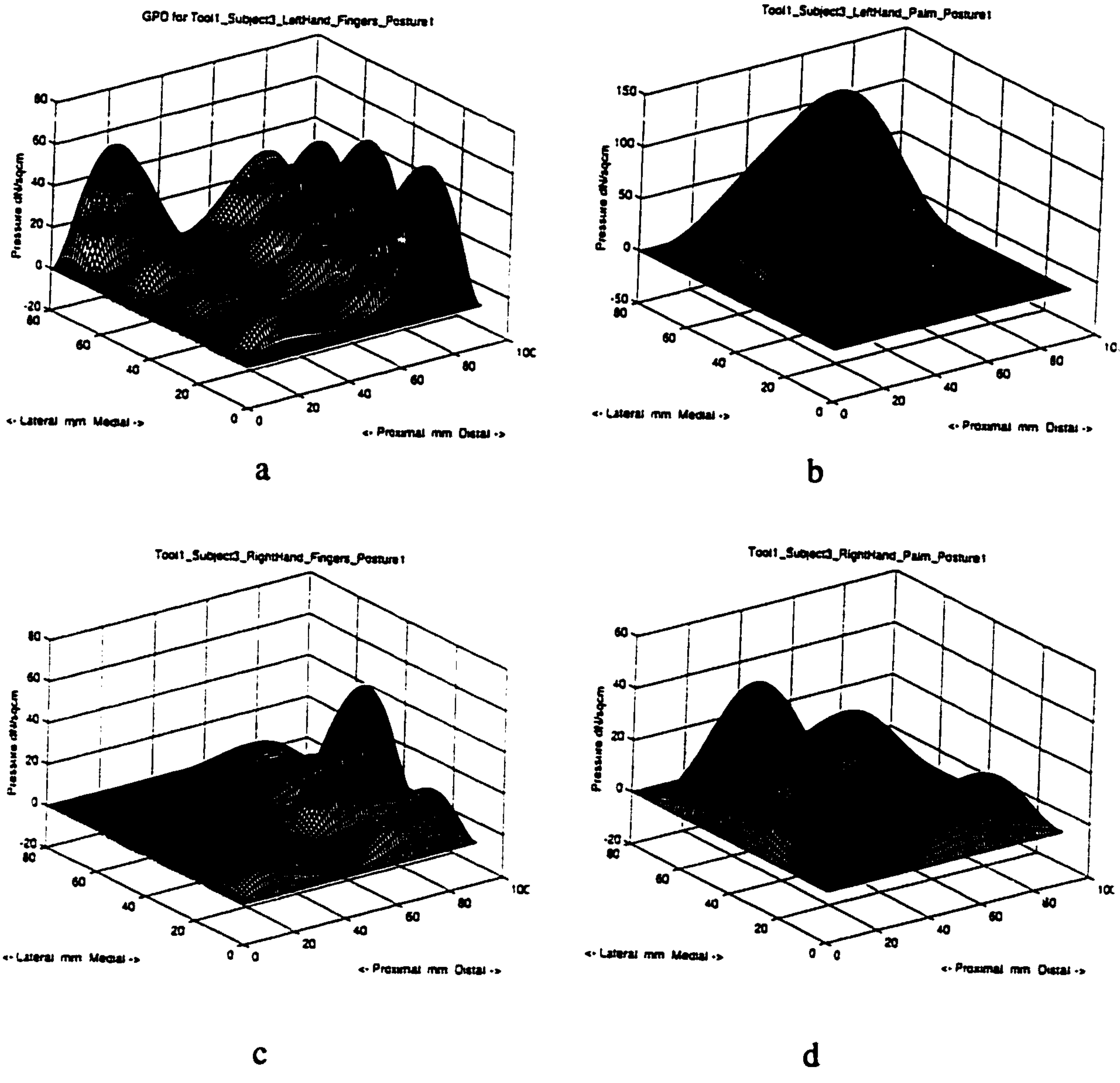


Figure 3.12. Grip Pressure Distribution (GPD) on both the hands of subject 3 working with tool 1, in the posture 1.

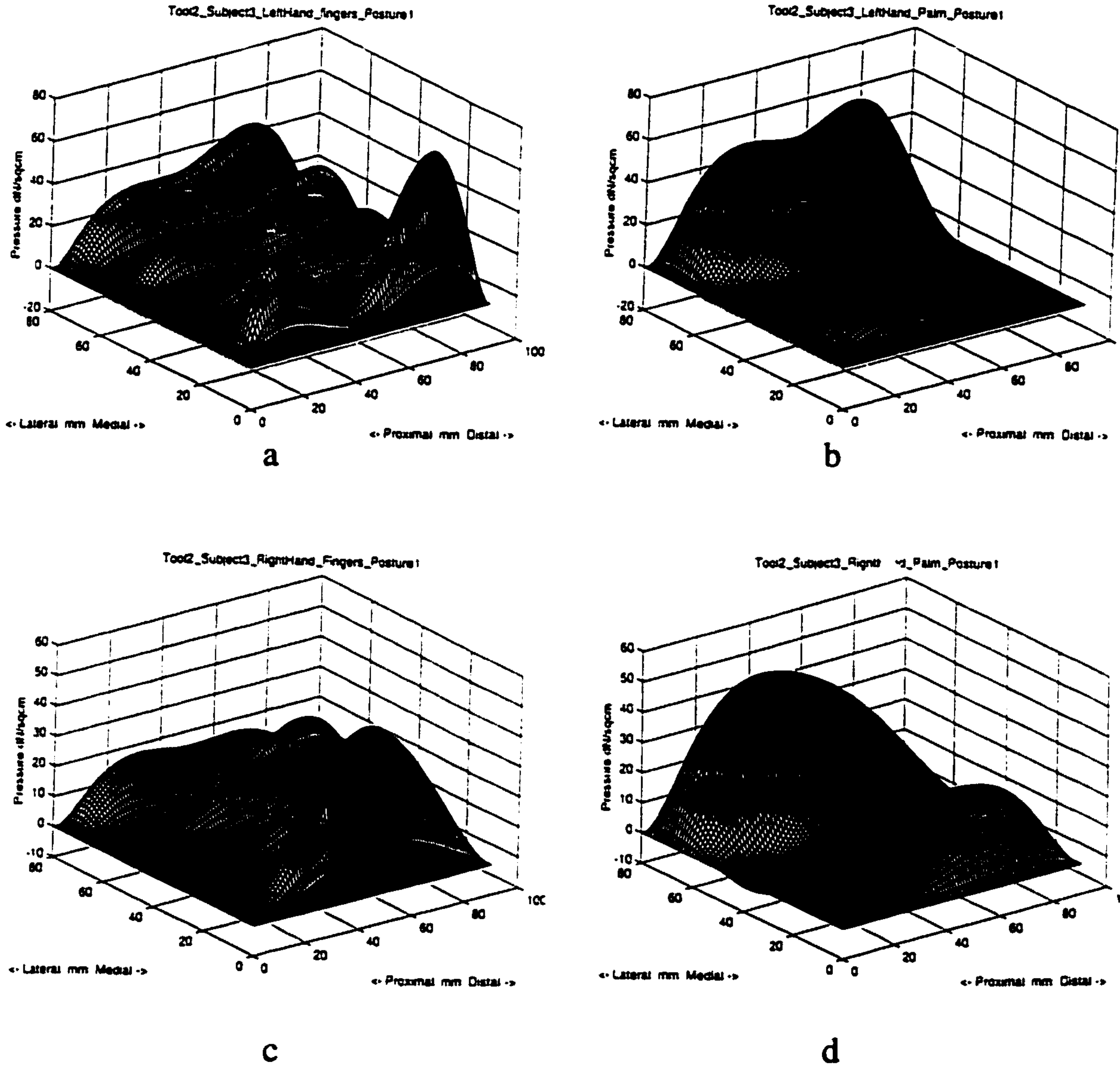


Figure 3.13. Grip Pressure Distribution (GPD) on both the hands of subject 3 working with tool 2, in the posture 1.

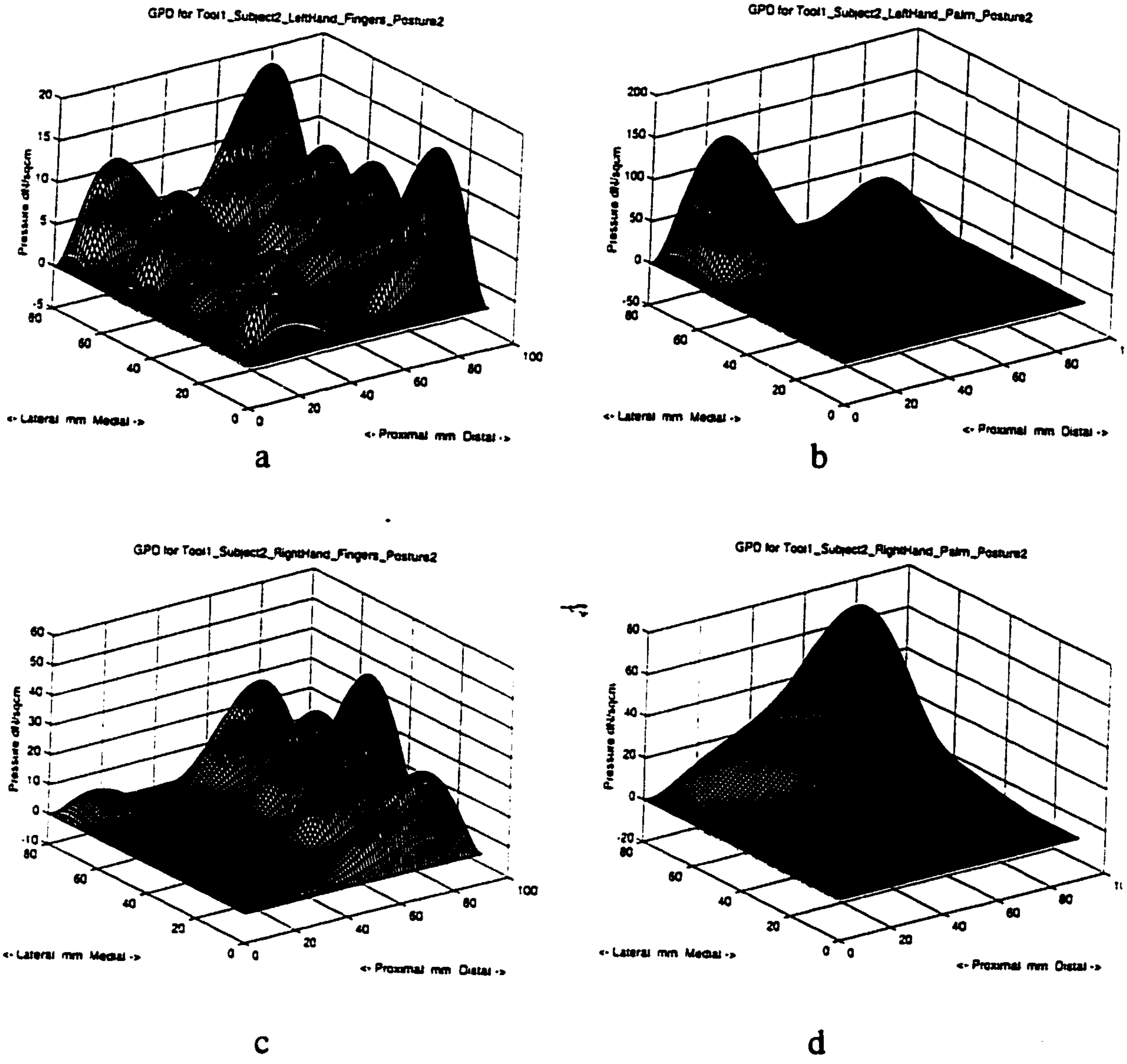


Figure 3.14. Grip Pressure Distribution (GPD) on both the hands of subject 2 working with tool 1, in the posture 2.

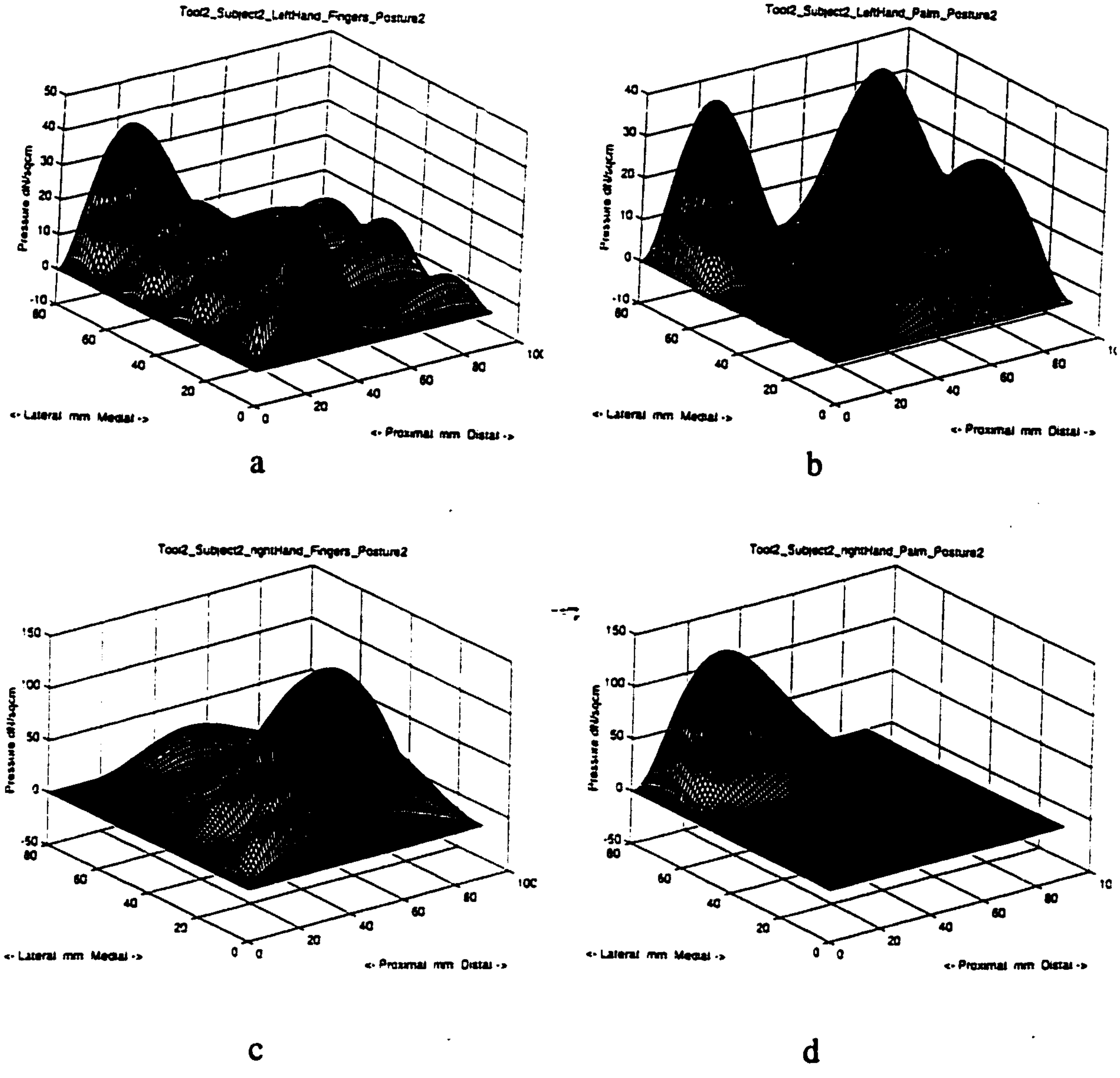


Figure 3.15. Grip Pressure Distribution (GPD) on both the hands of subject 2 working with tool 2, in the posture 2.

from the GPD in 'a' and 'c' of figures3.10-3.16). In almost all of the cases except for posture-III, comparatively higher amount of grip pressures are observed on the lateral half of the palmar region than the medial half ('b' and 'd' of figures 3.10-3.17). But, in case of posture-III higher grip pressures are observed on the medial and proximal portions of the palmar region.

In the static conditions the amount of grip pressure exerted by the hand depends on the weight of the tool as the tool was studied for its balance. The diameter of the left handle of each tool was not large enough for a normal hand to exert a fully spread out grip. Instead, localized pressures were exerted at different points on the hand. The amount of grip pressure during dynamic conditions depends upon the reaction forces at the tool-work piece interface. In other words, the operator of the power driven grinding tool had to apply high pressure on the tool to oppose the reactions due to the high moments present at the tool-work piece interface. This was clear from studying the grip pressure distribution in the dynamic conditions.

In general, large percentage of forces are present on the index and middle fingers of the left hand and little finger of the right hand and the lateral-distal half of the palms of both the hands. The highest pressure recorded of all the experiments was of 140 dN/cm^2, which is equivalent to 20.3 Psi. This pressure was recorded on the proximal phalanx of the index finger of left hand holding the smaller tool in the second posture.

This study was made using two different tools whose left hand side handles were different in diameter. The grip pressure distribution (GPD) is closely related to the force applied on the handle, since pressure equals force per unit area. The grip pressure distribution is dependent on the diameter of the cylinder. During grip exertion around the cylindrical handles, the pressure is evenly distributed over the fingers for larger diameter. With decrease in handle diameter, the distribution of pressure shifts towards an increasingly higher proportion being applied to the proximal phalanx of the index finger and medial-proximal region of the palm. This could be compared to a shift from a distributed grip towards a grip more similar to a pinch grip. The diameter of the right hand side handle of each tool (the body of the tool itself) is much larger in diameter and provided a better span of grip pressure distribution. For the tool with lesser weight, high localized pressures were present at the fingers side of right hand and more distributed pressures were present at the fingers side of the left hand (comparing figures 3.10a and c). When the tool weight was increased high localized pressures were present at the fingers side of left hand and more distributed pressures were present at the fingers side of the right hand (comparing figures 3.11a and c). This can be observed in both postures one and two (figures 3.10, 3.11 and 3.12, 3.13).

As a whole this study throws light on obtaining valuable information about the nature grip pressure distribution under various conditions, thereby suggesting how the work environment can be improved with better tool, tool handles, postures, and reduce localized and potentially dangerous grip pressures which are harmful to the human hand.

Chapter 4

Development and Analysis of Mathematical Models of the Hand-Handle System

4.1 Introduction

As it was clearly described in the previous chapters, in industries where manpower is considered to be vital, workers who are involved in manual handling tasks using hand-held power tools, such as chain saws, grinders, chisels, and drills experience certain considerable problems called as occupational disorders. These occupational disorders are mainly due to vibration and high grip forces at the hand-tool interface. Hand-arm and tool form a coupled system (Wasserman et al., 1977; Brammer et al., 1982). Transmission of tool vibrations to the hand-arm is strongly related to the grip force and push/pull force applied. The development of several occupational disorders is thought to be directly related to high local pressures at the hand-handle interface.

Mathematical models were developed and analyzed for various forces applicable on the hand-handle systems using ANSYS 'finite element analysis' package. The models use relevant anthropometric data of the hand as well as the results obtained from the grip pressure distribution measurement done as described in the chapters 2 and 3. The deformations, stress intensity, and strain levels pertaining to the human hand are studied in detail. In this chapter the development and analysis of the mathematical models of hand-handle system are described in detail.

The functions of the hand and digits are widely studied in the fields of orthopedic surgery, physical medicine and rehabilitation where the major concern has been to relate the kinematic characteristics of individual digits with the electrical activity of muscle or muscle components. Workers using hand-held vibration tools frequently experience numbness and pain in the arms and hands. During VWF attacks, blood flow to the affected segments of the fingers is reduced or completely shut off by contraction of muscles, resulting in severe pain (Pyykko, 1975). Evidences of nervous disorders, indicating involvement of central nervous system, among operators of vibrating tools have been reported. The symptomology alleged to be associated with vibration induced disturbances of the central nervous system induces anxiety, depression, headache, irritability and emotional instability (Habu, 1984).

The major result of Vibration White finger Disease was the blanching of fingers. One reason may be the application of high local pressures causing the collapse of blood vessels that carry blood to various parts of the hand and fingers. This can be justified by the following examples. People who are confined to bed or use wheel chairs for a long time are at a higher risk of developing serious or even life-threatening pressure sores called the bedsores. These are injuries to the skin and tissue underneath it, which occur when one sits or lies in the same position for some time (Agency for health care policy and research, AHCPR, 1994, recommends that patients be moved every 15 minutes to avoid bedsores). Another example is, if one sits with one knee over the other in the same position for too long, there is compression of the body part and resulting in a pins and needles sensation in one's leg. Keeping these facts in mind mathematical models were developed using finite element analysis to study the stresses and deformations in regions with blood vessels and nerves of the fingers and palm. Prior to developing the models an in depth study was made to understand the material properties of the soft tissues, blood vessels as well as the bones present in human hand.

4.2 Properties of Soft tissues, Blood vessels and Bones

4.2.1 Flow in collapsible tubes:

The prevalence of vessel collapse, and the variety of associated phenomena, have made it a topic of great interest to biomechanical engineers for over twenty years. Virtually all fluid vessels are elastic and can collapse when the transmural (internal minus external) pressure falls below a critical value (Kamm, R.D., and Pedley, T.J., 1989). At certain range of transmural pressures the cross-section is very compliant and even a small viscous or inertial pressure drop accompanying fluid flow through the tube may be enough to cause a large reduction in area, i.e., collapse. Examples of physiological vessels which normally, or at least routinely, experience collapse are systemic veins above the heart, as a result of the gravitational decrease in internal pressure with height; intramyocardial coronary blood vessels during systole; systemic arteries compressed by a sphygmomanometer cuff; pulmonary blood vessels in the upper levels of the lung; etc.

4.2.2 Relationship between the arterial pressure and the heart period:

It has been well known for a long time in the medical practice and scientific literature that a relationship between arterial blood pressure and the heart rate does indeed exist. An increase of blood pressure stimulates the arterial receptors to produce nervous reflexes that slow down the heart rate and depress both the cardiac contractility and arterial resistance, so as to counteract the pressure increase (Iacovelli, F., et al. 1989). On the other hand, recent studies performed on conscious animals in different behavioral situations (sleeping, resting, eating, etc.) have found that both the blood pressure and the heart rate increase with the level of vigilance (Iacovelli, F., et al. 1989). The sympathetic and parasympathetic activities entering the vascular system depend not only on the afferent activity from the cardiovascular receptors, but also on a central setting of the gain of the feedback loop; such a setting mechanism, which is mainly influenced by the behavioral conditions and is obviously lacking in anesthetized animals, is used by the autonomic nervous system, under actual behavioral situations, to set suitably steady-state values for both the heart rate and the blood pressure.

4.2.3 Blood vessels and the pressure of blood flowing through them:

There are three kinds of blood vessels: the arteries, the capillaries, and the veins. The arteries carry oxygenated blood away from the heart. They have thicker walls than the other vessels and are composed of three layers of tissue, the most functional of which is made up of smooth muscle fibers and elastic connective tissue (Jacob, S.W., and Francone, C.A., 1976). The largest artery in the human body is the aorta, which leaves from the powerful left ventricle of the heart. Slightly smaller arteries branch off the aorta, and still smaller arteries branch off these. The smallest arteries are called arterioles, and they pass the blood into the tiny capillaries.

Blood pressure is the pressure exerted by the blood against the walls of the vessels as it is forced through the circulatory system. Figure 4.1 shows blood pressure, blood velocity, and cross-sectional area of the vascular tree in various segments of the circulatory system. The blood pressure is highest in the brachial artery at the time of contraction of the ventricles. This is known as systolic pressure. Pressure during ventricular diastole (dilation or relaxation) is called diastolic pressure.

Blood pressure is usually expressed as a ratio – for example, as 120/80, in which 120 represents systolic pressure and 80, diastolic pressure. The units are in terms of millimeters of mercury (Hg). In general, the healthy individual has a systolic pressure of 100 to 120 mm. Hg and a diastolic pressure of 60 to 80 mm. Hg. The upper limits of normal blood pressure are usually defined as 140 mm Hg. systolic, and 90 mm. Hg diastolic. The pressure of blood in the arterioles is shown to be as 60-70 mm Hg (or 1.16 – 1.35 Psi or 8.0 – 9.3 dN/cm^2) and about 30-40 mm Hg in the capillaries (or 0.58 – 0.77 Psi or 4.0 – 5.1 dN/cm^2).

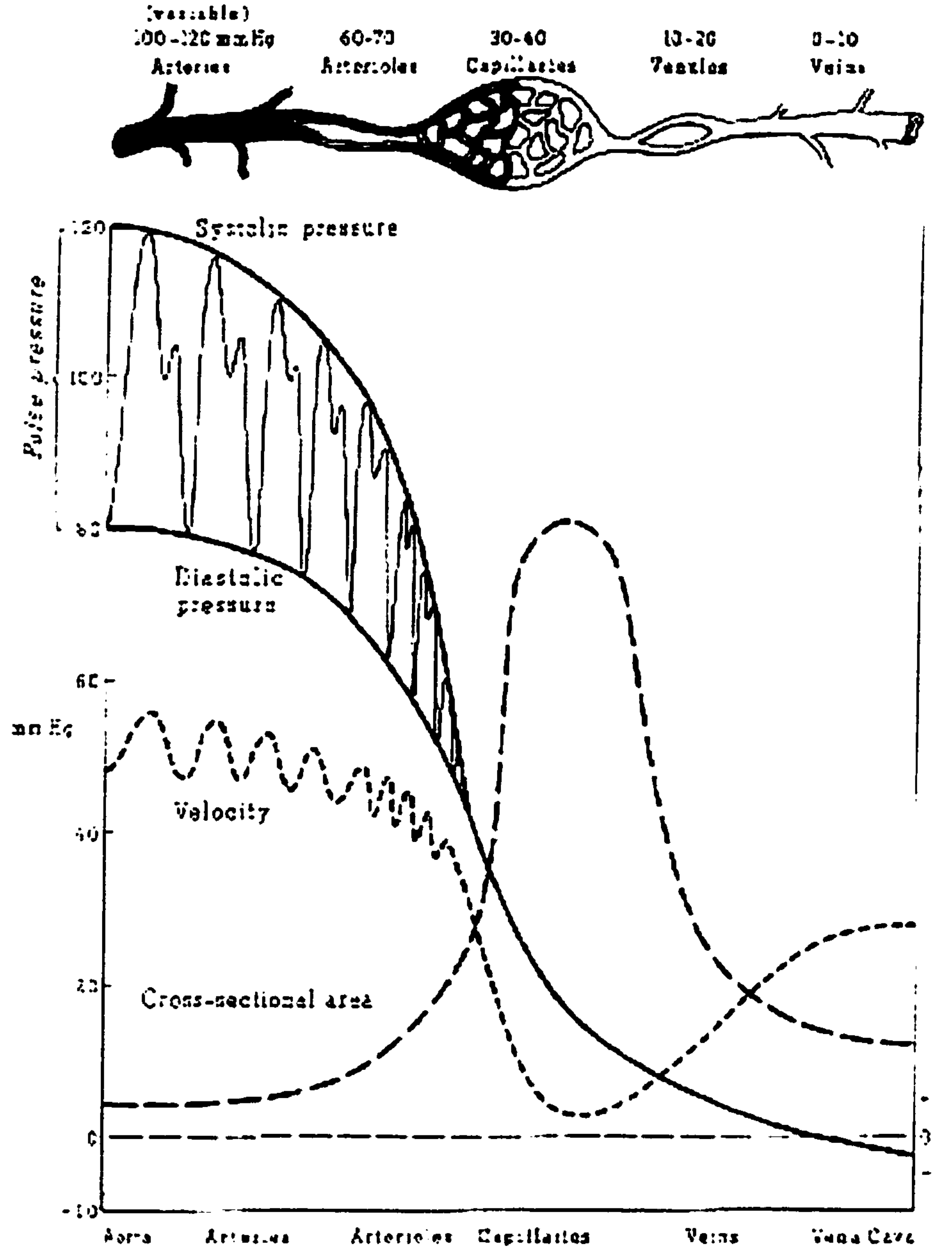


Figure 4.1. Blood pressure, blood velocity, and cross-sectional area of the vascular tree in various segments of the circulatory system (Jacob, S.W., and Francone, C.A., 1976).

4.2.4 Location of blood vessels and nerves in human hand (finger and palmar regions)

To investigate the causes of blanching of fingers and what kind of stresses prevail at the regions of blood vessels and nerves, it is important to learn the exact locations of these human parts. So, a few magnetic resonance images of various cross-sections of the fingers and the palm are studied. The advantage of this technique includes an ability to provide sectional images in any plane with excellent spatial and contrast resolution and the capability of revealing considerable physiologic and histologic data (Kang, H.S., and Resnick, D., 1991).

The Figures 4.2 – 4.4 show different cross-sections of the finger and the palm photographed by magnetic resonance imaging. Figures 4.5 – 4.6 also show the arteries of the hand and fingers. The locations of the arteries and nerves in the human hand and digits are clear. The finite element analysis made in this chapter uses the physiologic and anthropometric data from these figures. The stresses at the blood vessel and nerve location are studied.

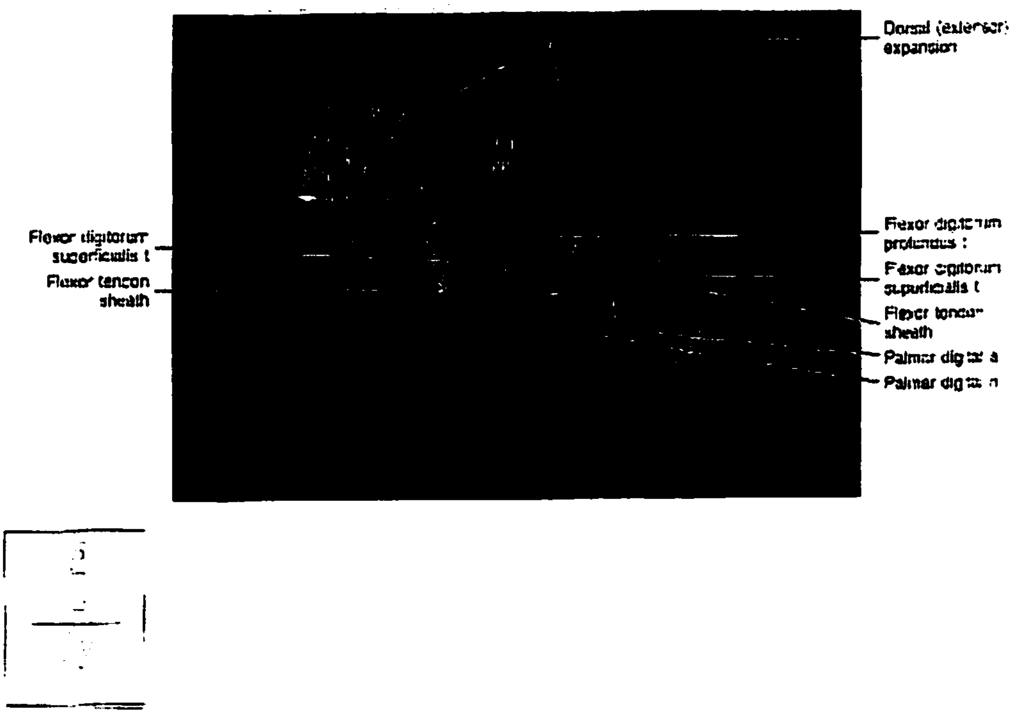


Figure 4.2. Magnetic resonance image of the finger at the cross-section of the proximal phalanx (P.P.) in the transverse plane (Kang, H.S., and Resnick, D, 1991).

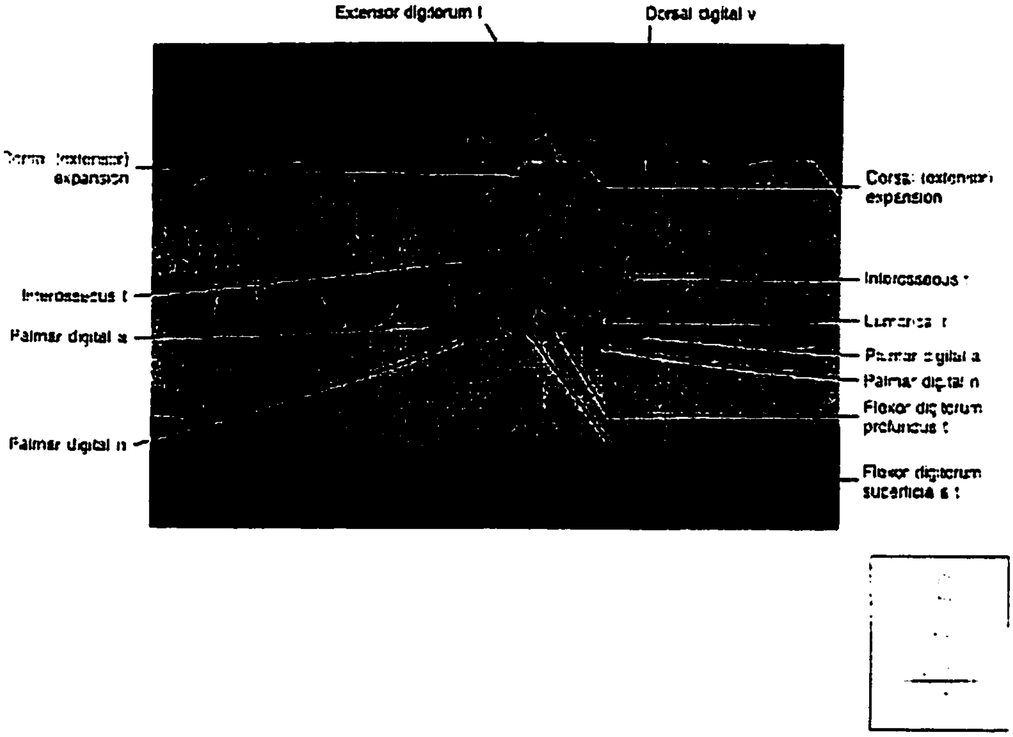


Figure 4.3. Magnetic resonance image of the palm at the cross-section near the proximal phalanx (P.P.) in the transverse plane (Kang, H.S., and Resnick, D, 1991).

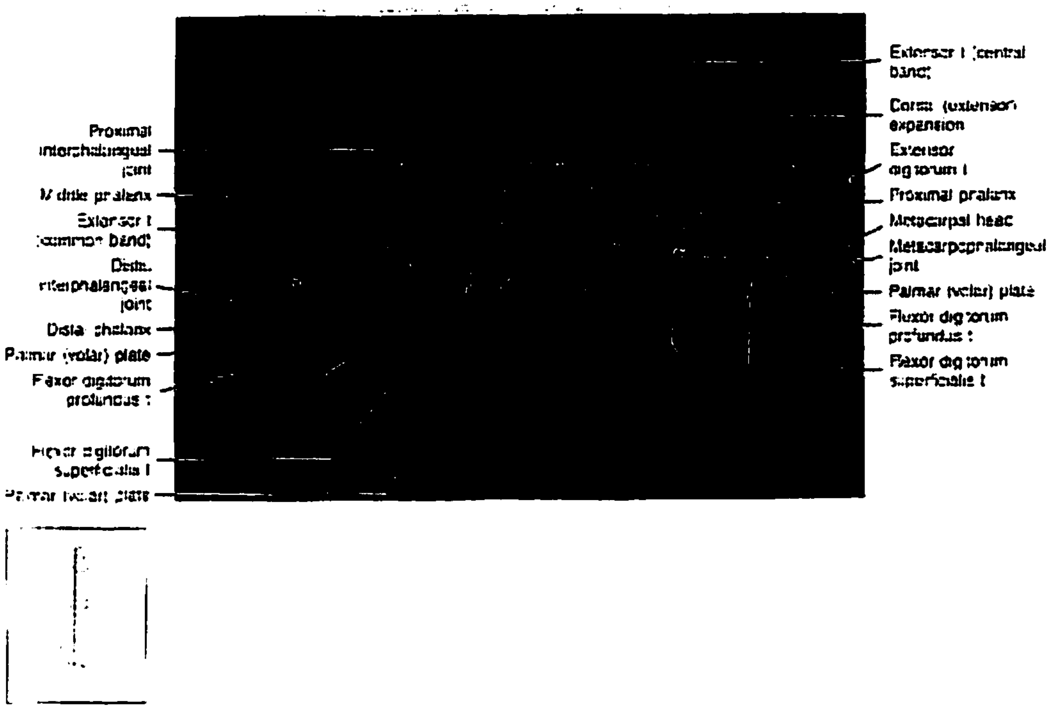


Figure 4.4. Magnetic resonance image of the finger at the cross-section of the finger in the sagittal plane (Kang, H.S., and Resnick, D, 1991).

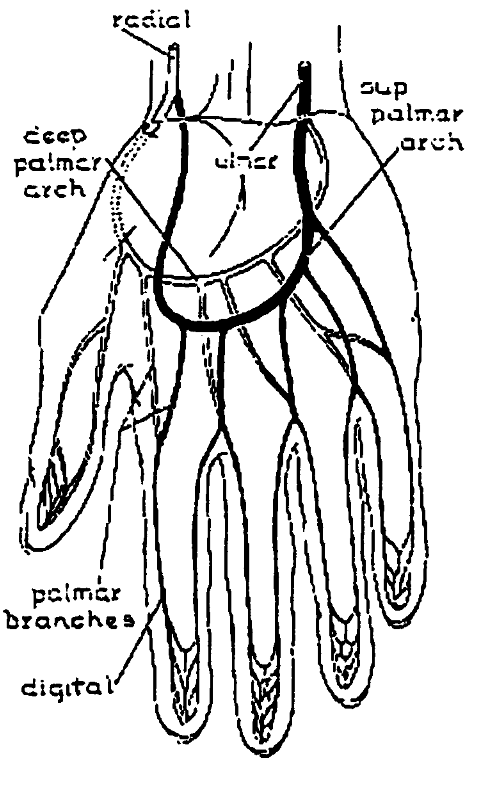


Figure 4.5 Scheme of arteries of the hand (Basmajian, J.V., 1978).

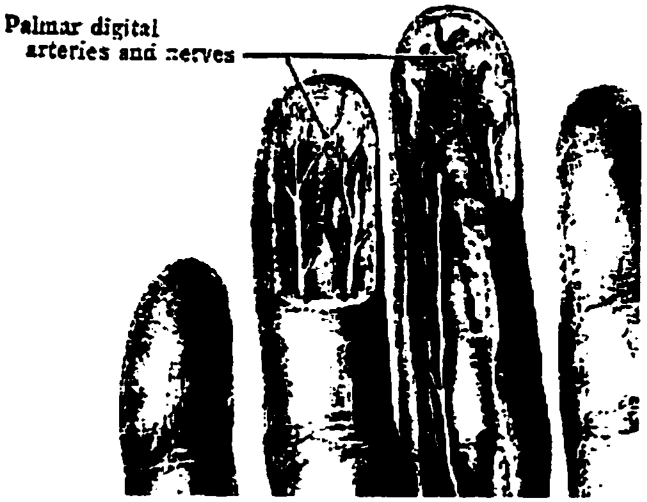
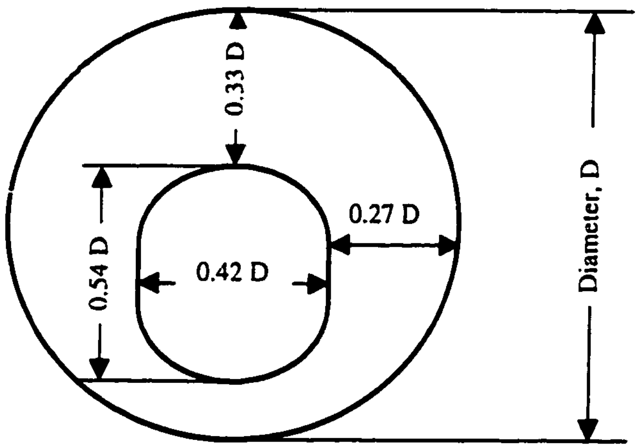


Figure 4.6. Palmar digital arteries and nerves (Anderson, J.E., 1978).

Palmar (Anterior)



Dorsal (Posterior)

Figure 4.7. The dimensions of the finger, bone taken from the magnetic resonance imaging pictures as shown in figure 4.2.

In order to build the finite element models, the dimensions of the bone and soft tissue of the finger are taken from the pictures of magnetic resonance imaging. Figure 3.5 shows the dimensions of a finger at the cross-section of the proximal phalanx in the transverse plane. Appropriate loads for the finite element models can be obtained from the experimental results described in the previous chapters. The selection of the loads is described in the next section.

4.3. Description of the Finite Element models

From the static study of grip pressure distribution as described in the second chapter, and the dynamic pressure measurements in the third chapter, the range of pressures applicable to the human hand while working with the hand-held tools is inferred. The lowest pressures were recorded at the distal phalanx of the little finger, and the highest pressures were recorded at the distal and the middle phalanges of the index and the middle fingers. Also on the palmar region, lowest pressures were recorded at the proximai and medial regions of the palm, and the highest pressures were recorded at the distal and lateral regions of the palm. This was observed in all the subjects.

Under dynamic conditions (chapter – 3), higher grip pressures were observed at the proximal and distal phalanges of both the left and right hand fingers, and lower grip pressures were observed at the middle phalanges of both the hand fingers. In these experiments, on the palmar region, higher grip pressures were observed in the lateral half of the palm of both the left and right hands, and lower grip pressures were observed in the medial half of the palm of both hands of all the subjects. According to the above inferences (chapter – 2), the lowest pressure on the finger side is taken as 2 dN/cm^2 (0.3 Psi) and the highest pressure is taken as 255 dN/cm^2 (35 Psi). On the palmar side the lowest pressure is taken as 5 dN/cm^2 (0.7 Psi) and the highest pressure is taken as 220 dN/cm^2 (32 Psi). From the results in chapter – 3, the highest pressures were acting at the distal phalanx of the index finger of the left hand, when one of the subjects was working with the heavier tool. This pressure was recorded as 140 dN/cm^2 (20.3 Psi).

As explained in the previous sections, the anthropometric and physiologic data obtained by the pictures photographed by magnetic resonance imaging is used to develop the mathematical models in ANSYS finite element program. Two models have been developed to study the stresses and deformations of the human hand. Each of these models is described below. Both models require the specification of material properties (Young's modulus and Poisson's ratios). Bone material is a composite of collagen and hydroxyapatite (Fung, Y.C., 1988). The Young's modulus of bone is intermediate between that of apatite and collagen. Young's modulus of the bone was chosen to be as 2.6×10^6 lb/in^2. Poisson's ratio of the material of bone was chosen as 0.27. Young's modulus of soft tissue was chosen to be as 14.5 lb/in^2, the Young's modulus of skin (Skalak, R., and Chien, S., 1987), and the Poisson's ratio as 0.5. The Young's modulus of the tool handle was chosen to be as 30×10^6 lb/in^2, and the Poisson's ratio as 0.33, the properties of steel.

4.3.1 Model I – A finger-handle model

This model was developed on the basis of the cross-sectional view of the proximal phalanx in the transverse plane identical to the model shown in figure 4.2. The finite element model was developed for a two dimensional cylindrical finger loaded by a force through a cylindrical handle resembling a hand-handle system at the digital region. Only one finger was considered in this model. Solid quadrilateral four node 8 degrees of freedom (PLANE42) element with elasto-plastic hardening capabilities was used for both the hand and handle regions, using ANSYS finite element analysis. The most important

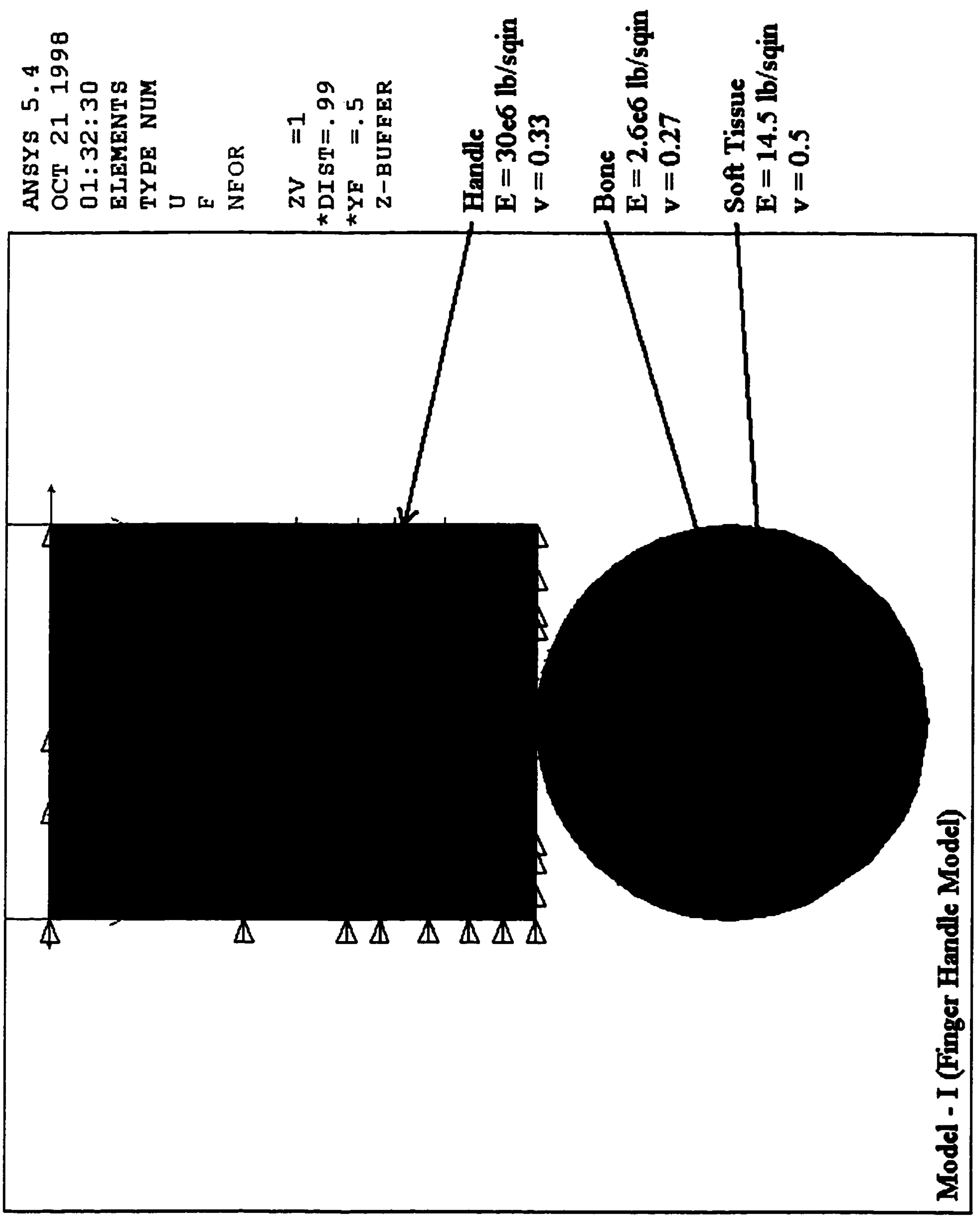


Figure 4.8 Finite Element Model-I (Finger-Handle Model)

assumption made in this model is that the bone was fixed at its bottom, giving prominence to the deformations in the soft tissue region. One of the other assumptions is that loads are applied at the top edge of the handle. Figure 4.8 shows the finite element model for the finger-handle model.

Plane42 element was selected for meshing the hand and handle regions due to the fact that the generated 2D contact elements (CONTACT48), are not compatible with elements that contain mid-side nodes. The contact was modeled using a 2-D point to line contact element (CONTACT48) which has a stiffness of 10^{10} lb/in^2. The modeling was carried out such that the dimensions of the contacting bodies are about four times higher than the finely meshed contact region. The contact elements are generated on the line where it is predicted that contact would occur. The contact elements are generated automatically by using the contact, target component grouping features of the software.

4.3.2 Model II – **A palm-handle model**

The second model was developed on the basis of the cross-sectional view of the palmar region that is adjacent to the proximal phalanx. This cross-sectional view is present in the transverse plane identical to the model shown in figure 4.3. The finite element model was developed for a two dimensional rectangular cross-section of the palmar region loaded by a force through a cylindrical handle resembling a hand-handle system at the palmar region. Unlike the first model where only one finger was considered, four Meta carpal regions (1MC, 2MC, 3MC, 4MC as shown in figure 4.3),

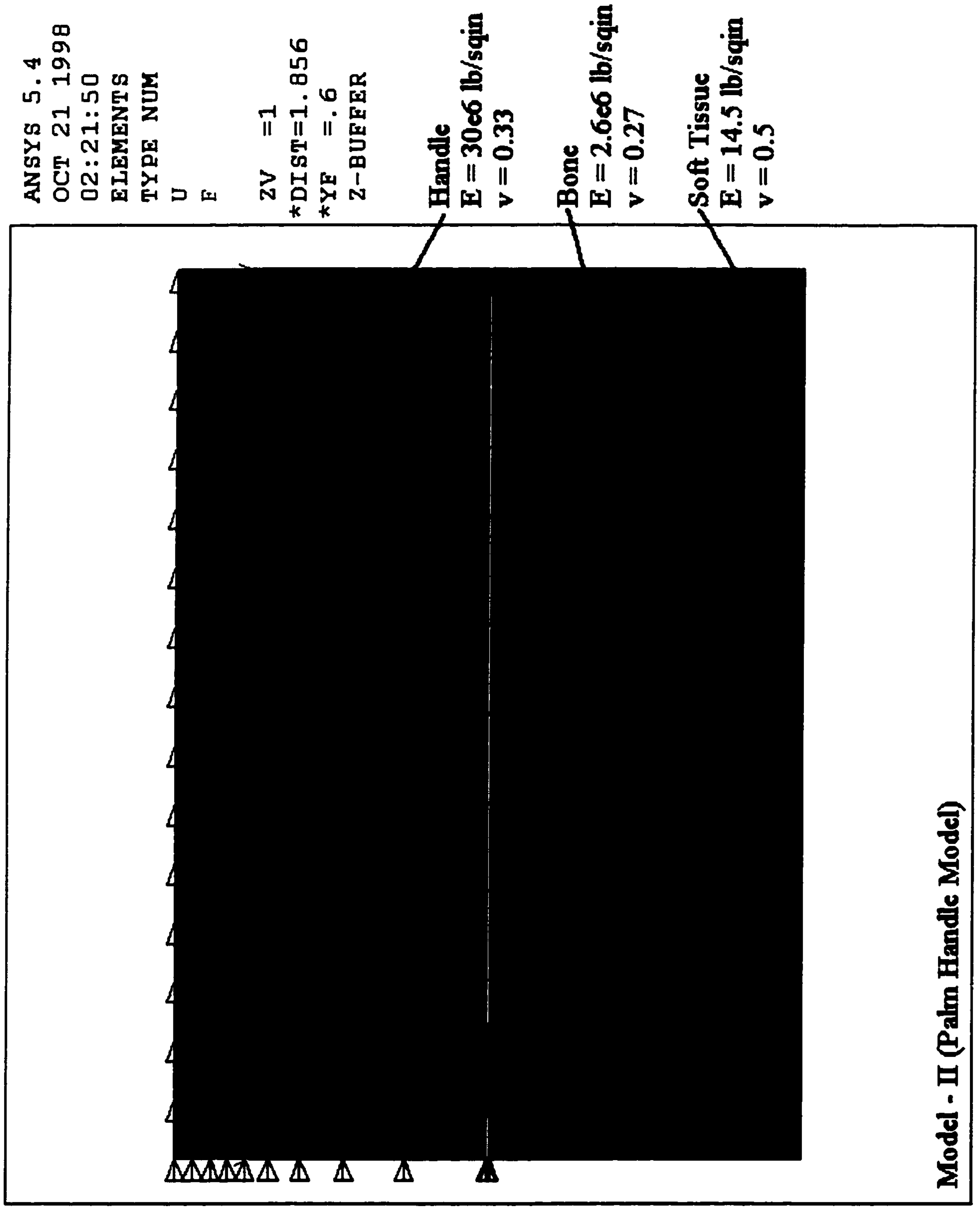


Figure 4.9 Finite Element Model-II (Palm-Handle Model)

(PLANE42) element with elasto-plastic hardening capabilities was used for both the hand and handle regions, using ANSYS finite element analysis. Like the first model the most important assumption made in this model is that the four Meta carpal regions, or the bone materials were fixed at their bottom, giving prominence to the deformations in the soft tissue. One of the other assumptions is that loads are applied at the top edge of the handle.

Plane42 element was selected for meshing the hand and handle regions due to the fact that the generated 2D contact elements (CONTACT48), are not compatible with elements that contain mid-side nodes. The contact was modeled using a 2-D point to line contact element (CONTACT48) which has a stiffness of 10^{10} lb/in^2. The contact elements are generated on the line where it is predicted that contact would occur. The contact elements are generated automatically by using the contact, target component grouping features of the software.

4.4 Results and Discussion

In the first model, forces were applied in steps starting from 0.2 Pounds to 2.4 Pounds. The loading was stopped at 2.4 Pounds, because constant stresses were observed after 2.4 Pounds loading. The stress intensity at the locations of the arteries and nerves was noted down. Figure 4.10 show the region of the location of the digital artery and digital nerve. Apparently, as one cannot judge the exact locations of the blood vessels and nerves, an approximate range of region was selected to study the stresses. Figure 4.11 show the stress intensity contour plot of model-I when 0.8 pound force is applied. The other contour plots at different levels of loading are shown in the Appendix-III.

Figure 4.12 shows the plot for Stress Intensity (Psi) as a function of the Force (Pound) applied to the handle at the locations of the blood vessels and nerves. It is clear that until the force of 1.8 Pounds, the stress intensity increased proportionally (linearly) to the applied force. From the 1.8 Pound loading the stress intensity started to shoot up to as high as 18 Psi. Since the pressure in arterioles may vary from 60-70 mm Hg (1.2-1.4 Psi), collapse may occur at loads of about 1 Pound and higher. Loading above 1.8 pounds causes a tremendous increase in the external pressure on the blood vessel, thereby almost certainly causing a collapse of the vessel and blockage. According to the results from chapter-2 and chapter-3, the lowest pressure on the finger side is taken as 2 dN/cm^2 (0.3 Psi) and the highest pressure is taken as 255 dN/cm^2 (35 Psi), at the tip of the index finger.

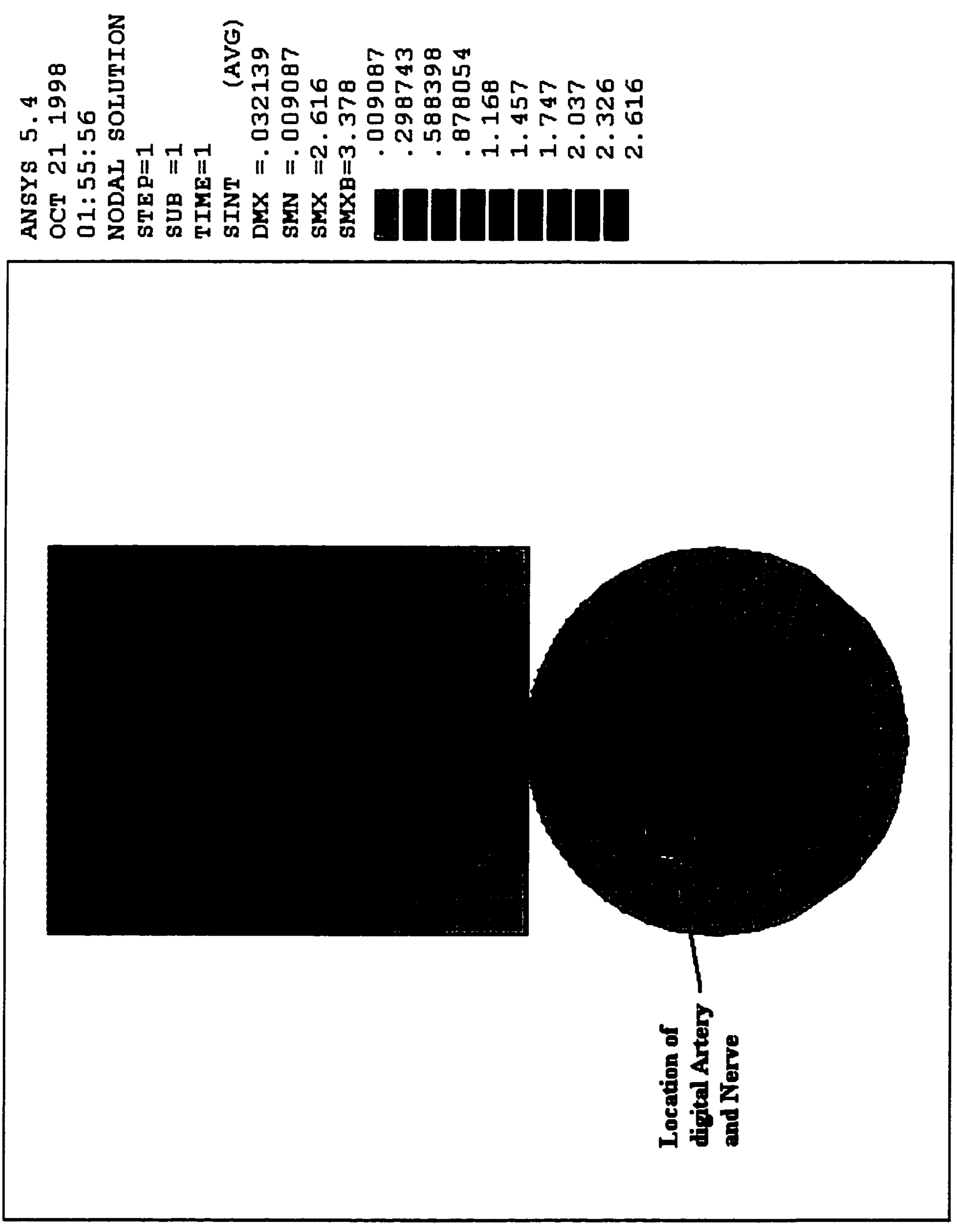


Figure 4.10 Location of digital artery and digital nerve in the stress intensity contour plot of Model-I (Finger-Handle Model)

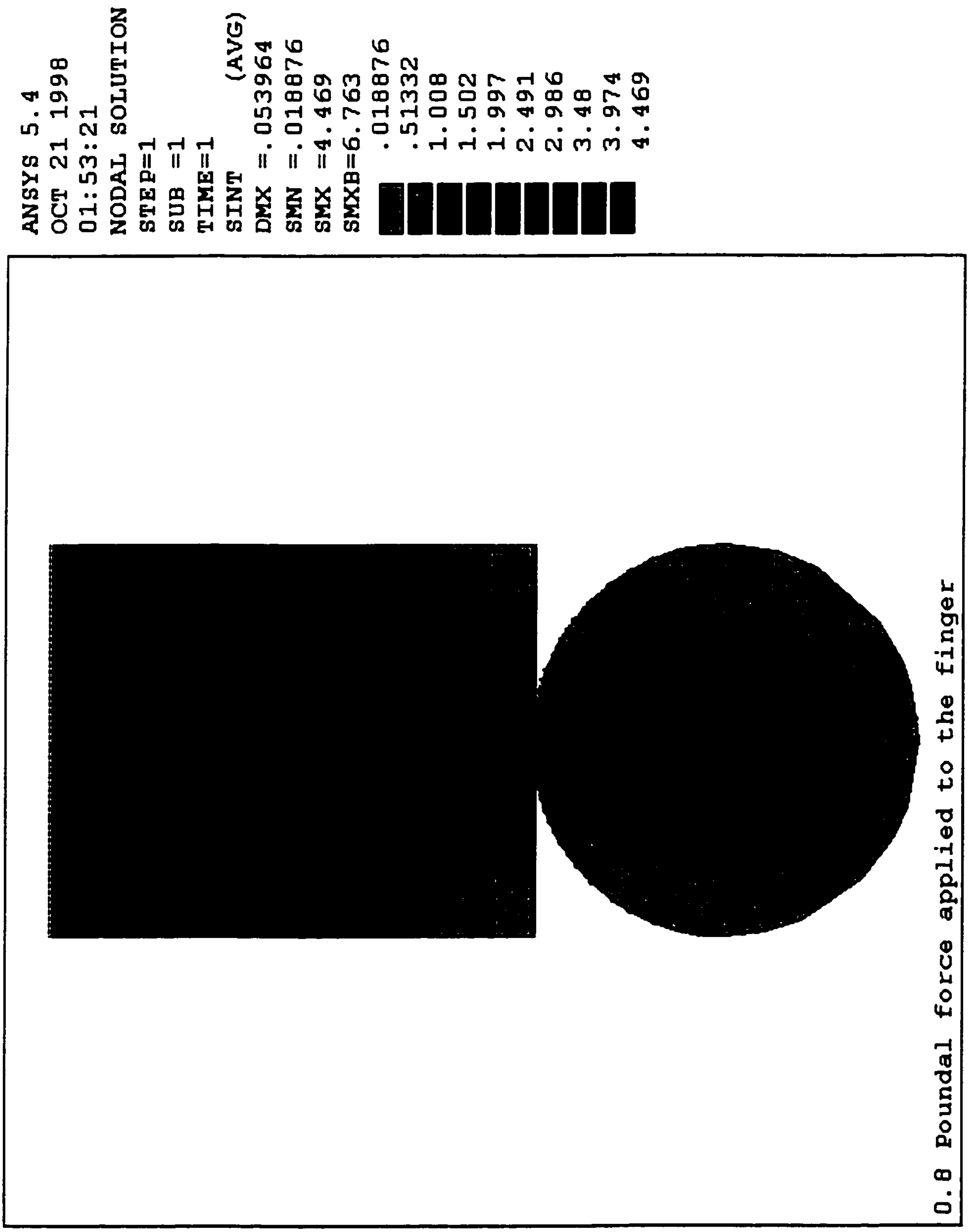


Figure 4.11 Stress Intensity contour plot of Model-I (Finger-Handle Model)

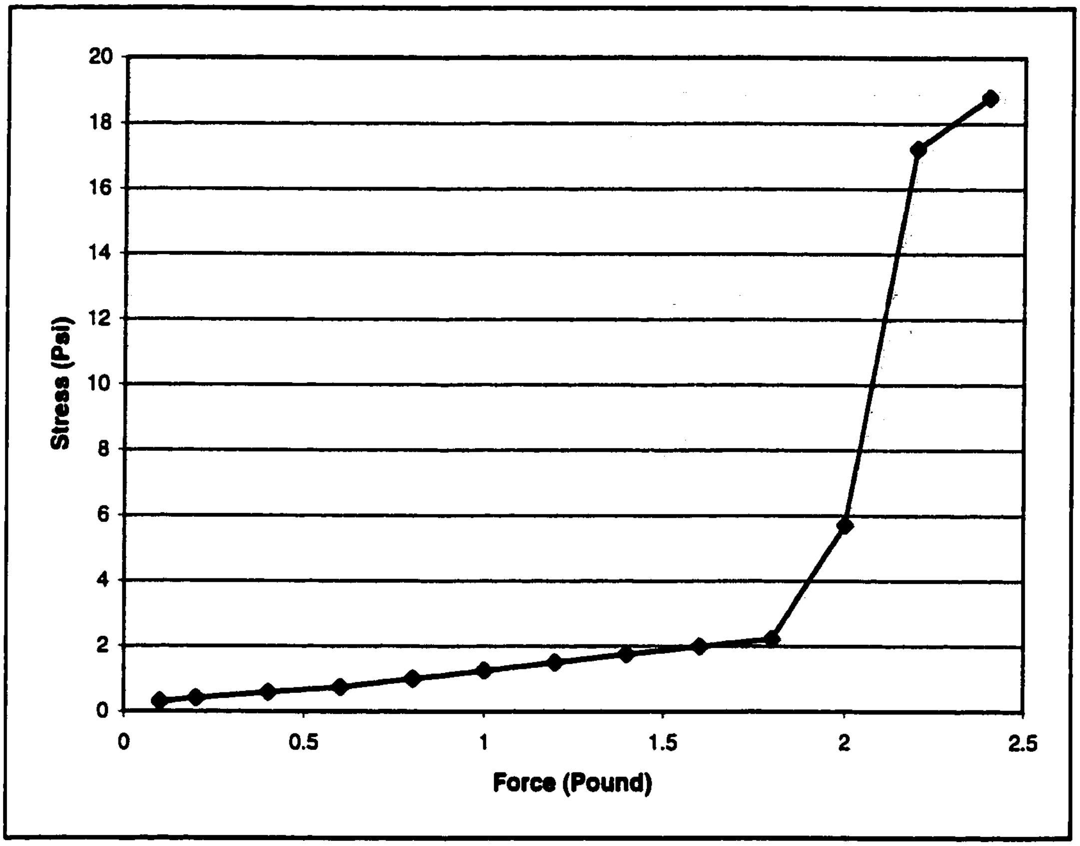


Figure 4.12 Stress Intensity in the region of the artery Vs Applied Force curve for Model-I (Finger-Handle model)

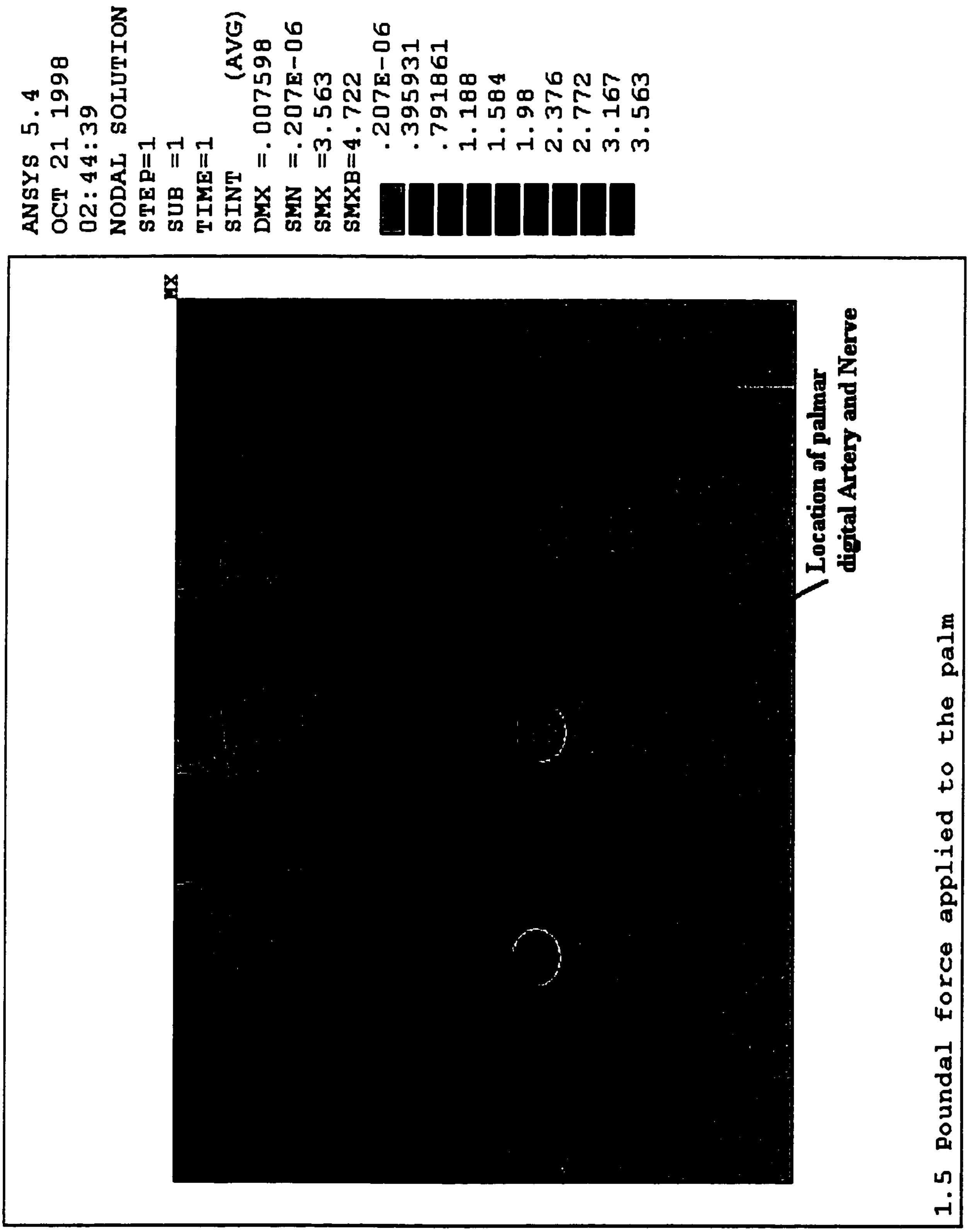


Figure 4.13 Location of palmar digital artery and palmar digital nerve in the Stress Intensity contour plot of Model-II (Palm-Handle Model)

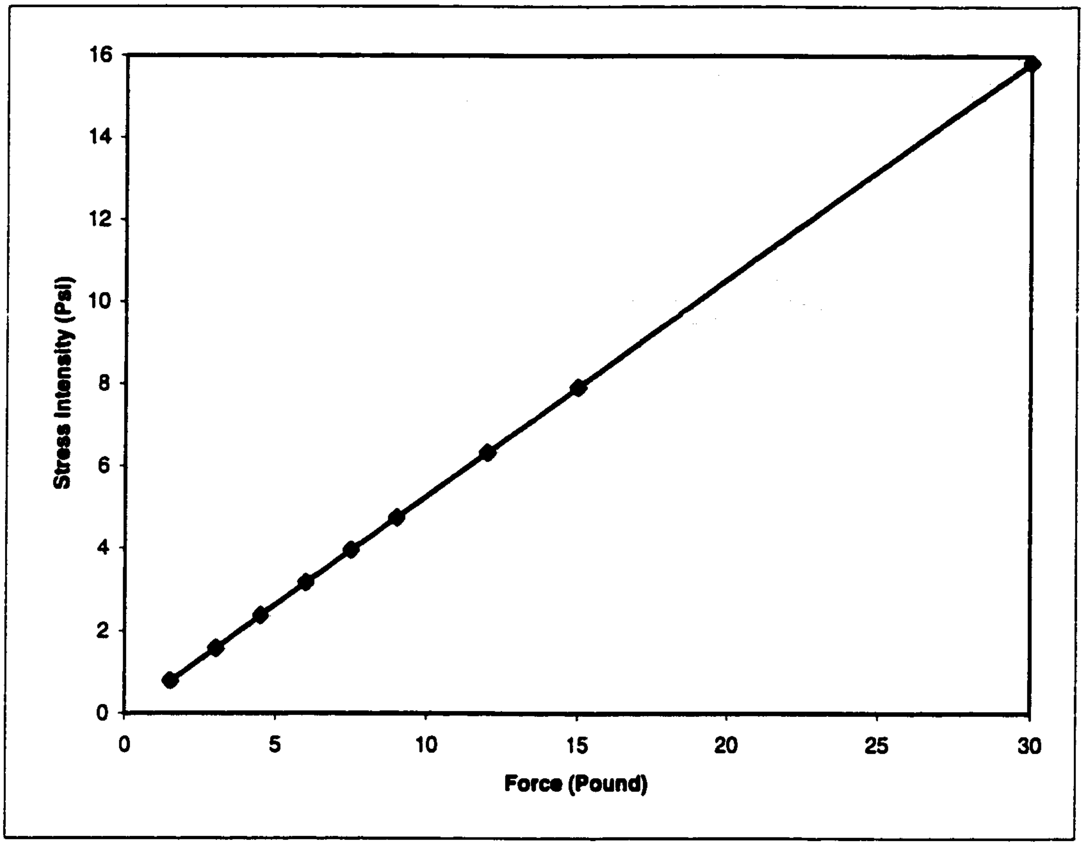


Figure 4.14 Stress Intensity in the region of the artery Vs Applied Force curve for Model-II (Palm-Handle model)

The second model shows the deformations and the stress intensity of the soft tissue in the palmar region of the human hand. Figure 4.13 shows the contour plot of the stress intensity when 1.5 pound force is applied on the palm. This plot shows large amounts of stresses lying in the region above the bone. Figure 4.14 shows the plot for stress Intensity (Psi) as a function of the force (Pound) applied to the handle at the region of the blood vessels and nerves. Similar to the first model the stress intensity in the region of the blood vessels are higher than their internal pressures when the forces applied on the handle are as high as 4.0 Pounds (approx.). This is higher than the force that makes the blood vessel in the finger to collapse. This reveals that the palmar region can withstand to high amount of forces than the fingers individually. According to the results from the chapter – 2 and chapter – 3, on the palmar side the lowest pressure is taken as 5 dN/cm^2 (0.7 Psi) and the highest pressure is taken as 220 dN/cm^2 (32 Psi).

The study and analysis in this chapter reveals a possible cause of the VWF (vibration white finger) disease. Workers gripping hand-held tools frequently experience numbness and pain in the arms and hands. The results of the finite element models clearly show that the application of high grip pressures on the finger and palmar regions, results in reduced or completely shut off of blood flow to the affected segments of the fingers or palm.

Chapter 5

Conclusions and Recommendations for Future Work

5.1 Introduction

The primary focus of this research was to contribute to the accomplishment of a safer operating environment for workers of hand-held power tools through systematic studies on:

1) Study of the loading of the hand: Development of a methodology to obtain a overall hand grip pressure distribution and forces/moments at the hand-handle interface applicable to most power tools,

2) Perform appropriate field tests using actual power tools, to study the hand grip pressure distribution and operator posture in the dynamic conditions,

3) Development of mathematical models of hand-handle system.

5.2 Conclusions

Following conclusions are drawn from the results of analytical and experimental studies performed in this dissertation research:

Chapter – 2 (Study of the loading of the hand)

1) Flexible variable capacitance sensors can be effectively used to measure the hand grip pressure distribution at the hand-handle interface under static loading conditions.

2) Using Spline interpolation technique a smooth and more accurate overall grip pressure distribution (GPD) can be obtained, which facilitates the analysis.

3) Forces and Moments applied to the hand can be calculated from the GPD at the hand handle interface. These give important information about the loading of the hand.

4) In the experiments of static gripping of a cylindrical handle, the finger phalanges are exposed to the largest pressure, while comparatively less pressure is applied to the palmar region.

5) Under static conditions, high grip pressures are present at the tips of the index and middle fingers. Also, higher grip pressures are present on the lateral side of the hand than that on the medial side.

6) The fingers exhibiting higher amount of forces are the index finger with approximately 38.36% of the total force on the distal side, the middle finger with approximately 27.64% of the total force. Lower amounts of forces are applicable to the ring and the little fingers with the rest of the total force on the distal side.

Chapter – 3 (Hand GPD Under Static and Dynamic Conditions Using Typical Power Tools)

7) The grip pressure distribution is dependent on the diameter of the cylindrical handle and the weight of the tool. With increasing cylinder diameter, and the weight of the tool, pressure is more evenly distributed and higher proportions of pressures are present at the distal phalanges of the index and the middle fingers.

8) The amount of grip pressure during dynamic conditions depends upon the reaction forces at the tool-work piece interface. The operator of the power driven grinding tool had to apply high pressure on the tool handle to oppose the reactions due to the moments present at the tool-work piece interface.

9) Due to the unbalance of the power grinders, during dynamic conditions, higher forces are present on the little and ring fingers and the lateral half of the palm.

10) The highest pressure recorded of all the experiments was of 140 dN/cm^2, which is equivalent to 20.3 Psi. This pressure was recorded on the distal phalanx of the index finger of the left hand.

11) Knowing the magnitudes of applicable hand grip pressures, and the extent to which human hand can withstand these pressures, localized and potentially dangerous grip pressures that are harmful to the human hand, can be identified.

Chapter – 4 (Development and Analysis of Mathematical Models of the Hand-Handle System)

12) Finite Element Analysis (FEA) is an effective tool that can be extensively used to study the complex characteristics of the human hand and how it reacts to the grip pressures applicable when operators use hand held tools.

13) In the finger-tool interface mathematical model, until 1.8 pound force loading the stress intensity increased linear (proportional) to the applied force. From the loads above 1.8 pounds, the stress intensity started to shoot up to as high as 18Psi. This shows, that high local grip pressures causes a tremendous increase in external pressure of the blood vessels and nerves.

14) In the palm-tool interface mathematical model, the stress intensity in the region of blood vessels are higher than their internal pressures when the forces applied are as high as 4.0 Pounds. The palmar region can withstand to high amount of forces than the fingers individually.

15) The high local grip pressures on the finger and palmar regions result in reduced or complete shutoff of blood flow to the affected segments of the fingers. Even normal generation of the grinding tools tested causes significantly large pressures to block blood flow. The high external pressures causing the compression of the nerves can result in numbness and the loss of sensation.

5.3 Recommendations for future work

1) A more efficient, flexible and finer array of sensors is recommended for measuring the grip pressure distribution as the sensors used in this study cover an area of 1 cm^2 and are not able to measure localized pressures precisely at a point on the surface of the hand.

2) When using power tools, GPD between tool and fingers and palm of left and right hands should be measured simultaneously.

3) As not all hand held tool handles are cylindrical, it is recommended the study be extended to typical tool handles of different shape.

4) The study should be further extended to obtain an optimum design of tool handles to ensure more uniform pressure distribution in the hand, which would reduce high localized pressures at the hand-handle interface.

5) The mathematical models of the finite element analysis should be more complex to resemble the complex nature of human hand. Three-dimensional finite element models of the human hand might give good results.

6) Impairment of blood flow to the fingers may be related to the concentration of high pressures at the distal phalanges of the index and middle fingers. The VWF disease, related to the impaired blood flow, is known to cause blanching of fingers. Further studies on measurement of finger blood flow when different pressures are applied, can thus provide significant knowledge on the mechanism of VWF disease.

7) The studies related to grip pressure distribution at the hand-handle interface should be extended on a large number of subjects of different percentiles under a wide range of tool-related factors such as weight of the tool, tool balance, shape of the tool handle and type of the tool.

8) Studies should be carried out to investigate the extent to which protective gloves or a redesign of the tool could help to minimize concentration of high pressures at the hand-handle interface.

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Appendix - I

(Calibration curves of capacitive pressure sensors)

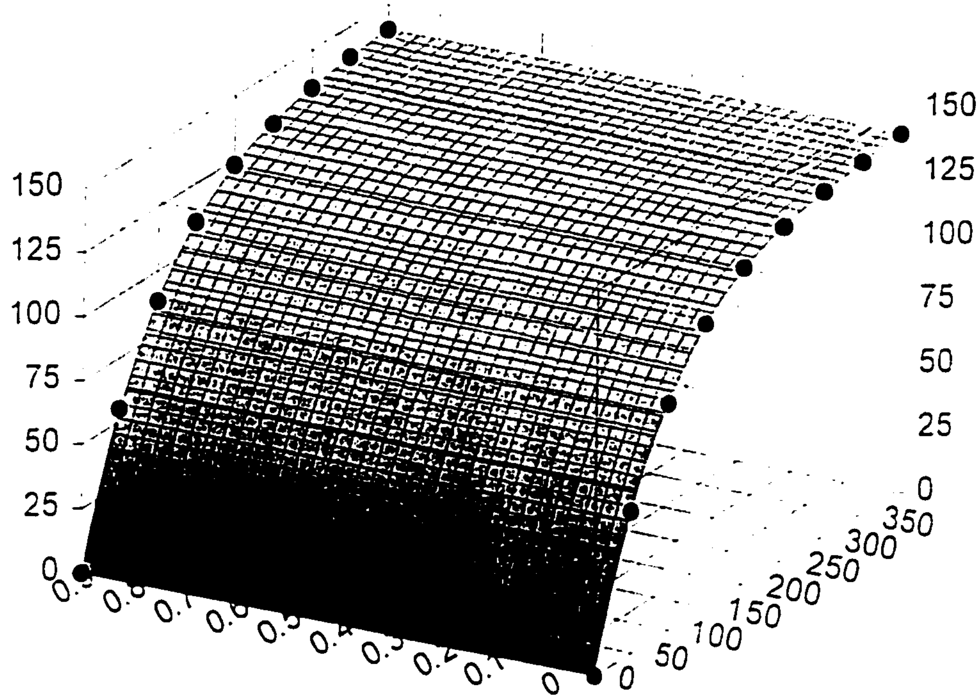
Sensor 1

Rank 1 Eqn 1097 $z=(a+bx+cx^2+dx^3+ey)/(1+fx+gy)$

r^2=0.99994865 DF Adj r^2=0.9999127 FitStdErr=0.40912294 Fstat=35698.807

a=0.14130954 b=1.3656952 c=-0.0022911919 d=2.0736159e-06

e=-0.021767661 f=0.0030786737 g=-0.00021317623



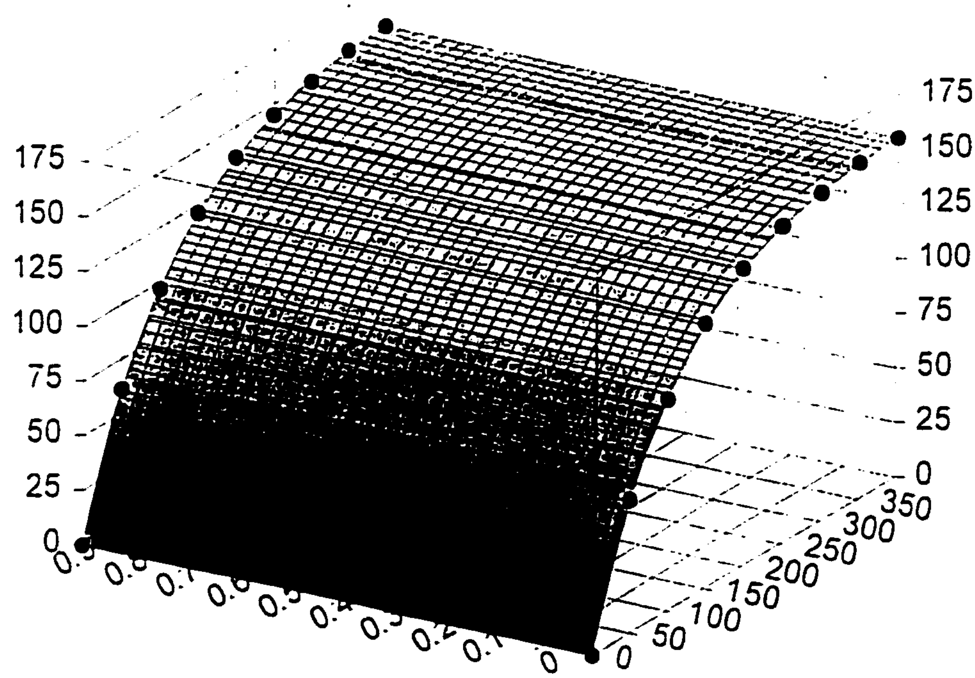
Sensor 2

Rank 4 Eqn 1052 $z=(a+bx+cx^2+dy)/(1+ex+fx^2+gy)$

r^2=0.99991858 DF Adj r^2=0.99986159 FitStdErr=0.57294911 Fstat=22516.169

a=0.15173733 b=1.5608693 c=-0.0004712447 d=-0.078640234

e=0.0052970423 f=2.6525905e-06 g=-0.00069490634



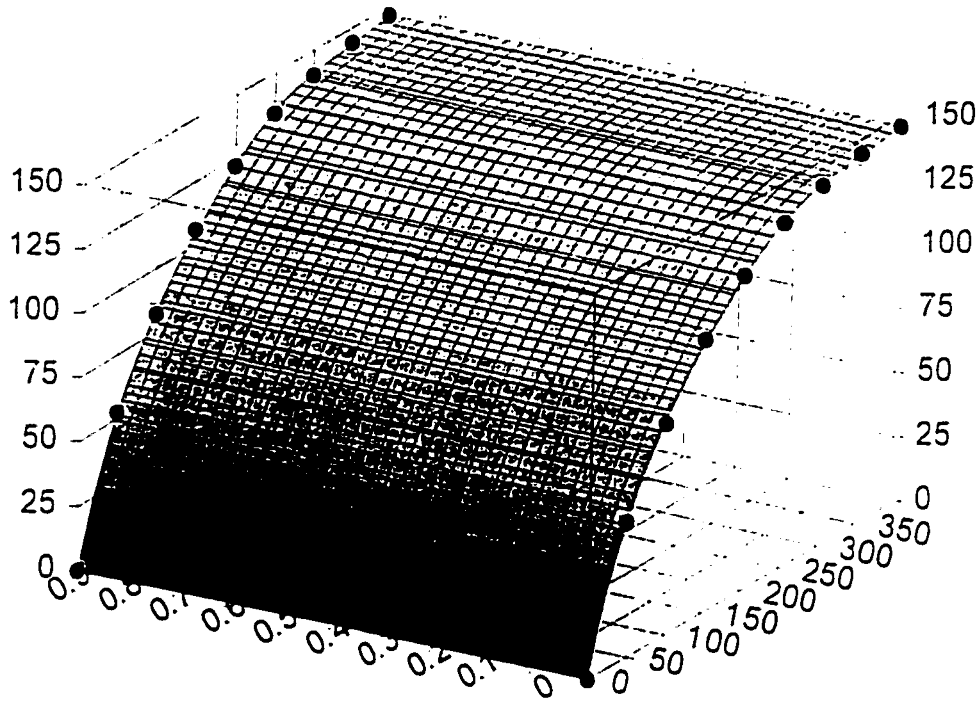
Sensor 3

Rank 2 Eqn 1103 $z=(a+bx+cx^2+dx^3+ey)/(1+fx+gx^2+hx^3+iy)$

r^2=0.99977682 DF Adj r^2=0.99952573 FitStdErr=0.99172105 Fstat=5039.548

a=0.096676901 b=1.4006029 c=-0.0092510075 d=1.7727475e-05 e=-0.020624323

f=0.00042523733 g=-3.4783138e-05 h=9.1638784e-08 i=-0.0002003442



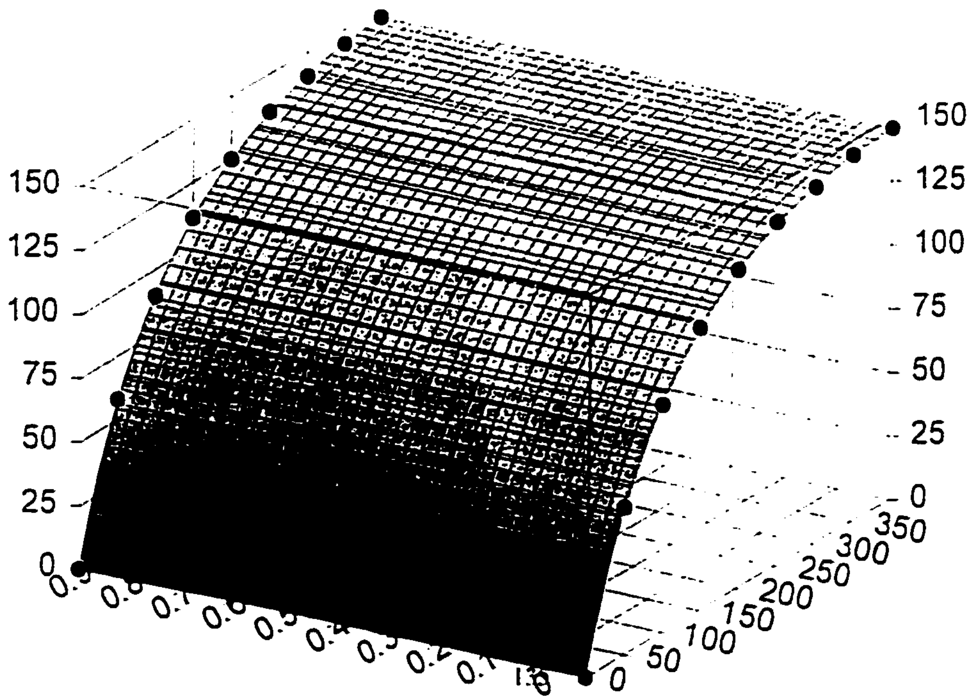
Sensor 4

Rank 3 Eqn 1052 $z=(a+bx+cx^2+dy)/(1+ex+fx^2+gy)$

r^2=0.9999035 DF Adj r^2=0.99983594 FitStdErr=0.5809623 Fstat=18995.608

a=0.20274983 b=1.562897 c=-0.002249569 d=-0.056710898

e=0.0057908226 f=-9.3410726e-06 g=-0.00053811079



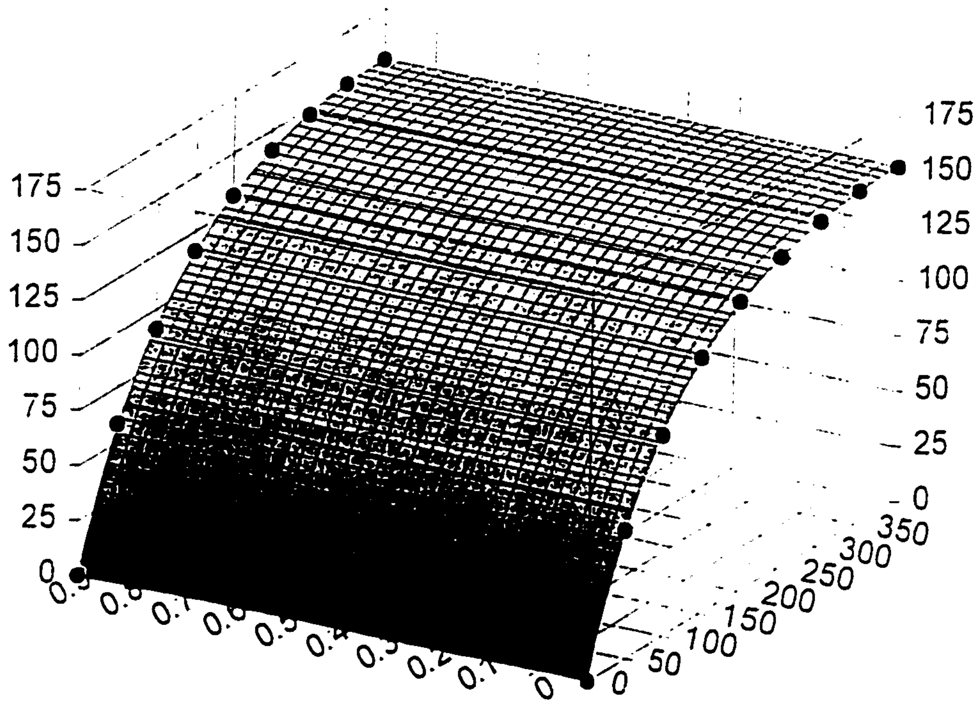
Sensor 5

Rank 3 Eqn 1052 $z=(a+bx+cx^2+dy)/(1+ex+fx^2+gy)$

r^2=0.9998082 DF Adj r^2=0.99967394 FitStdErr=0.86316223 Fstat=9556.6229

a=0.34228922 b=1.4875505 c=-0.0017370878 d=-0.085169857

e=0.004749082 f=-5.0630705e-06 g=-0.0007762316



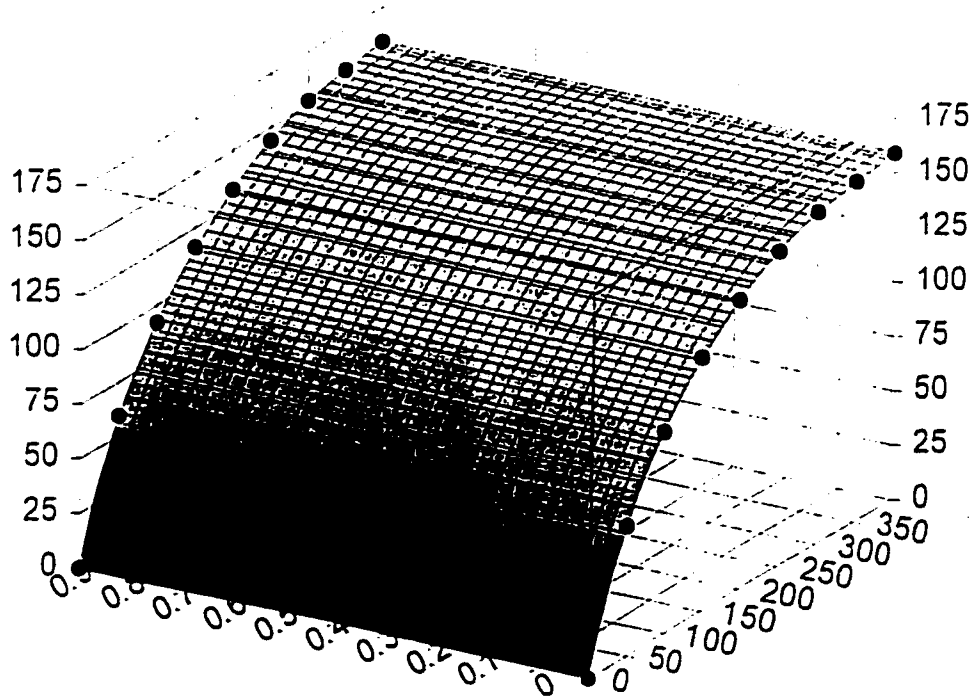
Sensor 6

Rank 2 Eqn 1103 $z=(a+bx+cx^2+dx^3+ey)/(1+fx+gx^2+hx^3+iy)$

r^2=0.99991757 DF Adj r^2=0.99982484 FitStdErr=0.64744351 Fstat=13647.18

a=0.053633027 b=1.6484547 c=-0.010638381 d=2.0497767e-05 e=-0.0094165654

f=0.0014612769 g=-3.9455629e-05 h=1.0032458e-07 i=-8.386847e-05



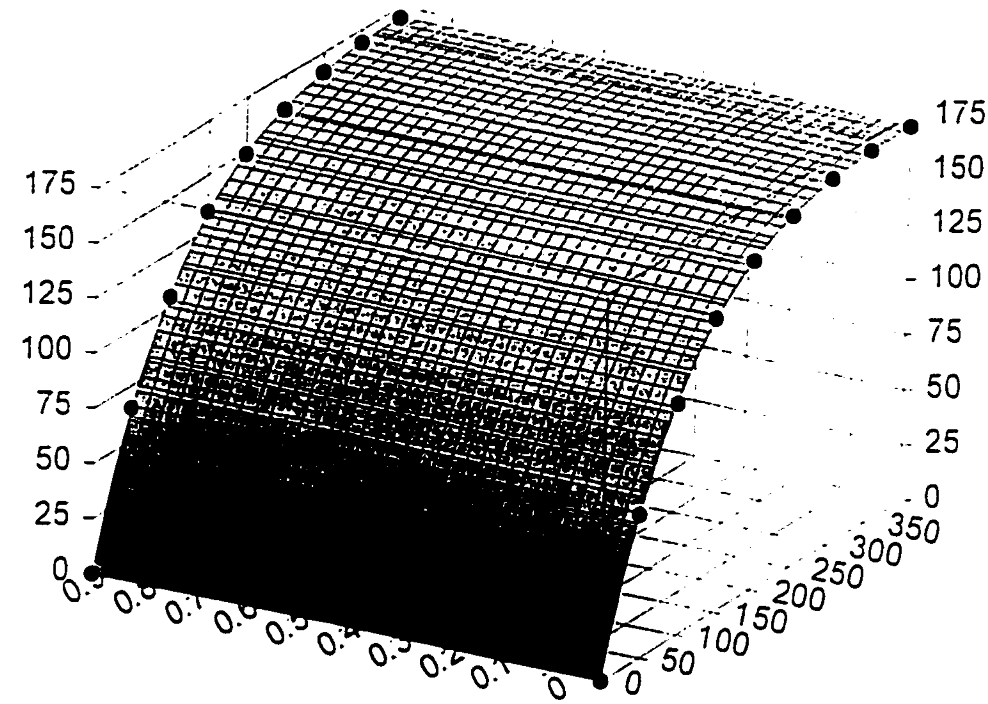
Sensor 7

Rank 2 Eqn 1007 $z=(a+bx+cy)/(1+dx+ex^2+fx^3+gy)$

r^2=0.99993376 DF Adj r^2=0.99988739 FitStdErr=0.57081926 Fstat=27674.783

a=0.16401116 b=1.6085432 c=-0.059321328 d=0.0046593027

e=5.6247252e-06 f=3.2684018e-10 g=-0.00047839781



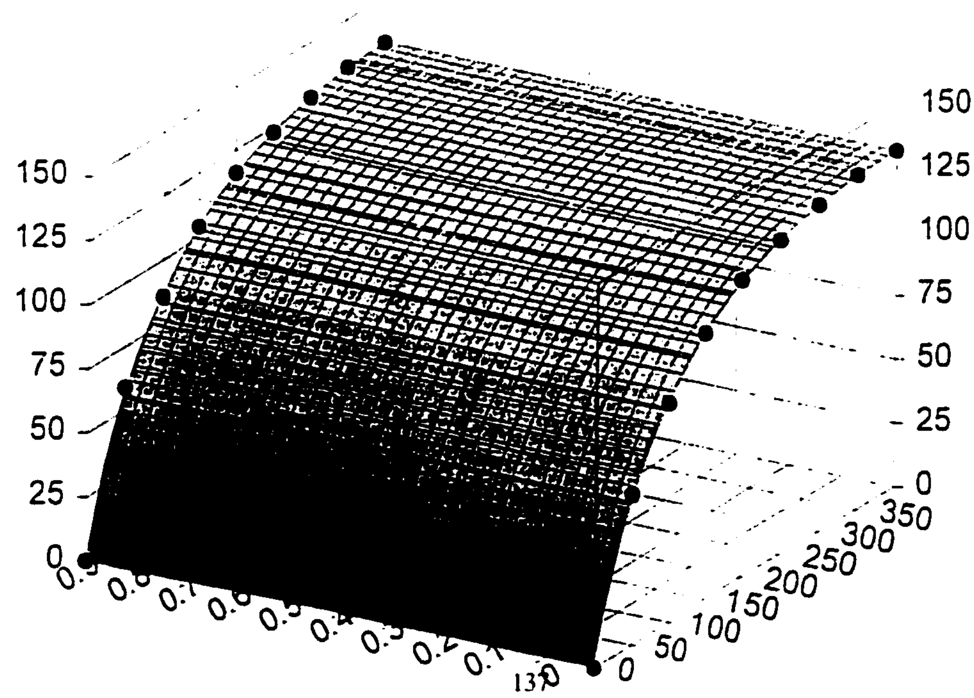
Sensor 8

Rank 2 Eqn 1007 $z=(a+bx+cy)/(1+dx+ex^2+fx^3+gy)$

r^2=0.99981673 DF Adj r^2=0.99968845 FitStdErr=0.71656953 Fstat=10001 888

a=0.49581145 b=1.761071 c=-0.13979838 d=0 010814534

e=-5.4878863e-06 f=1.3953194e-08 g=-0 0014321974



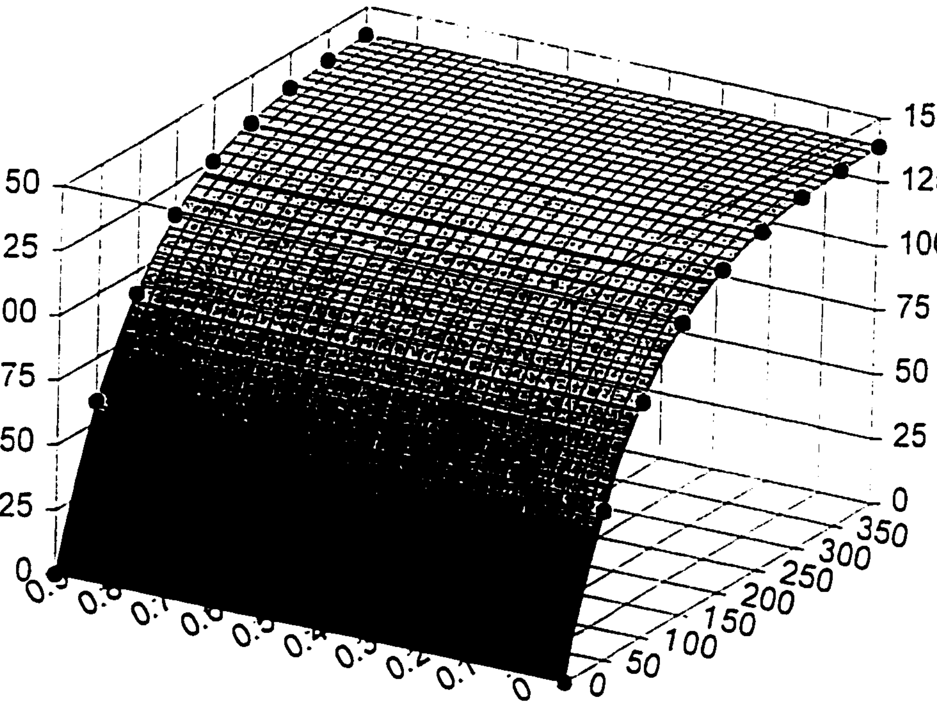
Sensor 9

Rank 1 Eqn 1097 $z=(a+bx+cx^2+dx^3+ey)/(1+fx+gy)$

r^2=0.99988072 DF Adj r^2=0.99979722 FitStdErr=0.62051694 Fstat=15368.14

a=0.25206387 b=1.4686439 c=-0.002251812 d=1.9124078e-06

e=-0.066485108 f=0.0037865753 g=-0.00064271318



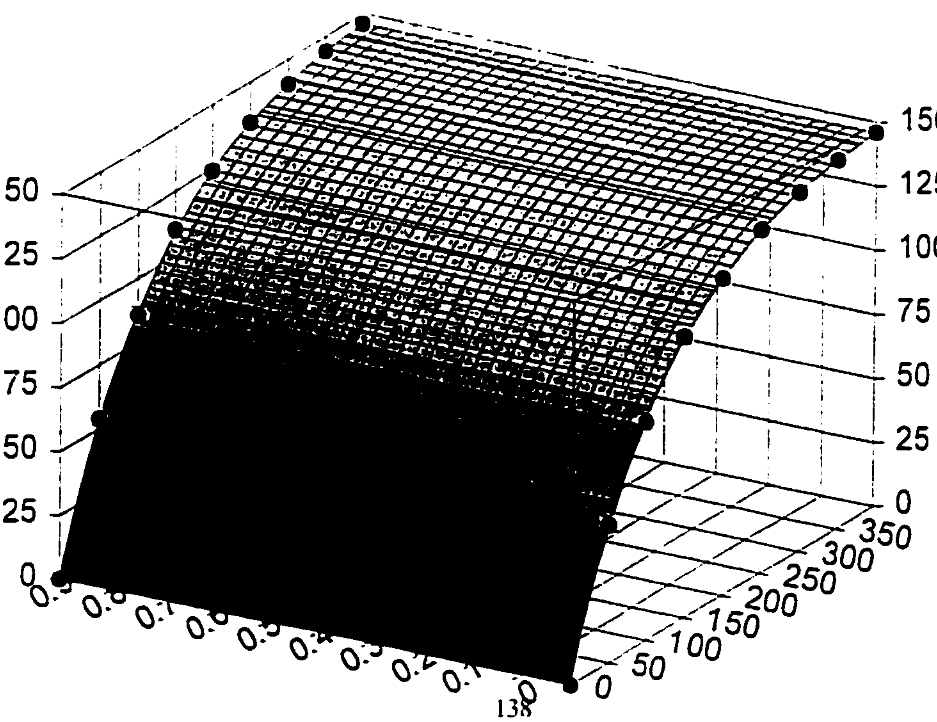
Sensor 10

Rank 5 Eqn 1049 $z=(a+bx+cx^2+dy)/(1+ex+fy)$

r^2=0.99982284 DF Adj r^2=0.99972621 FitStdErr=0.76178496 Fstat=13544.694

a=0.24344749 b=1.3432635 c=-0.00076875544

d=-0.08471616 e=0.0046041797 f=-0.00081327513



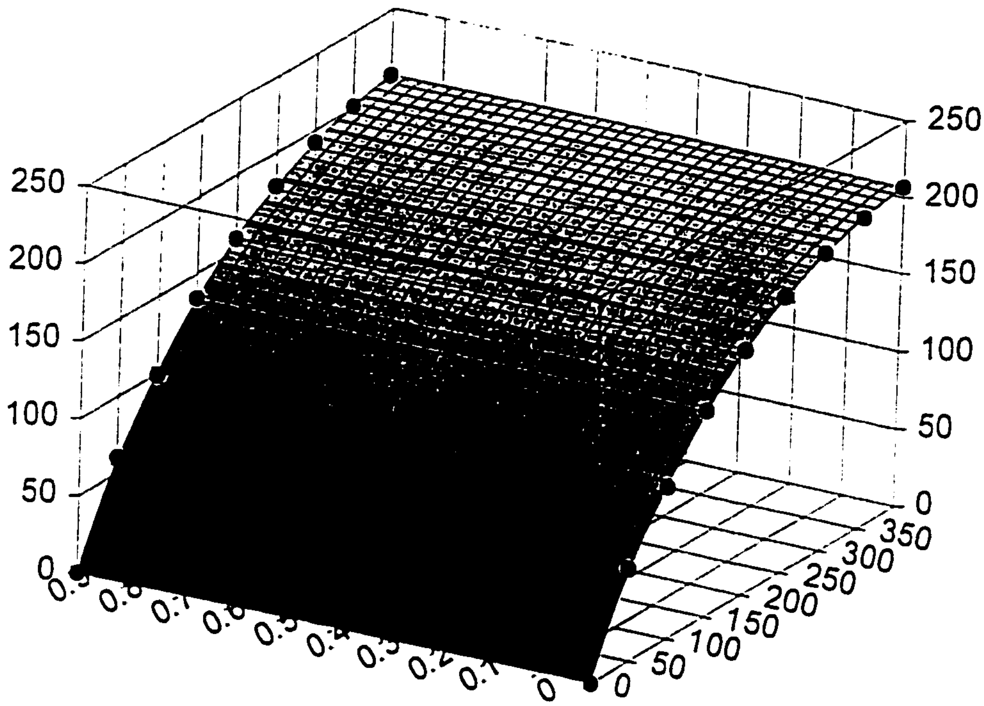
Sensor 11

Rank 2 Eqn 1007 $z=(a+bx+cy)/(1+dx+ex^2+fx^3+gy)$

r^2=0.99979241 DF Adj r^2=0.9996471 FitStdErr=1.2320253 Fstat=8829.7213

a=0.70288316 b=1.394672 c=-0.10683475 d=0.0041411582

e=-3.3866518e-06 f=9.1556849e-09 g=-0.0007820356



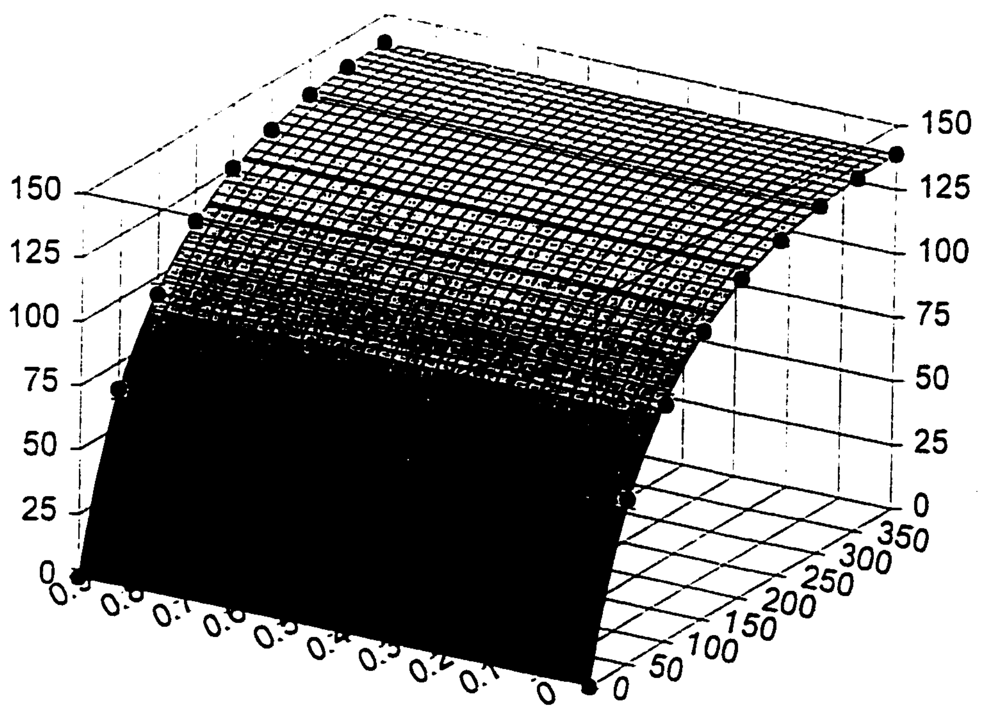
Sensor 12

Rank 3 Eqn 1052 $z=(a+bx+cx^2+dy)/(1+ex+fx^2+gy)$

r^2=0.99969698 DF Adj r^2=0.99948487 FitStdErr=0.97209889 Fstat=6048.3677

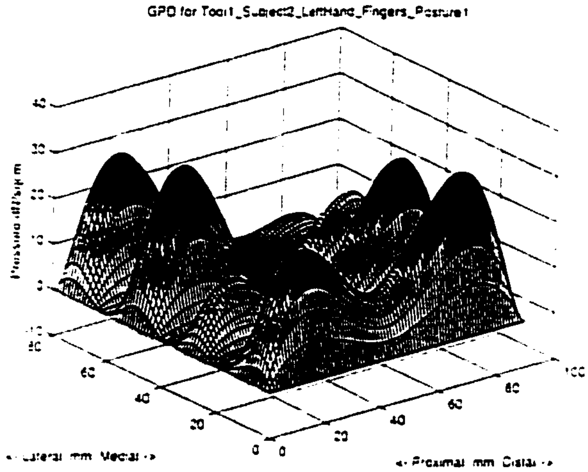
a=0.47502782 b=1.8905693 c=-0.0028920885 d=-0.19367776

e=0.0083922162 f=-1.3980097e-05 g=-0.0018553484



Appendix - II

(Grip pressure distribtion on the hands of operators working with power tools under dynamic conditions)


GPD for Tool1_Subject2_LeftHand_Fingers_Posture1
Pressure dF/sqcm
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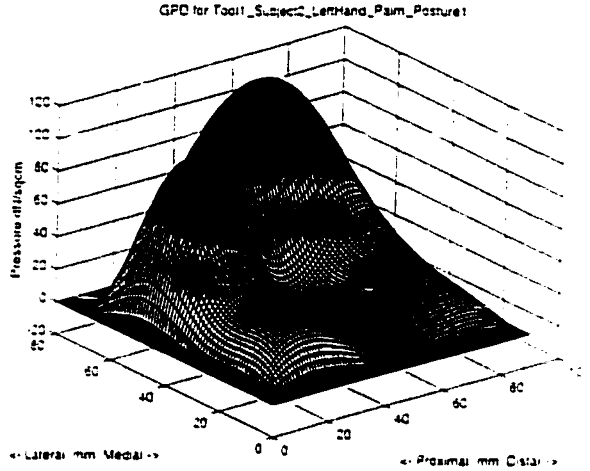
<- Proximal mm Distal ->


GPD for Tool1_Subject2_LeftHand_Palm_Posture1
Pressure dF/sqcm
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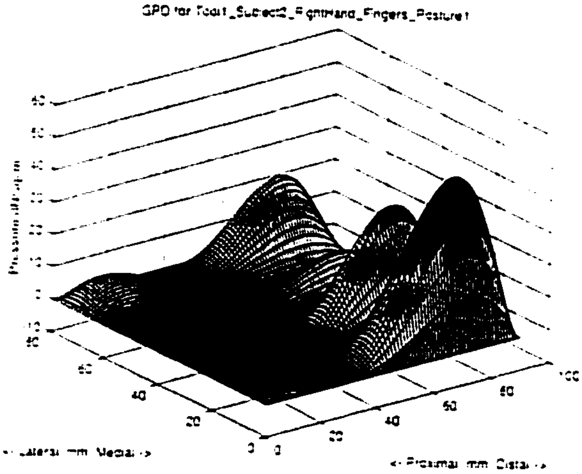
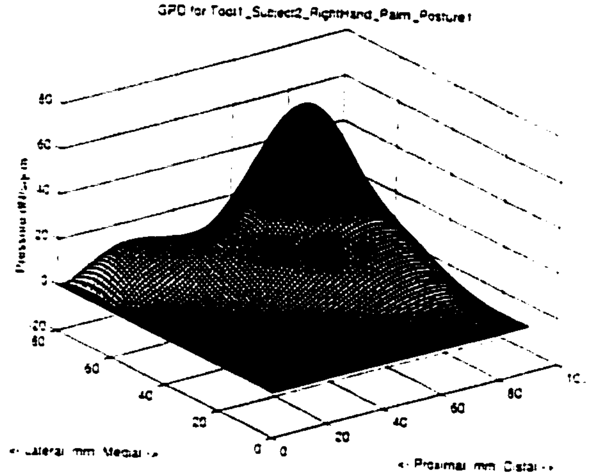
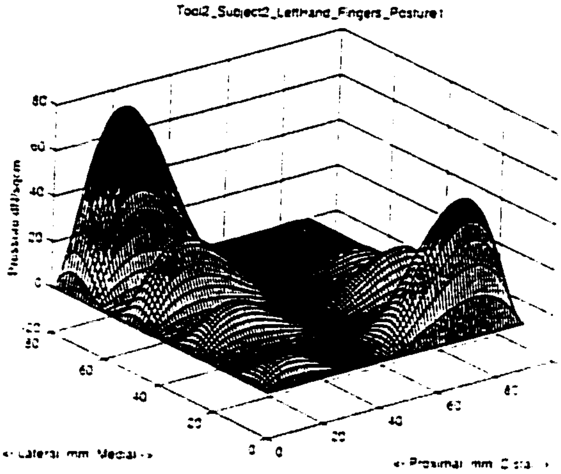
<- Proximal mm Distal ->


GPD for Tool1_Subject2_RightHand_Fingers_Posture1
<- Lateral mm Medial ->
<- Proximal mm Distal ->


GPD for Tool1_Subject2_RightHand_Palm_Posture1
<- Lateral mm Medial ->
<- Proximal mm Distal ->


Tool2_Subject2_LeftHand_Fingers_Posture1
Pressure (lf)/sqcm
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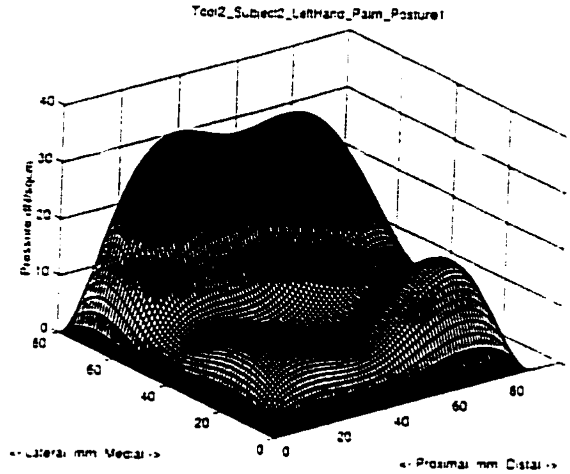
<- Proximal mm Distal ->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Pressure (lf)/sqcm
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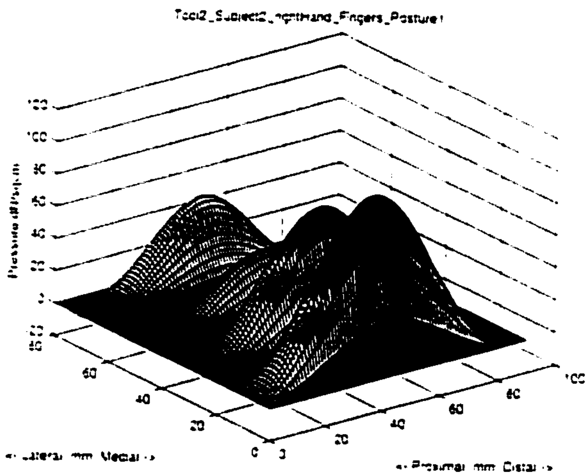
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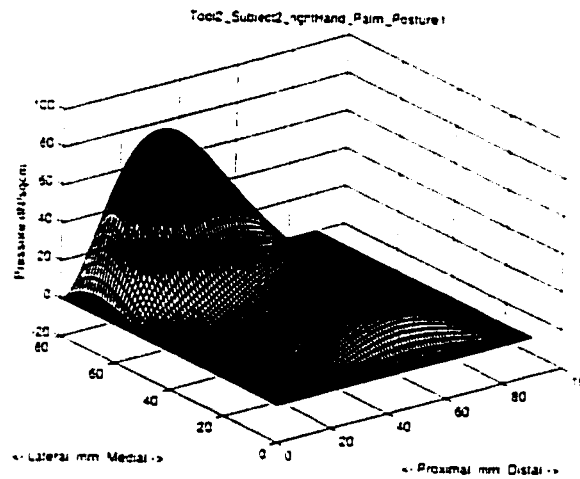
Pressure (lf)/sqcm
<- Lateral mm Medial ->
<- Proximal mm Distal ->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Pressure (lf)/sqcm
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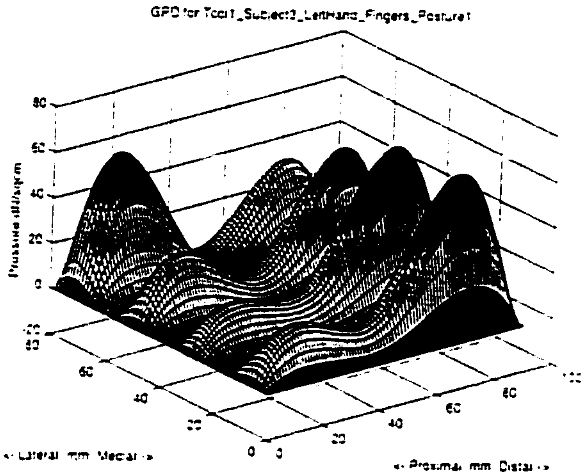
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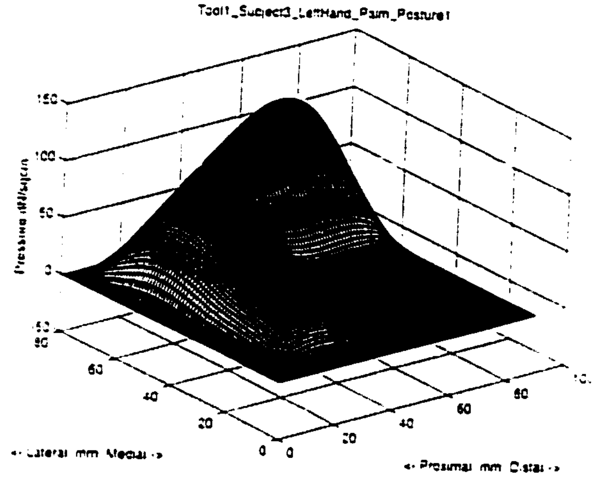
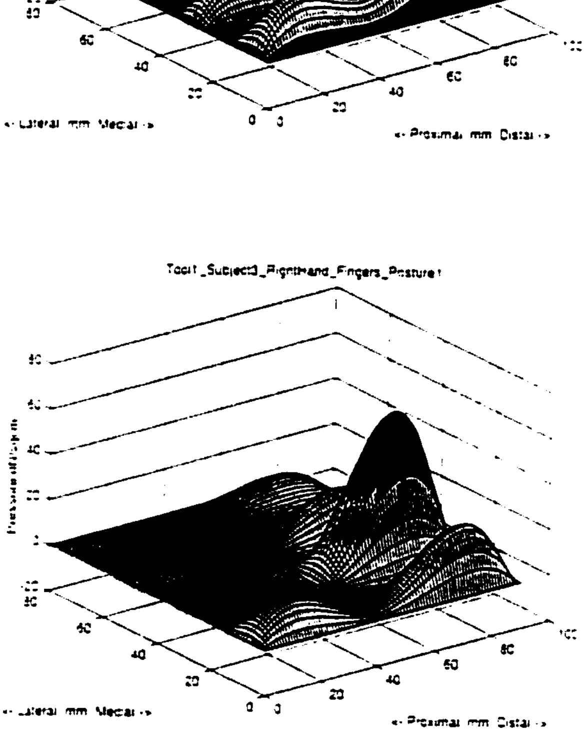
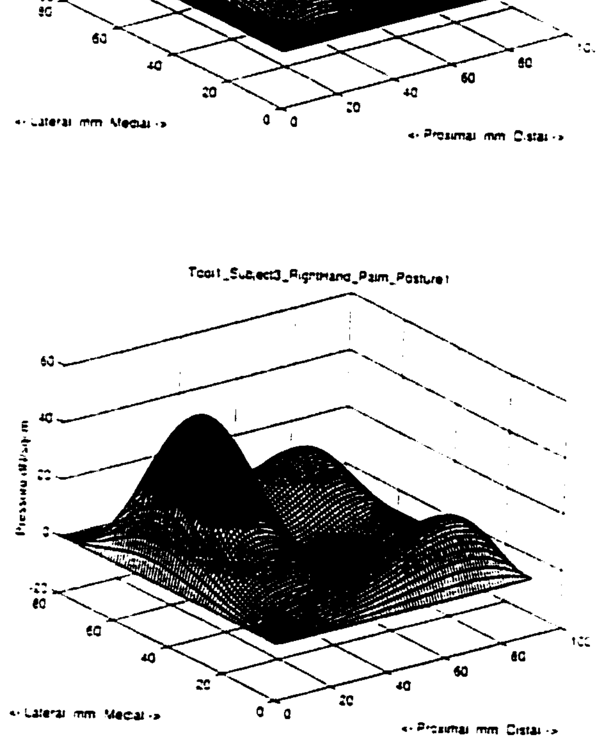
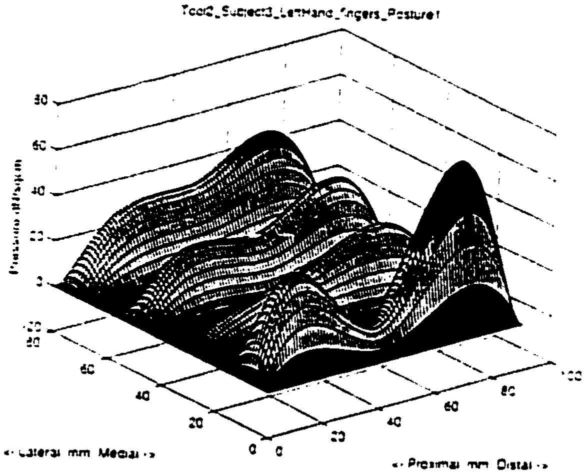
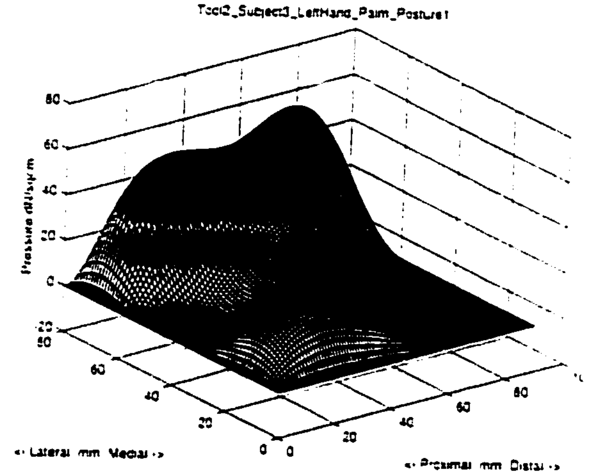
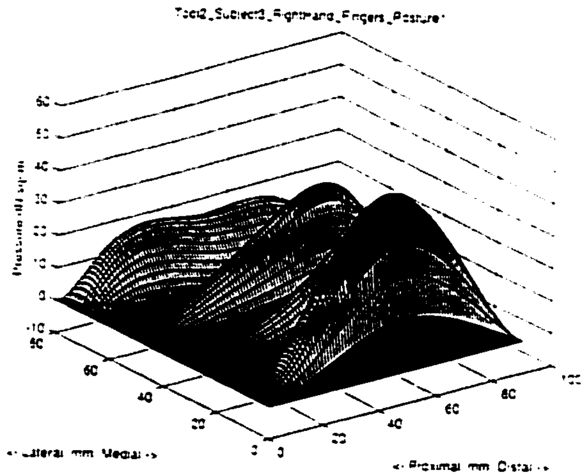

Tool1_Subject3_LeftHand_Palm_Posture1
<- Lateral mm Medial ->
<- Proximal mm Distal ->

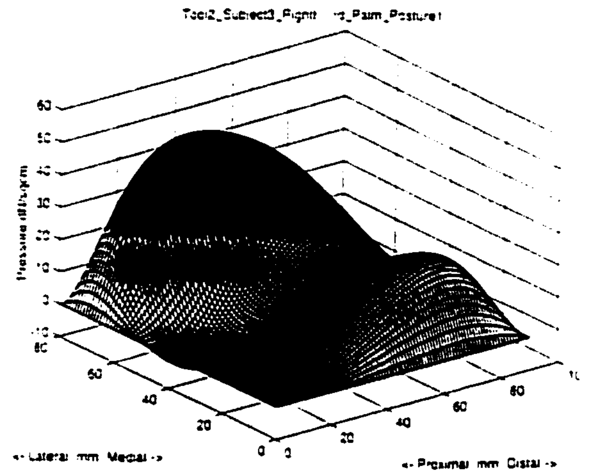

Tool1_Subject3_RightHand_Fingers_Posture1
<- Lateral mm Medial ->
<- Proximal mm Distal ->

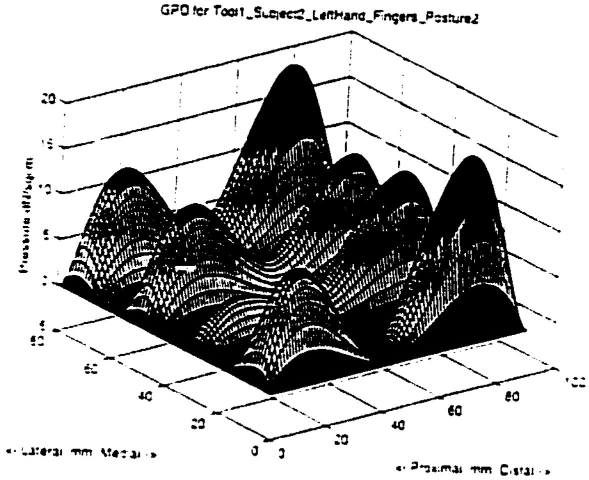

Tool1_Subject3_RightHand_Palm_Posture1
<- Lateral mm Medial ->
<- Proximal mm Distal ->

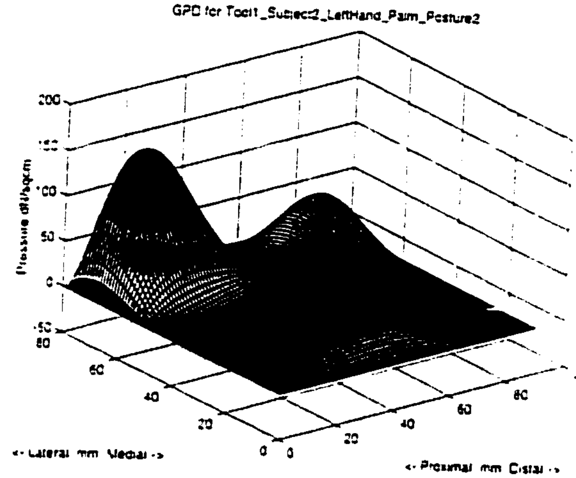

Tool2_Subject3_LeftHand_Fingers_Posture1
Pressure dB/sq.m
<- Lateral mm Medial ->
<- Proximal mm Distal ->

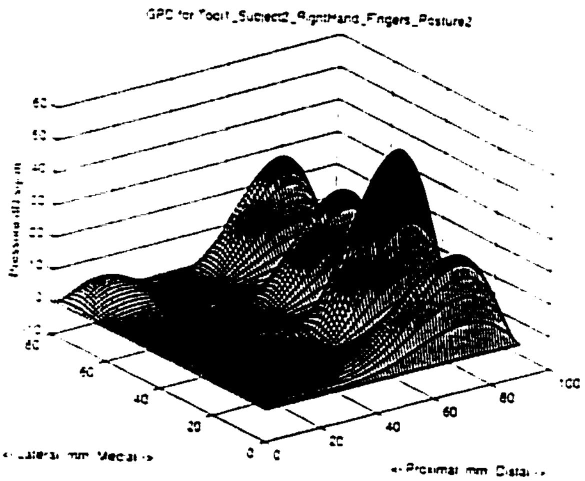

Tool2_Subject3_LeftHand_Palm_Posture1
Pressure dB/sq.m
<- Lateral mm Medial ->
<- Proximal mm Distal ->

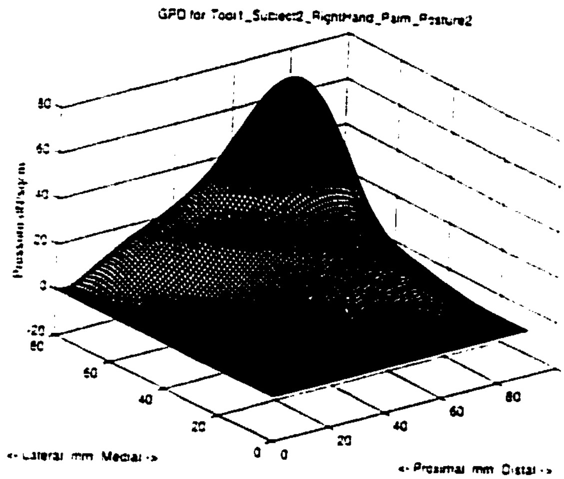

Tool2_Subject3_RightHand_Fingers_Posture1
Pressure dB/sq.m
<- Lateral mm Medial ->
<- Proximal mm Distal ->

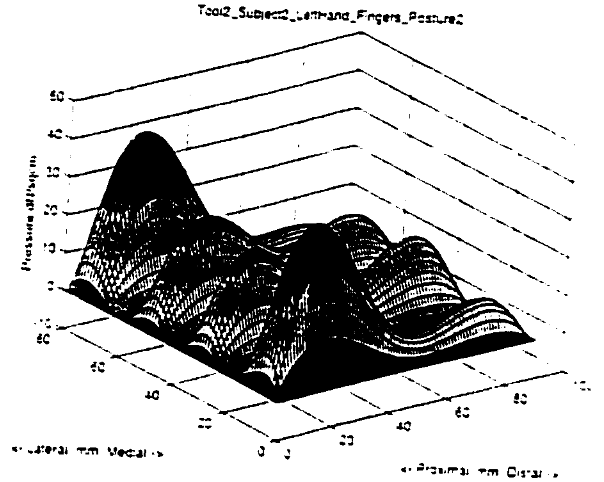

Pressure dB/sq.m
<- Lateral mm Medial ->
<- Proximal mm Distal ->

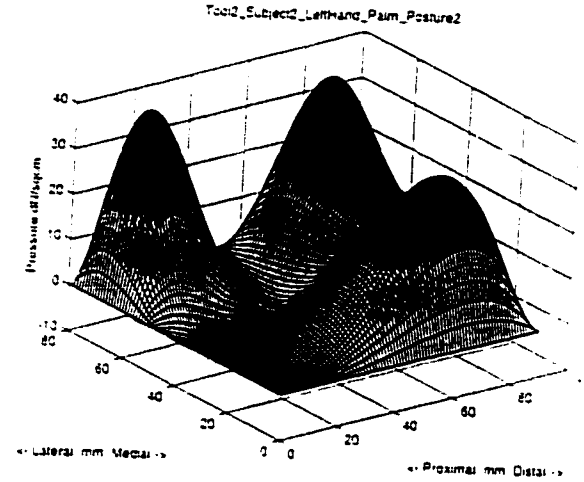

GPD for Tool1_Subject2_LeftHand_Fingers_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

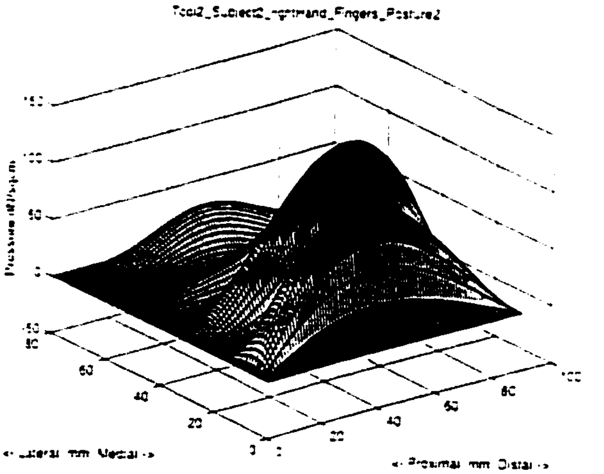

GPD for Tool1_Subject2_LeftHand_Palm_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

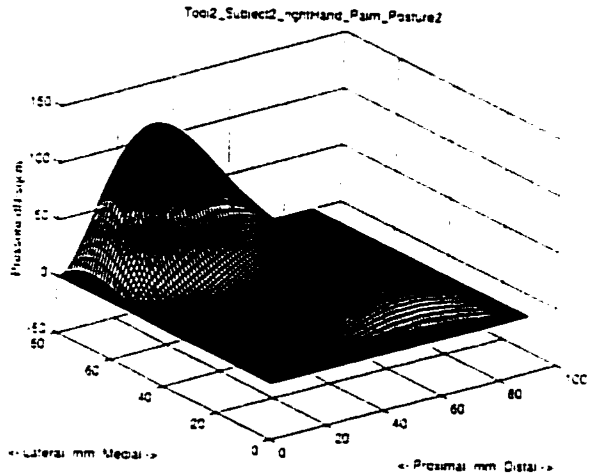

GPD for Tool1_Subject2_RightHand_Fingers_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

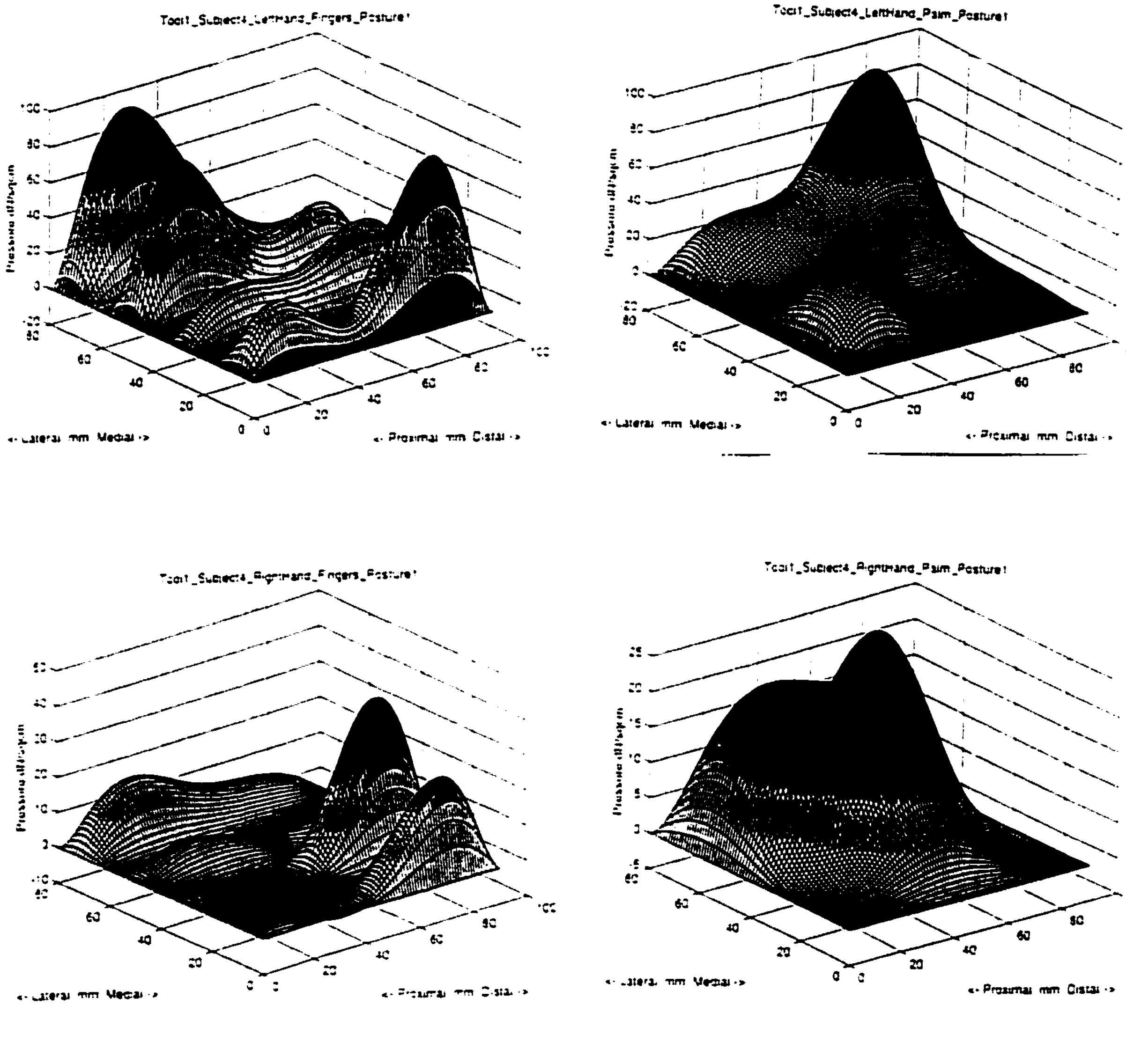

GPD for Tool1_Subject2_RightHand_Palm_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

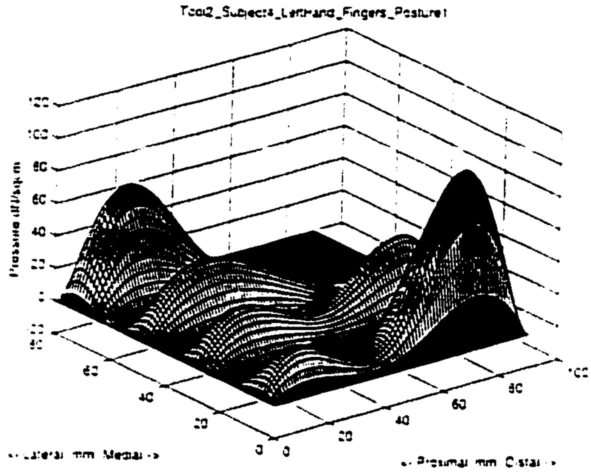

Tool2_Subject2_LeftHand_Fingers_Posture2
Pressure (lbf/sq.in)
<- Lateral mm Medial ->
<- Proximal mm Distal ->

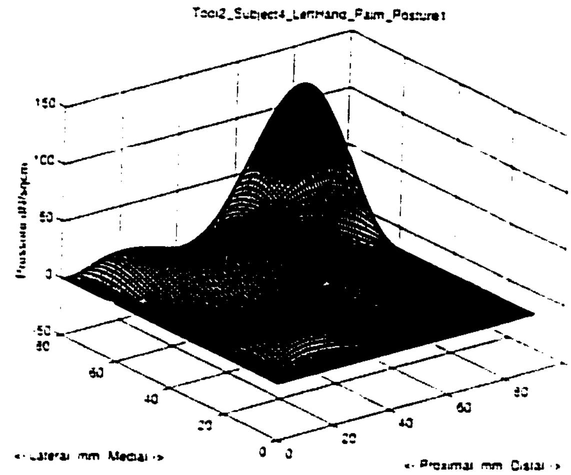

Tool2_Subject2_LeftHand_Palm_Posture2
Pressure (lbf/sq.in)
<- Lateral mm Medial ->
<- Proximal mm Distal ->

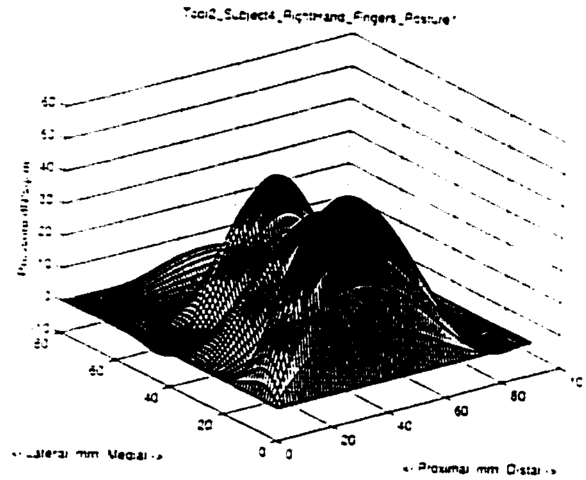

Tool2_Subject2_rightHand_Fingers_Posture2
Pressure (lbf/sq.in)
<- Lateral mm Medial ->
<- Proximal mm Distal ->

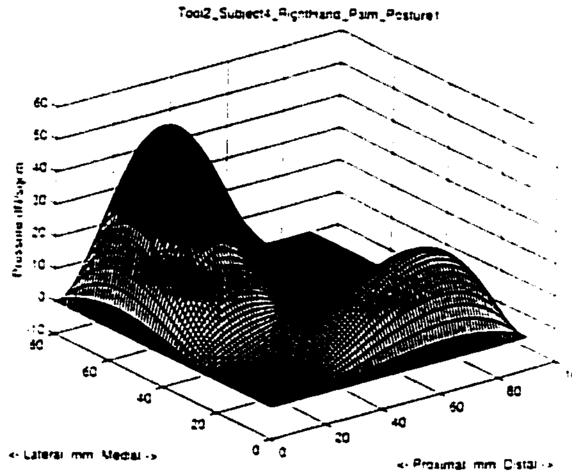

Tool2_Subject2_rightHand_Palm_Posture2
Pressure (lbf/sq.in)
<- Lateral mm Medial ->
<- Proximal mm Distal ->

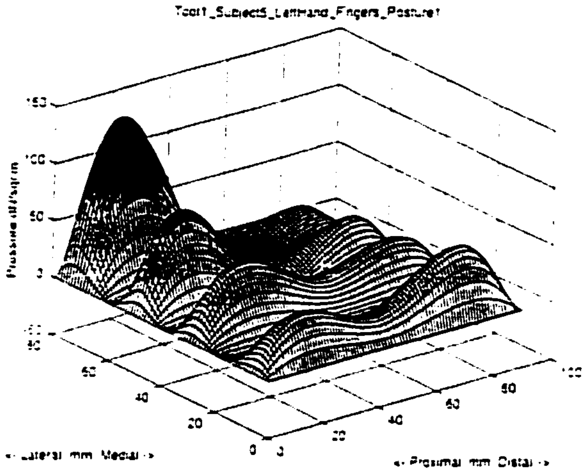

Tool1_Subject4_LeftHand_Fingers_Posture1
Tool1_Subject4_LeftHand_Palm_Posture1
Tool1_Subject4_RightHand_Fingers_Posture1
Tool1_Subject4_RightHand_Palm_Posture1
<- Lateral mm Medial ->
<- Proximal mm Distal ->

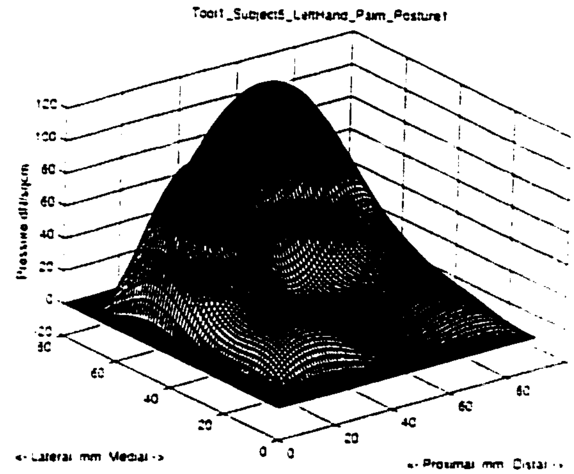

Tool2_Subject4_LeftHand_Fingers_Posture1
<- Lateral mm Medial ->
<- Proximal mm Distal ->
0
20
40
60
80
100

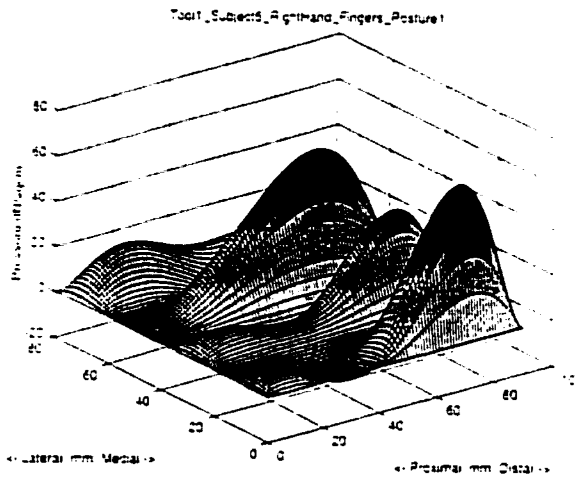

Tool2_Subject4_LeftHand_Palm_Posture1
150
100
50
0
-50
<- Lateral mm Medial ->
<- Proximal mm Distal ->

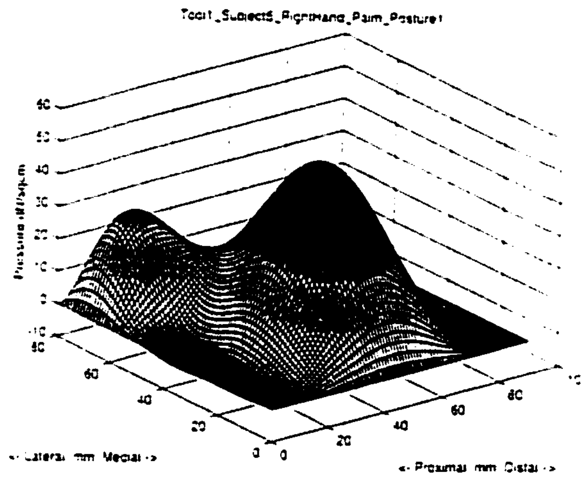

Tool2_Subject4_RightHand_Fingers_Posture1
<- Lateral mm Medial ->
<- Proximal mm Distal ->

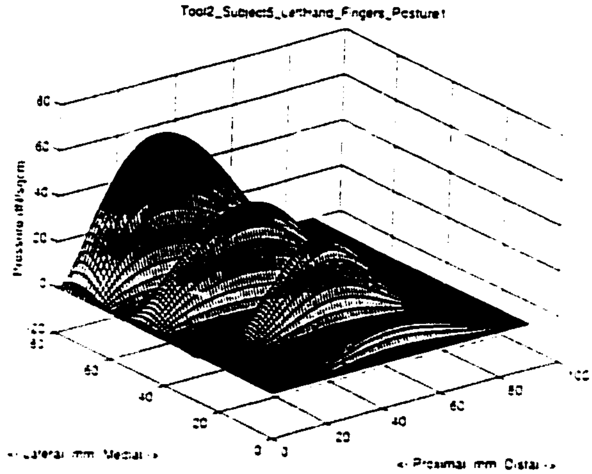

Tool2_Subject4_RightHand_Palm_Posture1
60
50
40
30
20
10
0
-10
<- Lateral mm Medial ->
<- Proximal mm Distal ->
100

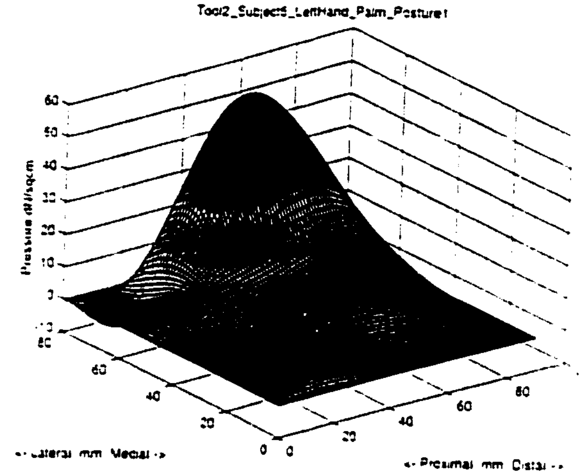

Tool1_Subject5_LeftHand_Fingers_Posture1

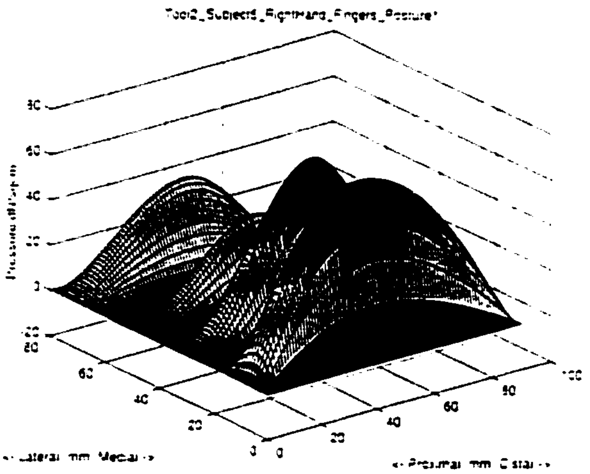

Tool1_Subject5_LeftHand_Palm_Posture1

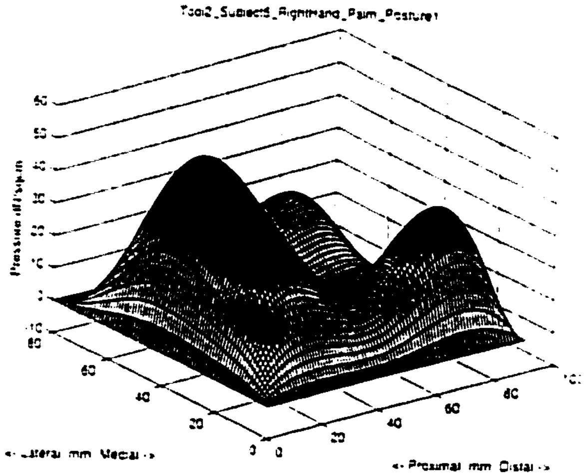

Tool1_Subject5_RightHand_Fingers_Posture1

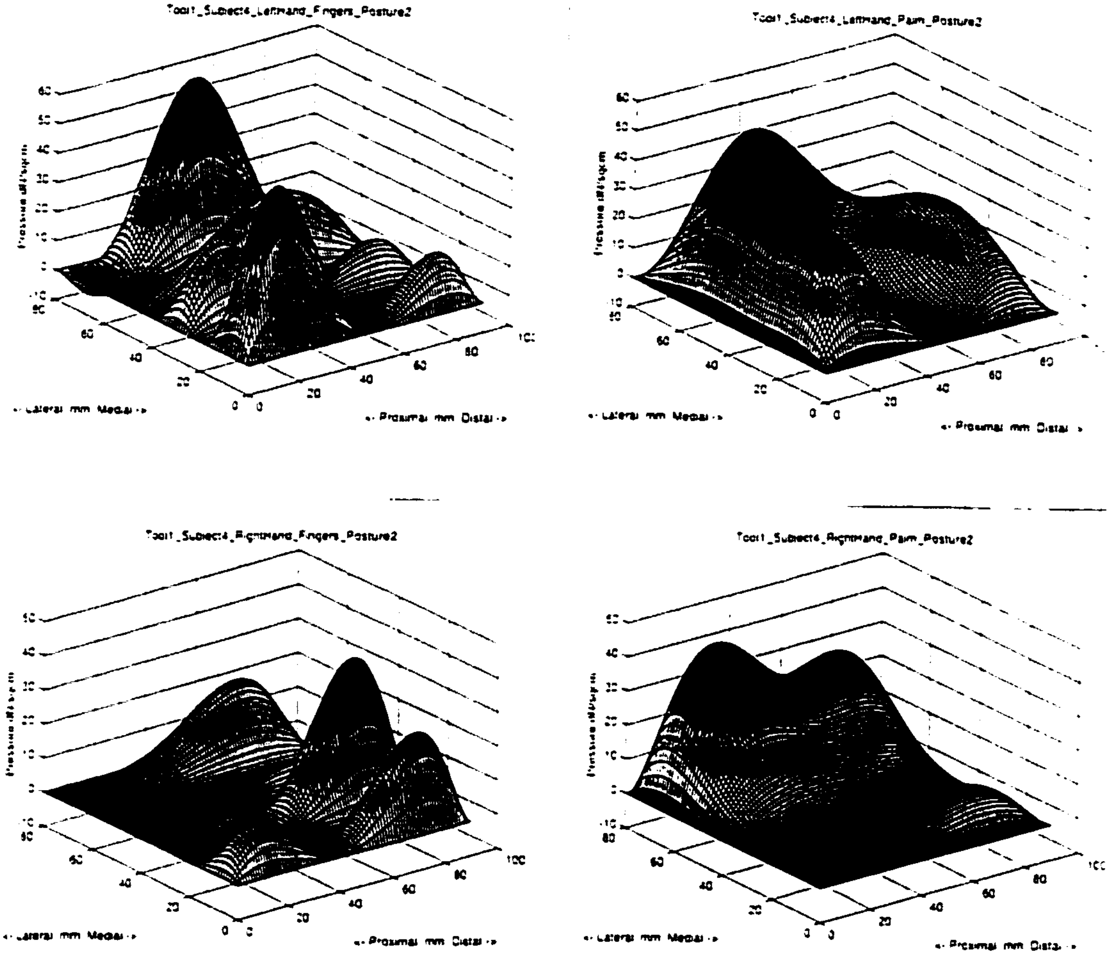

Tool1_Subject5_RightHand_Palm_Posture1

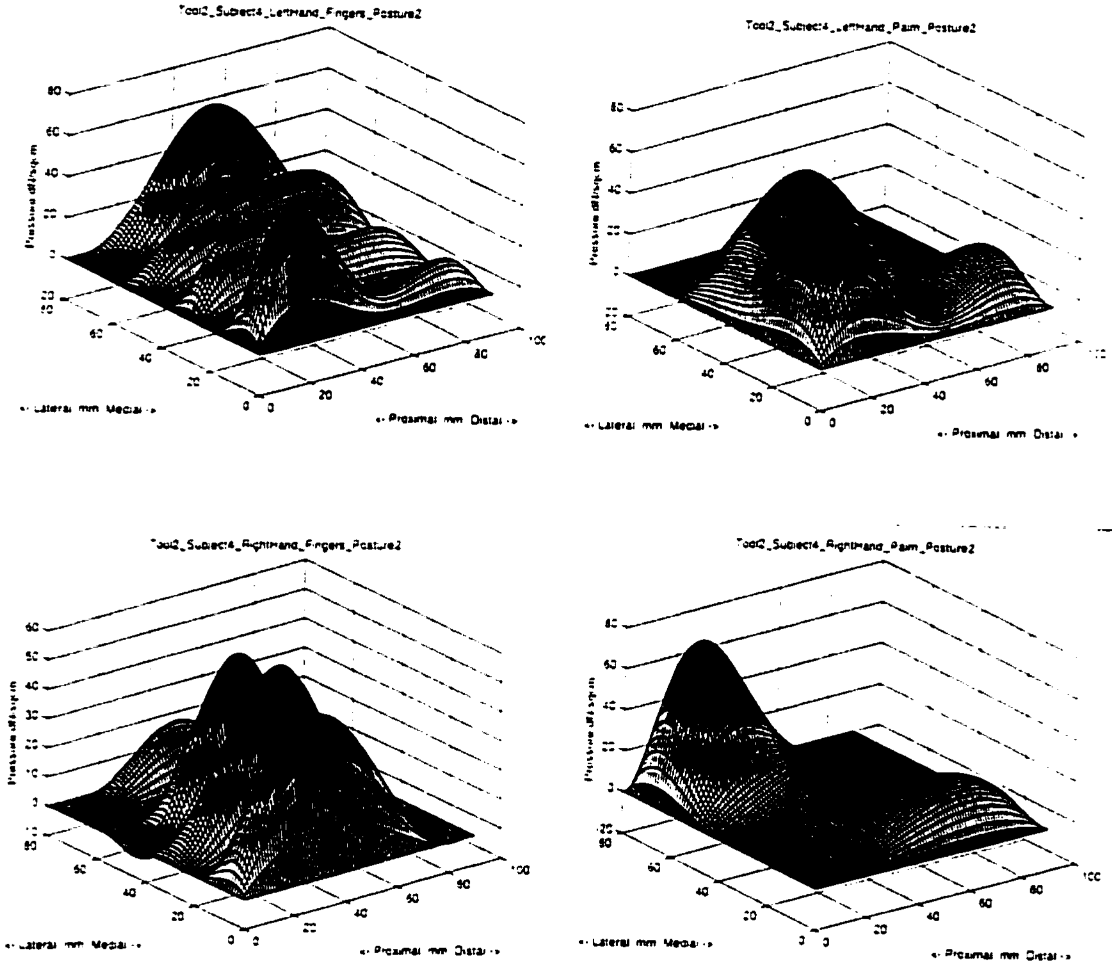

Tool2_Subject5_LeftHand_Fingers_Posture1
<- Lateral mm Medial ->
<- Proximal mm Distal ->

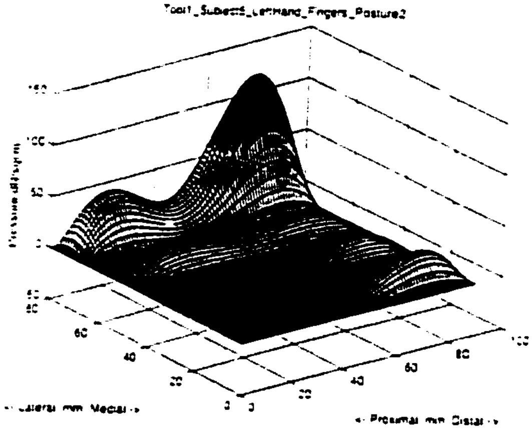

Tool2_Subject5_LeftHand_Palm_Posture1
<- Lateral mm Medial ->
<- Proximal mm Distal ->

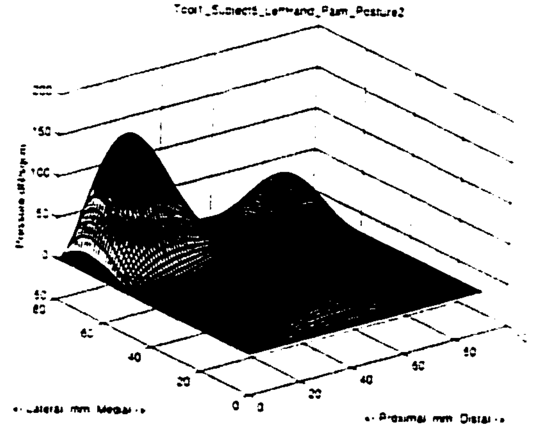

Tool2_Subject5_RightHand_Fingers_Posture1
<- Lateral mm Medial ->
<- Proximal mm Distal ->

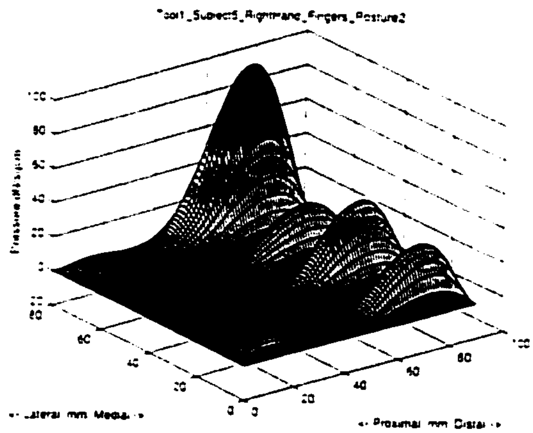

Tool2_Subject5_RightHand_Palm_Posture1
<- Lateral mm Medial ->
<- Proximal mm Distal ->

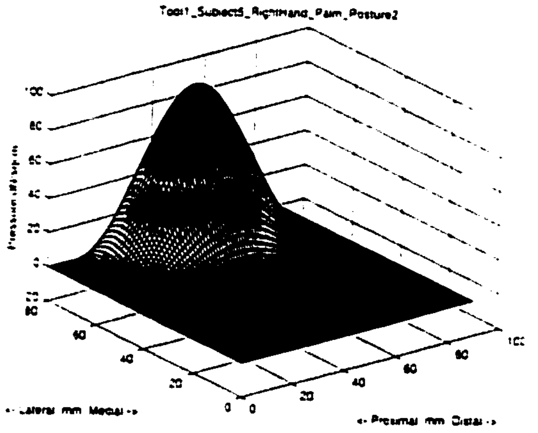

Tool1_Subject4_LeftHand_Fingers_Posture2
Tool1_Subject4_LeftHand_Palm_Posture2
Tool1_Subject4_RightHand_Fingers_Posture2
Tool1_Subject4_RightHand_Palm_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

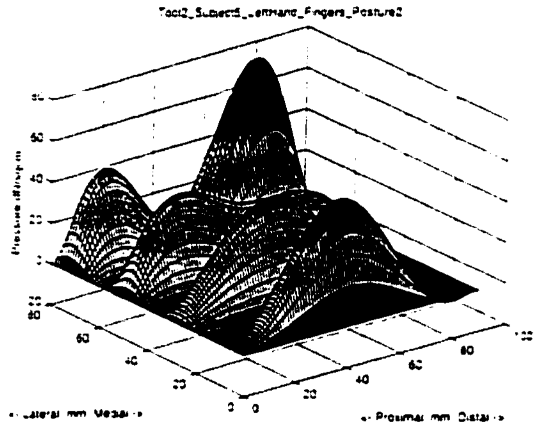

Tool2_Subject4_LeftHand_Fingers_Posture2
Tool2_Subject4_LeftHand_Palm_Posture2
Tool2_Subject4_RightHand_Fingers_Posture2
Tool2_Subject4_RightHand_Palm_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

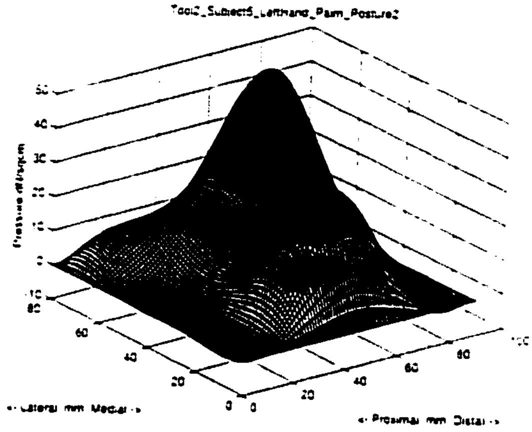

Tool1_Subject5_LeftHand_Fingers_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

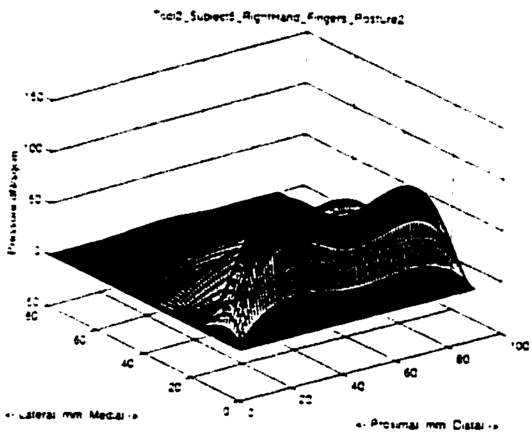

Tool1_Subject5_LeftHand_Palm_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

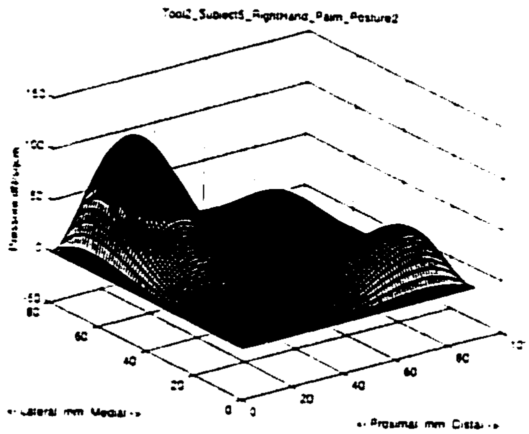

Tool1_Subject5_RightHand_Fingers_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

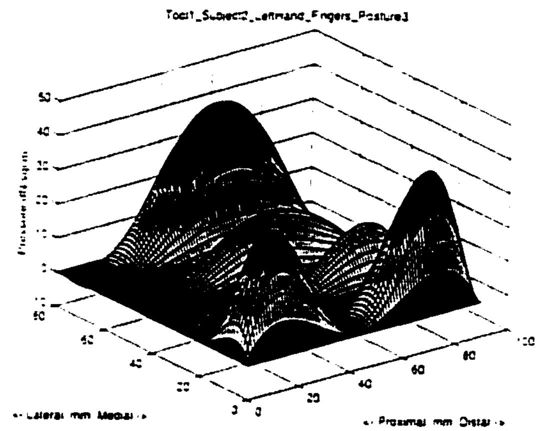

Tool1_Subject5_RightHand_Palm_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

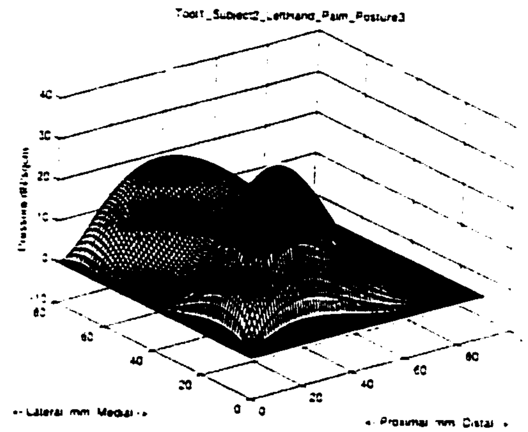

Tool2_Subject5_LeftHand_Fingers_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

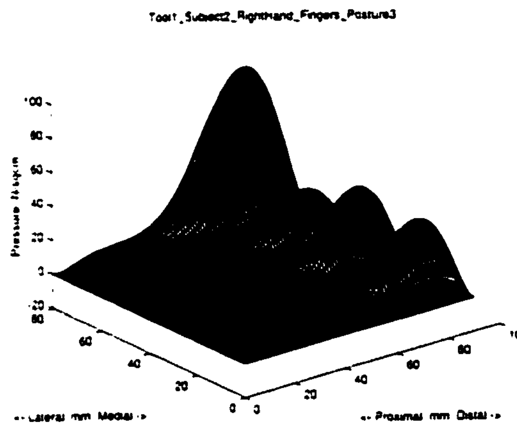

Tool2_Subject5_LeftHand_Palm_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

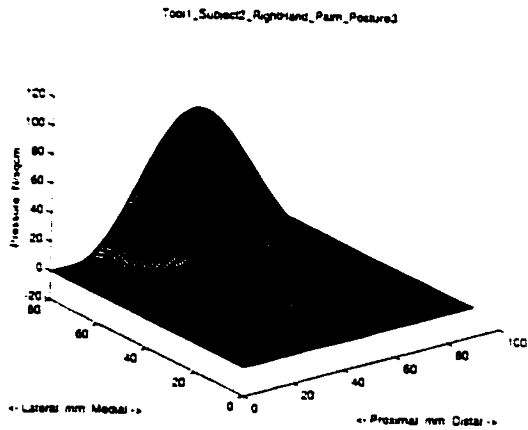

Tool2_Subject5_RightHand_Fingers_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

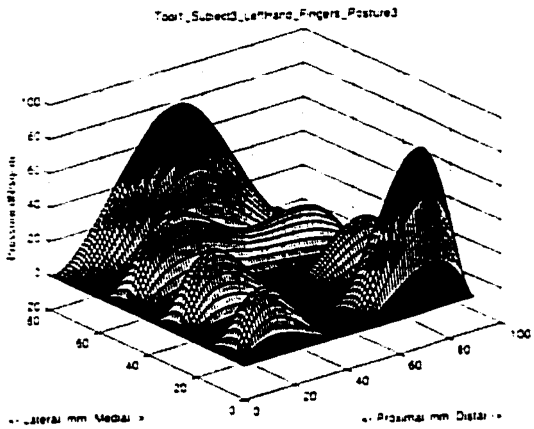

Tool2_Subject5_RightHand_Palm_Posture2
<- Lateral mm Medial ->
<- Proximal mm Distal ->

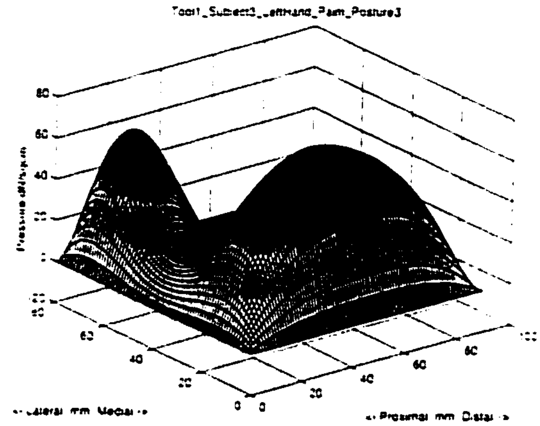

Tool1_Subject2_Lefthand_Fingers_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->

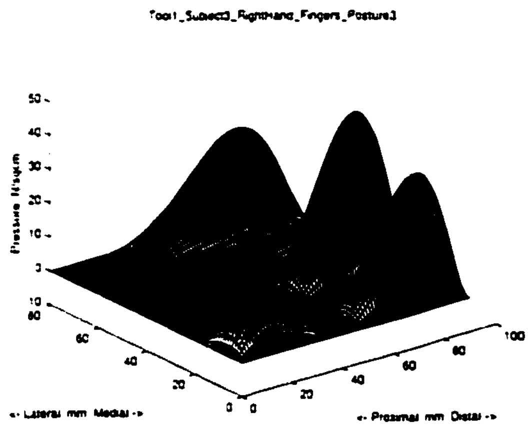

Tool1_Subject2_Lefthand_Palm_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->

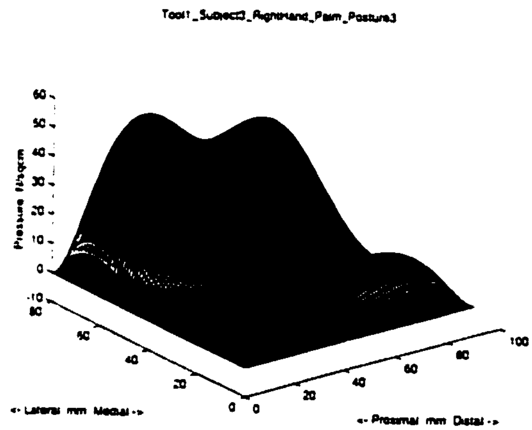

Tool1_Subject2_RightHand_Fingers_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->

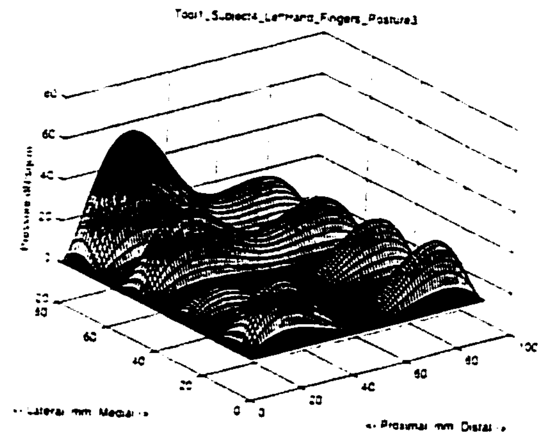

Tool1_Subject2_RightHand_Palm_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->

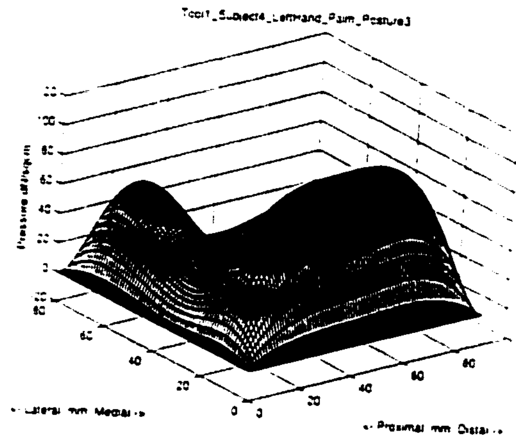

Tool1_Subject3_LeftHand_Fingers_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->

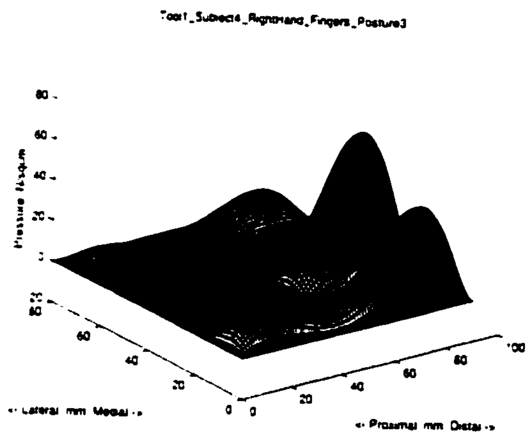

Tool1_Subject3_LeftHand_Palm_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->

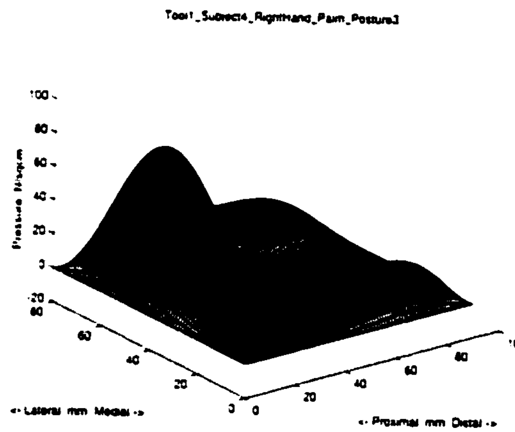

Tool1_Subject3_RightHand_Fingers_Posture3
Pressure N/sqcm
<- Lateral mm Medial ->
<- Proximal mm Distal ->

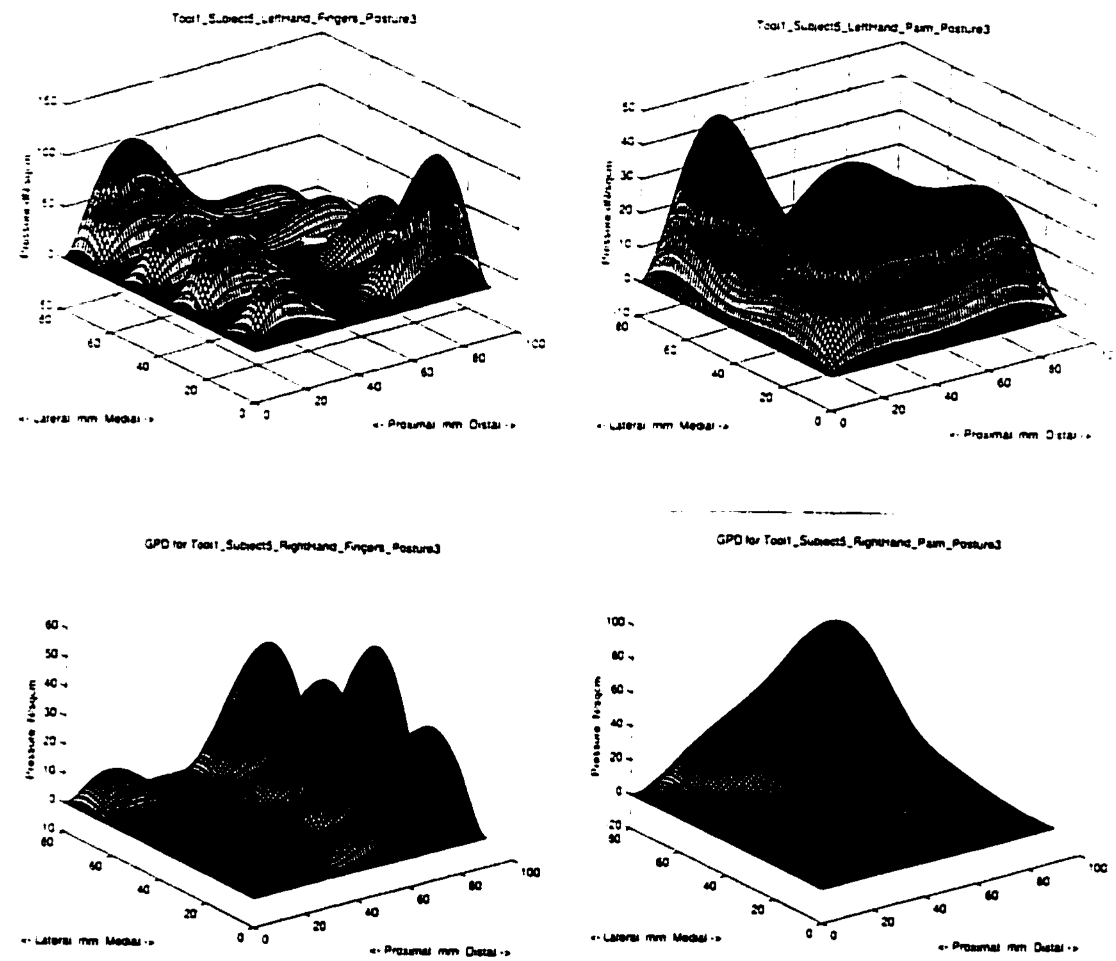

Tool1_Subject3_RightHand_Palm_Posture3
Pressure N/sqcm
<- Lateral mm Medial ->
<- Proximal mm Distal ->

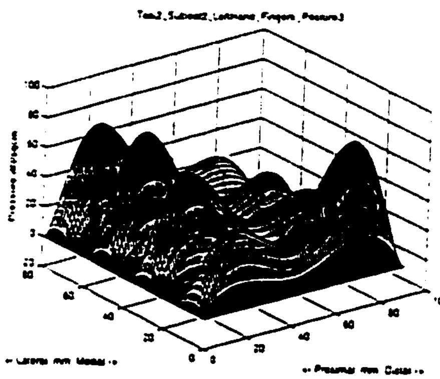

Tool1_Subject4_LeftHand_Fingers_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->


Tool1_Subject4_LeftHand_Palm_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->


Tool1_Subject4_RightHand_Fingers_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->


Tool1_Subject4_RightHand_Palm_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->


Tool1_Subject5_LeftHand_Fingers_Posture3
Tool1_Subject5_LeftHand_Palm_Posture3
GPD for Tool1_Subject5_RightHand_Fingers_Posture3
GPD for Tool1_Subject5_RightHand_Palm_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->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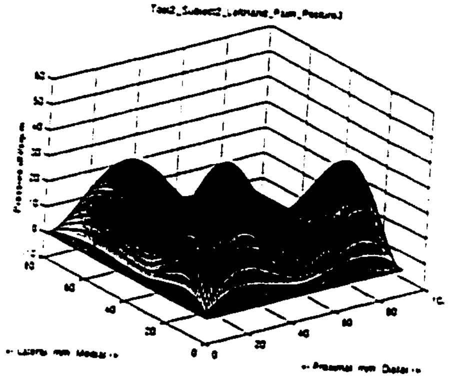
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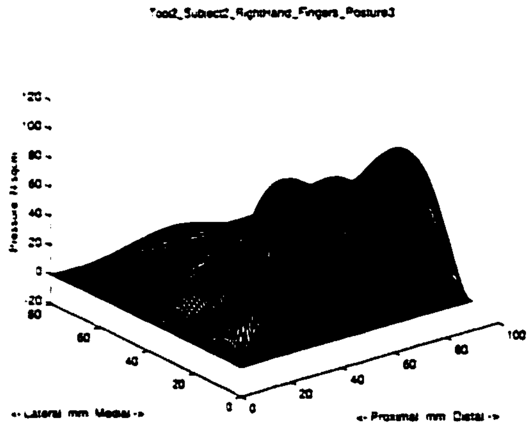
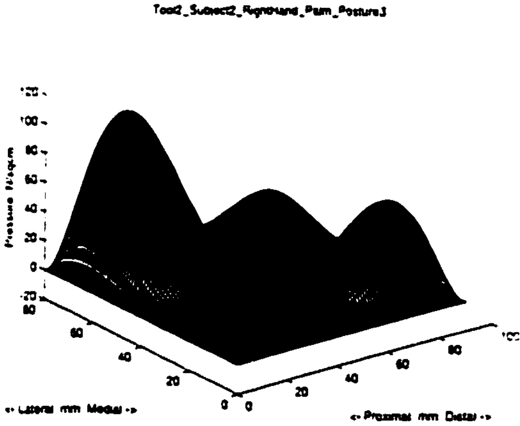
<- Proximal mm Distal ->


Tool2_Subject2_Righthand_Fingers_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->


Tool2_Subject2_Righthand_Palm_Posture3
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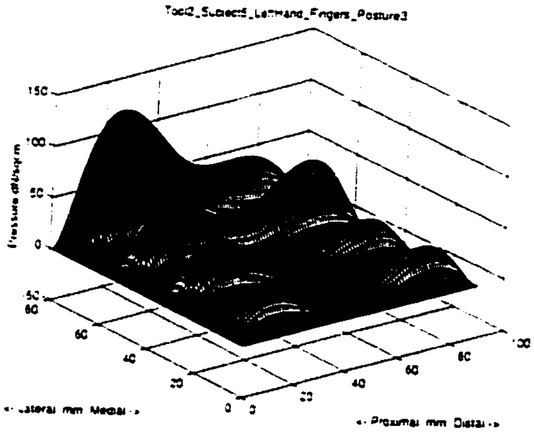
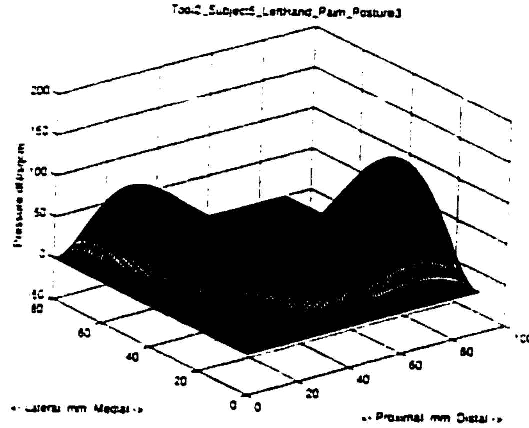
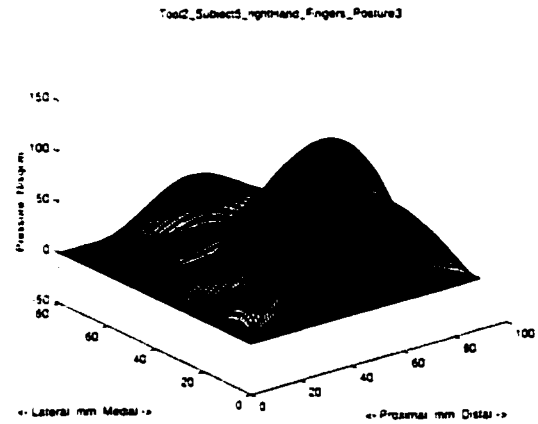
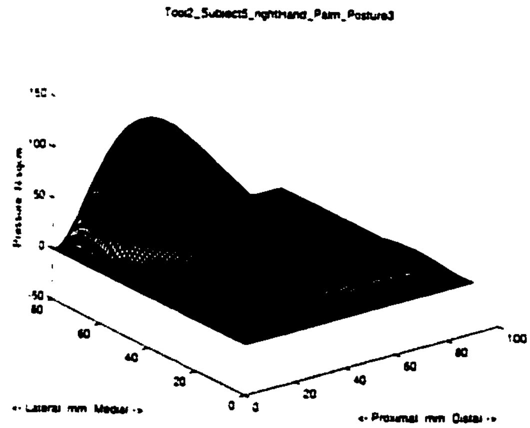
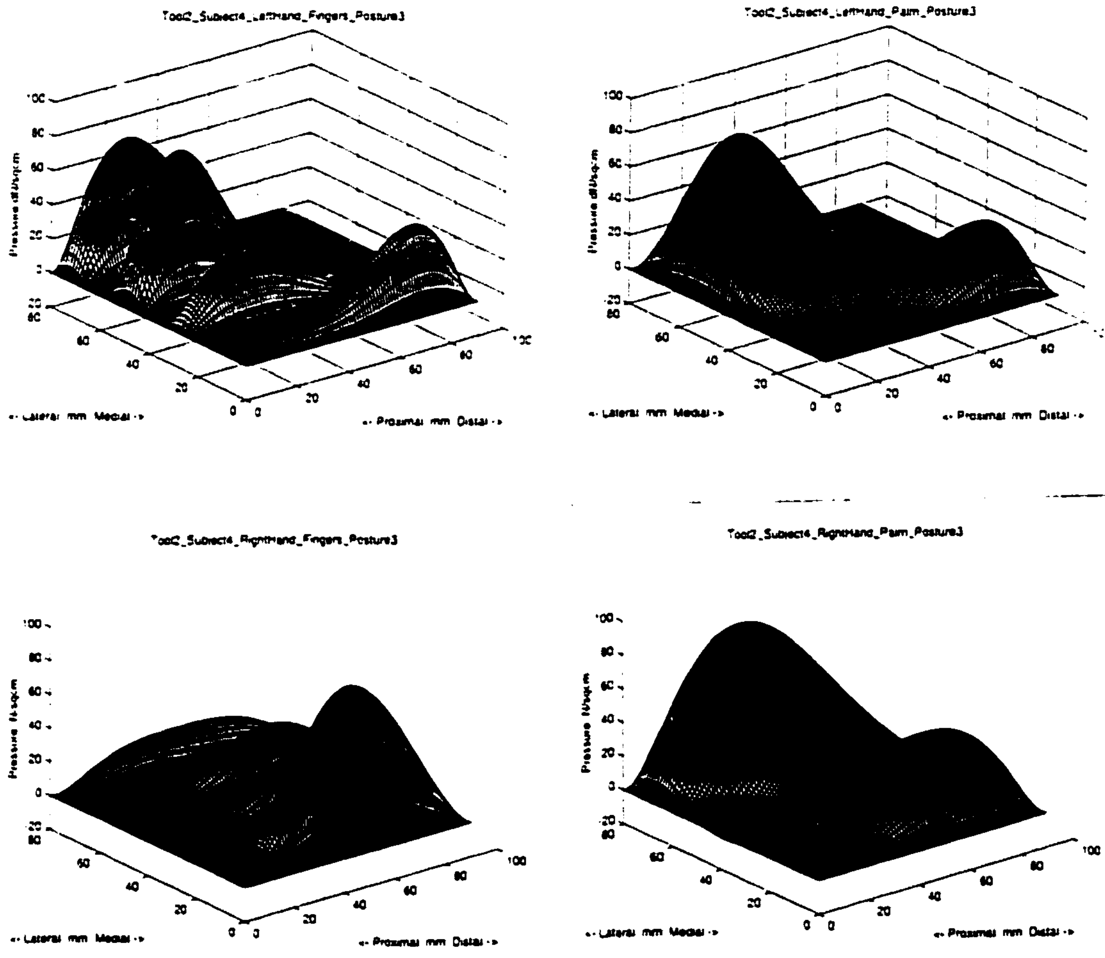
<- Proximal mm Distal ->

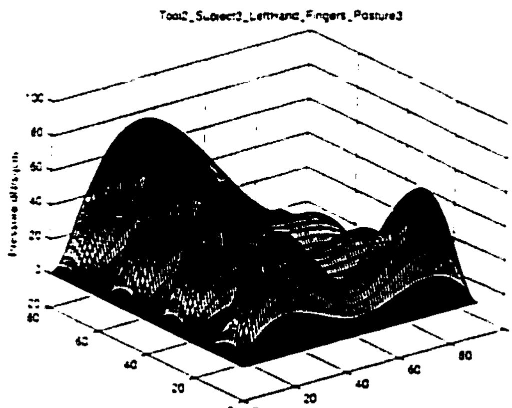

Tool2_Subject5_LeftHand_Fingers_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->

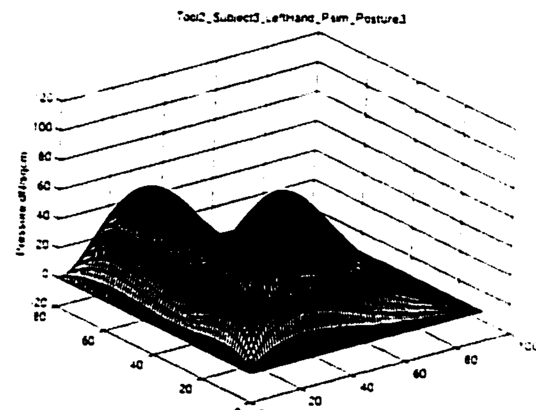

Tool2_Subject5_LeftHand_Palm_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->

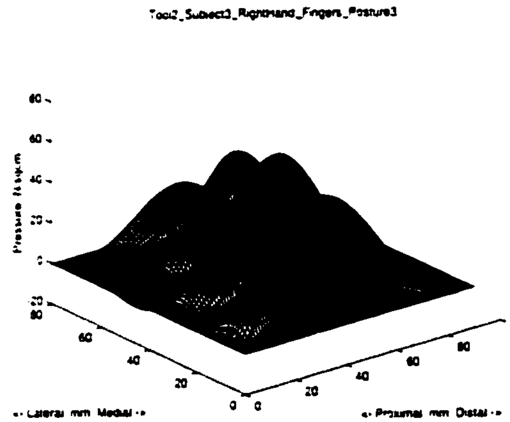

Tool2_Subject5_rightHand_Fingers_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->

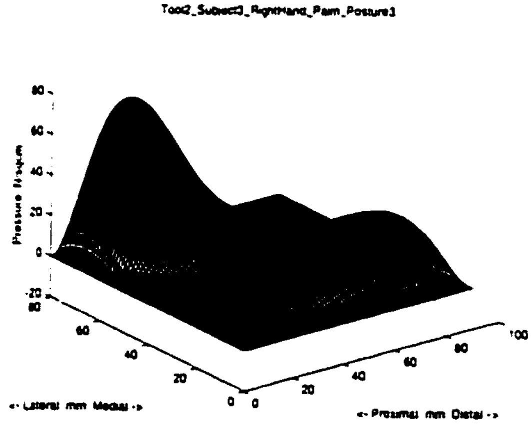

Tool2_Subject5_rightHand_Palm_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->


Tool2_Subject4_LeftHand_Fingers_Posture3
Tool2_Subject4_LeftHand_Palm_Posture3
Tool2_Subject4_RightHand_Fingers_Posture3
Tool2_Subject4_RightHand_Palm_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->


Tool2_Subject3_LeftHand_Fingers_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->

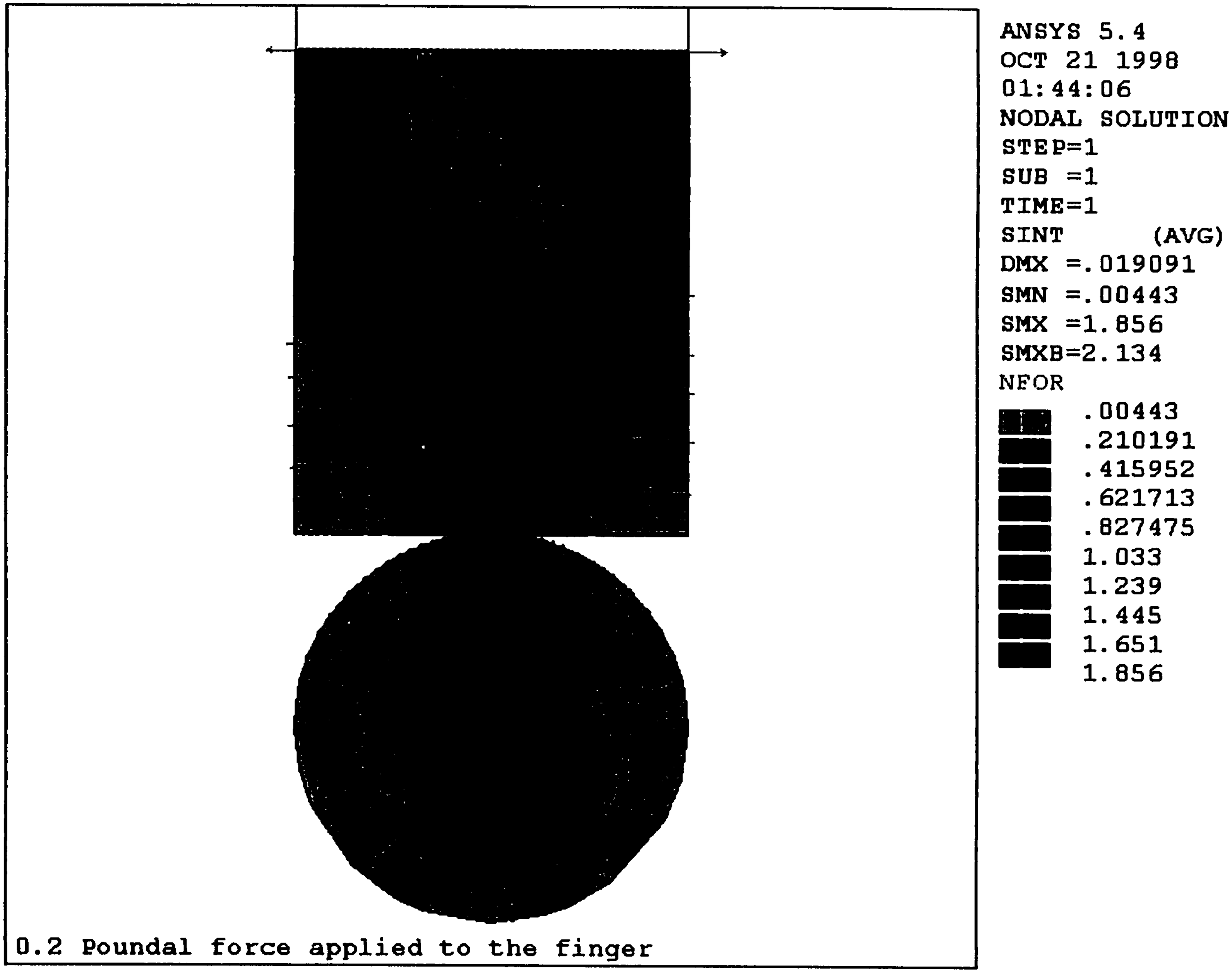

Tool2_Subject3_LeftHand_Palm_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->

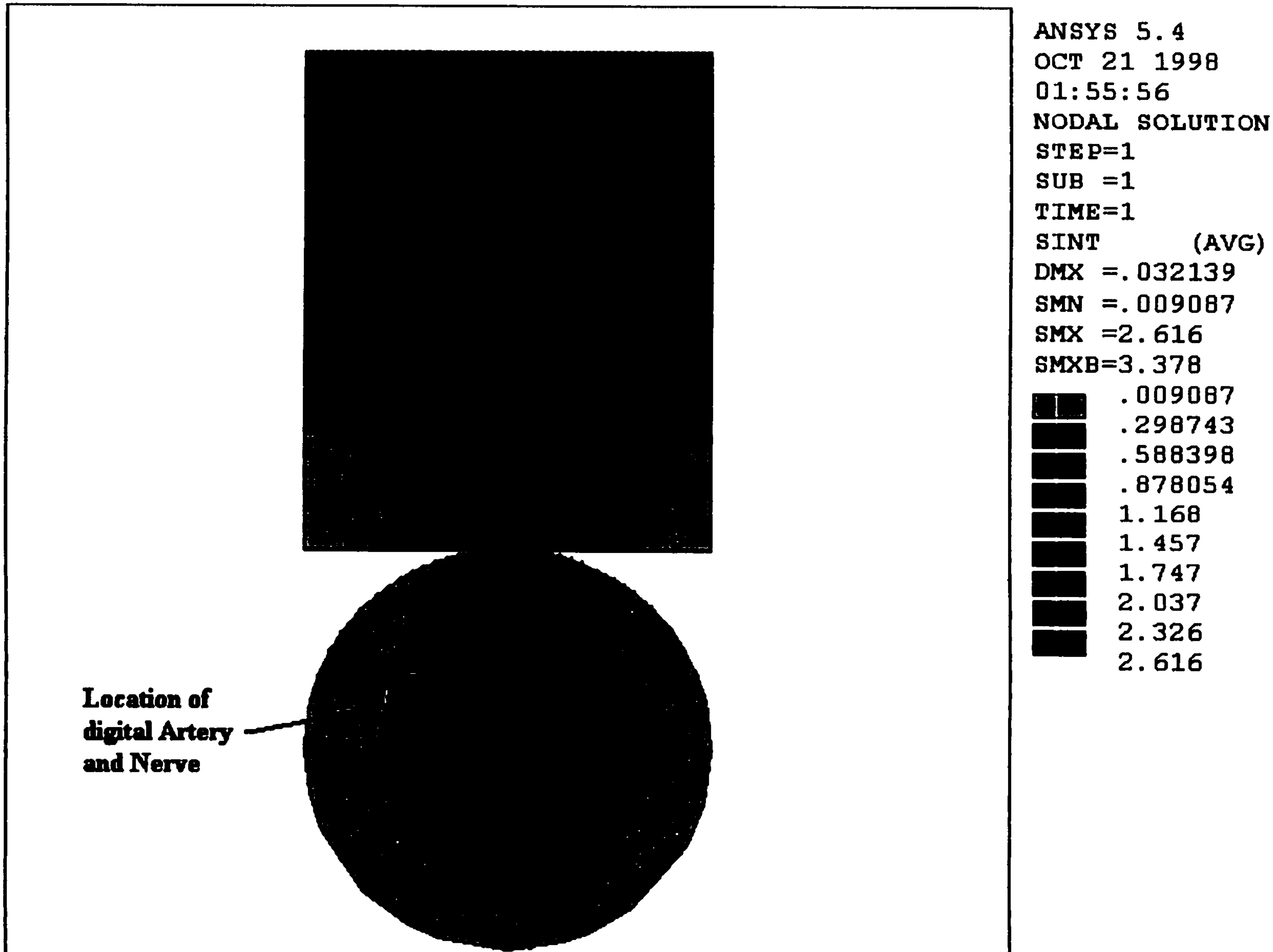

Tool2_Subject3_RightHand_Fingers_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->


Tool2_Subject3_RightHand_Palm_Posture3
<- Lateral mm Medial ->
<- Proximal mm Distal ->

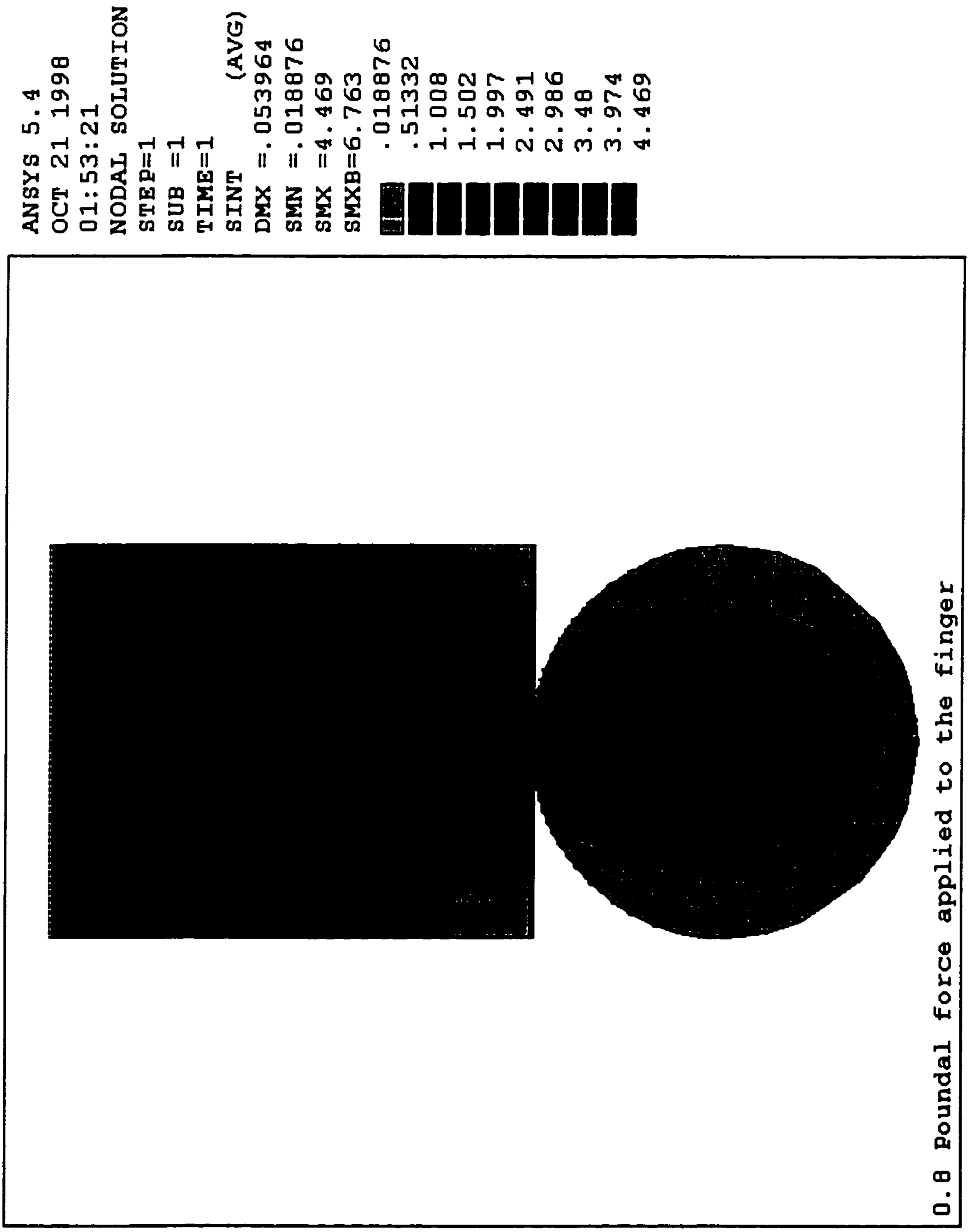
Appendix - III

(Finite Element Analysis)

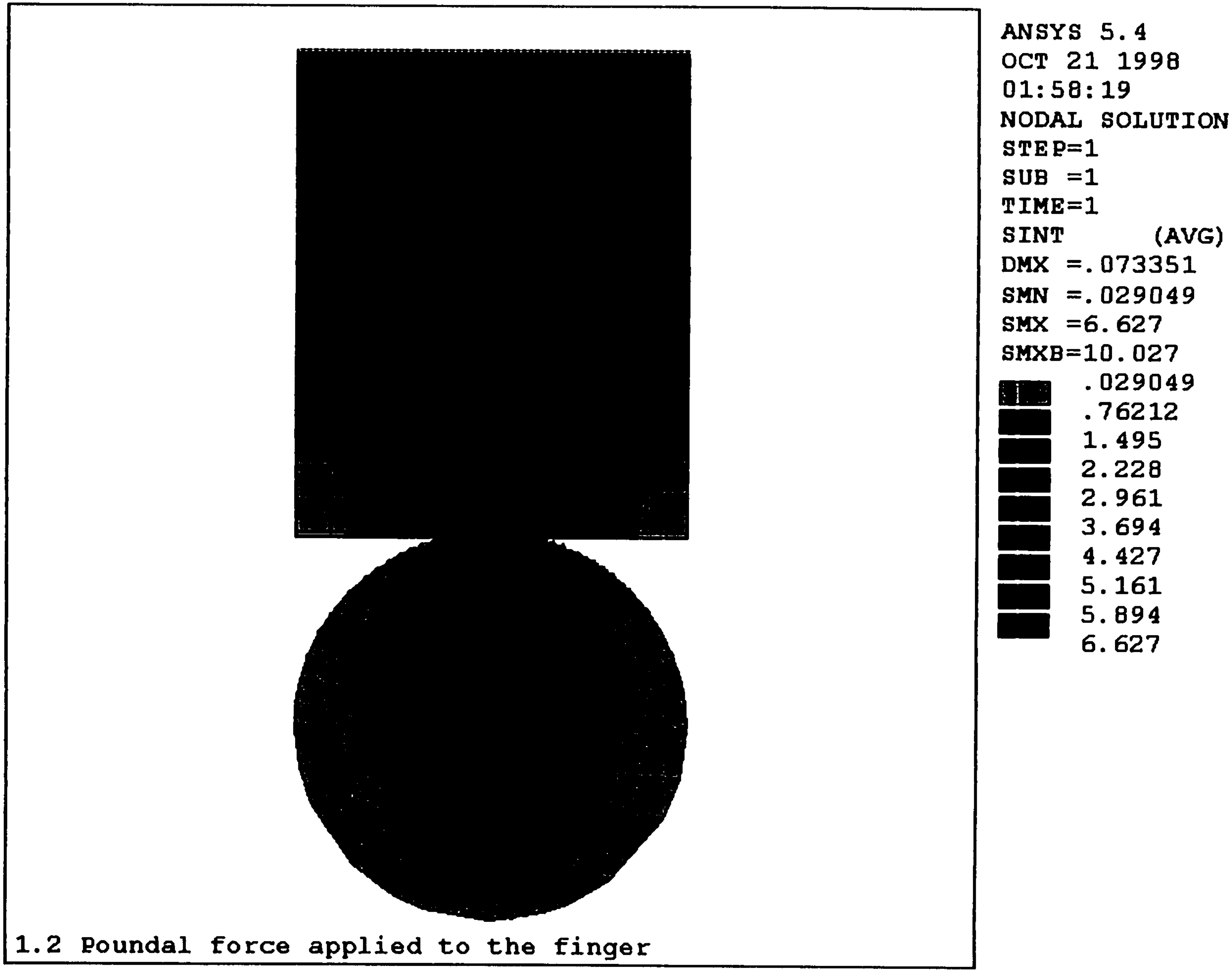

ANSYS 5.4
OCT 21 1998
01:44:06
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SINT (AVG)
DMX =.019091
SMN =.00443
SMX =1.856
SMXB=2.134
NFOR
.00443
.210191
.415952
.621713
.827475
1.033
1.239
1.445
1.651
1.856
0.2 Poundal force applied to the finger



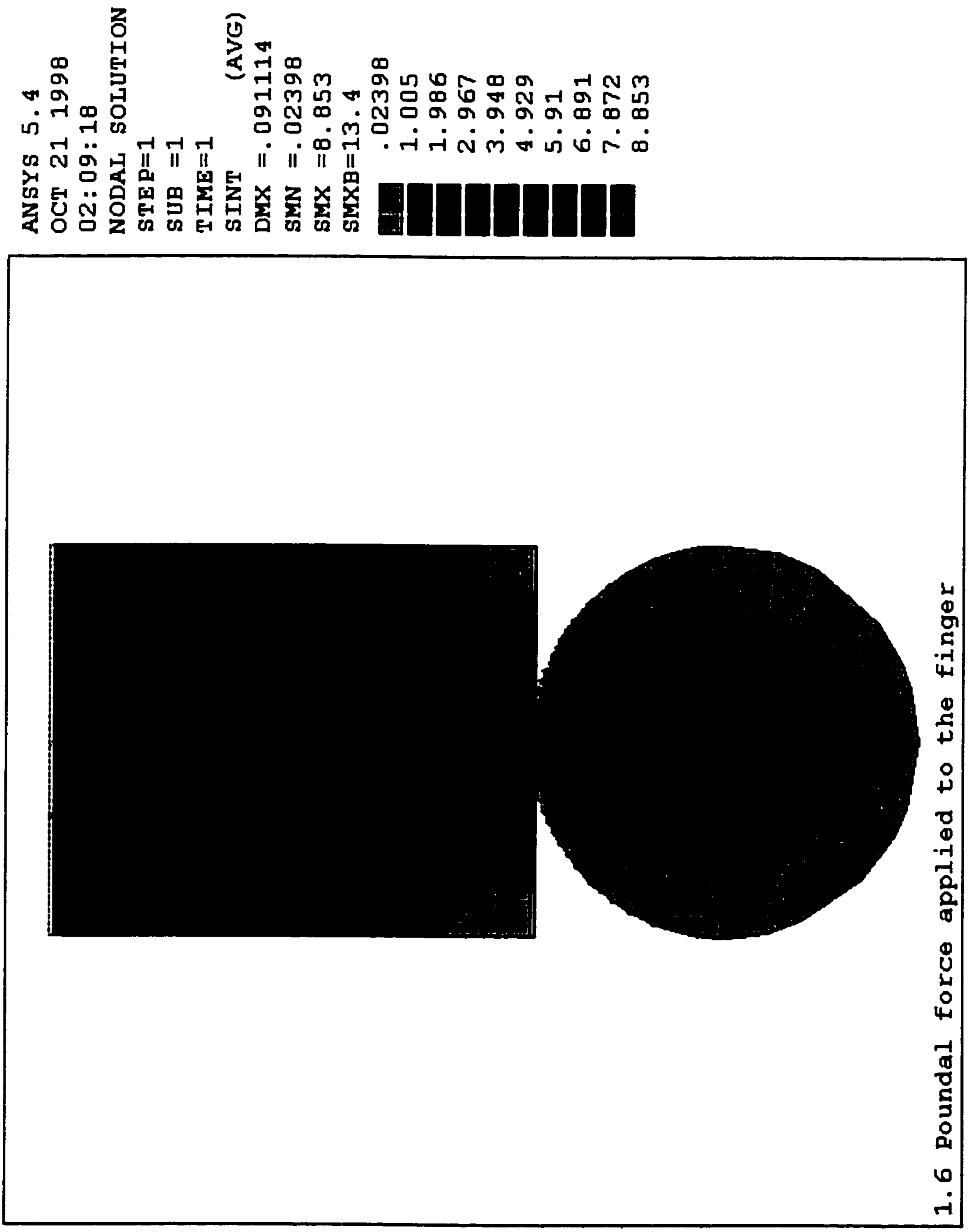
0.4 Poundal force applied to the finger



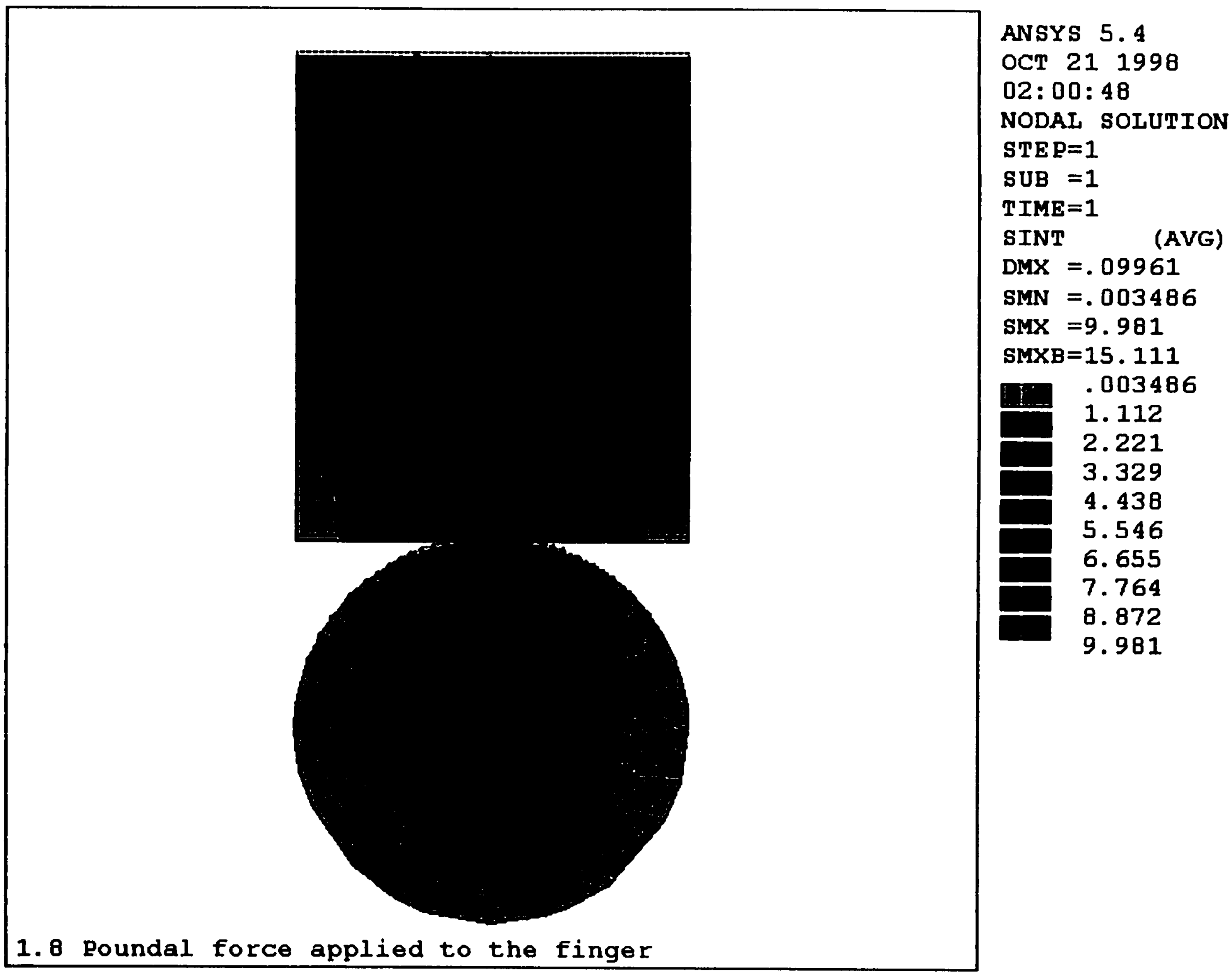
0.8 Poundal force applied to the finger



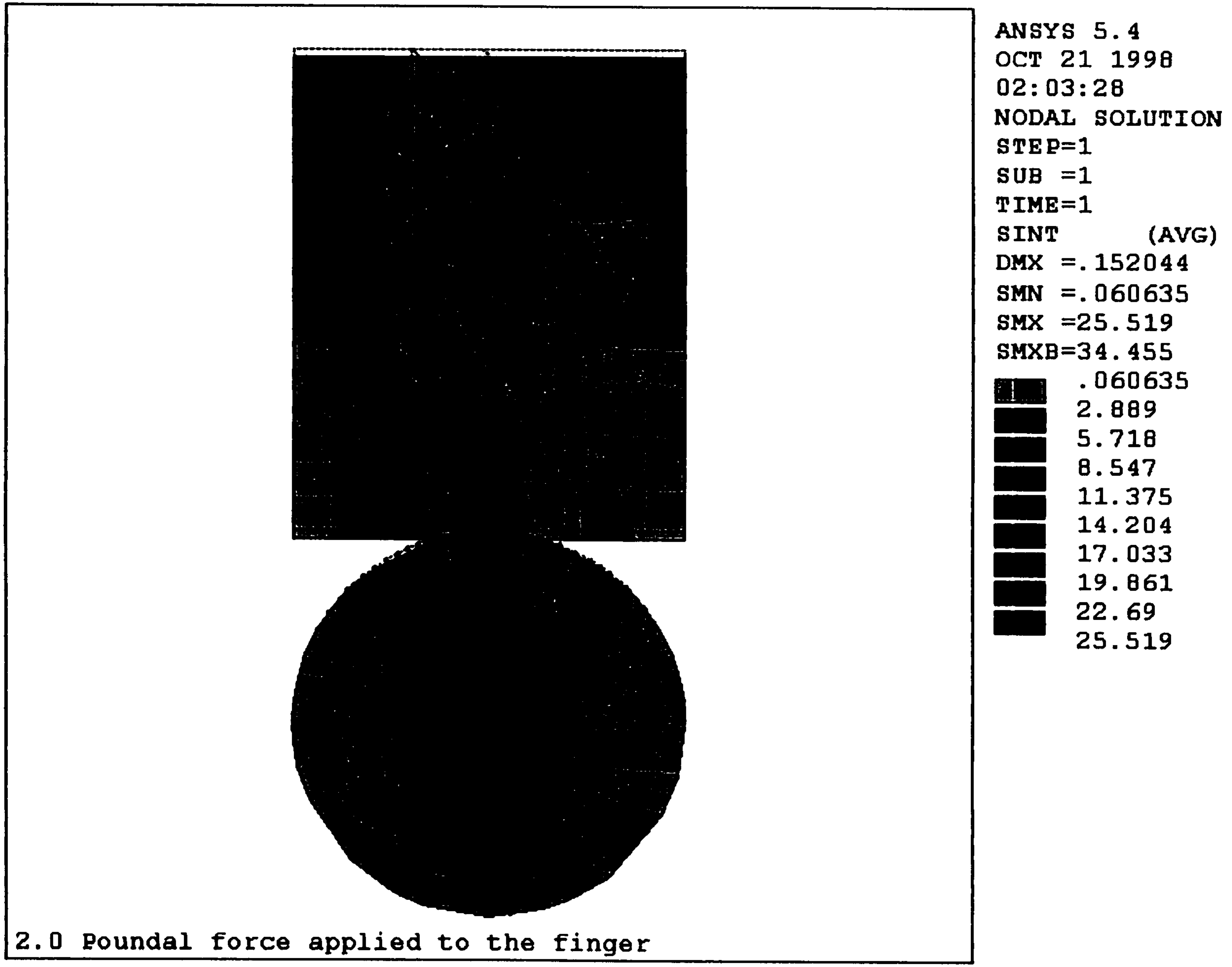
1.2 Poundal force applied to the finger



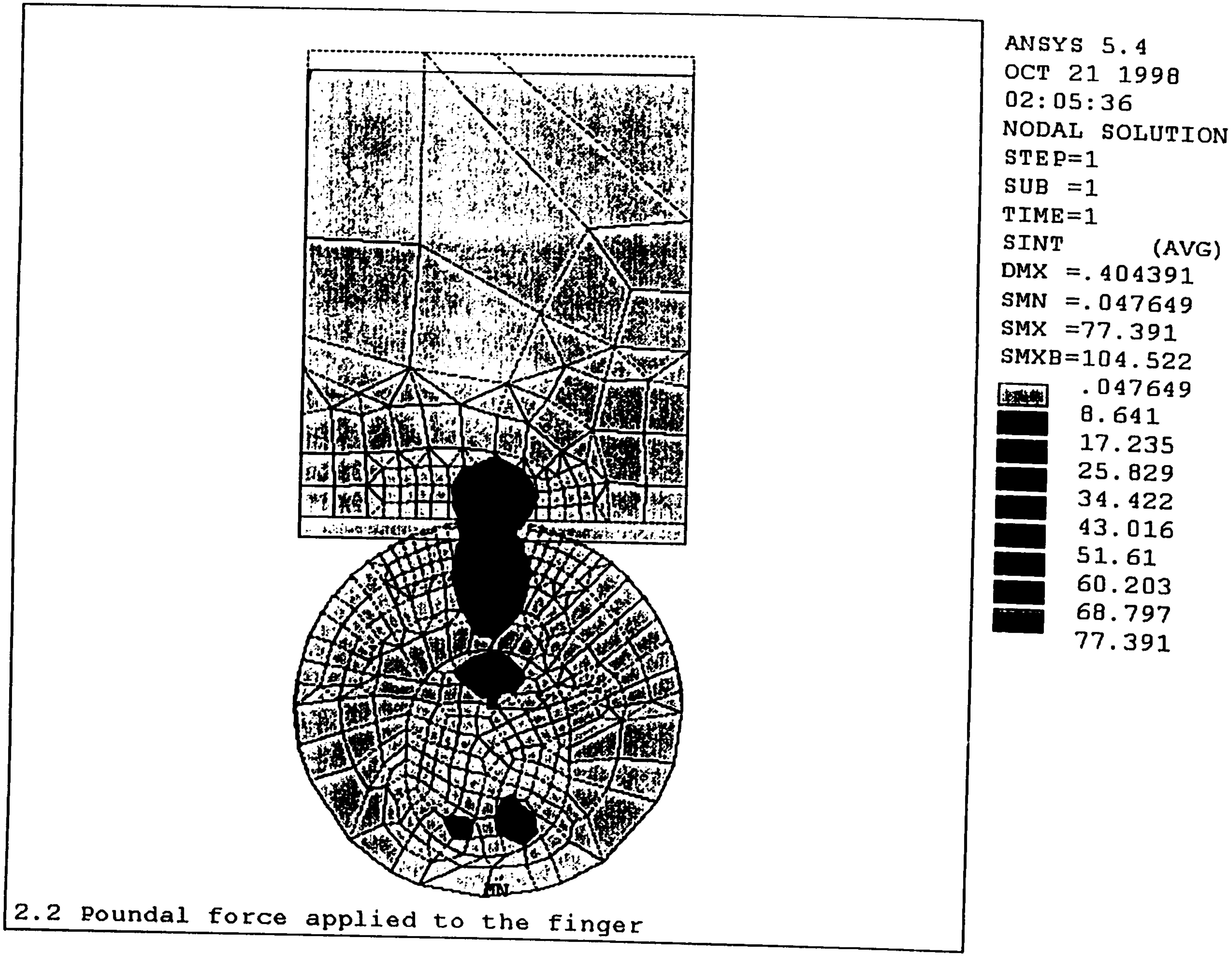
1.6 Poundal force applied to the finger



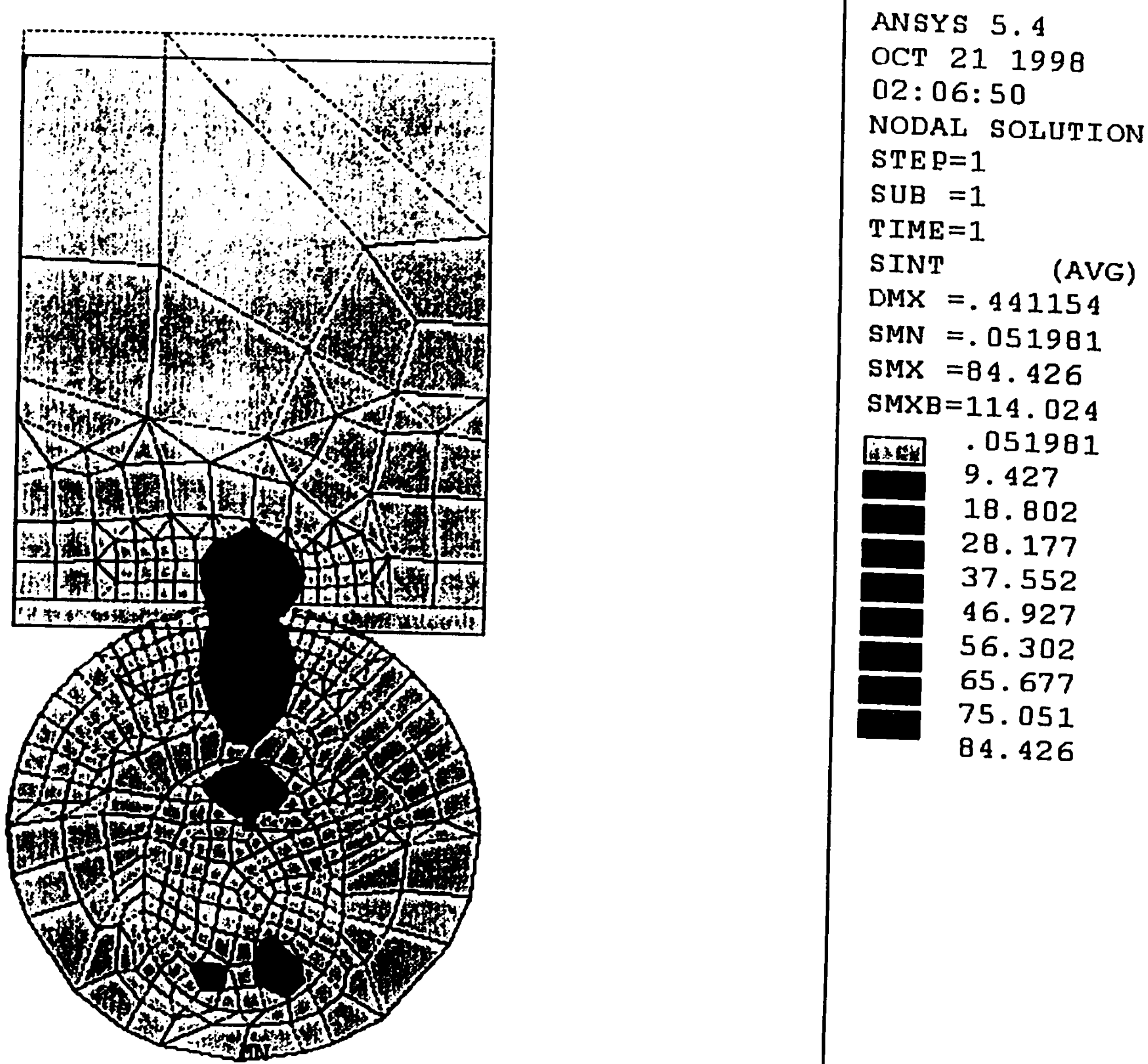
1.8 Poundal force applied to the finger



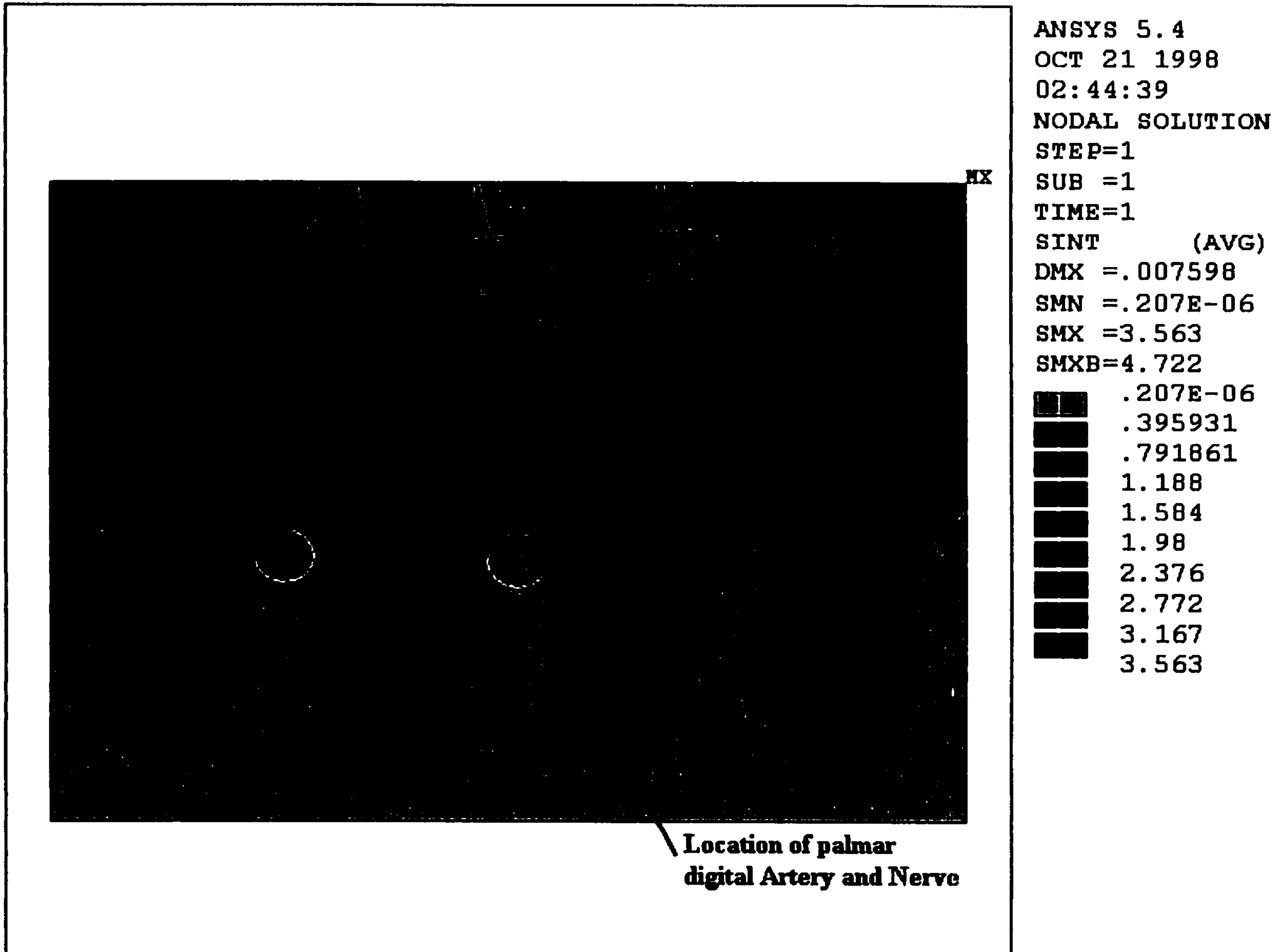
2.0 Poundal force applied to the finger



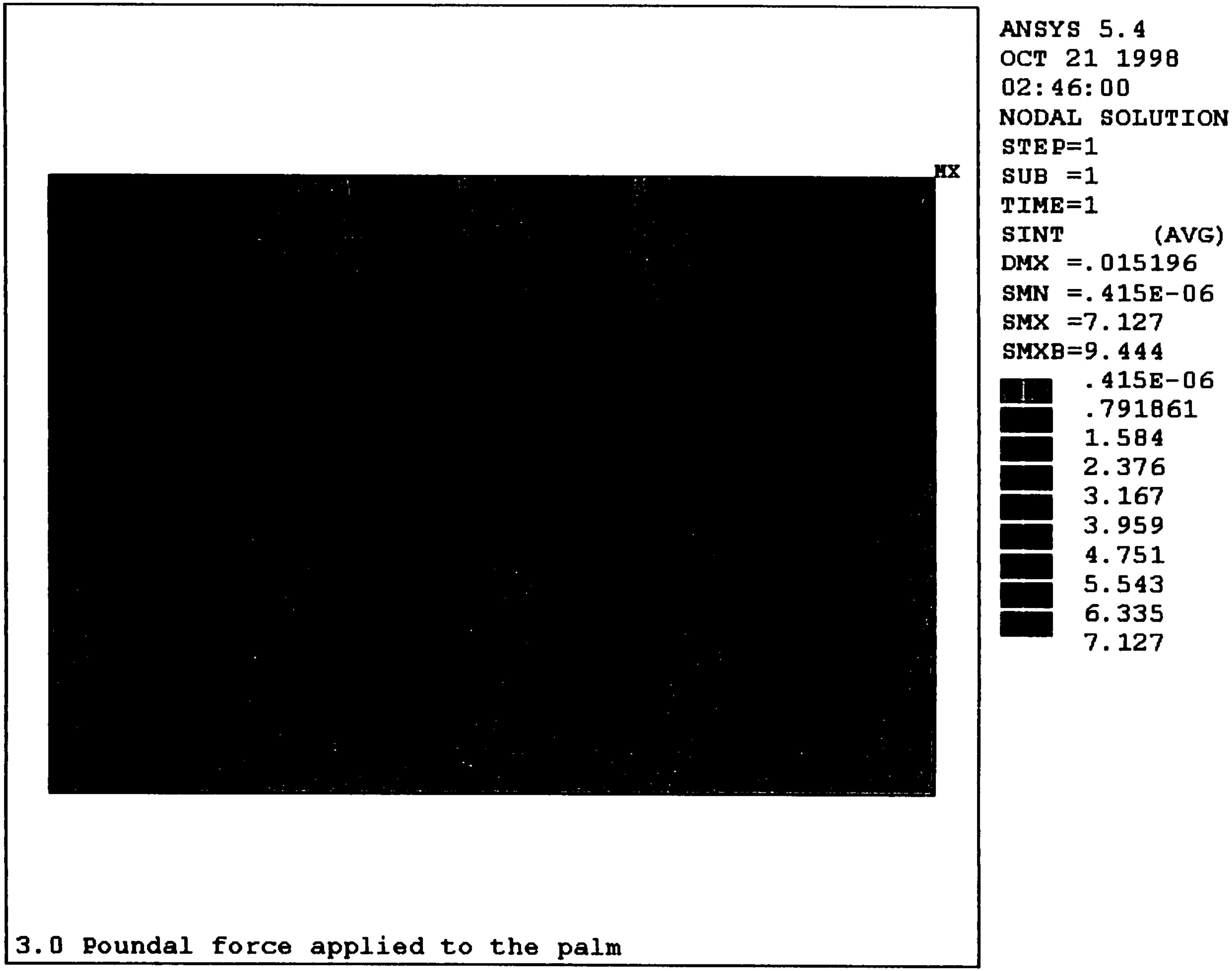
2.2 Poundal force applied to the finger



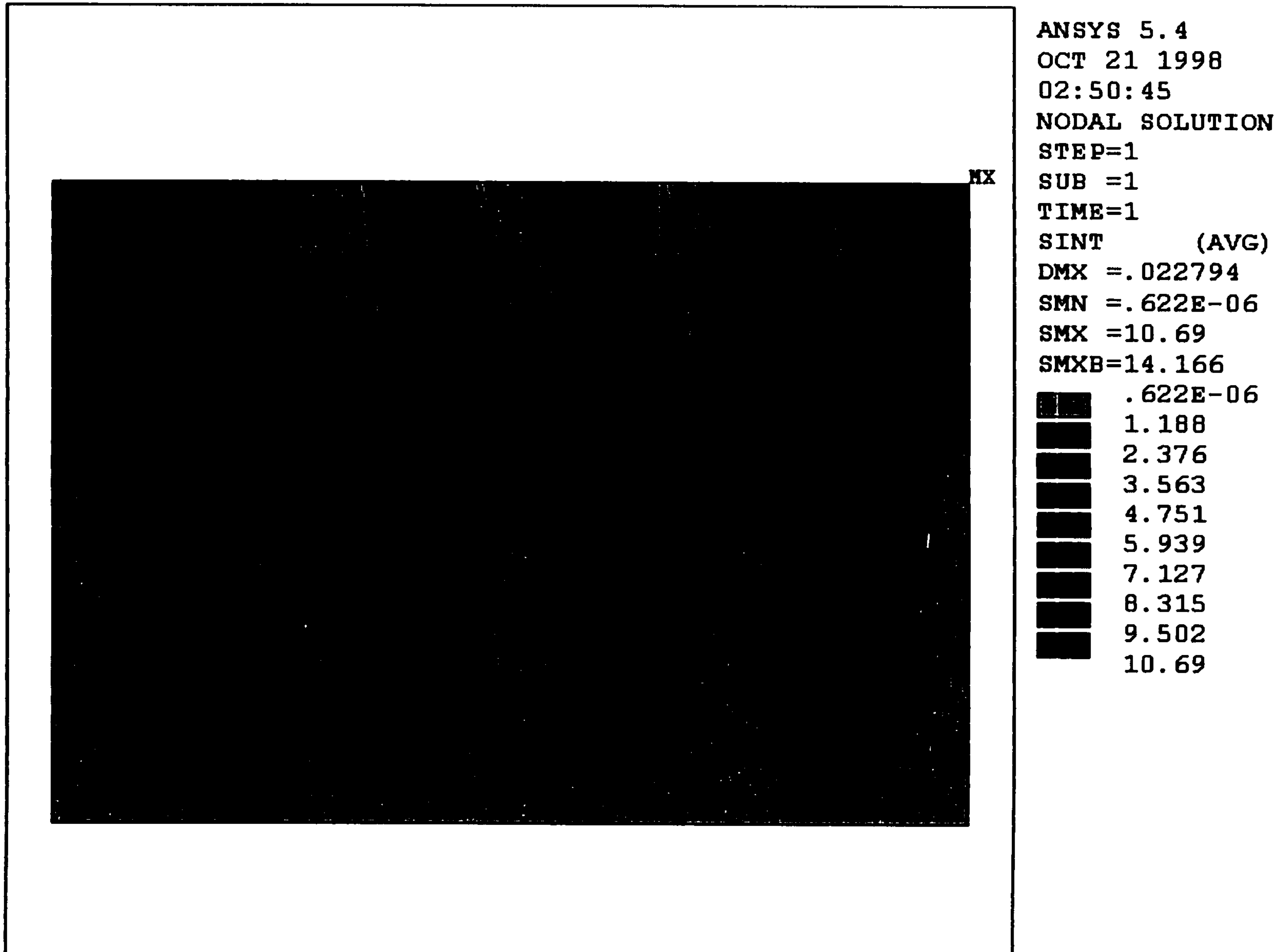
2.4 Poundal force applied to the finger



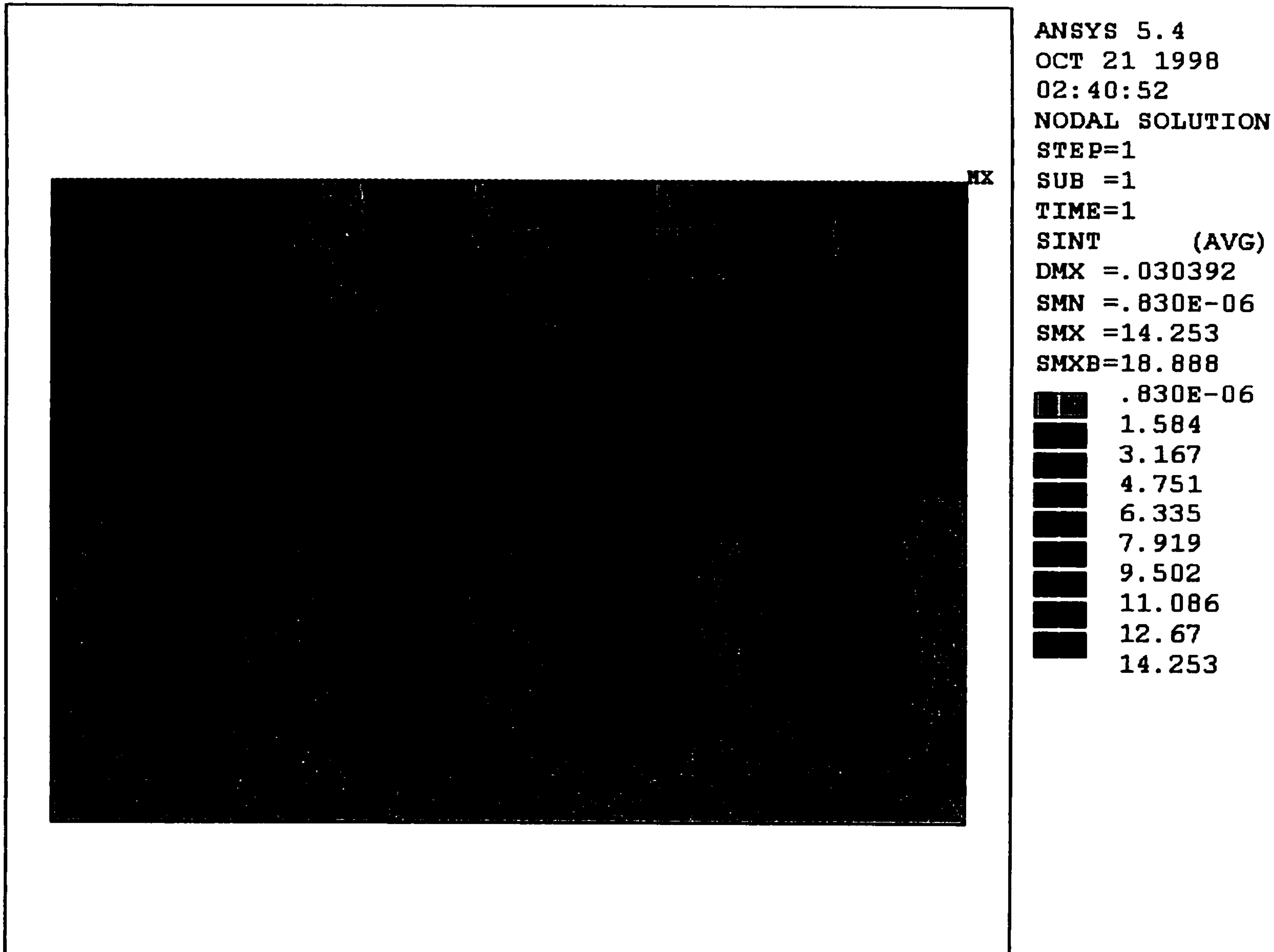
1.5 Poundal force applied to the palm



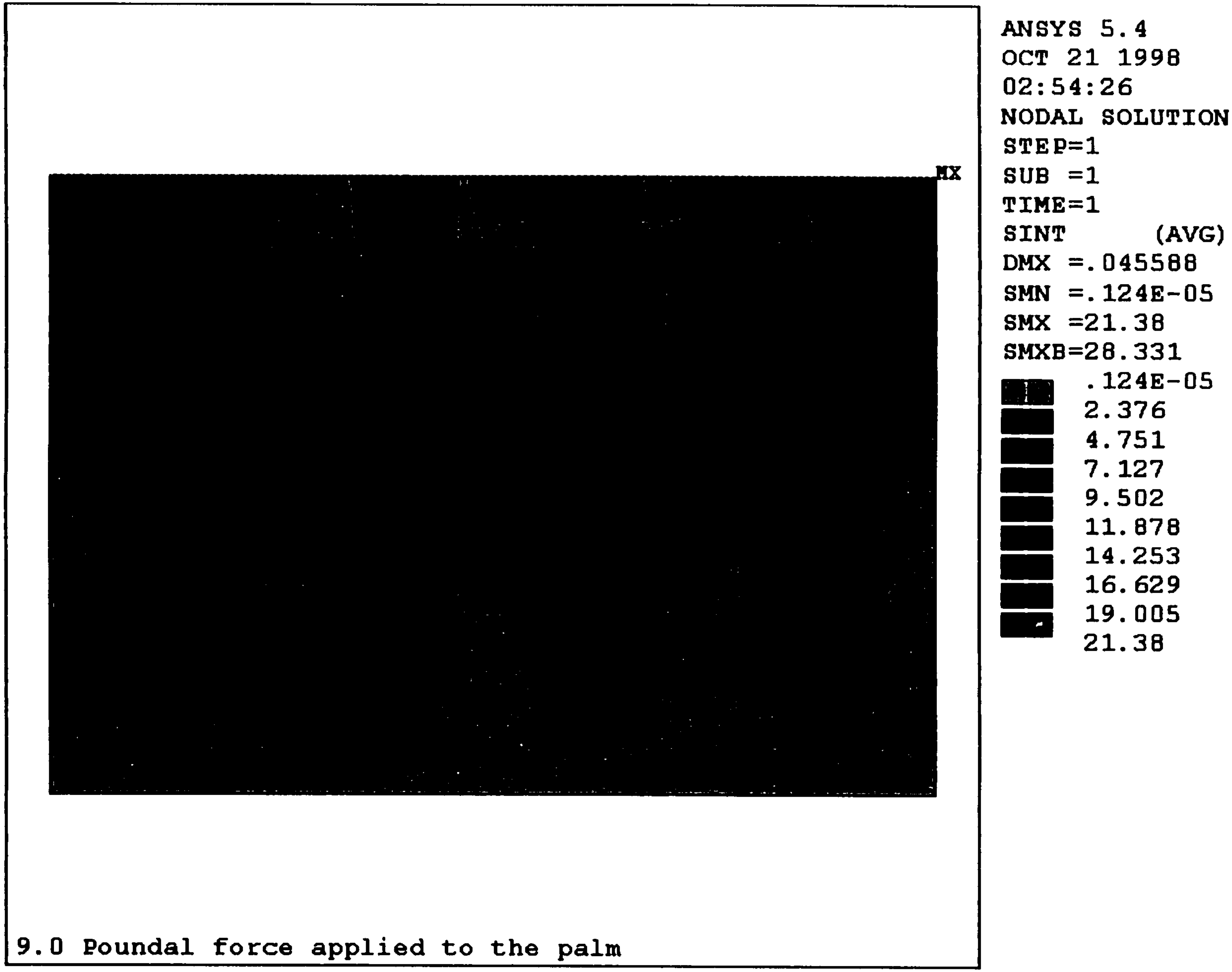
3.0 Poundal force applied to the palm



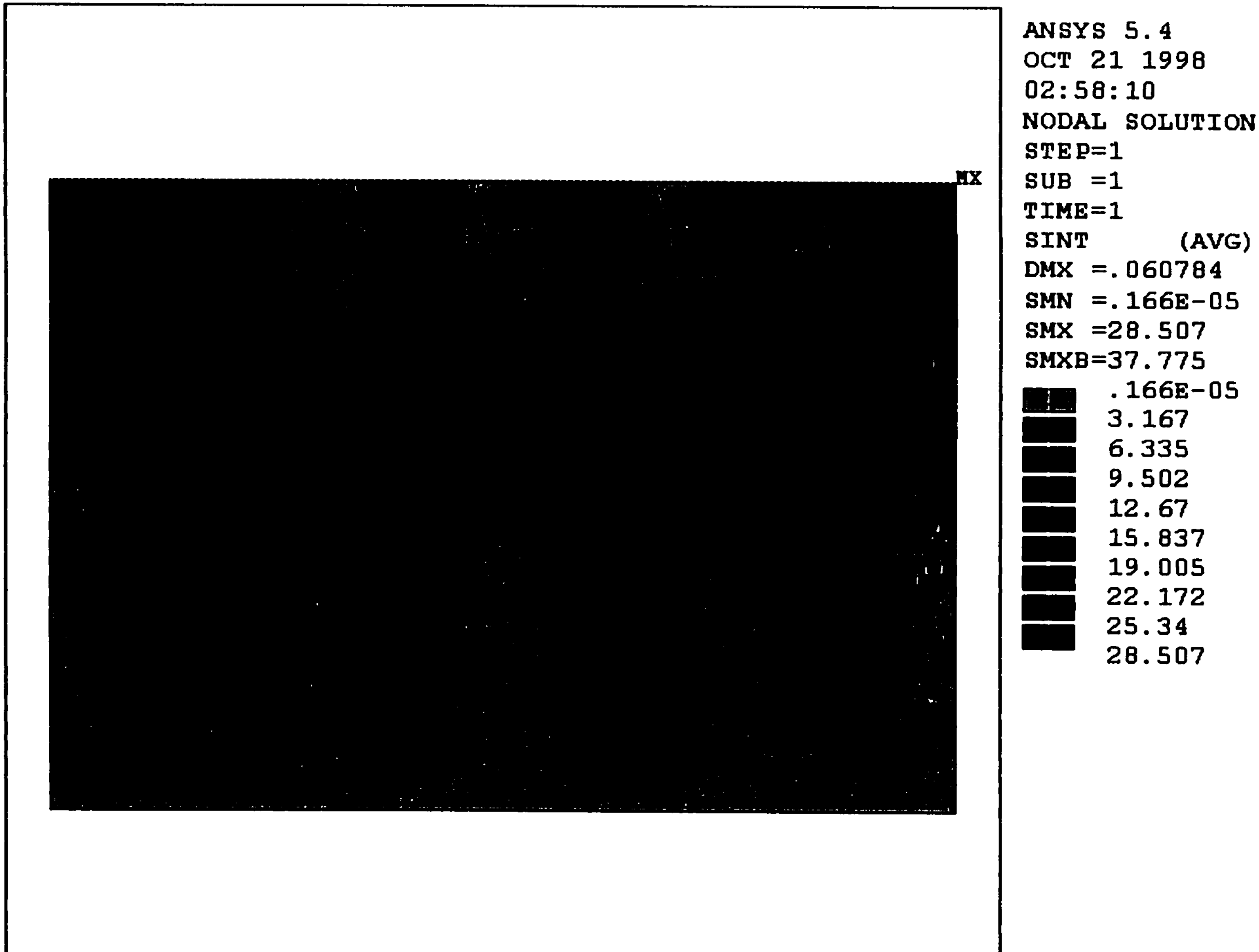
4.5 Poundal force applied to the palm



6.0 Poundal force applied to the palm



9.0 Poundal force applied to the palm



12.0 Poundal force applied to the palm

Glossary of Medical Terms

Abduction: To draw away from the midline of the body or from an adjacent part or limb.

Adduction: To draw inward toward the median axis of the body or toward an adjacent part or limb.

Anterior: Located on or near the front of an organ or on the front surface of the body in human beings.

Anthropometry: The study of human body measurement for use in anthropological classification and comparison.

Arteries: Any of a branching system of muscular, elastic tubes that carry blood away from the heart to the cells, tissues, and organs of the body.

Articulation: A fixed or movable joint between bones.

Bursa: A sac or saclike bodily cavity corresponding to the palm, especially one containing a viscous lubricating fluid and located between a tendon and a bone or at points of friction between moving structures.

Cardiopulmonary Resuscitation: An emergency procedure often employed after cardiac arrest, in which cardiac massage, artificial respiration, and drugs are used to maintain the circulation of oxygenated blood to the brain.

Carpus: The group of eight bones forming the joint between the forearm and the hand, also called wrist.

Condyloid: A rounded prominence at the end of a bone, most often for articulation with another bone.

Collateral ligaments: Ligament that is situated or running side by side; parallel.

Coronary artery: Either of two arteries that originate in the aorta and supply blood to the muscular tissue of the heart.

Diastole: The dilation of the heart cavities, during which they fill with blood.

Distal: Situated away from the center of the body.

Dorsal side: Of, toward, on, in, or near the back or upper surface of an organ, a part, or an organism.

Ellipsoid: A geometric surface, all of whose plane sections are either ellipses or circles.

Epidemiology: The study of the relationships between the various factors that determine the frequency and distribution diseases in human and other animal populations.

Extension: The act of extending or the condition of being extended. The amount or range to which something extends or can extend.

Extensors: A muscle that extends or straightens a limb or body part.

Extrinsic: Not forming an essential or inherent part of a thing: extraneous. Originating from the outside.

Flexion: The act of bending a joint or limb in the body by the action of flexors.

Flexor: A muscle that when contracted acts to bend a joint or limb in the body.

Flexor digitorum profundis: Surface that flexes a finger's DIP (Distal Interphalangeal) joint, as well as the PIP (Proximal Interphalangeal) joint, the MCP (Metacarpophalangeal) joint (only after flexion has been initiated) and the wrist along with other muscles, which flex the wrist.

Flexor digitorum superficialis: Surface that flexes a finger's PIP (Proximal Interphalangeal) joint, as well as the MCP (Metacarpophalangeal) joint (only after flexion has been initiated) and the wrist, weakly, along with other muscles, which flex the wrist.

Frontal: Relating to the anterior part of the body, Plane which divides body into front and back parts.

Intercalated: To insert, interpose, or interpolate.

Intrinsic: Situated within or belonging solely to the organ or body part on which it acts. Used of certain nerves and muscles.

Lateral: On the side; Farther from the median or the midsagittal plane.

Ligaments: A sheet or band of tough, fibrous tissue connecting bones or cartilages at a joint or supporting an organ.

Lumbrical: The surface that flexes a finger's MCP (Metacarpophalangeal) joint and extends the PIP (Proximal Interphalangeal) and DIP (Distal Interphalangeal) joints.

Medial: Relating to the middle or center.

Metacarpus: The part of the human hand that includes the five bones between the fingers and the wrist.

Muscles: A contractile organ consisting of a special bundle of muscle tissue, which moves a particular bone, part, or substance of the body.

Myocardial: The muscular tissue of the heart.

Nerve: Any of the cord like bundles of fibers made up of neurons through which sensory stimuli and motor impulses pass between the brain or other parts of the central nervous system and the eyes, glands, muscles, and other parts of the body.

Orthopedic: The branch of medicine that deals with the prevention or correction of injuries or disorders of the skeletal system and associated muscles, joints, and ligaments.

Palmar: Referring to the palm of the hand.

Pronation: Rotation of the forearm in such a way that palm of the hand faces backward when the arm is in the anatomical position, or downward when the arm is extended at a right angle to the body.

Pathomechanics: Pathomechanics is a branch of physical science that investigates static and dynamic physical forces and their effect on a human body which may also have neurological, muscular, and skeletal disorders.

Peristaltic: The wavelike muscular contractions of the alimentary canal or other tubular structures by which contents are forced onward toward the opening.

Phalanx: A bone of a finger or toe.

Physical Medicine: The branch of medicine that deals with the treatment, prevention, and diagnosis of disease by essentially physical means, including manipulation, massage, and exercise, often with mechanical devices, and the application of heat, cold, electricity, radiation, and water. Physical medicine is also called as physiatrics, physiatry.

Physiology: The biological study of the functions of living organisms and their parts.

Posterior: Located behind a part or toward the rear of a structure.

Proximal: Nearest the trunk, or said part of the body so situated.

Pulmonary: Of, relating to, or affecting the lungs.

Radial: Relating to the radius (bone of the forearm), to any structures named from it, diverging in all directions from any given center.

Rehabilitation: To restore to good health, condition, operation, capacity or useful life, as through therapy and education.

Rheumatoid Arthritis: A chronic disease marked by stiffness and inflammation of the joints, weakness, loss of mobility, and deformity.

Sagittal Plane: Frontal plane. Relating to the anterior part of a body.

Sheath: An enveloping tubular structure that surrounds the tissue that encloses a muscle or nerve fiber.

Sphygmomanometer: An instrument for measuring blood pressure in the arteries, especially one consisting of a pressure gauge and a rubber cuff that wraps around the upper arm and inflates to constrict the arteries.

Supination: Rotation of the forearm in such a way that palm of the hand faces foreward when the arm is in the anatomical position, or upward when the arm is extended at a right angle to the body.

Synovia: A clear, viscid lubricating fluid secreted by membranes in joint cavities, sheaths of tendons, and bursae.

Systole: Contraction of the heart.

Tendons: A band of tough, inelastic fibrous tissue that connects a muscle with its bony attachment.

Thenar eminence: A rise in the fleshy mass on the palm of the hand, at the base of the thumb.

Thorax: The part of the human body between the neck and the diaphragm, partially encased by the ribs and containing the heart and lungs; the chest.

Transverse: Plane lying across the long axis of the body or of a part.

Ulnar: The bone extending from the elbow to the wrist on the side opposite to the thumb in human beings.

Veins: Any of a branching system of membranous tubes (blood vessels) that carry blood to the heart.