# EVALUATION OF KNEE JOINT STRESSES DURING KNEELING WORK

by

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## STATEMENT OF THESIS APPROVAL

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# ABSTRACT

Kneeling is a daily activity for some occupations like carpet layers, miners, tile layers, floor layers, electricians, shipbuilders and many others. Several studies have shown that there is an association between kneeling or squatting and development of osteoarthritis of the knee joint. Even though this relationship has been established, few research studies have been conducted to estimate actual knee stresses and the role of kneepads in reducing these stresses while kneeling. Hence, this study looks at estimating the stress on the knees during simulated kneeling work while wearing six different types of kneepads. Custom force sensors were fabricated using FlexiForce™ Sensors and were placed on both knees over anatomically defined landmarks on the patella and tibial tubercle. Ten participants were recruited and consented to perform a series of kneeling tasks. Five wooden platforms were placed in five different locations surrounding two force plates and custom made three-axis load cells where the participants knelt. A set of five lettered, ceramic tiles were given to each participant and randomly placed on each platform with a corresponding letter. Estimated kneeling reaction forces derived from sensor values were used to quantify the effectiveness of each design in reducing the applied forces on the knee joint. Also these forces were used to verify the significance of location on force. The data from both the sensors and the force plates and load cells were analyzed for results. Two-way analysis of variance (ANOVA) with repeated measures, where kneepad and location were the independent variables and calculated applied force was the independent variable was used to analyze the results. There was a significant relationship between force and kneepad and also between force and location. The placement of the sensor on the knee was found to be a major factor for the estimation of the force on the knees. It is apparent that proper kneepad design and selection can be an effective abatement to reduce the stress accumulated on the knee during kneeling work.

# TABLE OF CONTENTS

# LIST OF FIGURES

**Figures**

# LIST OF TABLES

**Tables**

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# 1. INTRODUCTION

The human body is a complex system comprised of different types of bones, muscles, ligaments, tendons, organs, tissues, fluids, etc. Each of these components and subsystems play an important part in the proper function of the body. For example, the muscles, tendons and ligaments are essential for movement. These structures are subjected to diseases and injuries from overuse, overloading, and congenital disorders. This research concentrates on determining the effects of commercially available kneepads on stresses in the knee joint during kneeling.

Before describing the details of the present study, a review of the important role and function of each part of the knee joint is presented. A greater understanding of the function and structure of the knee joint will help to further understand the biomechanical consequences of kneeling work that may be related to predicting injury and better designing protective equipment for the knee joint.

## 1.1 Components of the Knee Joint

The knee joint is a complex part of the human body that bears most of the weight of the body while standing. The load from the whole body applies force on the bottom end of the femur, which in turn loads the medial and lateral menisci (further discussed in section 1.1.4). The menisci help distribute the weight of the body over a larger area to reduce concentrating the whole force at a single point. The menisci also act as a shock absorber, during movement, by absorbing or releasing the synovial fluid present in the menisci. As the knee joint is a complex joint, it allows different types of movement at the joint enabling a person to adopt different postures. Because of the different postures, the weight distribution at the knee joint varies with the adopted posture. This makes evaluation of the weight distribution and the force vectors at the knee joint a very complex task.

### 1.1.1 Bones

The knee joint is made up of four bones, namely the femur, tibia, fibula and patella. The femur is the largest bone in the human body and is located in the thigh. The distal condyles of the femur form the upper portion of the knee joint. The tibia and fibula form the lower portion of the knee joint and are located on the medial and lateral sides of the limb. The patella or kneecap is a sesamoid bone which forms the anterior part of the knee joint. It protects the knee joint from anterior impacts. The arrangement of the four bones that make up the knee joint is shown in Figure 1.1.

The ends of the bones are covered with a smooth and flexible material called articular cartilage. The cartilage makes it easier for the bones to glide over each other by reducing the friction. This helps keep the movement in the joints pain free.

### 1.1.2 Ligaments

Ligaments are tough bands of tissue that connect the ends of bones together. The knee joint has four major ligaments: the Anterior Cruciate Ligament (ACL), the Posterior Cruciate Ligament (PCL), the Medial Collateral Ligament (MCL), and the Lateral Collateral Ligament (LCL). These ligaments help in the up and down and rotational

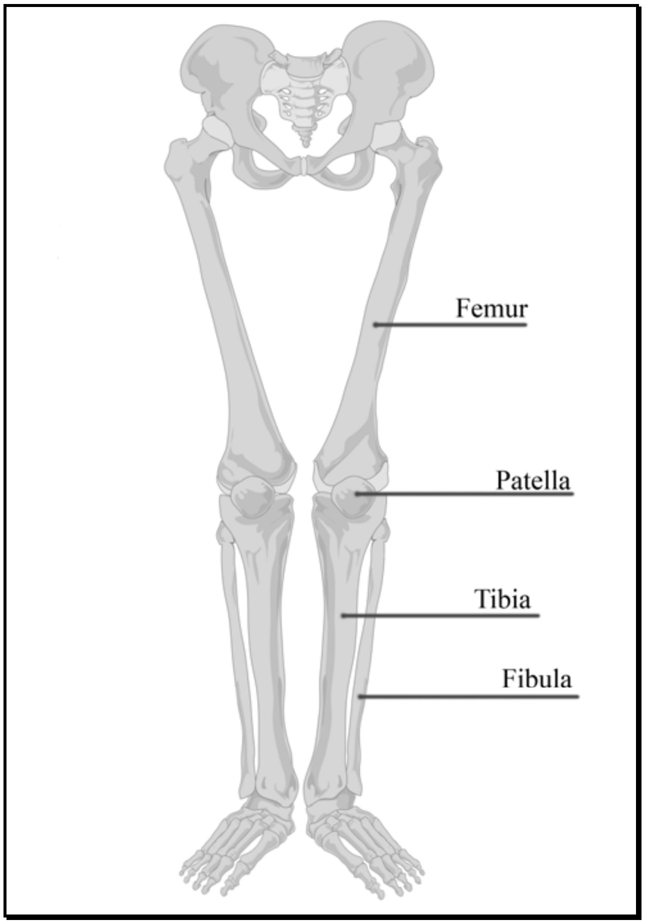


**Figure 1.1**: The four bones femur, tibia, fibula and patella which make up the knee joint adapted from (Villarreal, 2007).

movement and stability of the joint.

The ACL originates on the anterior part of the tibia and attaches to the posterior part of the femur and helps in preventing hyperextension of the knee.

The PCL originates at the posterior part of the tibia and attaches to the anterior part of the femur and prevents the hyperflexion of the knee. The ACL and PCL are shown in Figure 1.2.

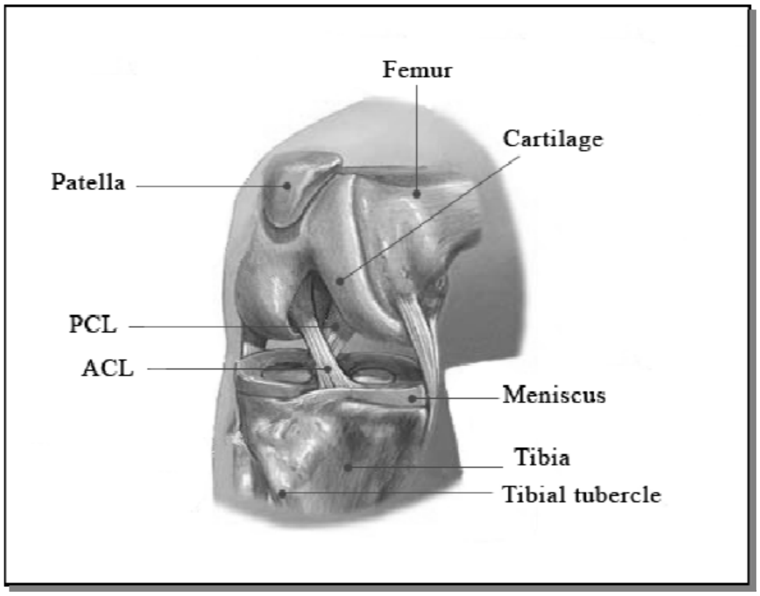


**Figure 1.2**: ACL, PCL which control the hyperextension and hyperflexion of the knee joint, respectively adapted from (A.D.A.M., 2010).

The MCL and the LCL connect the femur and tibia, and femur and fibula, respectively, as shown in Figure 1.3. Both collateral ligaments provide stability to the knee and prevent excessive movement either to the lateral side or medial side.

### 1.1.3 Tendons and Muscles

Tendons are also tough bands of tissues but they connect muscle to bone. There is one main tendon on the knee joint that spreads over the patella from the quadriceps muscle to the tibia. The tendon below the patella is called the patella tendon and the tendon above is called the quadriceps tendon.

Muscles help in the movement of the knee. Quadriceps muscles are present on the front of the knee, and hamstrings on the back of the knee, in the thigh region. The tendons and the muscles present in the knee joint are shown in Figure 1.4.

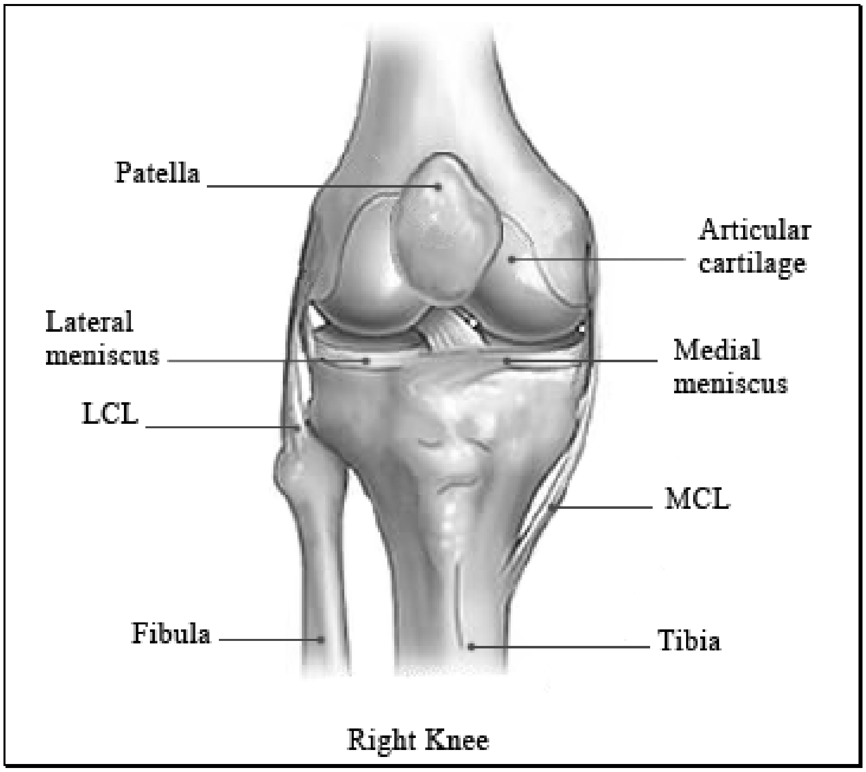


**Figure 1.3**: MCL, LCL which control the sidewise movement in the knee joint and also help in maintaining knee stability adapted from (ACL Solutions).

### 1.1.4 Meniscus

Menisci are half moon shaped pads which are present between the femur and the tibia. There are two menisci: the lateral meniscus and the medial meniscus as shown in Figure 1.5. The meniscus is helpful in distributing force over a larger area effectively reducing the pressure at a single point. The synovial fluid present in the meniscus and cartilage helps lubricate the cartilage to reduce wear and improves healing after an injury to the meniscus. The healing process, however, is slow and inefficient due to a lack of direct blood supply to the structure. Injuries to the menisci generally heal slowly if they heal at all.

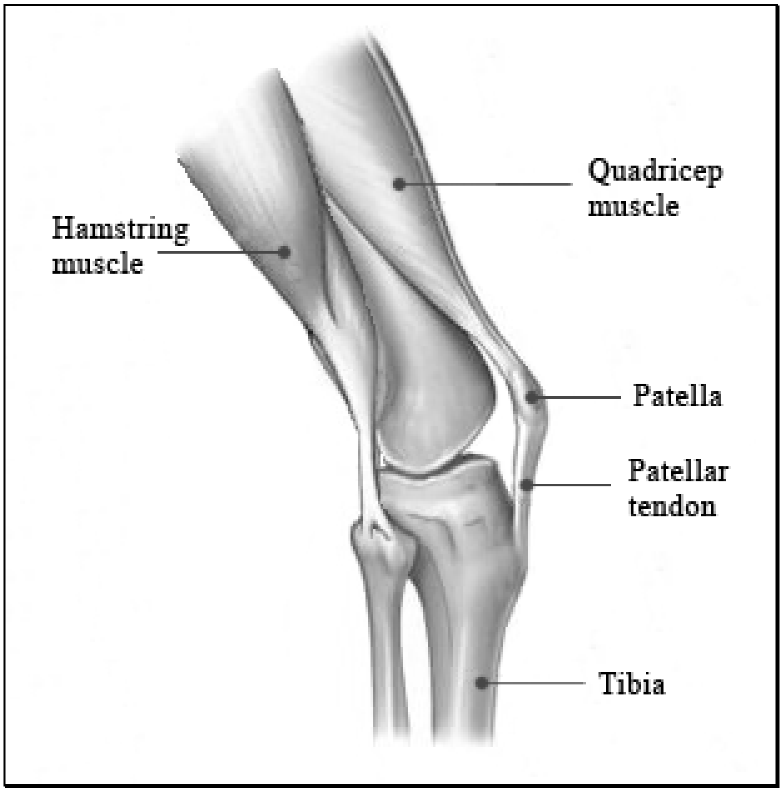


**Figure 1.4**: Different tendons and muscles which help in the movement at the knee joint adapted from (ACL Solutions).

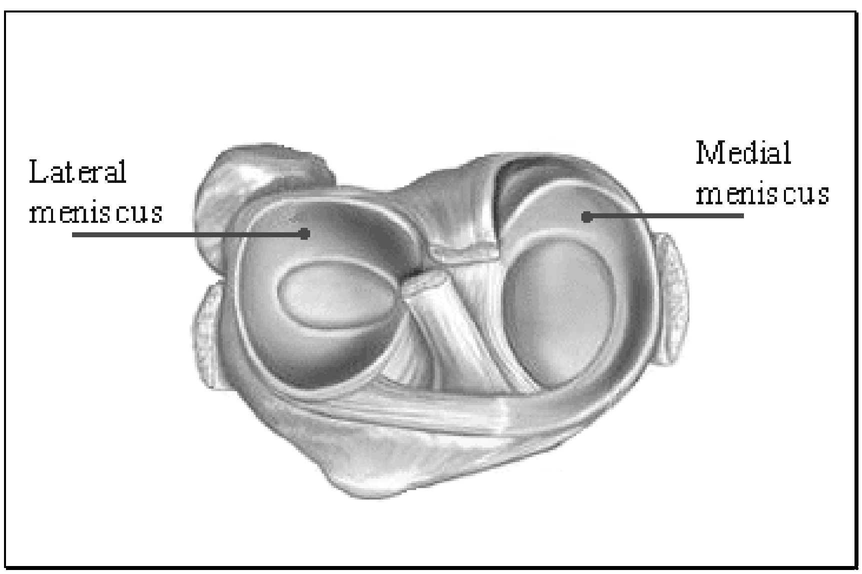


**Figure 1.5**: Top view of the meniscus on the right knee joint adapted from (http://www.indianarthroscopy.co.in/what_is_wrong_with_your_knee.html).

## 1.2 Background

The knee is the largest joint in the human body. It is a hinge-like joint that is subjected to constant pounding, bending, and twisting from everyday activities, as well as the impact of falls and the effects of arthritis (American Academy of Orthopaedic Surgery, 1997). It is also considered the most complex joint in the human body. Since the knee supports nearly the entire weight of the body and has high joint mobility, it is one of the most susceptible to injuries (Moore & Dalley, 1999). Also, according to an article in eOrthopod, the knee joint, unlike the other joints in the body, lacks a stable bony configuration. For example the hip joint is a ball that sits inside a deep socket, the ankle joint has a shape similar to a mortise and tendon (eOrthopod). Hence the knee relies on ligaments, menisci, cartilage and bones in the joint to maintain its load bearing capacity. Any damage to these ligaments can affect knee mobility and stability, which in turn may result in abnormal knee kinematics and may even cause damage to the tissues surrounding the joint.

Researchers have estimated that the incidence of knee injury could be at 2 in1000 people a year among the general population (Miyasaka, Daniel, Stone, & Hirshman, 1991) and an even greater rate for those involved in sports activities (Bruesch & Holzach, 1993). Common causes for knee injuries are overuse, sudden stops or twists, or direct blows to the knee. Musculoskeletal disorders are very common in the general population and are the predominant cause of disability among construction workers (Arndt et al., 2005). The prevalence of knee pain in the general population ranges from 10% to 60% depending on age, occupation and the definition used (Miranda, Viikari-Juntura, Martikainen, & Riihimaki, 2002). The most common type of knee injuries are ligament tears and meniscal tears. Since proper functioning of the ligaments is an essential characteristic of healthy joints, the ligaments which are torn or not properly healed can result in long term joint instability and premature OA. Although there have been many studies related to ligaments, the question that still remains is what is the role played by the ligaments in maintaining the stability of the knee joint and also the cause and effect of specific injuries and surgical procedures? There are very limited numbers of experiments and clinical studies which have been done on the applied stresses of the knee, particularly while kneeling.

Knee osteoarthritis (OA) is a common chronic joint disorder and a major source of disability. It is characterized by an imbalance between the synthesis and degradation of the articular cartilage, leading to the classic pathologic changes leading to the destruction of the cartilage (Arden & Nevitt, 2006). Knee OA is related to age and several other factors such as gender, genetic predisposition, previous knee injuries, obesity and some sports activities (Hunter, March, & Sambrook, 2002). According to Lopez et al., (2006) OA is an increasingly important health concern in most developed countries (Lopez, Mathers, Ezzati, Jamison, & Murray, 2006).

It is estimated that nearly 46 million Americans currently have some form of joint arthritis (Hootman & Helmick, 2006). In 2006, OA was the principal diagnosis for about 90% of 547,000 knee surgery hospitalizations. Hospitalizations for OA increased from about 322,000 in 1993 to 735,000 in 2006, according to the News and Numbers from the Agency for Healthcare Research and Quality (HCUP Facts & Figures, 2006). The large increase in OA hospitalizations is primarily related to the increase in knee replacement surgery. From 2000 to 2006, knee replacement surgery increased 65%. According to the

NSC Injury Facts Report, the average incurred cost for knee injury claims was $17,000 in 2002. Hence, a large amount of revenue is obtained by the insurance companies from knee injuries.

Cartilage degeneration increases with age and hence may become more prevalent among older generations, increasing the risk of developing osteoarthritis (Felson & Zhang, 1998; Felson et al., 1997; Forman, Malamet, & Kaplan, 1983). Several studies have shown that there is a casual relation between kneeling or squatting and the risk of developing knee osteoarthritis. The following are some of the findings made by authors from different articles suggesting this association.

> Floor layers have an increased risk of developing knee disorders including pre and infrapatellar bursitis, osteoarthritis, and meniscal lesions. (Jensen, 2008, 72; Rytter, Jensen, Bonde, Jurik, & Egund, 2009, p. 1512)

> Occupational kneeling pose risk in the development of medial tibiofemoral osteoarthritis, and further that there seems to be a dose response association between trade seniority and tibiofemoral osteoarthritis among floor layers. (Rytter, Egund, Jensen, & Bonde, 2009, p. 19)

> Floor layers had a higher prevalence of tibiofemoral osteoarthritis compared to graphic designers. Floor layers aged 50-59 years had a 3.6 times greater likelihood (OR = 3.6, 95% CI = 1.1-12.0) of having TF OA than graphic designers at the same age. (Rytter, Egund et al., 2009, p. 19)

> Prolonged squatting is a strong risk factor for knee osteoarthritis in elderly Chinese subjects. (Zhang et al., 2004, p. 1187)

> Prolonged kneeling increases a person's risk of developing musculoskeletal knee disorders such as osteoarthrosis, meniscal lesions, chondromalacia, and bursitis. (Wurzelbacher, Johnston, & Hudock, 2006, p. 6)

> Work involving kneeling and/or squatting is causally associated with an increased risk of osteoarthritis of the knee. (McMillan & Nichols, 2005, p. 567)

Apart from studies showing the relation with kneeling/squatting, there are several studies that found the risk for developing knee OA increases with BMI (Anderson &

Felson, 1988; Felson, Anderson, Naimark, Walker, & Meenan, 1988; Sandmark, Hogstedt, Lewold, & Vingard, 1999).

According to McMillan and Nichols (2005), the little animal experimentation evidence available indicates that the articular cartilage of the knee joint is susceptible to damage if placed under sustained pressure. Kneeling or squatting place a high level of force on the knee. High force, when combined with repetition of movement further increases the potential for a knee injury (National Institute for Occupational Safety and Health (NIOSH), 1997). Awkward body postures may also be responsible for high levels of occupational knee morbidity (Bhattacharya, Mueller, & Putz-Anderson, 1985).

Kneeling or squatting is a day-to-day activity for a number of different occupations. Some of these occupations include carpet layers, floor layers, tile layers, miners, electricians, shipbuilding, plumbing, construction work and others. Such workers put 70% of their body weight on a few cubic centimeters of the tibia and patella while kneeling, as opposed to putting 22% of their body weight on each knee while walking (Wurzelbacher et al., 2006). According to Moore et al. (2009), greater than 60%, of the pressure during kneeling is experienced on the combined patella tendon and tibial tubercle for all postures. But, according to Wallenquist (1987) (as cited in Jensen, Rytter, & Bonde, 2010) the extent of the static forces being experienced on one or both the knee varies between 22% and 68% of the total body weight depending on the kneeling work posture. Also the external knee joint forces were lowest when participants were kneeling back on the heels (0.3 times body weight) and highest when they were in crawling and in gluing work positions (3-3.5 times body weight) (Jensen et al., 2010). It is important to note that the greater the force required to sustain a posture, the shorter the time it takes for an individual to become fatigued (Hagberg et al., 1995). Therefore, as the kneeling or squatting time increases, an individual can become more fatigued, thus increasing the risk of developing knee injury. According to Dembe et al. (2004) one of the six specific hazardous job activities that can increase occupational injuries is kneeling or crouching.

### 1.2.1 Kneeling in Mining

Knee injuries associated with working in low-seam mines have been a longstanding problem for the U.S. mining industry. In the early 1960s, Sharrard and Liddell's (1962) study reinforced that miners are likely to suffer cartilage injuries by showing that more coalminers than would be expected from the experience of the general population underwent meniscectomy. Injuries to the knee and lower back are the two leading body parts in terms of injury cost and together are responsible for 28.6% of the total costs incurred by the eight mining companies studied. These two body parts also lead in terms of injury frequency in these data (Gallagher, Moore, & Dempsey, 2009). According to the Mine Safety and Health Administration (MSHA) injury database, 227 knee injuries were reported in underground coal mining in 2007. Miners have to work for a large percentage of their days kneeling or crawling. Although kneepads are often used in a mining environment, the high frequency of knee joint injury suggests that kneepads alone are not a sufficient means to control these injuries and that additional measures need to be taken (Gallagher et al., 2009). MSHA is jointly working with mines' operators, NIOSH and educational institutions to develop knee protective devices to protect miners from injuries.

### 1.2.2 Kneeling Among Carpet Layers and Floor Layers

Trained work inspectors were used for ranking trades on a construction site. The range for knee-strain in a specific trade was estimated from 1 (highest exposure) to 19 (no exposure). Carpet and floor layers were ranked as "1" in comparison with white-collar workers, who were ranked as "19" (Ekstrom, Engholm, Nyqvist, & Wallenquist, 1983). Carpet layers make up less than 0.06% of the U.S. workforce, but they file 6.2% of all workers' compensation claims for traumatic knee injury; also the claims for carpet layers is 13 times greater than for carpenters, sheet metal workers and tinsmiths, whereas it is 6 times greater for the floor layers (Tanaka, Smith, Halperin, & Jensen, 1982). Carpet layers and floor layers spend more than half of their daily working time in kneeling, knee supporting or squatting work positions (Jensen, 2005; Jensen, Eenberg, & Mikkelsen, 2000; Jensen et al., 2010; Rytter, Jensen, & Bonde, 2007). Carpet layers are probably more prone to knee injury because in addition to kneeling they also use a knee kicker, a device used to stretch carpet during installation. Knee impact forces during the use of this device have been shown to be as high as four times body weight (Bhattacharya et al., 1985). According to Thun et al. (1987) "Carpet and floor layers have received relatively less attention as workers with high risk of knee trauma"(p. 611).

### 1.2.3 Kneeling Among Electricians

Similar situations are seen in the case of electricians who have to crouch and kneel often in their daily job. These postures assumed approximately 50% of the working electrician's time during certain activities (Yorke, 2006). In 2005, a survey from Occupational Health Clinics for Ontario Workers (OHCOW) found that 67.6% of reporting union members experienced work related aches, pain, discomfort or numbness of the knees (Yorke, 2006).

Little research has been done in other occupations that involve considerable amounts of kneeling or squatting postures among the workforce. NIOSH is working on intensifying the effort to educate the workforce about the hazards of kneeling and crouching and encouraging them to use knee pads. Specifically in the case of carpet layers who use knee kickers to stretch the carpet, alternative products like power stretchers and carpet air stretchers are to be used to avoid morbidity to the knee and also the formation of bursitis (Thun et al., 1987; Village, Morrison, & Leyland, 1993).

## 1.3 Significance of This Study

It can be seen from the background information that kneeling or squatting is a leading risk factor in developing OA and is highly prevalent in construction workers like carpet layers, floor layers, miners, and electricians. Many research studies have been published that are related to kneeling or crouching and their impact on occupational knee injuries. Most of them are based on self-answering of questionnaires or simple clinical examination or radiographic knee examinations. It is astonishing to know that even though a lot of people are being affected by this problem, a relatively small research effort is being made to analyze the knee stressors due to contact forces while performing kneeling work. In fact, to the author’s knowledge only two studies were conducted which tried to find the stresses being experienced on the knee during different kneeling work positions. As with most musculoskeletal or repetitive strain injuries, the complexity of the diseases or disorders is great, and the true causal relationship among risk factors is unknown.

The study investigating knee joint stresses conducted by Jensen et al. (2010), which measured the external knee forces in 5 different kneeling work positions in 10 floor layers using Computer Dynography, is discussed. The study showed that floor layers spent a high percentage of time in knee straining work positions and high external forces were experienced while in crawling or gluing position when compared to kneeling back on the heels.

Another study conducted by Moore et al. (2009), which measured the pressure applied to the knee during static postures used in low seam mining while not wearing kneepads and while wearing two kneepads commonly used in the industry, one articulated and other nonarticulated. Ten subjects simulated five different postures assumed in low-seam mines and a custom made capacitive pressure sensor was used to collect the pressure data. The results from this study indicated that the majority (>60%) of the pressure was on the combined patella tendon and tibial tubercle for all postures.

It was observed from the two studies that both tried to measure the stress on the knee during different kneeling positions. But the first study did not study different kneepads and the reduction in force obtained because of the kneepad material and design. Though the second study accounts for some kneepads, it used only two kinds of kneepads that were commonly worn in a mining environment.

Hence a major goal of this study was to measure the stress on the knee without kneepads as well as with five different types of kneepads which are commonly used by workers in various occupations and environments, therefore taking into account a larger majority of occupations and situations to which the worker may be exposed. This study compared five different kneepads, their advantages and disadvantages, and finally we developed some guidelines to establish the best protective device. Kneeling work stress was calculated dynamically at the knee and included components from postural stressors as a function of the kneeling position. This study also describes a method to establish a functional kneeling work envelope and the corresponding stresses on the knee. Hence the objectives of this study can be written in terms of the hypotheses as:

Hypothesis I: $\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5 = \mu_6 = \mu_7$

All the kneepads are the same and there is no difference between the kneepad in reducing the forces. Where $\mu_1$ to $\mu_7$ represent different types of kneepads used in this study including the without kneepad condition.

Hypothesis II: $\Psi_1 = \Psi_2 = \Psi_3 = \Psi_4 = \Psi_5$

All the locations induce the same amount of stress on the knees and there is no difference between the locations. Where $\Psi_1$ to $\Psi_5$ represent the different locations in the kneeling work envelope.

The dependent variable Mean Peak ($H_{01}$), Mean Average ($H_{02}$) and Mean Area ($H_{03}$) which were normalized by location and cycle were used to test these hypotheses.

# 2. METHODS

In this section, the different forms of data collected along with the setup and procedure adopted in collecting the required data are discussed. In this study there were mainly three types of data collected.

1. Questionnaire Data
2. Force Data
3. Motion Data

Each one of the above presents different insight into the current problem being studied, which is the stress on the knee joints during kneeling work. The Questionnaire data collected give the insight into the participants rating of the pain during kneeling and also the rating of the different kneepads used in the study. The Force data give the experimentally derived force at different points on the knee at different positions during the kneeling tasks. And finally the Motion data give us the posture of the different segments of the body during kneeling work, which will help in the future to determine the internal knee muscle forces and bone-to-bone contact forces during kneeling. Although the motion data were not used in analyzing the recorded force data, they were collected to be used for future work. All these will be discussed further in the following sections in this chapter.

## 2.1 Questionnaire Data

A questionnaire was given to each participant after the completion of the kneeling task for each kneepad. The questionnaire contains two sections, General and Trial Specific.

### 2.1.1 General

In the general section, participants were asked questions pertaining to injury history relating to the knee joint, participation in different sports, etc. The electronic questionnaire given to each study participant can be found in the Appendix.

### 2.1.2 Trial Specific

In the trial specific section, participants were asked questions on the subjective rating of the different kneepads used in the study and the scaling of the pain, if any, during kneeling work.

All the data obtained from the questionnaire were saved into a spreadsheet. The questionnaire was helpful to describe participant demographics, which was used in putting together different statistics based on the user rating of the kneepad, pain scale, age of the participant, etc.

## 2.2 Force Data

One of the major data sets collected in this study was the force data. The force data were later used in determining the best kneepad among the kneepads that were being tested in the study. Two forms of force data were collected:

1. Sensor Data

2. Force Plate Data

The sensor data gave the direct contact force and its position on the knee joint, whereas the force data obtained from the force plate provided complete reaction forces and moments and were useful in comparing the force data obtained from the sensors. Different instrumentation was developed in order to acquire the sensor data and are discussed further in their respective sections. All the force data obtained both from the Sensors and the Force Plates were measured in volts and converted to Newtons (N) using sensor specific volt-force calibration equations.

### 2.2.1 Sensor Data

The selection of the force sensors for this study was a daunting task as the requirements for the sensors included flexibility, thinness and ability to measure loads of up to 100 lbs. Two different types of force sensors were used for collecting data as the first force sensors used for the study started failing during the process of data collection. The two force sensors are hereby named as:

Generation I Sensors

Generation II Sensors

The different characteristics of each sensor generation are further discussed in the following sections. The sensor data for both generations of sensors were collected using custom designed circuits and force sensors located at different points on the kneecap and tibia tubercile on both knees. Two sensor assemblies with eight force sensors each were designed, one for each knee. A similar circuit was adopted from the guide provided by the respective manufacturer for both sensor generations, and were used in acquiring the output from each of the force sensors. The circuit and the force sensors were powered using an external power amplifier that also served as a transfer box for the outputs from the force sensors. A 15-pin cable was used to transfer the output from each sensor to the transfer box. A 25-pin cable was used to connect the output from the power source unit/transfer box to the A/D board, which in turn was connected to the computer. Hence the output from each of the force sensors was directly transferred to the computer and stored in Vicon Motus (ViconPeak, Centennial, CO). The whole setup can be seen in Figure 2.1. The same setup was used for both generation sensors for the wiring, except for the change in the circuit, voltage supply and the configuration of the force sensors.

#### 2.2.1.1 Generation I Sensor

The Generation I Sensors were made using Force Sensing Resistors (FSRs) developed by Interlink Electronics. FSR is a polymer thick film device which exhibits a decrease in resistance with an increase in the force applied to the active surface. FSRs are made up of three layers: firstly there is a flexible substrate with printed semiconductor, which is followed by a spacer adhesive, and the third layer is a flexible substrate with printed interdigitating electrodes as shown in Figure 2.2.

At the low end of the FSR, a switch-like response (Figure 2.3) is evident. This is because FSRs have a greater resistance than 100k$\Omega$; as the force is applied on the sensing area of the FSR, its resistance decreases, allowing voltage output. These FSRs are very thin with a thickness of about 0.012 inches or 0.3 mm. Hence these sensors can be used where there is a limitation in space. Also these sensors are flexible and reasonably low cost. The FSRs used in Generation I are shown in Figure 2.4.

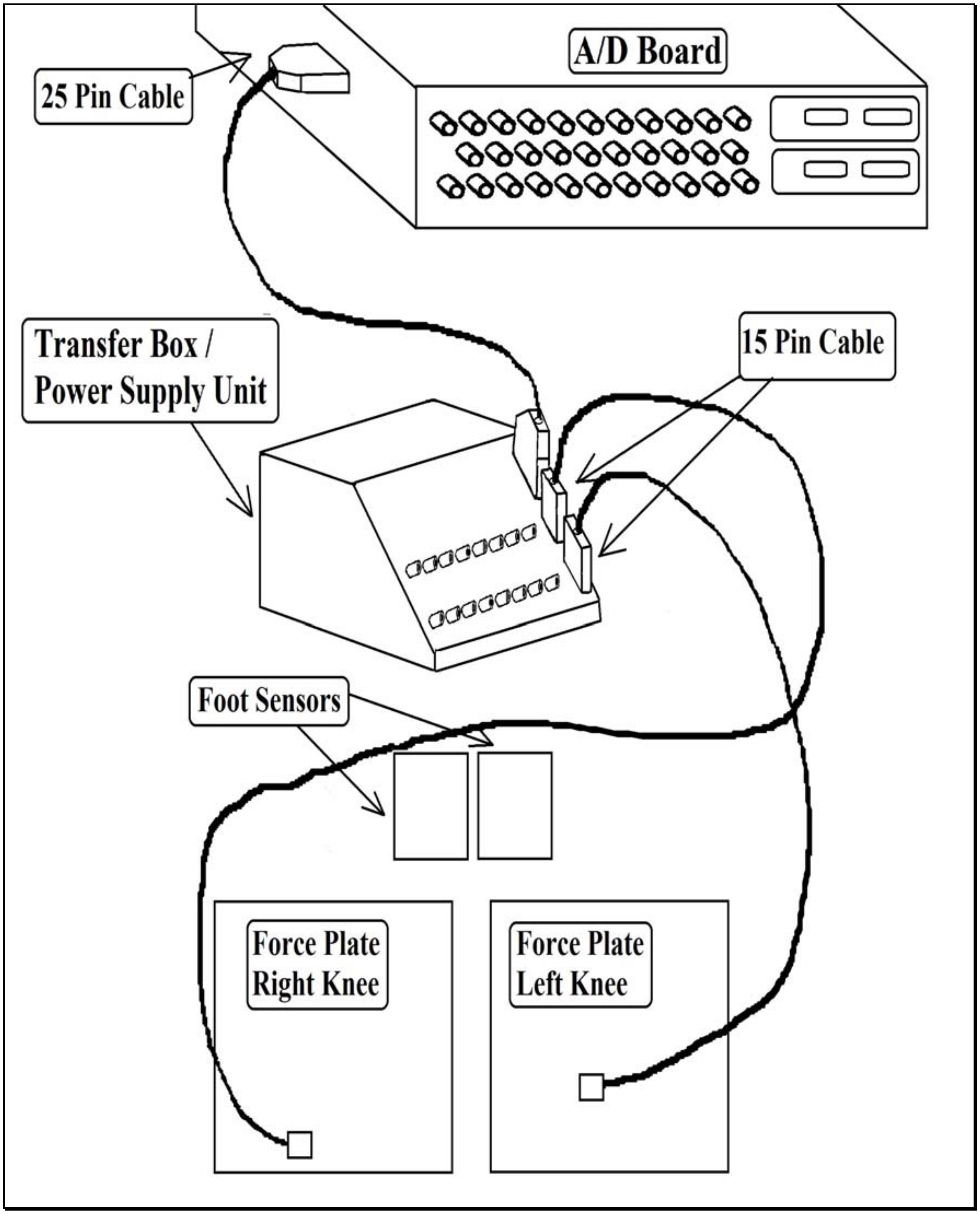


**Figure 2.1**: Setup for the sensor force data collection

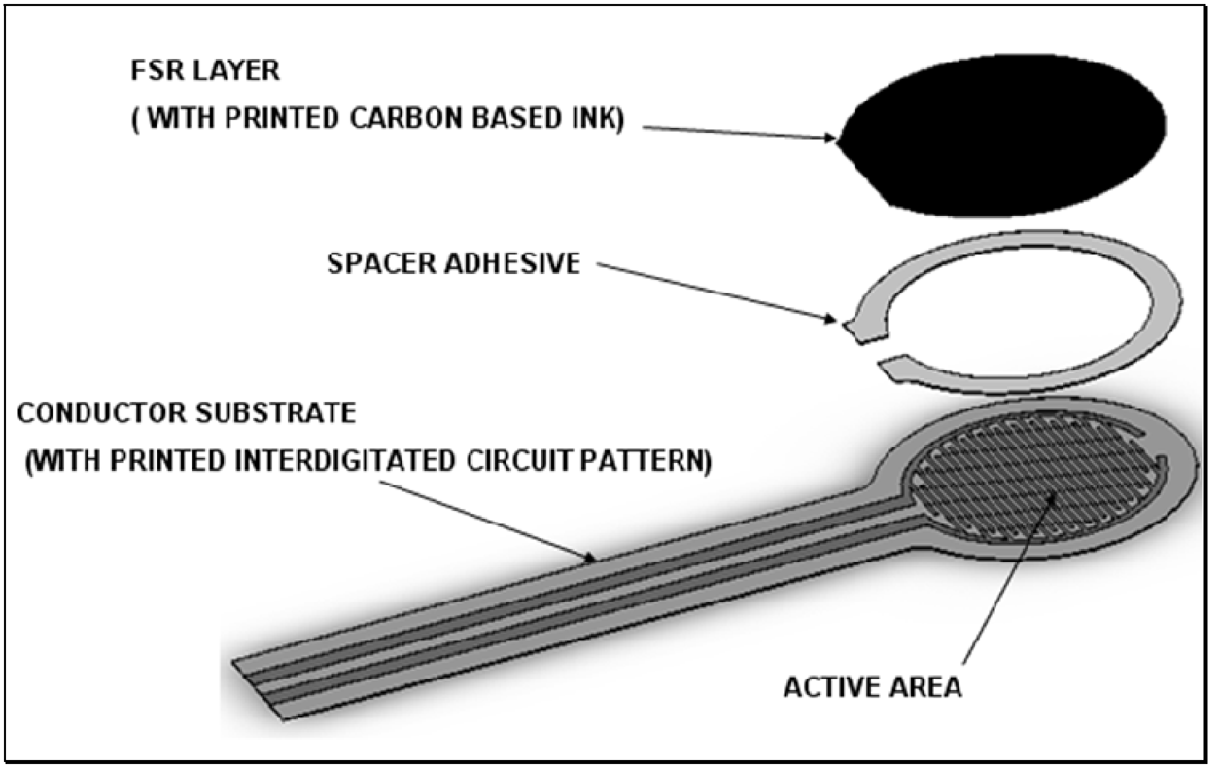


**Figure 2.2**: Different layers in an FSR (Interlink Electronics, 2009).

Although these sensors have all these advantages, they also have some disadvantages, such as low precision, and they get damaged if pressure is applied for a longer period of time, or the sensor surface becomes flexed. For example, many sensors had to be replaced after considerable experimentation because their expected life was reached quicker than anticipated because of the large amount of pressure applied to them. The contour of the sensors on the knees was also suspected as a cause of the premature failure of the sensors.

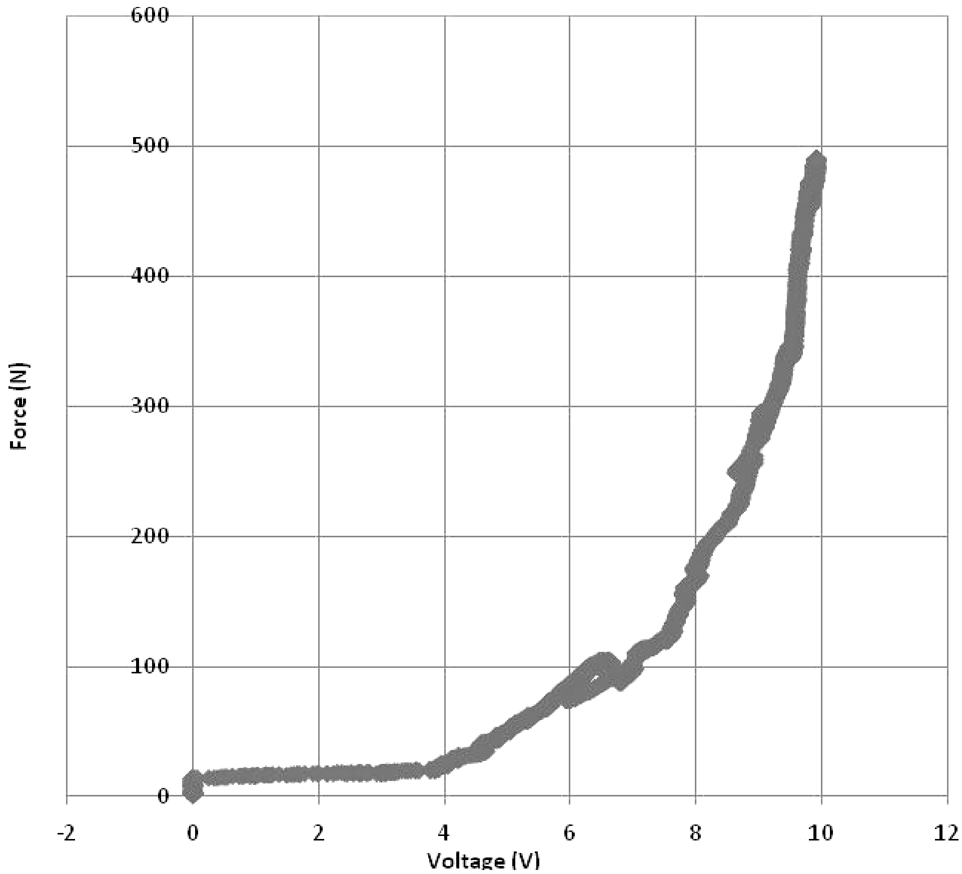


**Figure 2.3**: A typical voltage versus force characteristic curve.

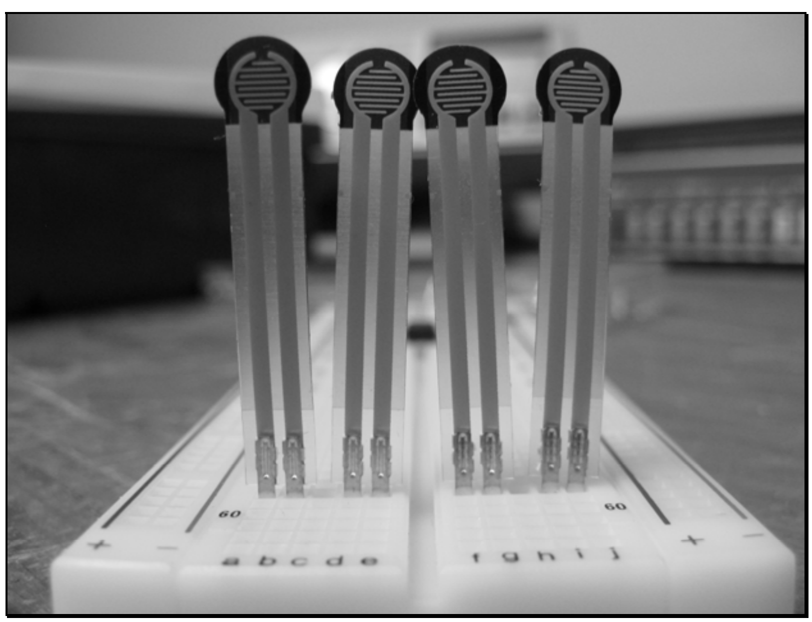

**Figure 2.4**: Force Sensing Resistors (FSRs) used in this study

#### 2.2.1.1.1 Making of Sensor and Circuitry

A custom made array of eight FSRs was designed for each knee. Five FSRs were placed on the periphery of the patella, two on the center of the patella and the other sensor was placed on the tibial tubercle of the knee. The configuration of their placement was chosen based on research that described the average size of the patella of a human being and also from Moore et al. (2009), where the author concluded that most of the pressure is applied on the patellar tendon and tibial tubercle during the kneeling process. The placement of the FSRs is shown in Figure 2.5 and the average dimensions of the patella are shown in Figure 2.6.

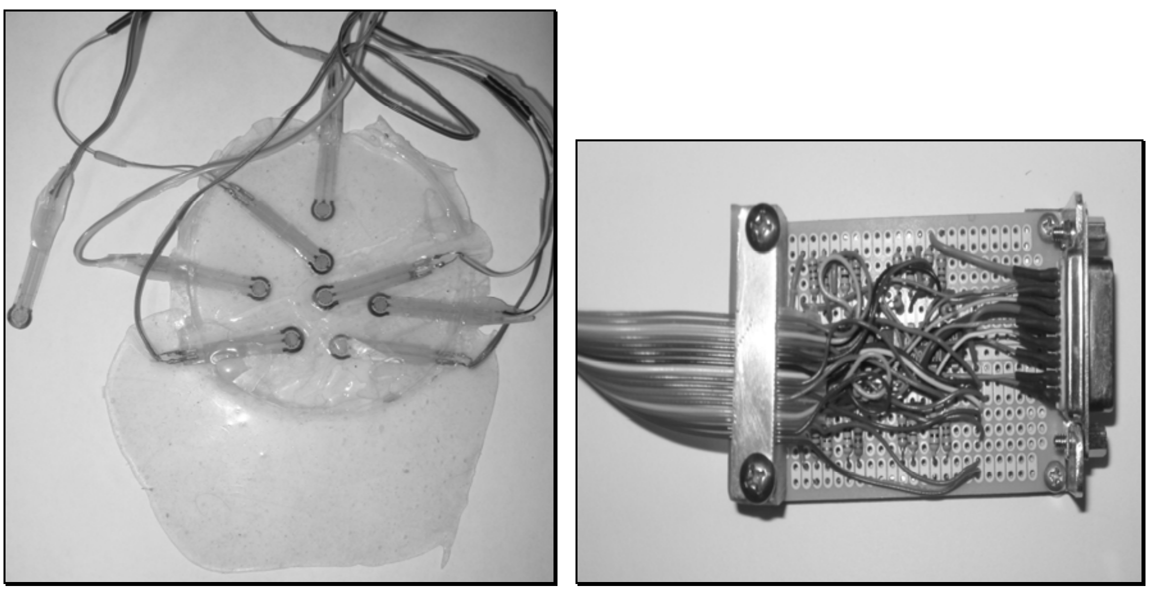

**Figure 2.5**: The FSR layout on the sensor along with the circuit board.

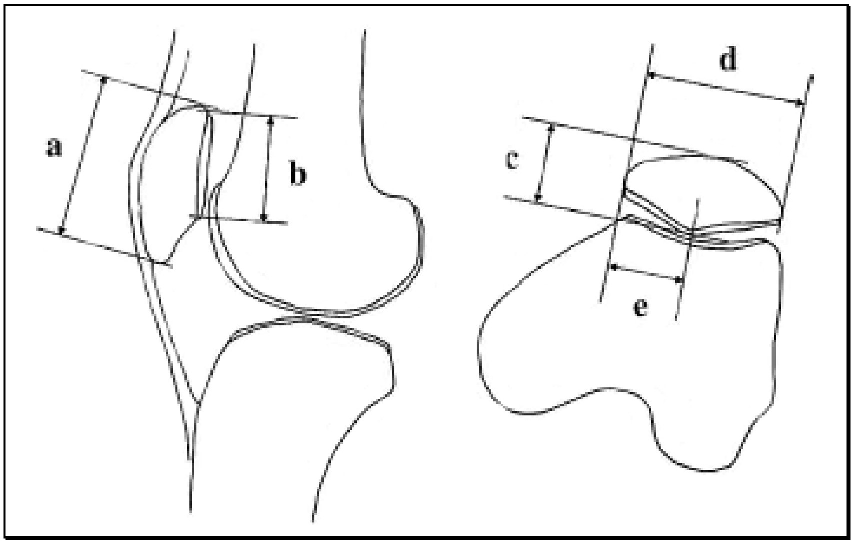


**Figure 2.6**: Average patella dimensions as given in paper by Yoo et al., (2007). Where Whole longitudinal length a = 44.6 mm, Longitudinal length of articulating surface b = 32.9 mm, Thickness c = 22.3 mm, Width d = 45.8 mm, Distance from medial edge of patella e = 19.9 mm.

In order to avoid movement of the FSRs with respect to each other and to avoid excessive loading, a silicon rubber or Dragon Skin™ was used to encase the FSRs in the desired configuration. The FSRs were placed at required locations and the Dragon Skin was poured in a mold and allowed to cure. The thickness of the Dragon Skin was maintained as thin as possible so that it did not affect the sensitivity of the FSRs. A picture of the cured dragon skin with the FSRs is shown in Figure 2.5.

Once the sensors were laid and ready to be used, the circuit for the sensors to record the output voltage from the FSRs was created. The circuit design was adopted from example circuits given in the FSR guide book (Interlink Electronics, 2009). A basic voltage divider circuit was used and the output voltage was amplified twice in order to increase the difference in the output voltage obtained for a given load. As observed from the voltage versus force characteristic curve, the FSRs tend to exhibit a more linear behavior at higher forces; hence by amplifying the voltages outputs, the higher forces have a larger difference in voltage output hence maintaining the distinction in voltage output for different forces. Though the amplification of 3 and 4 were also conducted, they could not be used as the output voltage often exceeded 10V. The A/D board used to convert the analog voltage to a digital signal could not exceed 10V. The basic circuit used for a single FSR is as shown in Figure 2.7.

In order to have eight FSRs on each knee, two op-amps, LM324, were used on a small chip board along with the required resistors. Two 15-pin cables, as discussed earlier, were used to transfer the output from each sensor to the power source unit/transfer box. A 25-pin cable was then used to transfer the outputs from two sensors to the computer.

#### 2.2.1.1.2 Calibration

Calibration is the process of converting the electrical output to an actual engineering unit such as Pounds or Newton's. As the output from the FSRs is in terms of

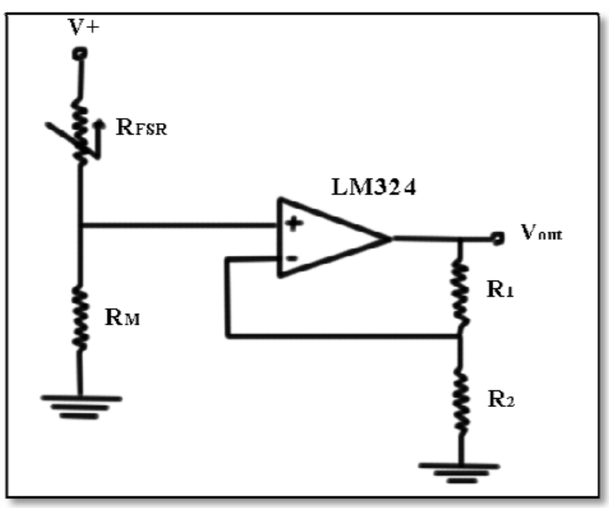


**Figure 2.7**: The basic circuit for a single FSR

voltage, this needs to be converted to force or pressure in order to interpret the stresses on the knee. The whole sensor was placed on a force plate and a force dynamometer (Chatilon) was used to apply force on each FSR. The force applied from the dynamometer was increased from zero to about 100 lbs. The higher limit was placed because from the experiments conducted on the FSRs, it was seen that they were saturating at about 100 lbs for the same thickness of the dragon skin. The voltage output data from the FSRs and the force data from force plate were collected and a relation between force and voltage was obtained. The same procedure was followed for each and every FSR and a calibration equation for each FSR was determined. Though the same FSRs were used in different locations of the sensor, each needed to be calibrated separately because of their difference in sensitivity from manufacturing, which would magnify because of the amplification of the output voltage. Also, sometimes the thickness of the dragon skin changed from one FSR to another, changing its sensitivity. The equations obtained from the force and voltage data calibration procedure were used in calculating the stresses on the knee during kneeling work.

#### 2.2.1.1.3 Troubles with FSRs

- The most common problem with these sensors was that they needed to be calibrated if any small change was made to the thickness of the dragon skin, either to change the position of the FSR or because of replacement.
- The FSRs had to be changed after many trials as they reached their life cycle early. The FSRs had a lower load bearing range than expected and hence when loaded with almost the whole weight of the body, and kneeling on them for hours at a time changed their sensitivity and eventually led to failure.

- Breaking of the FSRs at the soldered connections was another major problem. When the sensor was put on the knee with the help of knee brace sometimes the load was applied on the metal leads of the FSR and led to breaking.
- The orientation of the FSR was in different directions which put a strain on the FSRs and the wire connecting them, hence accelerating the process of breaking when wearing the sensor on the knee.

These problems led to inaccurate results. Also, some of the above problems were hard to detect if a single FSR was damaged. The results obtained from the tests were plotted in the form of graphs as the summation of all the FSR forces, and it was difficult to look at each FSR every time the sensor was used, which made the problem hard to find. Also, some of these sensors failed at the time of data collection and forced us to look for different force sensors which were able to take larger loads and were more reliable than the FSRs and this led us to the Generation II sensors.

#### 2.2.1.2 Generation II Sensor

The Generation II Sensors were FlexiForce Sensors (FFS), and were developed by Tekscan Inc. They are ultra thin and are used in measuring both static and dynamic forces up to 1000 lbf. The FFS used resistive based technology. The FFS followed the same principle of inverse proportionality with force as the FSRs. The FFS acted as a variable resistor in an electrical circuit. When the FFS was unloaded, its resistance was very high, greater than 5 MΩ. An increase in force decreases the resistance of the FFS. The FFS were constructed with two layers of flexible substrate on the outside. This substrate was composed of polyester film. A conductive material (silver) was applied on the two layers of the substrate and pressure sensitive link layers were placed on the sensitive end of the sensor. An adhesive was then used to laminate the two layers of substrate together to form the FFS. Silver extended from the sensing area to the connectors at the end of the FFS, forming the conductive leads. The active sensing area was 0.375 inches in diameter. Different layers in the FFS are as shown in Figure 2.8.

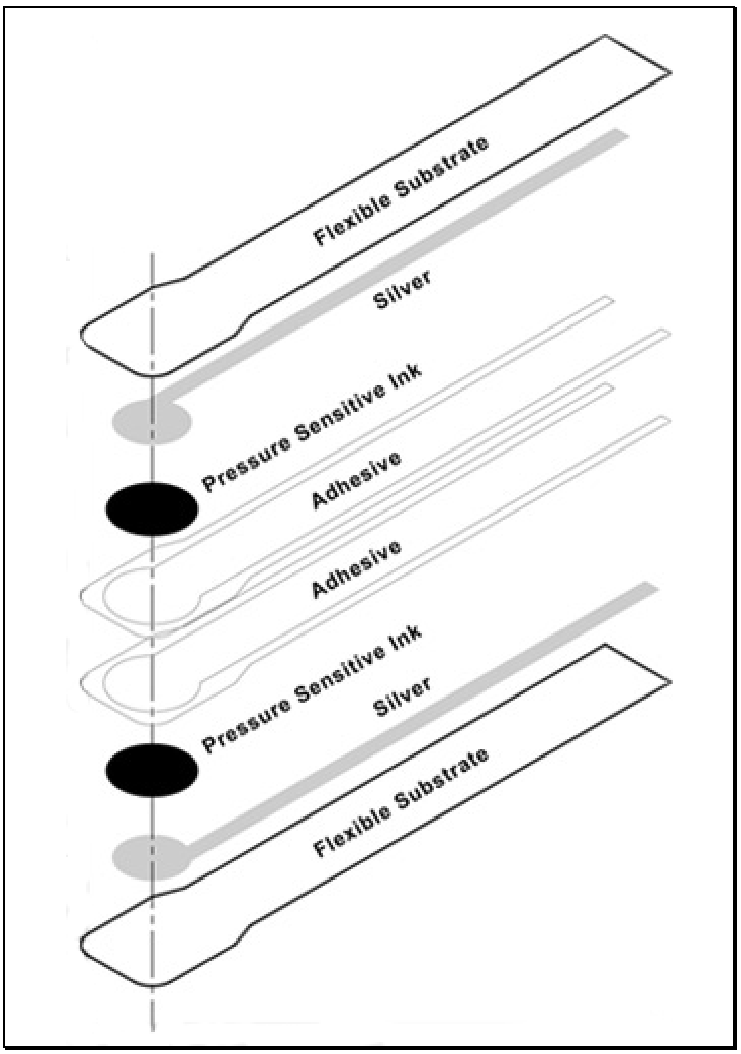


**Figure 2.8**: Different layers in a FlexiForce Sensor (Tekscan, 2010).

#### 2.2.1.2.1 Making of Sensor and Circuitry

The FFS (Figure 2.9) comes in different tail lengths. Four-inch and eight-inch sensors were used in this case. The 4-inch sensors were used at the top of the layout and the 8-inch were used at the bottom of the layout. The FFS were laid out like the layout in the Generation I sensors. But the only change was that all the FFS were placed in a way such that all the male connectors from the sensors came out at the top of the sensor. This was done in order to avoid the breaking of the FFS at the connectors, which was the case in the Generation I sensors. The placement of the FFS is as shown in Figure 2.10.

Initially dragon skin was used to avoid the movement of the FFS with respect to each other, to avoid flexing and also to avoid excessive loading. But the output voltage from the sensor decreased drastically with the kneepads.

Also, because of the higher force range of these sensors than that of the FSRs, the FFS were directly placed on the knee with the help of two-way adhesive stickers. Small

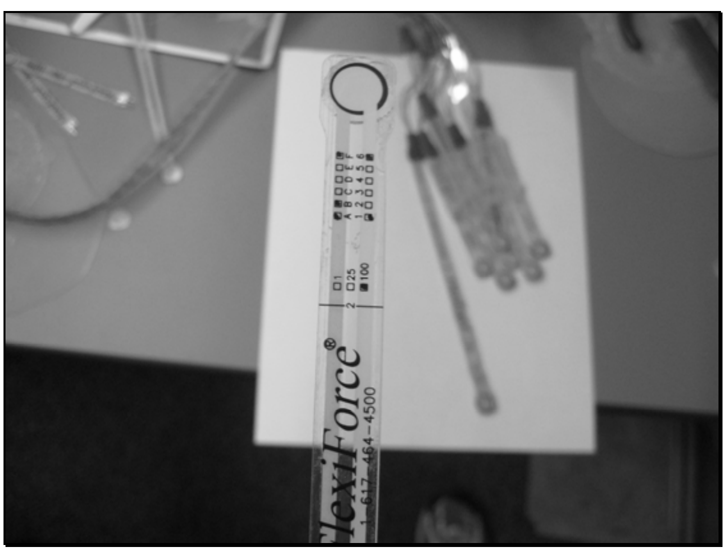

**Figure 2.9**: A FlexiForce sensor used in this study.

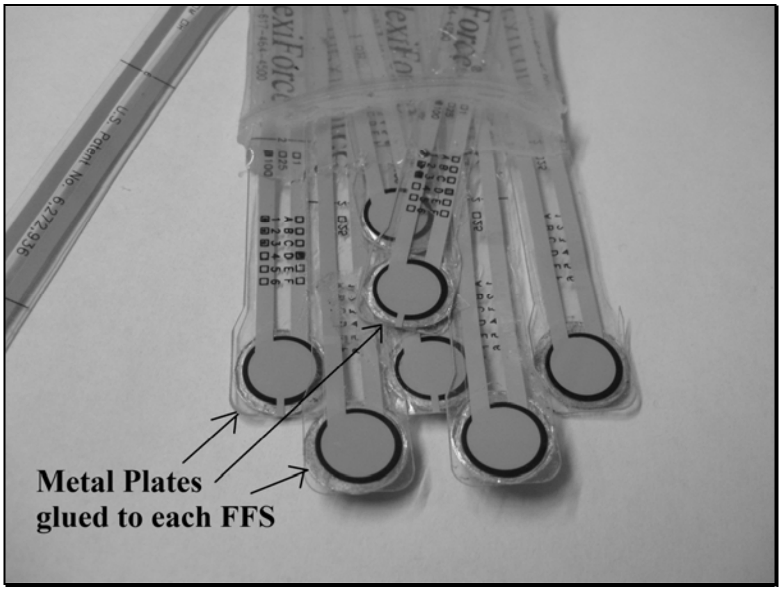


**Figure 2.10**: The FlexiForce sensor's layout.

metal plates of little thickness were glued to the sensitive area to avoid the flexing of the FFS. The layout of the FFS on the knee was the same as the layout of the FSRs. The layout of the FFS with the glued metal plates is shown in Figure 2.10.

The circuit used for the Generation II sensors was the same voltage divider circuit used for the Generation I sensors. Although the amplification used in the Generation I sensors was not used, instead the voltage supply to the circuit and the op-amp was increased to 12 V. The same op-amp LM324 was used. The basic circuit used for a single FFS is as shown in Figure 2.11. The circuit consists of a drive voltage $V_T$, FFS resistance $R_{FLEXIFORCE}$ and fixed resistance $R_D$ of 100 kΩ. The output voltage can be calculated using

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$$V_{out} = (R_D/(R_D + R_{FLEXIFORCE})) * V_T$$

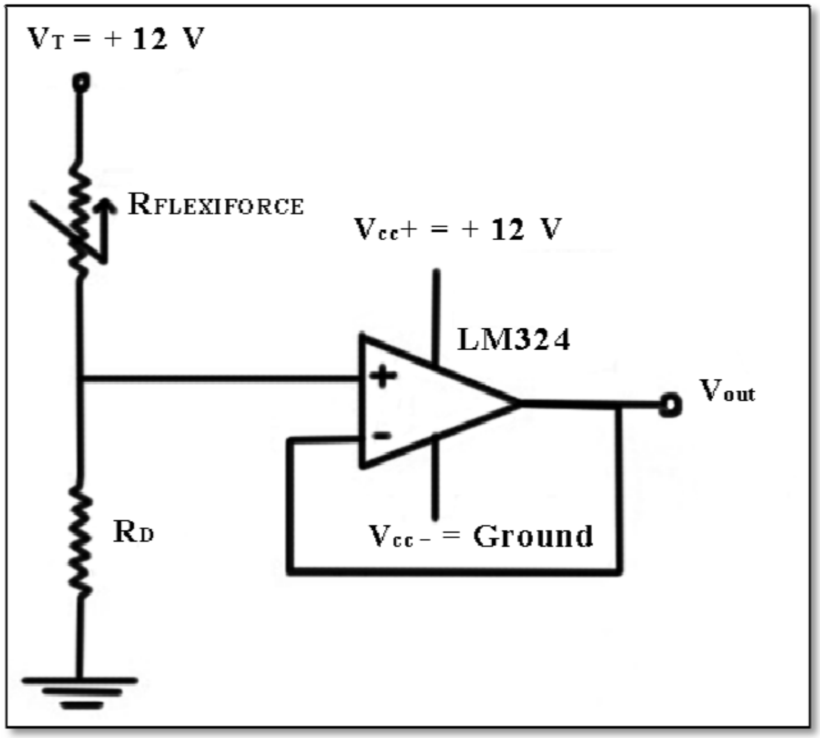


**Figure 2.11**: The basic circuit for a single FSR

The sensitivity of the sensor can be changed by changing both the drive voltage and/or the fixed resistance. A higher force range is obtained with a lower fixed resistance and/or drive voltage and vice versa. The fixed resistance can be varied from 1 kΩ to 100 kΩ. In order to determine the required resistance, the drive voltage was maintained constant at 12V and the FFS were tested with different resistors in the given range. After testing the circuit with different resistance, the optimum resistance was determined to be 100 kΩ. Also, the output voltage was taken into consideration in determining the reference resistance because of the limitation on the A/D board, which was 10V.

The wiring from the FFS to the circuit, from the circuit to the power box unit, and from the power box to the A/D convertor, remained the same. A complete picture of the connection used for the sensor is shown in Figure 2.1.

#### 2.2.1.2.2 Calibration

The voltage output obtained from the FFS was directly recorded in the Vicon Motus software. A dynamometer as used for the Generation I sensors was used in applying the force on each FFS, with the FFS on the force plate. The force was increased from zero to a force of about 100 lbs and then back to zero. Though the FFS were capable of measuring higher forces than 100 lbs, they were limited because of the maximum force that could be applied by the researcher. The voltage output data from the FFS and the force data from the force plate were collected and a relationship between force and voltage was obtained. The same procedure was followed for each and every FFS and an equation for each FFS was formed. A fifth-order polynomial was fit to each curve. Like the graphs obtained from the Generation I sensors, the Generation II sensors followed almost the same relation between the force and the voltage output. A typical calibration graph for the Generation II sensors is as shown in Figure 2.12.

These equations obtained from the force and voltage data were used in calculating the stresses on the knee during kneeling work.

#### 2.2.1.2.3 Troubles with FFS

There was a lot of noise in the voltage output obtained from the FFS when compared to the Generation I sensors. Aside from this there were not many troubles as seen with the Generation I sensors.

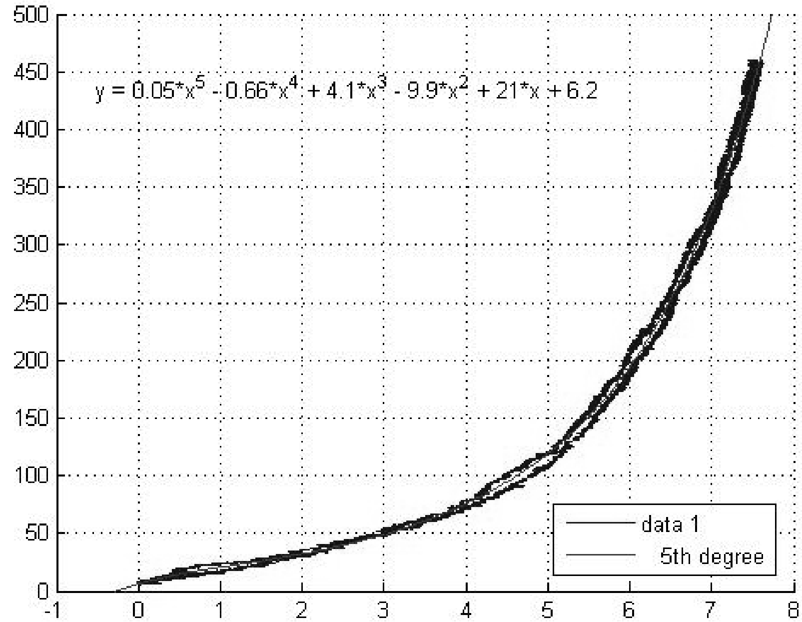


**Figure 2.12**: Sensor response graph for force versus voltage along with the calibration equation for one of the FFS.

### 2.2.2 Force Plate Data

Force plates are measuring instruments that measure the ground reaction generated by the body positioned on it or moving over it. Generally force plates can be used for biomechanics, engineering, medical research, orthopedics, rehabilitation evaluation, prosthetics, and general industrial uses. The force plates used in this study, AMTI OR6-5 and AMTI OR6-7, use strain gauges to measure the forces applied. The force plates measure the three orthogonal force components along the X, Y, and Z axes, and the moments about the three axes, producing a total of six outputs. It is also capable of measuring the point of application of the force, center of pressure, and its direction which is obtained from the applied force and moment's component in all the axes. The force plate uses a right handed coordinate system with the positive Z axis oriented downwards and the positive Y axis oriented away from the connector.

Two force plates were used in this study. They were placed next to each other so that both the plates were oriented in the same way. The participants were asked to kneel on the force plates with each of their knees on each plate. The force plates were oriented such that the participant would be facing in the positive Y axis direction of the force plates. Two foot sensors were placed behind the force plate such that each foot was comfortably placed at the center of the foot sensor. The foot sensors accounted for the forces lost from the foot which would be used in a different study. The foot sensors data were not used in this study. This arrangement can be seen in Figure 2.13. The force plates were calibrated before their use. The force data obtained from the force plates were used as a redundant measure to compare the force data obtained from the sensors with the actual applied force to the knees. The force data, which were in the form of voltage output obtained from the force plate, were transferred to the computer with the help of a transfer cable and an A/D board. Vicon Motus software is used in data acquisition from the force plate, as well as from the sensors.

### 2.2.3 Force Data Acquisition

Data from both the sensors and the force plate were recorded with the help of Peak Motus software developed by the Vicon Motion systems. Vicon Motus software is 3D, 2D or analog-only data collection software used in analyzing biomechanics of the body by video recording and data from the force plates. The data collected from the force plate were in the form of voltage that was converted to force by a calibration matrix present in the software. The data from the sensor were collected in the form of voltage

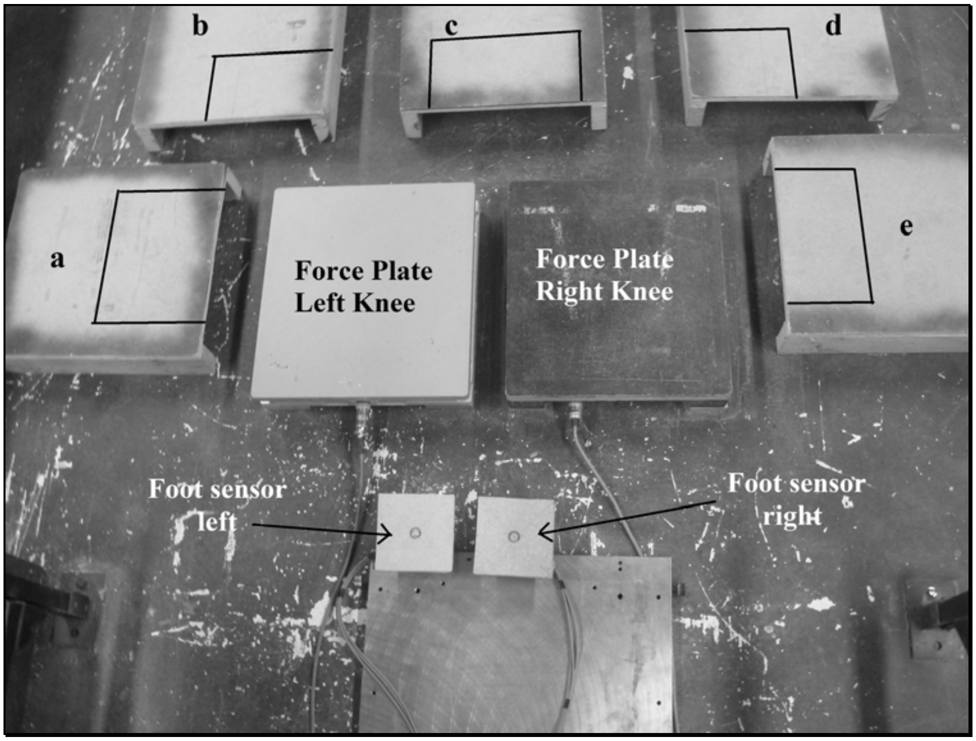


**Figure 2.13**: Placement of the force plates along with the foot sensors.

but the calibration equations were used outside the software to convert them into force data. This software was capable of collecting both video as well as analog data, but for this study the software was only used for collecting the analog data and a different system was used to collect the 3D video data in the form of markers. This software has many tools which can be used to evaluate the collected data in the form of graph plots. It is also capable of calculating the center of pressure on the force plate from the data obtained from the forces and moments in all the three coordinate axes. This software was set to collect data at 1000 Hz. The data collected were exported into an Excel file for further analysis. The foot sensor data were collected using Labview software at the same frequency.

## 2.3 Motion Data

Although the motion data were not directly analyzed in this study, a brief discussion is given. The motion data for each participant were collected with the help of reflective markers placed at different body segments of the participants. In order to collect the motion data, an 18 camera OptiTrack Motion system developed by NaturalPoint Company was used. The cameras were connected to the computer and recorded motion data with the help of Arena Motion Capture software. A 36 marker set was used to recognize and build a digital model of the participants. Before the camera system could be used it needed to be calibrated. The calibration was performed using a three-point wand. The wand was waved in the workspace to create a capture volume. Once there were enough samples collected by each camera, the results were calculated and the Arena software let the user know whether the results were good enough to be used. The ground plane was set such that the positive Z axis aligned with the positive Y axis of the force plates. The ground plane was set such that the ground was level with the force plate. Later the calibration was tested by performing some basic maneuvers in the workspace. The motion data obtained from the Arena software will later be used in a different project for calculating the muscle forces in the knee joint. The Arena system was used for triggering all the data collection systems: Arena, Peak Motus and Labview and syncing them.

Once all systems were checked for proper operation, the force data collected were used in accomplishing one of the major goals of the project, which was recording the contact forces for different kneepads.

## 2.4 Kneepads

Kneepads are considered personal protective equipment (PPE) used on knees for protection against impact, injury, or to provide padding in case of extended kneeling. Kneepads are used in many industries by different workmen for protection of their knees. Apart from them, kneepads are also used in different sports and recreational activities. Different types of kneepads are used depending on the environment in which they need to be used and also depending on the user preference. In this study, five different kneepads (Figure 2.14) were selected to represent differences in their design and materials. The five kneepads used in this study are discussed in the following sections.

### 2.4.1 Ultra Light Kneepad

This kneepad was made up of thick molded foam for maximum comfort and protection of the knee. An adjustable elastic strap with Velcro was used to tighten the kneepads to the knee. The kneepad was made so that one size fits all. These kneepads were used in work environments in which it was important to protect the work surface.

### 2.4.2 Rubber Nonskid Kneepad

This kneepad was made up of foam padding on the interior side for the knee and tough and light weight fabric covering the outside. The cap was shaped in the form of a groove in order to avoid the thread abrasion. A double strap was used to fasten the kneepad on the knee. These kneepads were designed to be used on delicate flooring; the linings on the cap prevent it from slipping.

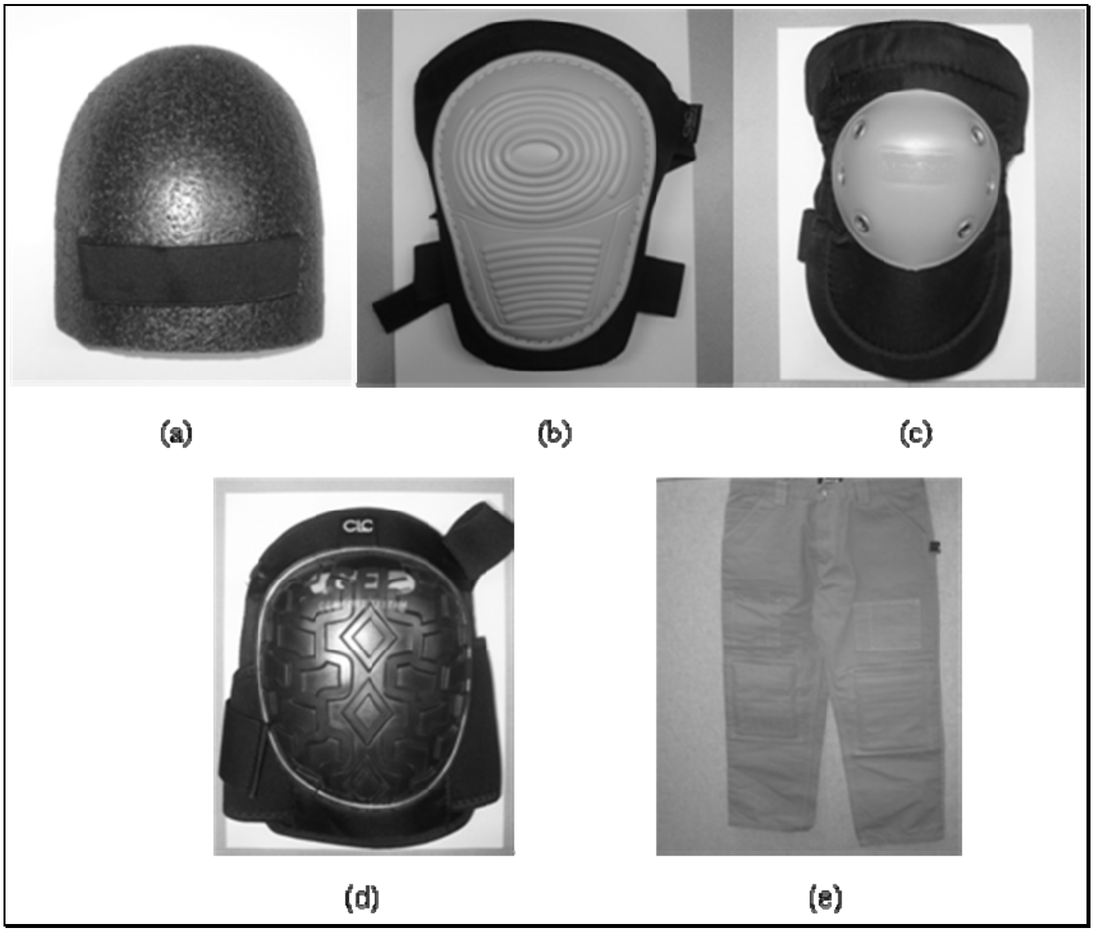


**Figure 2.14**: Different kneepads used in this study (a) Ultra light kneepad (b) Rubber Nonskid kneepad (c) Hard Cap kneepad (d) Professional Gel kneepad (e) Armor Pant kneepad.

### 2.4.3 Hard Cap Kneepad

This kneepad was made up of thick foam on the internal side with some extension onto the tibial tubercle; the outer side was made up of a hard plastic cap that was shaped in the form of a kneecap. A double strap was used to fasten the kneepad onto the knee. These kneepads were good for longer duration kneeling and mostly used for carpentry, masonry, floor covering and all household maintenance.

### 2.4.4 Professional Gel Kneepad

This kneepad had an oversized cap on the outer side to increase the area of protection and a gel filled center for maximum cushioning. Also, ¾-inch foam was placed for increased comfort. It was considered comfortable for extended periods of kneeling. A double strapped fastening was used for added stability.

### 2.4.5 Armor Pant Kneepad

These kneepads were not like the typical kneepads seen so far. This kneepad was flat and rectangular in shape and was made up of foam. A pant with built in knee pockets was used, where the kneepads can be easily inserted. Enough space was provided for inserting a second set of kneepads for added comfort. These kneepads relieved the worker from the usual stress applied by the straps of the other kneepads. These were often used by painters. In this study both the one-pad and two-pad conditions were taken into consideration.

## 2.5 Experimental Procedure

This section discusses the whole process of the data collection starting from the recruitment process to the point of completing the kneeling tasks including the arrangement of the instruments discussed in the earlier sections.

### 2.5.1 Recruitment

A flyer was posted in the Merrill Engineering Building in order to recruit participants in the study. The study population was comprised of healthy males between the ages of 22 and 54. This age group represents the typical worker population performing kneeling and crouching jobs. Interested participants were brought into the laboratory and interviewed to ensure enrollment requirements were met. The participants were informed about the nature and duration of the tasks being performed, possible risks, and possible benefits to be incurred from the study. The participants willing to participate under the conditions explained were given a copy of the informed consent form to be approved or signed. After a signed consent form, the participant was considered as an actual study participant. The participant was also given the option of withdrawing from the study at any point if the participant felt uncomfortable or unwilling to continue.

### 2.5.2 Instrumentation Setup

The force plates were placed so that each knee could be placed on a single force plate. The foot sensors were place behind each force plate. The foot sensors also acted as a surface providing support to the foot while kneeling. The force plates were connected to the computer by means of a wire to an A/D board. Five small wooden platforms were positioned at different locations surrounding the force plates to simulate different postures being adopted by the workers while performing a kneeling task. In this study the small wooden platforms were placed in the following locations:

a) Left Side

b) Left Front Corner

c) Front Middle

d) Right Front Corner

e) Right Side

This layout was illustrated in Figure 2.13. A stacked set of tiles were provided to simulate the work environment in a kneeling task. The participant had to place the tiles on the small wooden platforms in order to complete their task. A trigger was used in order to mark events. An event was defined as the start from neutral position (Figure 2.15) to picking up a tile then placing it and then coming back to neutral position.

Before the kneeling tasks began, the measurements of body segment dimensions and body weight of each participant was taken. Reflective markers were placed at each of the following locations: head, back, shoulder, elbow, wrist, hand, hip, knee, ankle, and toe. A standard 36-marker set used by Arena motion capture system was followed in placing the markers at the locations on the body. After the markers were placed the sensors were placed on each knee of the participant. But in order to place the sensors, markings were made on the kneecap so as to maintain the same position on the knee for different tasks and also to create reference or visual points.

A paper written by Yoo et al., (2007) was used in measuring the average patella size of human beings. A vertical line was drawn dividing the kneecap into two halves. Then, point marks were made such that the bottom two FFS were at the edge of the kneecap in a horizontal line, while the knee was in a 90˚ flexion, and were 10mm (lower points) from the central vertical line on either side. The other two points were marked parallel to the first ones, 10mm from the lower points on the vertical towards the top. These two points (upper points) were 16mm apart from the vertical line on either side. The same process was followed for the other knee. The sensor was then placed on the knee such that the FFS match the marked points on the knee. The placement of the sensor on the knee with markers is illustrated in Figure 2.16.

**Figure 2.15**: Neutral position adopted while placing the tiles.

The FFS that was not on the sensor was stuck to the tibial tubercle. In order to avoid the movement of the sensor on the knee while performing kneeling tasks, a two-way adhesive sticker was applied to each sensor.

Once the participant was ready with all the markers and force sensors, he was asked to step into the workspace and stand with his arms stretched and facing the positive Z axis. This is referred to as a T-pose. Recording a T-pose was critical in calibrating the participant specific marker set and for the accuracy of the motion tracking sessions.

The participant was asked to stand in the T-pose for several seconds and then asked to perform some basic movements. These movements were used later to check the calibration. Once the recording was completed, the height and shoulder width of the participant was entered into Arena. A reliable frame was selected from the recording in order to fit the standard skeleton in the software.

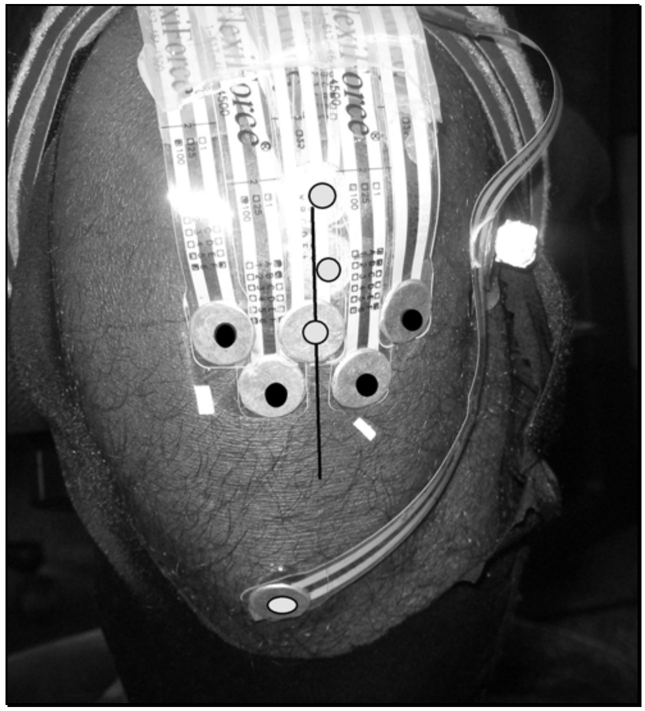

**Figure 2.16**: The dark circles on the sensors showcase where the points are marked on the knee to place the sensors and the lighter circles represent the other sensors.

Once a fit was found, the recording was played through the time line to verify the movement of the skeleton with the movement of the marker set on the participant. If any discrepancy was found, the T-pose was recorded again and the same process was followed until there were no discrepancies. The placement of the sensors on the knee was checked before the participant went into kneeling posture. This is important because the sensors might have moved while taking the T-pose and any movement of the sensor might have led to erroneous data.

### 2.5.3 Data Collection

The participant was then asked to sit in a kneeling posture with the knee at 90˚ flexion and each knee on a single force plate. The feet were placed on the foot sensors, which measure the force at the foot. The foot sensors also acted as a support for the feet while performing kneeling tasks. In order to simulate kneeling tasks, a stack of five tiles were placed in front of the participant to be placed on five small wooden platforms placed around the participant. The small platforms were named with letters from ‘a’ to ‘e’, starting from left to right. The tiles were also named with the same letters and were arranged in random order for each kneepad so that there would be no sequential effects on the results obtained from the study. The participant was then asked to place the tile within a limit line on the small platforms so that we had control over the reach of the participants. Every time the participant started at neutral position and then picked up the tile placed at the required location and then came back to neutral position. Once the participant reached a neutral position the trigger was pressed in order to record an event. The same process was followed for the placement of the five tiles totaling six trigger events. Later the trigger events were used in extracting just the data between the events in order to compare the location forces for different kneepads for all the participants.

The participants were first asked to complete the kneeling task without any kneepads and then with different kneepads in randomized order for each participant. The task without the kneepad served as the control. The task of the participant would be to match the tile with the platforms and place the tiles within the limit line on each platform. Three trials were conducted for each kneepad, including without kneepad. The participants were asked to perform the task with six kneepads. Each time the kneepad was changed the sensors on the knee were checked for any movement and adjusted before wearing a new kneepad.

The questionnaire consisted of questions regarding the rating on each kneepad. The task of completing the placement of five tiles took about 35 seconds, which was the duration of data collection. Later the data were divided into five sections, corresponding to the locations on the floor and any data outside the regions were not used for analysis. A program was written in Matlab in order perform the extraction and cutting of data at the trigger points. The motion data were collected using the Arena motion capture software and the force plate and sensor data were collected using Vicon Motus software. An external pulsating sync was set in the Arena software to sync the motion, force and foot data together. The same process was followed for each participant and the data collected were stored. The data collected were stored under a name representing the participant number, kneepad and the trial number.

## 2.6 Data Processing

All the saved data files in Vicon Motus software were exported into Excel files. Each file consisted of the sensor as well as force data for the whole trial collection phase lasting 35 seconds. Once all the files for the participants were exported and saved, they were later converted from voltage to force data using the calibration equation obtained earlier.

The next step was to extract the force data between two trigger events and save them in their respective location files. For example the placing of the tile on the wooden platform ‘a’ was saved into a file representing the location ‘a’. Each location had a file for each knee totaling 10 files, 5 for the left knee and 5 for the right knee. Later the data were normalized to bring all the participant’s data onto the same scale for further analysis

(100% cycle). All the conversion and extraction process was performed with different Matlab programs written to obtain the above mentioned results.

## 2.7 Statistical Analysis

Once all the required data were processed and exported into excel files, statistical analyses were performed on the data set to compare different kneepads. JMP v9.0 (SAS Institute) was used in performing statistical analyses. Descriptive and inferential statistics were performed on the data obtained from the questionnaire whereas Univariate and Multivarite analysis of variance models were run on the force data. Also some statistical techniques like Tukey's method for post-hoc comparisons were employed during the analysis process.

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# 3. RESULTS

This chapter presents the results obtained from the questionnaire, the sensors, and the force plates. The data stored in the Vicon Peak Motus were extracted into excel files. Each excel file consisted of the force plate data, the sensor data and also the trigger event data.

## 3.1 Questionnaire Results

The questionnaire data obtained from the participants was analyzed for descriptive and inferential statistics in order to establish any relationship between different variables in the questionnaire, which are discussed further in the following sections.

### 3.1.1 Participant Demographics

Eleven male participants (average age of 30.45 years and a Standard Deviation (SD) of 9.52 years) participated in the study. The age of the participants ranged from 22 years to 54 years. The average weight and height of the participants was 154.63 lbs and 174 cm with a *SD* of 18.91 lbs and 5.87 cm, respectively. The sample size used for the questionnaire results varied from the sample size used in the laboratory study. The sample size of the lab study was reduced to 9 because of a modification of study protocol and sensor design after the first 2 participants, but this did not affect the results from the questionnaire. Most of the participants in the study were students from the University of

Utah and had 0-1 years experience in work where kneeling was required. Only 2 participants worked more than 5 years but less than 10 years where kneeling was required. The average time spent kneeling while working each day was less than 0.5 hrs for all participants.

### 3.1.2 Statistical Analysis

According to the analysis about 45.46% of the sample population experience some form of knee pain while kneeling and out of them 60% gave a pain rating of 5 or greater on a scale of 10, where 0 represented no pain and 10 being the worst pain imaginable. The severity scale of pain for each kneepad is shown in Figure 3.1. And the percentages for the rating for each kneepad are summarized in Table 3.1.

From Table 3.1 it can be established that kneeling without kneepad was rated very painful by 70% of the participants. Within the kneepads, Hard Cap kneepad was given a higher rating for being painful with a rating of 27.3% and Professional Gel kneepads had the highest rating of 54.5% reporting no pain.

The comfort ratings for each kneepad for all the participants were plotted in a bar plot and then fitted to a normally distributed curve. The distributions for Ultra Light, Rubber Nonskid and Hard Cap were normal distribution and the distribution for Armor Pant and Professional Gel were a little skewed. This can be seen in Figure 3.2.

The ratings for each kneepad were on a scale of 1 to 10, with 1 being the least comfort and 10 being the highest comfort while performing kneeling tasks. The ratings obtained are summarized in Table 3.2.

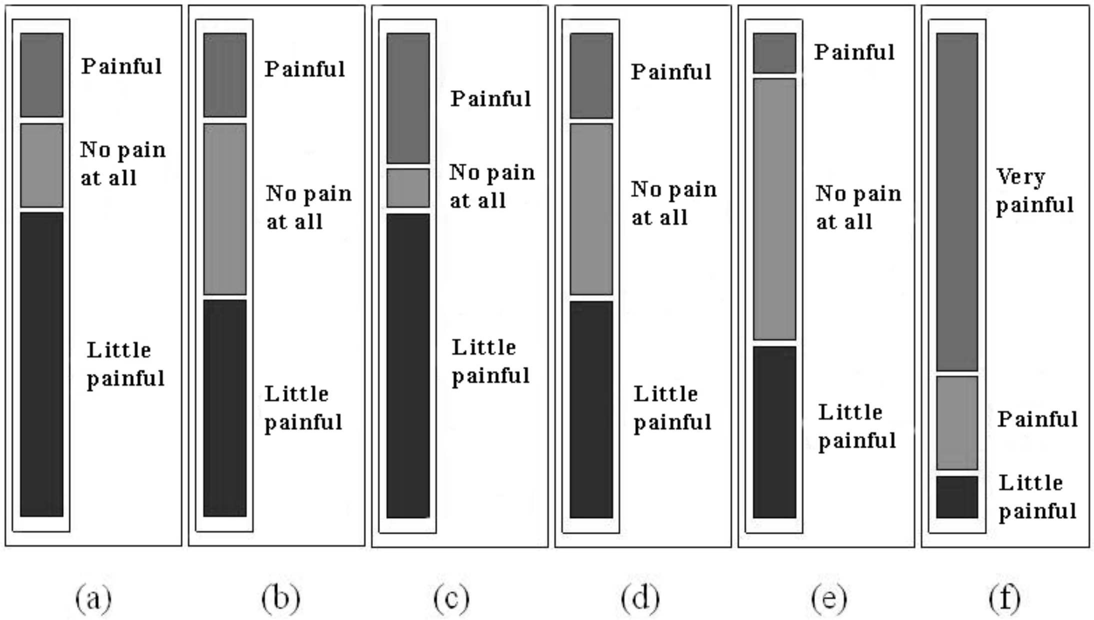


**Figure 3.1**: Severity rating of knee pain for each kneepad (a) Ultra Light (b) Rubber Nonskid (c) Hard Cap (d) Armor Pant (e) Professional Gel (f) Without Kneepad.

**Table 3.1**. Percentages of ratings for pain for each kneepad

| Pain Rating | Kneepads | | | | | |
|---|---|---|---|---|---|---|
| | Ultra Light | Rubber Nonskid | Hard Cap | Armor Pant | Professional Gel | Without Kneepad |
| Unbearably Painful | - | - | - | - | - | - |
| Very Painful | - | - | - | - | - | 70% |
| Painful | 18.2% | 18.2% | 27.3% | 18.2% | 9.1% | 20% |
| Little Painful | 63.6% | 45.5% | 63.6% | 45.5% | 36.4% | 10% |
| No Pain at all | 18.2% | 36.4% | 9.1% | 36.4% | 54.5% | - |

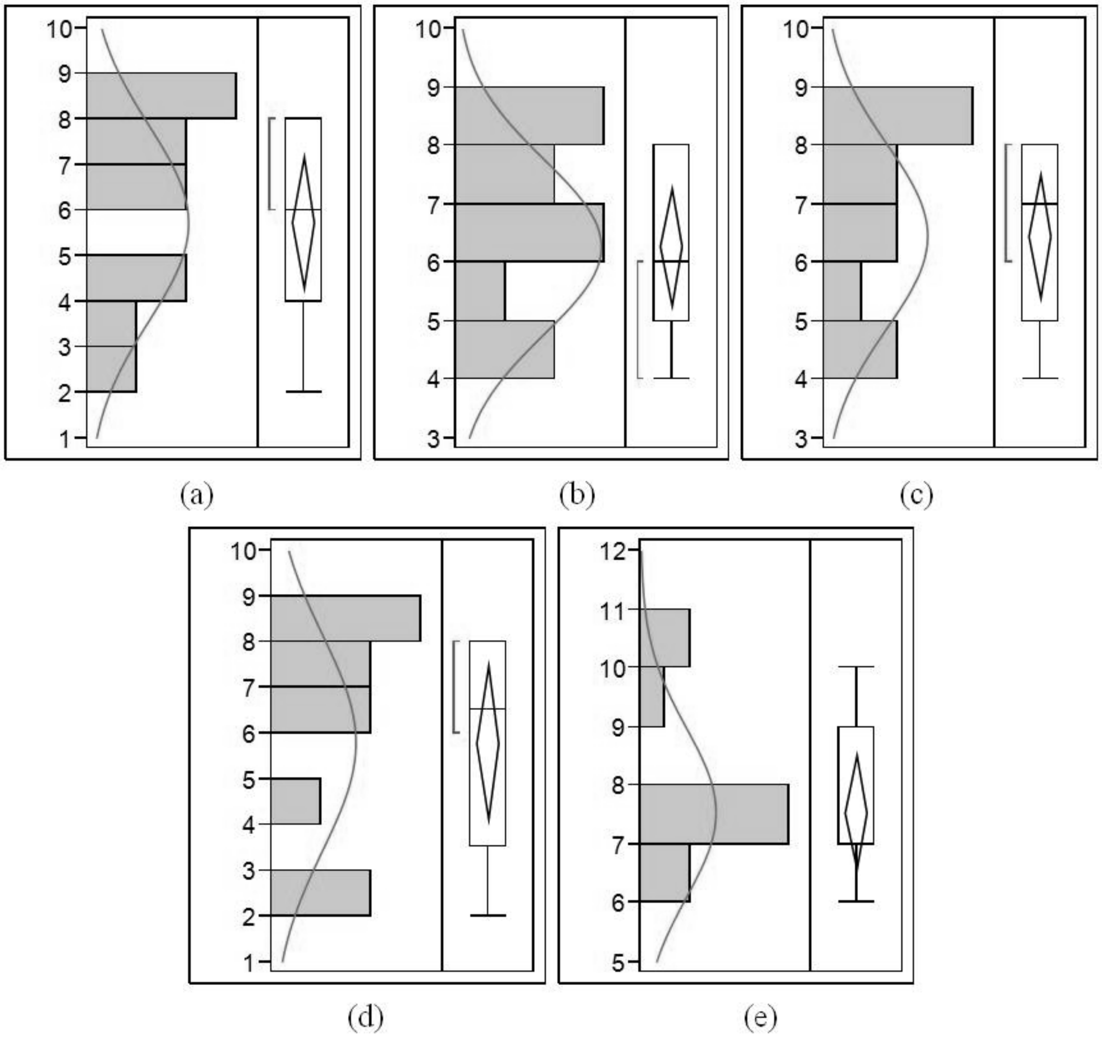


**Figure 3.2**: Comfort ratings of each kneepad for all the participants with a normal distribution curves (a) Ultra Light (b) Rubber Nonskid (c) Hard Cap (d) Armor Pant (e) Professional Gel.

It can be observed that The Professional Gel kneepad was the only kneepad to get a rating of 10 from some of the participants. It had the highest overall mean rating of 7.55 which was 24.1% higher rating than the lowest mean which was for the Ultra Light kneepad.

Although there were questions asked regarding the rating of the fit of the kneepads, both while kneeling and also while not kneeling, the participants rated all the

**Table 3.2**. Participant Comfort rating statistics for all the Kneepads.

| | Ultra Light | Rubber Nonskid | Hard Cap | Armor | Professional Gel |
|---|---|---|---|---|---|
| Min | 2 | 4 | 4 | 2 | 6 |
| Max | 8 | 8 | 8 | 8 | 10 |
| Mean | 5.73 | 6.27 | 6.46 | 5.80 | 7.55 |
| Range | 6 | 4 | 4 | 6 | 4 |
| SD | 2.15 | 1.49 | 1.57 | 2.35 | 1.44 |

kneepads similarly and hence a significant conclusion for the better kneepad in terms of fit could not be established. The Professional Gel kneepad was chosen as the most liked kneepad among the kneepads used for this study.

It was chosen by 55% of the population. The other kneepads which were modestly rated are the Rubber Nonskid, Ultra Light and Armor Pants Figure 3.3.

When asked the question if there was a difference in knee comfort with floor location, 72.7% of the sample population responded to the question, out of which 50% said that the locations ‘a’ and ‘e’ were uncomfortable whereas 37.5% said the locations ‘b’ and ‘d’ were uncomfortable and 12.5% said the location ‘e’ was uncomfortable. Location ‘e’ was rated as the most strenuous location on the knee to complete kneeling tasks with a mean rating of 6.5 on a scale of 1 to 10, 1 being least strenuous and10 being

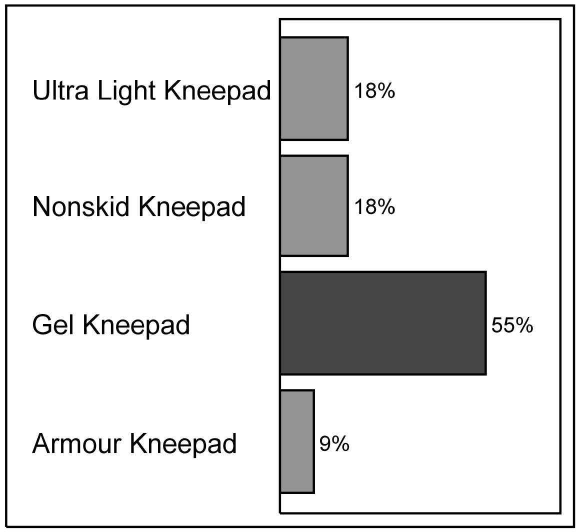


**Figure 3.3**: Participant rating of the most liked kneepad.

very strenuous. The next strenuous location was 'd' with a mean rating of 6.2 followed by location 'a' with 6.1 then 'b' with 5.8 and lastly 'c' with 3.8. When asked the effect of location on the whole body, location 'd' had a mean rating of 6.1 whereas the least was location 'c' with a rating of 4.7. The participant rating of the knee comfort and location is shown in Figure 3.4.

## 3.2 Sensor Results

The voltage output obtained from each FFS was converted to force in Newtons using the derived calibration equations discussed earlier. The force calculated was the summation of all the FFS except for the FFS at the tibial tubercle. All the conversion and the calculation of the forces were done using Matlab software. The data obtained were divided in the form of locations. Hence each trial on a kneepad was split into two groups of five files representing the five locations which are 'a', 'b', 'c', 'd' and 'e' for the left and right knee, respectively.

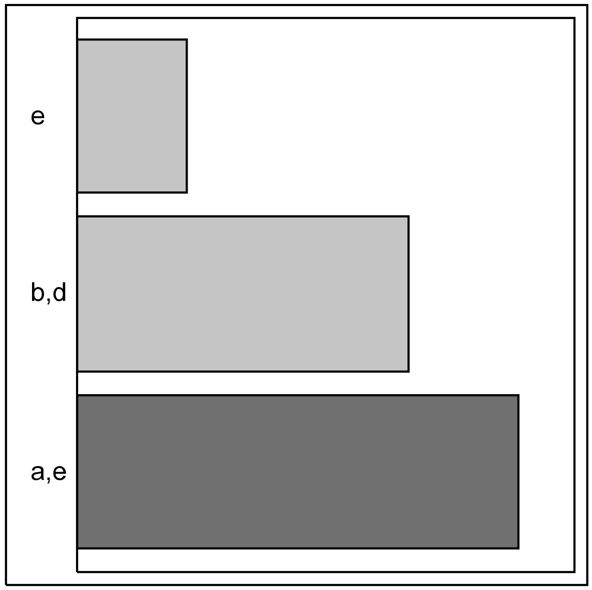


**Figure 3.4**: Participant rating of the knee comfort and location.

### 3.2.1 Sensor Versus Force Plate

Figure 3.5 shows the comparison of the force data obtained from both the sensor and the force plate for one of the trials without any kneepad for the left knee. The upper light colored line is the force plate readings, the lower darker line is the sensor readings and the vertical lines are the trigger events discussed in Section 2.5.2. Both the force plate and the sensor reading were collected over a time period of 35 seconds (time of data collection). The first vertical line represents the start of tile placing from neutral posture and the second vertical line represents the end of a task placing a tile at location ‘a’ and start of tile placing for location ‘c’ and so on. It can be seen that the sensor force data are less than the force data from the force plate. The reason for the difference will be discussed in the Section 4.1. But it can be seen from Figure 3.5 that the sensor force data followed the profile of the force plate data very well.

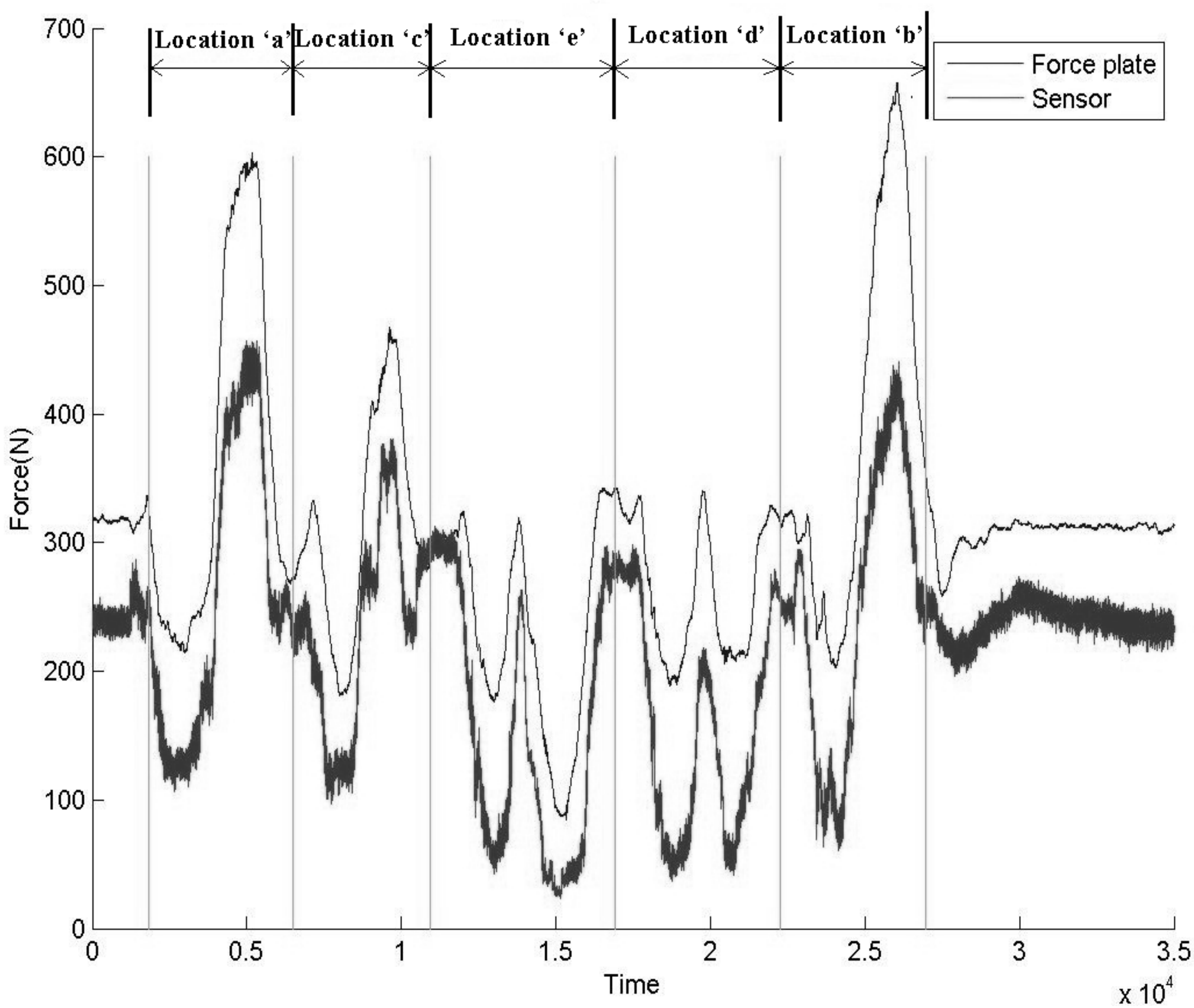


**Figure 3.5**: Sensor data versus Force plate data for without kneepad condition.

Although the peak force reached by the sensor changed from one participant to the other because of the weight of the participant, for the most part the sensor data followed the profile of the force plate data.

The sensor data obtained for kneepads were less than the sensor data obtained for the case without kneepad which was expected, but the force plate data remained almost the same even with the kneepads, as expected. This is because the force plate measures the force being applied on the plate rather than the measure of force at the interface between the knee and the kneepad by the sensors. Also, because of the cushioning on the kneepads, the sensitivity of the FFS may have been reduced.

### 3.2.2 Sensor Force Comparison for Different Kneepads

As the force plate data were not that useful in comparison of the sensor data with kneepads, the sensor data obtained for the kneepads were compared to the case without kneepad. As the time cycles varied from one kneepad to the other depending on the speed at which the placing of the tiles was completed, the comparison had to be done for the normalized data for each location of the participant.  Figure 3.6 shows one of the trials comparison of the force data for different kneepads and without kneepad for the location ‘c’ for the left knee. The curves represent the start from neutral position picking up the tile placing it at location ‘c’ and then coming back to the neutral position. The noise in the curves is because of the normalization of the curves by time for each kneepad.

### 3.2.3 Statistical Analysis of Sensor Data

The normalized sensor data files were used for statistical analysis to compare all participants across all trials, representing 100% cycle for each location. ANOVA, Tukey’s method for multiple comparisons and some multivariate analyses were used in order to verify any significance in relationships between different variables of the study.

Before any statistical analysis was performed on the dataset, the Peak force for each participant for each kneepad for each location for each knee was calculated for all three trials. Once the Peak forces were calculated for all the conditions, the same process was done for calculating the Average force and also the area under the curve giving the impulse force (N/time).

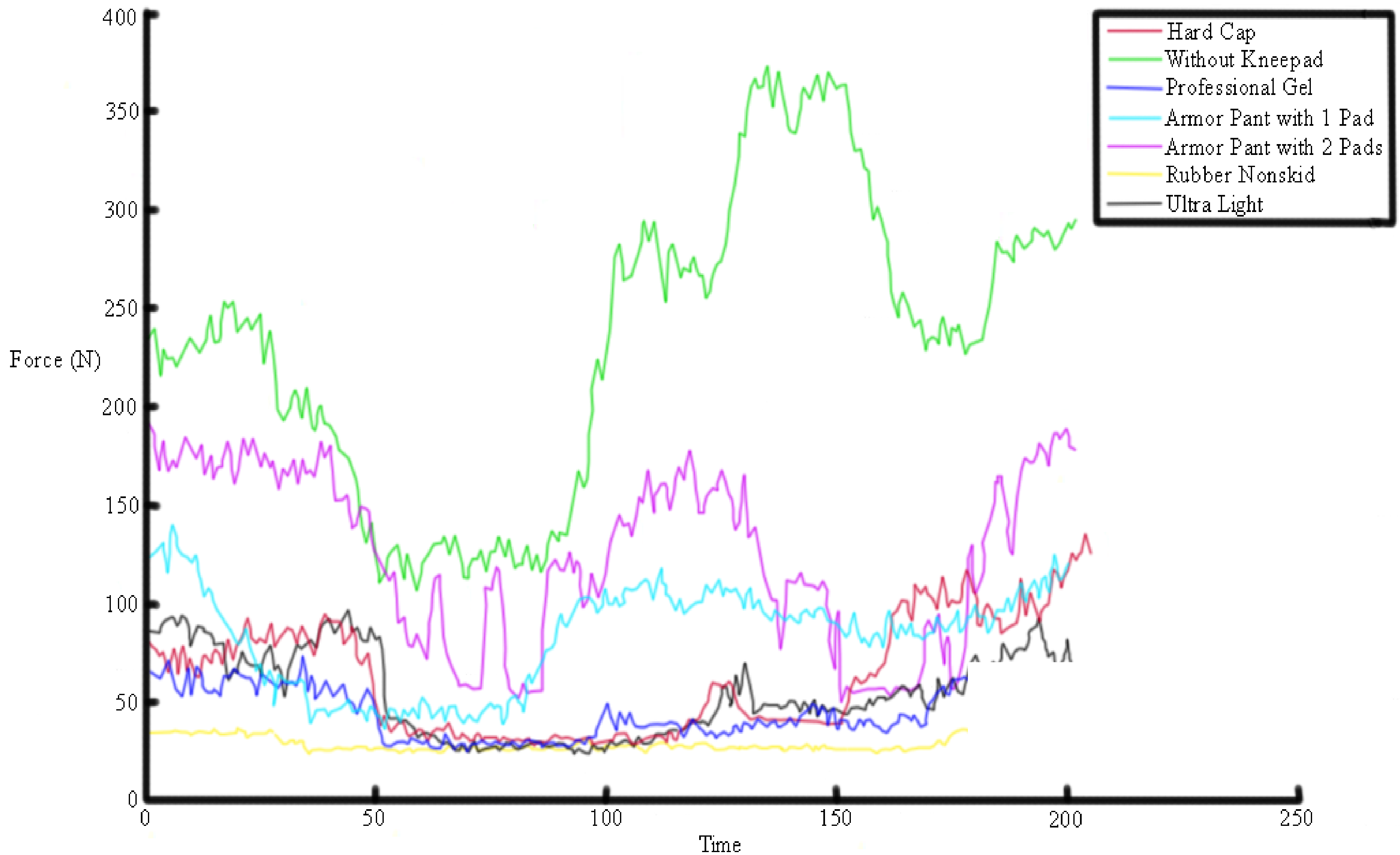


**Figure 3.6**: Sensor force comparison of different kneepads and without kneepad for the location ‘c’.

Once all the columns were populated, the mean of all the trials were taken for Peak, Average forces and also for the Area. The mean values were used in analyzing the data set.

In order to compare all the kneepads in the study, the main data used were the mean Peak force, mean Average force and the mean Area and all these were to be compared for each location for each kneepad. Later the same data were used to verify if the locations used in the study had any influence on the Peak, Average and Area. The following sections present the results from these analyses.

#### 3.2.3.1 Effect of Kneepads

The factors considered in this section are the kneepads and the response for the mean Peak, Average forces and the mean Area. A simple One-way ANOVA for each of the response data by kneepads was conducted starting with the mean Peak force.

##### 3.2.3.1.1 One-way Analysis of Mean Peak by Kneepad

The ANOVA analysis of the Mean Peak by kneepads gave the variance values as shown in Table 3.3. The *p*-value obtained was less than 0.001 indicating that there is a significant relationship between the two factors, Mean Peak forces and the kneepad. The box plot relationship is shown in Figure 3.7.

The comparison of means for all kneepads was prepared using Tukey-Kramer HSD method. The means obtained are summarized in Table 3.4. It can be seen that the kneepads were set in four groups depending on the Mean Peak values giving the order in which the kneepads have reduced the Mean Peak values.

**Table 3.3**. Analysis of variance for Mean Peak by kneepads

| Source | DF | Sum of Squares | Mean Square | F Ratio | Prob > F |
|---|---|---|---|---|---|
| Kneepad | 6 | 2319963 | 386660 | 53.4 | **< .0001** |
| Error | 603 | 4366883.3 | 7242 | | |
| C. Total | 609 | 6686846.3 | | | |

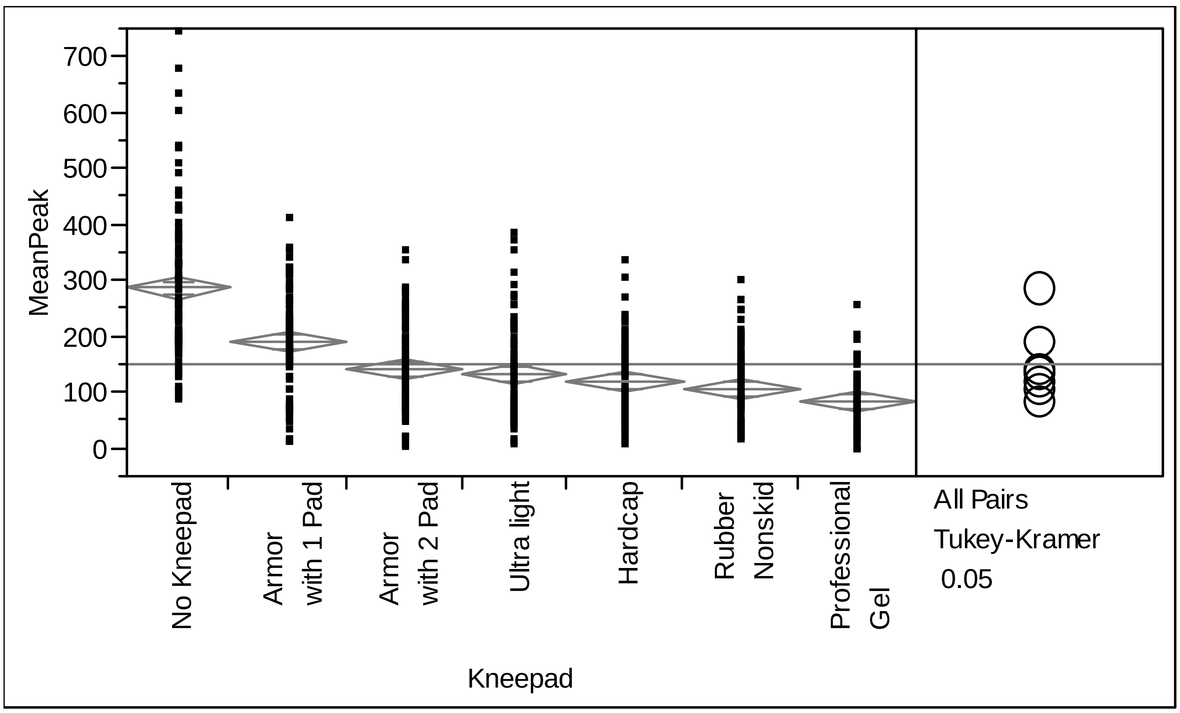


**Figure 3.7**: The box plot analysis of Mean Peak by kneepad along with the Tukey-Kramer comparison

**Table 3.4**. The grouping of kneepads depending on the Mean Peak forces; each letter represents a statistically different group ($p$<0.05).

| Kneepads | Groups | | | | Mean |
|---|---|---|---|---|---|
| No Kneepad | A | | | | 285.58 |
| Armor Pant with 1 Pad | | B | | | 189.90 |
| Armor Pant with 2 Pad | | | C | | 142.16 |
| Ultra Light | | | C | | 133.39 |
| Hard Cap | | | C | | 119.73 |
| Rubber Nonskid | | | C | D | 104.94 |
| Professional Gel | | | | D | 82.20 |

The Tukey-Kramer method also complements the results obtained from Oneway ANOVA analysis giving the same order in which the kneepads reduced the Mean Peak forces.

It can be seen that the means have reduced for all the kneepads when compared to the without kneepad condition. The reduction in Mean Peaks for all the kneepads in terms of percentages is shown in Table 3.5. The Professional Gel kneepad was the one with the highest % reduction in Mean Peak value when compared to other kneepads.

#### 3.2.3.1.2 One-way Analysis of Mean Average by Kneepad

The $p$-value obtained from the Mean Average force was 0.0001 and hence there was a significant relation between Mean Average and the Kneepads. The box plot relationship between Mean Average and kneepads along with the Tukey-Kramer comparison is shown in Figure 3.8. The box plot looks similar to the plot for the Mean

**Table 3.5**. Percentage reduction in Mean Peaks for all the kneepads.

| Kneepads | Mean Peak | % Reduction |
|---|---|---|
| Without Kneepad | 285.58 | Ref |
| Armor Pant with 1 pad | 189.90 | 33.50% |
| Armor Pant with 2 pads | 142.16 | 50.20% |
| Ultra Light | 133.39 | 53.30% |
| Hard Cap | 119.73 | 58.10% |
| Rubber Nonskid | 104.94 | 63.30% |
| Professional Gel | 82.20 | 71.20% |

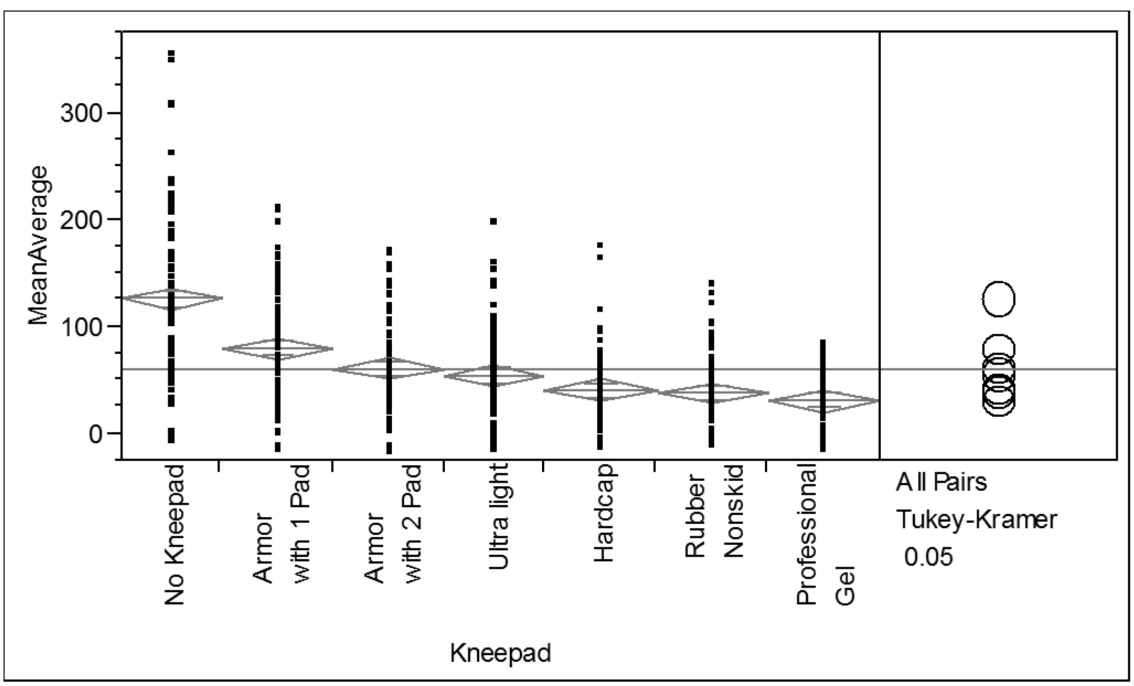


**Figure 3.8**: The box plot analysis of Mean Average by kneepad along with the Tukey-Kramer comparison.

Peaks except for a reduction in forces because of the averaging.

The reduction in Mean Average forces for all the kneepads in terms of percentages is shown in Table 3.6. The percentage reductions also follow the same trend as for Mean Peaks.

#### 3.2.3.1.3 One-way Analysis of Mean Area by Kneepad

Even in this case the *p*-value obtained was 0.0001 indicating a significant difference of cumulated force between kneepads. The box plot relationship between Mean Area and kneepads along with the Tukey-Kramer comparison is shown in Figure 3.9. The box plot looks similar to the plot for the Mean Peaks and Mean Averages except that the forces are in terms of area under the force curve.

**Table 3.6**. Percentage reduction in Mean Averages for all the kneepads

| Kneepads | Mean Average | % Reduction |
|---|---|---|
| Without Kneepad | 125.23 | Ref |
| Armor Pant with 1 pad | 78.88 | 37.00% |
| Armor Pant with 2 pads | 60.10 | 52.01% |
| Ultra Light | 53.70 | 57.12% |
| Hard Cap | 40.12 | 67.97% |
| Rubber Nonskid | 37.28 | 70.23% |
| Professional Gel | 30.06 | 77.99% |

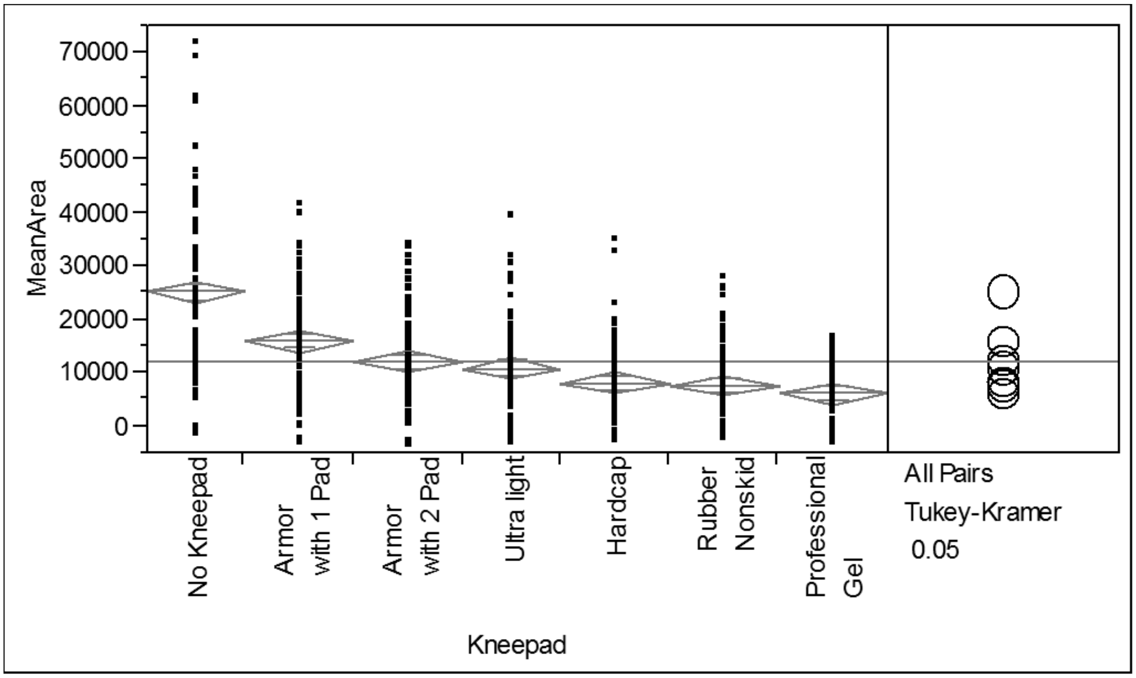


**Figure 3.9**: The box plot analysis of Mean Area by kneepad along with the Tukey-Kramer comparison.

The reduction in Mean Area for all the kneepads in terms of percentages is shown in Table 3.7. The percentage reductions also follow the same trend as for Mean Peaks and Averages.

It can be said from all three One-way analyses of the Mean Peak, Average and Area, that force is significantly modified by kneepads as measured as a percentage reduction in forces.

Ranking of the kneepads in term of force reduction:

1. Professional Gel Kneepads
2. Rubber Nonskid Kneepads
3. Hard Cap Kneepads
4. Ultra Light Kneepads
5. Armor Pant with 2 Pads

**Table 3.7**. Percentage reduction in Mean Area for all the kneepads

| Kneepads | Mean Area | % Reduction |
|---|---|---|
| Without Kneepad | 25002.3 | Ref |
| Armor Pant with 1 pad | 15751.5 | 36.99% |
| Armor Pant with 2 pads | 12020.2 | 51.92% |
| Ultra Light | 10739.3 | 57.05% |
| Hard Cap | 8013.1 | 67.95% |
| Rubber Nonskid | 7454.6 | 70.18% |
| Professional Gel | 6006 | 75.98% |

6. Armor Pant with 1 Pad

#### 3.2.3.2 Effect of Locations

From the questionnaire data it was seen that some locations were more uncomfortable than others. Hence the effect of location on all the forces needed to be verified. Oneway ANOVAs for Mean Peak, Mean Average and Mean Area were performed by location. The *p*-values obtained for all the three conditions are shown in Table 3.8. It can be seen that all three values have *p*-value greater than 0.05 and telling that there is no significant relation between all the three measures of stress (i.e., Mean Peak, Mean Average and Mean Area) by location. The box plot in Figure 3.10 shows this relationship.

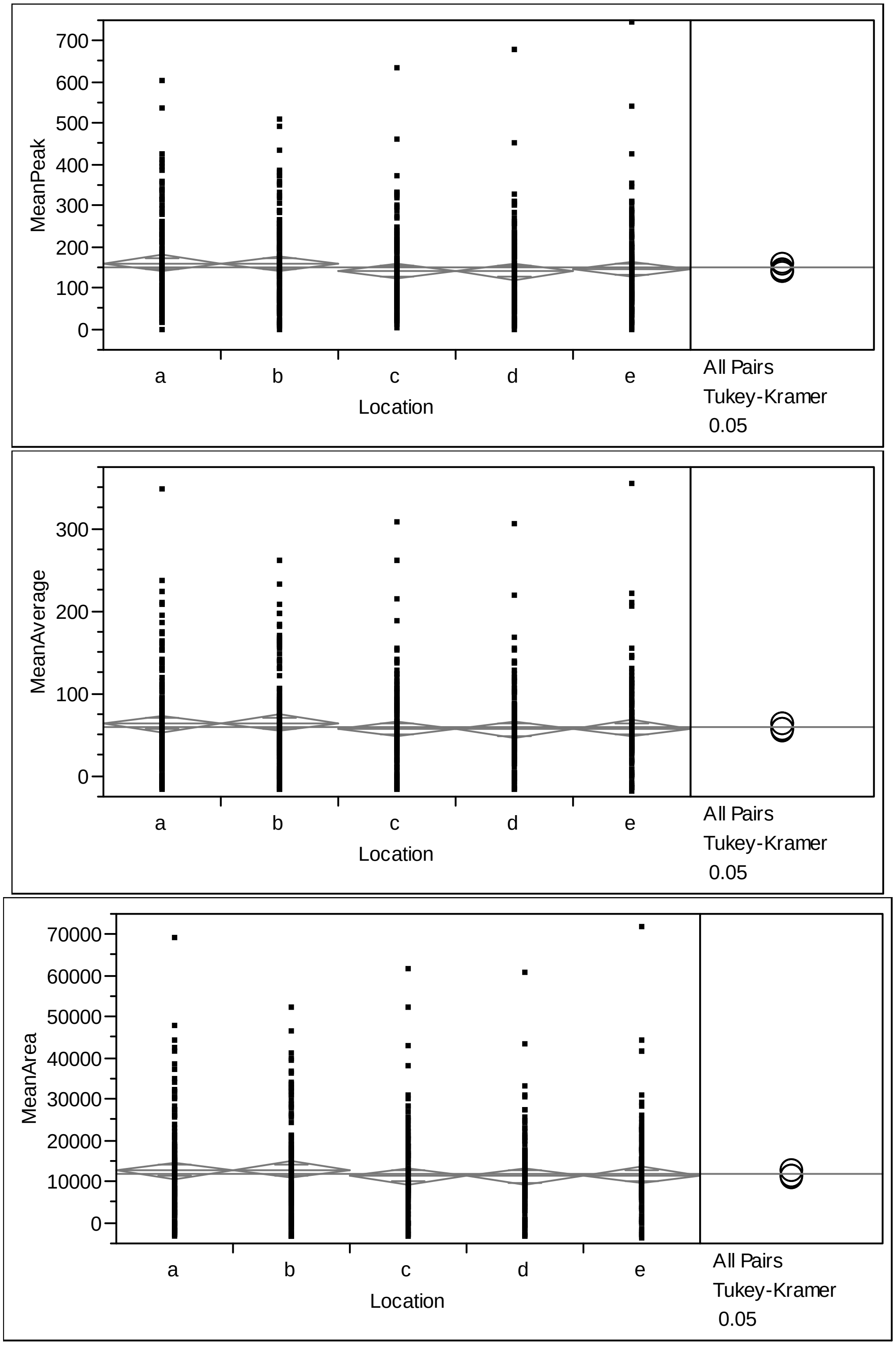


**Figure 3.10**: The box plot analysis of Mean Peak, Mean Average and Mean Area by location.

**Table 3.8**. *p*-values for all three kinds of forces

| Force | *p*-value |
|---|---|
| Mean Peak | 0.3109 |
| Mean Average | 0.6998 |
| Mean Area | 0.6907 |

Therefore the analysis was modified to see if there really was no relation between force and the placement location. Hence the same analysis was conducted but this time the force and the location were looked at by each knee to see if a significant relation between force and locations can be observed.

#### 3.2.3.2.1 One-way Analysis of Mean Peak by Location for Left Knee

The *p*-value obtained was significant with a value of 0.0191. Hence the location and Mean Peak force had a significant relation. The Mean Peak obtained for each location is summarized in Table 3.9. From the means for each location it can be seen that the locations 'a' and 'b' had a higher Mean Peak force values than other locations for the left knee. Though the significance was determined with ANOVA, Tukey-Kramer comparison was not significant to tell about which location had a significantly higher Peak force than the other. Hence all the locations were set into a single group. The box plot for Mean Peak by location for the left knee is shown in Figure 3.11.

Similar results were seen for the Mean Average and Mean Area. And like Mean Peak they were also significantly related to the location for the left knee.

**Table 3.9**. Mean Peak forces obtained by location for left knee

| Location | Mean Peak |
|---|---|
| a | 210.60 |
| b | 203.91 |
| e | 170.56 |
| d | 168.61 |
| c | 166.86 |

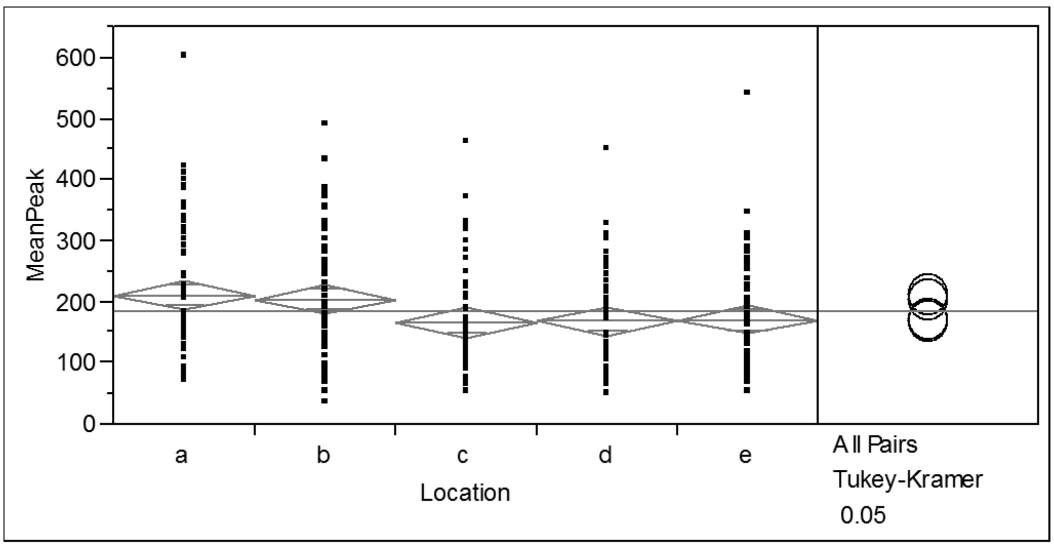


**Figure 3.11**: The box plot analysis of Mean Peak by location for left knee along with the Tukey-Kramer comparison.

**3.2.3.2.2 One-way Analysis of Mean Peak by Location for Right Knees**

The *p*-value obtained was 0.9723 hence the Mean Peak was not significantly related to location for the right knee. Even the mean values obtained for each location were very close to each other to articulate anything.

**3.2.3.2.3 One-way Analysis of Mean Average by Location for Right Knees**

Unlike the Mean Peak, the Mean Average force values were significantly related to location for right knee with a *p*-value of 0.0330. The mean values for each location are displayed in Table 3.10. It can be seen that the location 'd' and 'e' had the Mean Average forces significantly greater than other locations. The box plot for the Mean Average by location for the right knee is shown in Figure 3.12. The Tukey-Kramer comparison was not significant for the locations. Also a similar observation was made for oneway analysis of Mean Area with a *p*-value of 0.0311.

**Table 3.10**. Mean Average force obtained by locations for right knee

| Location | Mean Averages |
|---|---|
| e | 47.98 |
| d | 44.22 |
| c | 35.76 |
| b | 26.81 |
| a | 23.60 |

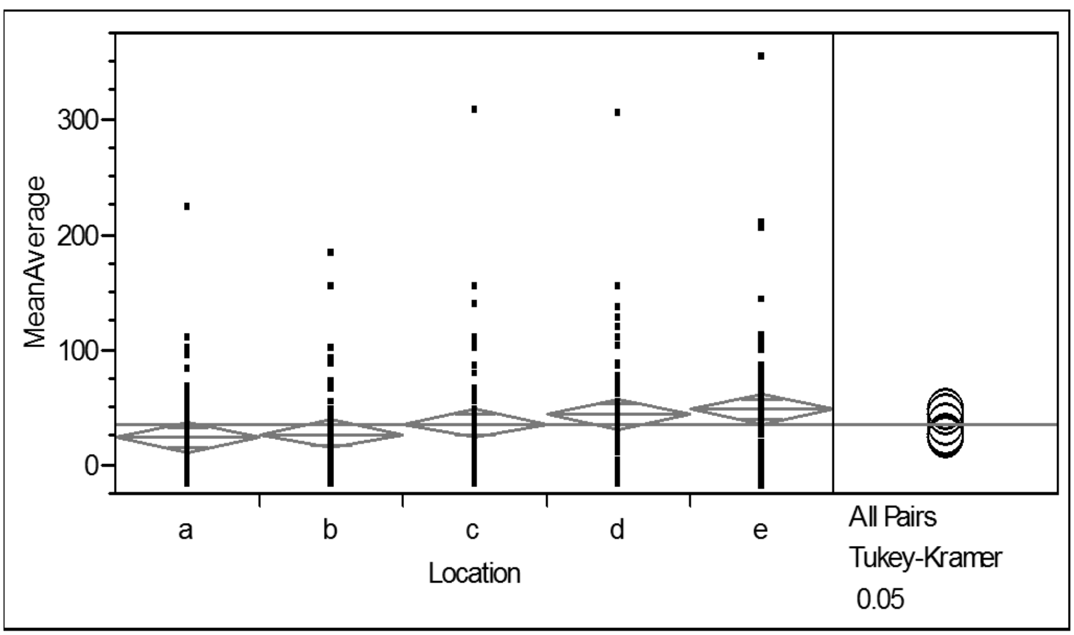


**Figure 3.12**: The box plot analysis of Mean Average by location for right knee along with the Tukey-Kramer comparison.

#### 3.2.3.3 **Kneepad Cost Analysis**

All the kneepads have shown a significant reduction in the force on the knee while in kneeling position. But the reduction in force should also be compared to the cost invested in the kneepad in achieving that reduction in force. For example two kneepads having percentage reduction in force of 50% and 55% and costing $ 30 and $ 50, respectively, it would be a considerably higher investment in obtaining an extra 5% reduction in force. Hence it would be dependent on the personal choice if a person would like to invest that extra cost in achieving that additional reduction. The cost and reduction in the force for each kneepad used in this study are tabulated in Table 3.11. Also the cost for 1% reduction in force for each kneepad was calculated to make the cost comparison easier.

It may be expected that the cost and reduction in force would follow a linear relationship but this was not observed in this study.

**Table 3.11**. Cost and percentage reduction in force for all the kneepads

| Kneepads | Cost | Cost spent for 1% reduction in force | % Reduction in force (Mean Peak) |
|---|---|---|---|
| Without Kneepad | Ref | Ref | Ref |
| Ultralight | $7.99 | $ 0.15 | 53.30% |
| Rubber Nonskid | $13.99 | $ 0.22 | 63.30% |
| Hard Cap | $27.99 | $ 0.48 | 58.10% |
| Professional Gel | $28.99 | $ 0.41 | 71.20% |
| Armor Pant with 1 Pad | $39.99 | $ 1.19 | 33.50% |
| Armor Pant with 2 Pad | $47.98 | $ 0.96 | 50.20% |

It can be observed from Table 3.11 that the most expensive kneepad was the Armor pant with two pads and the least expensive kneepad was the Ultra light kneepad. In terms of the cost spend for 1% reduction in force the Armor pant with one pad was the most expensive and the Ultra light was the least expensive of all the kneepads used in this study. The results shown above may not represent the whole picture because factors like material and durability of the kneepad, comfort level, working surface design are not taken into consideration. The comparison curves for the cost and the percentage reduction in force are shown Figure 3.13.

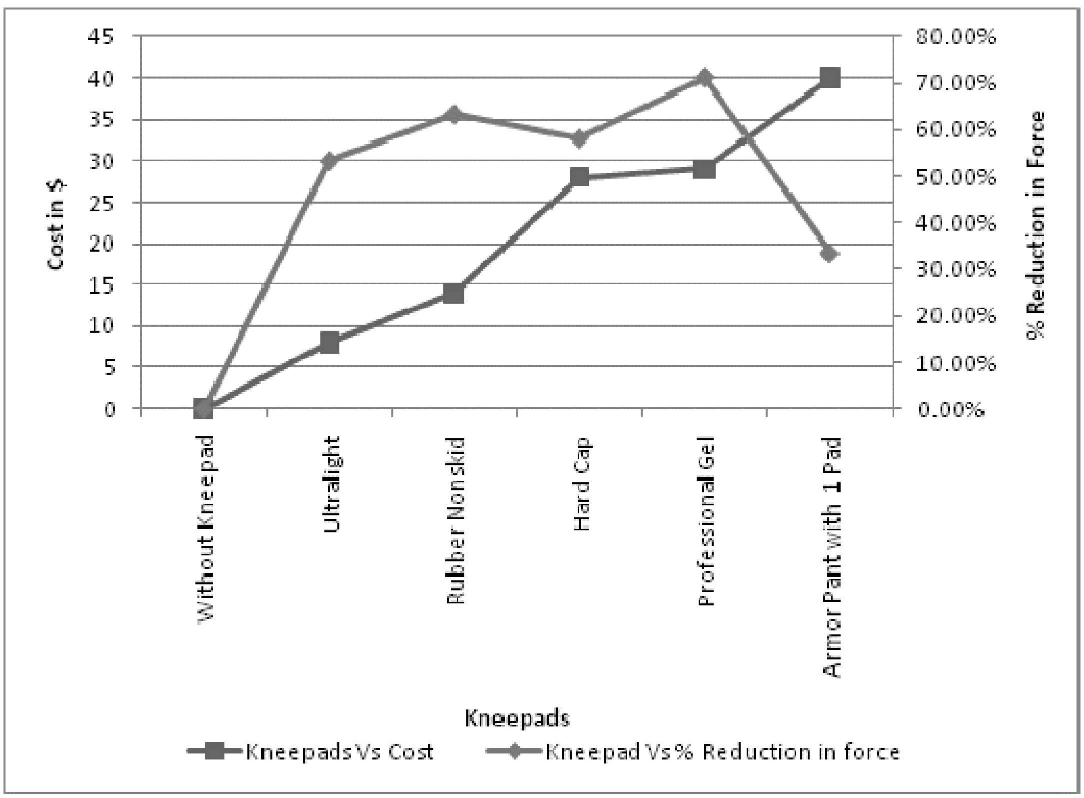


**Figure 3.13**: Comparison of the cost and percentage reduction in force of the different kneepads.

## 3.3 Summary of the Results

- The first hypothesis of the dependent variables Mean Peak ($H_{01I}$), Mean Average ($H_{02I}$), and Mean Area ($H_{03I}$) being equal across different kneepads was rejected establishing the relationship between force and kneepads with Professional Gel kneepad outperforming other kneepads.
- The second hypothesis of the dependent variables $H_{02II}$, $H_{03II}$ being equal for different locations was rejected establishing the relationship between force and location in the work envelope for Mean Average and Mean Area forces.
- The Hypothesis $H_{01II}$ was accepted ascertaining no relationship between force and location in work envelope for the Mean Peak force.
- Post-hoc Tukey's comparisons confirmed differences between groups of knee pads.
- Post-hoc Tukey's comparisons were not significant to establish groups by location in work envelope.

# 4. DISCUSSION

## 4.1 Underestimation of the Total Sensor Force

The Sensor data obtained from different trials likely represented an underestimation of the total force applied at the knee during kneeling. If we consider the condition where the participant was kneeling without the kneepad, the total force comparison of the force plate and the sensor were different in their amplitudes of the curve obtained. This was because the sensors placed on the knee did not cover the whole portion of the knee in contact with the force plate surface; hence there was loss in force on the sensor where the knee contacted the force plate with no FFS. This resulted in an underestimation of the sensor's total force.

In order to make good comparison for the force obtained for different kneepad conditions instead of comparing the force plate and the sensor, comparisons were made between the sensor data for the without kneepad condition and the different types of kneepads. This accounted for the underestimation by directly comparing the forces obtained from the sensor itself. One of the other reasons the comparison for different kneepads and force plate was not used was because the force plate data always represented the total reaction force applied to the knees which was similar for all the kneepads. But the sensor data, though similar for without kneepad, varied from the force plate for the kneepads as they represented the contact force between the knee and the kneepad used. Also, because there may have been an underestimation in force due to the soft nature of the kneepads, some part of the sensitivity could have been lost.

One of the other factors which could have led to an underestimation in sensor force is the sensor placement on the knee. Sensor placement was the most important part of the study because the placement on the right location on the knee gave a more reliable force output. Although the same technique of placing on the knee was adopted for all the participants, sometime the force from the sensors did not read the force as expected. This was attributed to the knee being a complex joint that changes shape from person to person. This factor of the study could not be controlled but depending on the force readings obtained, the placement of the sensors was slightly adjusted.

## 4.2 Choosing the Best Kneepad

The professional Gel kneepad was rated as the kneepad which was less painful on the knees, was more comfortable on the knees and was also the most liked kneepad among the participants. Also the data obtained from the force sensors showed a reduction in the smallest transferred force to the knee while wearing the Professional Gel kneepad as measured by reduction in the Mean Peak, Mean Average and Mean Area forces compared to the without kneepad condition. The Professional Gel kneepad was also the one which showed the highest percentage of force reduction among other kneepads. Hence from the participant point of view and the force measurements, the Professional Gel kneepads can be considered the best kneepad among the kneepads tested in this study, for performing kneeling tasks.

The Professional Gel kneepad unlike the other kneepads used in the study had a unique design that was a bit different in the interior cushioning provided. Although it had very thick foam padding like the other kneepads, it also had a small pocket at the center where the patella makes contact with the kneepad. The pocket had a thin foam layer and gel was filled beneath the foam giving the highest amount of cushioning to the knee. Therefore the force at the center of the knee reduced drastically and was spread over the exterior surface of the knee.

### 4.3 Interpreting Percentage Reduction in Forces

The percentage reduction in forces for each can be seen in Table 3.5, Table 3.6, and Table 3.7. It is difficult to see if the FFS have become less sensitive on the cushioned surface or the kneepad itself is providing a better padding, thus making the results interpretation more challenging. Although the percentage reductions are still valid, the actual force values are likely an inaccurate representation of the actual applied force to the knee.

### 4.4 Change in Force with Location

It was seen that the oneway ANOVA results of the forces by location was not significant but when the same analysis was conducted by each knee then the relationship for location and the force were significant, except for the Mean Peak on the right knee. One of the reasons for this could be the fact that one of the force readings from one FFS was completely removed as that force sensor was peaking throughout the experimental process and leading to inaccurate results. Removal of this FFS reading could have also removed any additional force which would have added to the total force. Hence this could be considered as the reason for insignificance.

But it can be seen that according to the left knee data the locations ‘a’ and ‘b’ have a higher force when compared to other locations and according to the right knee data locations ‘d’ and ‘e’ have high forces than other locations. This indicates that the left knee is loaded more when placing tiles on locations ‘a’ and ‘b’ while the right knee is loaded more when placing the tiles on locations ‘d’ and ‘e’. This supports the idea that locations that are at the end of reach (stretch) induce greater forces on the knee, and work practices should reduce exposure to tasks located in these areas.

## 4.5 Establishing Threshold Limit Values (TLV)

The results obtained from the percentage reduction in forces for each kneepad and also the groupings obtained from the post-hoc Tukeys’s method may be used in establishing TLV for the use and manufacturing of the kneepads. For example, a set of kneepads grouped by Tukey’s method with a similar percentage reduction in force may help the manufacturers decide on the type of padding to be used to improve the reduction of force on the knee while using kneepads. Also the same data can be used to interpret the duration of kneeling on a particular type of padded kneepad. Therefore a TLV could be established for the use and manufacturing of the kneepads.

## 4.6 Limitations

- The number of participants in the study was small to generalize the results.
- Although a wide variety of kneepads were used in the study, the kneepads used in the study were few compared to the large number of kneepads available commercially.

- All of the participants of the study were university students and did not represent the working population who would do kneeling as a part of their job.
- The force sensors used in this study were not able to read the entire applied force to the knee joint. Better force sensor arrays to cover the surface of the knee in its entirety would be required to estimate actual knee joint stress and reduction of stress as a function of wearing kneepads.
- The forces calculated from the sensor calibration equations were not a perfect fit at the lower end of the voltage output, and may have resulted in errors.
- The change in sensitivity of the sensors was hard to predict and the variability between participants' knees was difficult to address.
- Only one type of surface was used during the kneeling task whereas in real world the surfaces are different in different work environments.

# 5. CONCLUSIONS AND FUTURE SCOPE

In this section the conclusions drawn from the results and discussion section are presented along with the future scope for this study.

## 5.1 Conclusions

Different types of kneepads were compared in order to determine the best kneepad which can reduce the forces on the knee joint. The Professional Gel kneepad was best on both the questionnaire and the force data analyses.

A significant relationship was established between force and location of working envelope with respect to each knee. It can be concluded that the location at the end of the reach profile induces higher forces on the knee which is closest to that direction of the reach profile. But working at a location directly in front in a more neutral posture would reduce loading on individual knees.

Also, the placement of the sensor on the knee was a major influence on the estimation of the forces during each kneeling task.

The data obtained from this study should serve as a pilot study that warrants additional investigation of the statistical results obtained by setting up a larger study with more participants, more kneepads and different work surfaces. By conducting a larger study we may set the standards or Threshold Limit Values (TLV) for the use and manufacturing of the kneepads with appropriate degree of statistical power. It may also be possible to establish some guideline on what type of kneepads should be used in a particular environment with different working conditions.

By putting force data obtained from this study in the form of educational broachers, and spreading the results along with some guidelines to workers, the work force would become more educated on the disadvantages of kneeling without kneepads and how the kneepads would be helpful in reducing the stresses on the knees to help protect their knees. The force data obtained from this study should also serve as a baseline and provide information to develop a better sensor to estimate the stresses on the knee more accurately.

## 5.2 Future Scope

The foot sensor data which were not used in this study will be used to relate the force on the knee with the force at the foot. There may be an increase in force on the foot sensor with a decrease in the force on the knee as the participant may have leaned back on the foot while kneeling inducing greater forces at the foot than at the knee. Also the motion capture data along with the force data obtained from the study can be used in the future in estimating the internal muscle forces that contribute to compressive loading of the knee joints.

Future work should include the use of force data from this study and apply them to a knee joint model to analyze the induced joint forces at different parts of the lower extremity including the femur, tibia, menisci and ligaments. The motion data collected in this study will help establish the force angles at the time of the trial and the sensor data will help describe the magnitude of the forces. Expanding the sensor to measure the full area on the knee and not just the patella and the tibial tubercle would be something else to consider with future work.

# APPENDIX

# QUESTIONNAIRE

# Knee Pad & Knee Pain Questionaire

## General Questions

**1. What is your Subject ID?**

**2. What is your age (years)?**

**3. Gender**

- Male
- Female

**4. What is your Height (feets & inches)?**

**5. What is your Weight (lbs)?**

**6. For how long(years) have you worked where kneeling is required?**

- 0-1 years
- 1-2 years
- 3-5 years
- More than 5 years & less than 10 years
- More than 10 years

**7. How many hours do you kneel while working each day?**

**8. Do you experience any pain while kneeling?**

- Yes
- No
- N/A

**If yes, rate your pain from 0 to 10**

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No pain | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Worst pain imaginable |

**9. What type of work do you perform that requires kneeling?**

**10. Do you regularly use kneepads when performing kneeling work?**

- Yes
- No

**If Yes, what style of kneepad do you use(hardcap, soft, gel)?**

**If No, why?**

**11. Have you ever seen a health care provider for knee injury or pain?**

**12. Have you ever had a knee surgery? If yes, How long ago? what was the surgery for**

**13. Have you ever been diagnosed with arthritis or knee joint disorders?**

**14. How often do you exercise per week?**

**15. Which of the following best describes your exercise habits:**

- Regular
- Semi-regular
- Occasionally, but random
- Hardly ever
- Never

**16. Select any of the following sports that you participate in regularly:**

- Football
- Soccer
- Badminton
- Tennis
- Volleyball
- Basketball
- Ice hockey
- Weight lifting
- Skiing
- Racquetball
- Other outdoor sports

Continue »

# Knee Pad & Knee Pain Questionaire

## Kneepad/Trial Specific Questions

**17. For each Kneepad specify which part of the knee(s), if any, hurts?**

Please write the Kneepad name and what part hurts for each kneepad

**18. How do you describe knee pain for each kneepad**

| | Unbearably | Very | Painful | Little | No Pain |
|---|---|---|---|---|---|

| | painful | Painful | | Painful | at all |
|---|---|---|---|---|---|
| Ultra light kneepad | ○ | ○ | ○ | ○ | ○ |
| Nonskid kneepad | ○ | ○ | ○ | ○ | ○ |
| Hardcap kneepad | ○ | ○ | ○ | ○ | ○ |
| Armour kneepad | ○ | ○ | ○ | ○ | ○ |
| Gel kneepad | ○ | ○ | ○ | ○ | ○ |
| Without kneepad | ○ | ○ | ○ | ○ | ○ |

**19. a) Comfort level of Ultra light Kneepad**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least comfort | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Highest comfort |

**19. b) Comfort level of Nonskid Kneepad**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Comfort | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Highest comfort |

**19. c) Comfort level of Hardcap Kneepad**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Comfort | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Highest comfort |

**19. d) Comfort level of Armour Kneepad**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Comfort | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Highest comfort |

**19. e) Comfort level of Gel Kneepad**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Comfort | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Highest comfort |

**19. f) Comfort level for Without Kneepad**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Comfort | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Highest comfort |

**20. How do you describe the fit (wearability - not while kneeling)?**

| | Very Bad | Bad | Neither Good Nor Bad | Good | Very Good |
|---|---|---|---|---|---|
| Ultra light Kneepad | ○ | ○ | ○ | ○ | ○ |
| Nonskid Kneepad | ○ | ○ | ○ | ○ | ○ |
| Hardcap Kneepad | ○ | ○ | ○ | ○ | ○ |
| Armour Kneepad | ○ | ○ | ○ | ○ | ○ |
| Gel Kneepad | ○ | ○ | ○ | ○ | ○ |
| Without Kneepad | ○ | ○ | ○ | ○ | ○ |

**21. How do you describe the fit (while kneeling)?**

| | Very Bad | Bad | Neither Good Nor Bad | Good | Very Good |
|---|---|---|---|---|---|
| Ultra light Kneepad | ○ | ○ | ○ | ○ | ○ |
| Nonskid Kneepad | ○ | ○ | ○ | ○ | ○ |
| Hardcap Kneepad | ○ | ○ | ○ | ○ | ○ |
| Armour Kneepad | ○ | ○ | ○ | ○ | ○ |
| Gel Kneepad | ○ | ○ | ○ | ○ | ○ |
| Without Kneepad | ○ | ○ | ○ | ○ | ○ |

**22. a) What would you change,if any, about Ultra Light Kneepad?**

**22. b) What would you change,if any, about Nonskid Kneepad?**

**22. c) What would you change,if any, about Hardcap Kneepad?**

**22. d) What would you change,if any, about Armour Kneepad?**

**22. e) What would you change,if any, about Gel Kneepad?**

**22. f) What would you change,if any, about Without Kneepad?**

**23. Which Kneepad did you like the most?**

- Ultra Light Kneepad
- Nonskid Kneepad
- Hardcap Kneepad
- Armour Kneepad
- Gel Kneepad
- Without Kneepad

**23. a) What made the above kneepad the best?**

**24. Did you notice any differences between floor location and knee comfort?. If yes, what floor location(s) was the most uncomfortable to work in?**

**25. a) How strenuous would you rate working in "Location 1" on the knee?**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Strenuous | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very strenuous |

**25. b) How strenuous would you rate working in "Location 2" on the knee?**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Strenuous | | | | | | | | | | | Very strenuous |

**25. c) How strenuous would you rate working in "Location 3" on the knee?**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Strenuous | | | | | | | | | | | Very strenuous |

**25. d) How strenuous would you rate working in "Location 4" on the knee?**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Strenuous | | | | | | | | | | | Very strenuous |

**25. e) How strenuous would you rate working in "Location 5" on the knee?**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Strenuous | | | | | | | | | | | Very strenuous |

**26. a)How strenuous would you rate working in "Location 1" on the whole body?**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Strenuous | | | | | | | | | | | Very strenuous |

**26. b)How strenuous would you rate working in "Location 2" on the whole body?**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Strenuous | | | | | | | | | | | Very strenuous |

**26. e) How strenuous would you rate working in "Location 5" on the whole body?**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Strenuous | | | | | | | | | | | Very strenuous |

**26. c) How strenuous would you rate working in "Location 3" on the whole**

**body?**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Strenuous | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very strenuous |

**26. d) How strenuous would you rate working in "Location 4" on the whole body?**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Least Strenuous | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | Very strenuous |

**27. Do you have any other comments about the kneepads during this study that you would like to share with the research team to improve comfort and fit to a user? Please explain in detail how your knees felt during this study for each of the knee pads and tasks.**

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