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MATTRESS TESTING AND PRESSURE ULCER PREVENTION

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Executive Summary

Each year the U.S. health care industry spends 1.6 billion U.S. dollars (11 milliard DKK) in prevention and treatment of pressure ulcers (Whittington et al., 2001). Pressure ulcers not only result in large economic costs, but are painful for the patients, most of whom are suffering already from another aliment. The work of this IQP, along with work already done at the Danish Center for Technical Aids and Rehabilitation, focuses on the role mattresses play in pressure ulcer prevention, and how these mattresses can be effectively tested.

Pressure ulcers develop when the soft tissues of the body are compressed between an external surface, like a mattress or wheelchair cushion, and a harder tissue of the body, such as bone or cartilage. This pressure, over time, begins to destroy soft tissue cells by compressing the capillary networks that provide for blood transfer. If this pressure is not lessened over time, the underlying skin begins to disintegrate and eventually opens the underlying structure of bone and muscle to infection (Ducker, 2002).

The impact of pressure ulcers is large in both economic and social scales. Ducker (2002) estimates that treatment of a severe pressure wound can cost between forty and seventy thousand U.S. dollars (250,000 – 480,000 DKK) to treat. The majority of this cost lies in the extensive hospital stay, and the twenty-four hour care required. Prevention and risk analysis are important tools that must be incorporated into any acute care facility. Mattresses play an important role in this prevention, and understanding their impact on pressure ulcers is an important and relatively unexplored area.

Currently three major testing methods exist to determine a mattress's ability to prevent pressure ulcers: human volunteers, mannequins, and domed indenters. The domed indenter device, used by the Danish Center, provides reproducible data measurements for both indention

hardness and interface pressure. Although the domed indenter is the least proven design, it holds great promise for testing a wide variety of mattresses and mattress properties.

Many different mattress types are available in the medical equipment market today, many of which are specially designed for the prevention of pressure ulcers. The major category types include low-pressure foam, static fluid mattresses, and pressure alternating mattress (also called dynamic mattresses). Each type has its advantages in pressure ulcer prevention, and each is targeted at different severities of pressure ulcers. During the team's period at the Danish Center, the focus of the work was spent analyzing static foam and fluid mattresses.

The Danish Center for Technical Aids and Rehabilitation oversees the testing of hospital beds, mobile and stationary hoists, and adjustable beds and work chairs for the disabled. They, along with labs in the other Nordic countries, provide certification for all hospital equipment in Scandinavia. Currently the center is looking to extend their testing to mattresses, specifically to address the relationship between mattress properties and the development of pressure ulcers. Our project aims to fill this void by providing extensive testing of their tester, and relating those results to the tested mattresses. Our primary contact for the duration of the project was Mr. Bruno Wolff.

The project focused the collection and analysis on mattress properties, and their relationship to the development of pressure ulcers. To facilitate this, the team's initial methods focused strongly on developing effective protocols for this testing, and establishing the domed indenter as an effective piece of test equipment.

A major goal for the project was to deliver to our sponsor a recommendation for a final mattress testing protocol for the Danish Center's domed indenter. The protocol that was produced provides for reproducible, accurate, and informative data to be gathered through the use of the domed indenter. The data collected can then be graphed, and both mathematically and visually compared. To develop such protocols, research was conducted to establish what other protocols were currently in use, and to evaluate each protocol's strengths and weaknesses. The protocol list was then compiled from these sources and from input from scientist and doctors at the Danish Center and Bispebjerg Hospital. These sources, along with our experience with the capabilities of the domed indenter' led to the development of a single protocol for use at the Danish Center.

After an effective protocol was developed, the team moved its focus to mattress testing. In total, nine mattresses were tested using the domed indenter. Five of the mattresses were lent from the Bispebjerg Hospital for testing, and the four others belonged to the Danish Center.

As the protocol states, the first test run on each mattress was an indentation test. This test indents the domed indenter into the mattress at a slow rate until bottoming out occurs. This test allows for a force-deflection curve to be generated, illustrating how far a patient may indent into a mattress. These graphs can then be compared from mattress to mattress, both visually and mathematically.

The second test aims to establish the visco-elastic properties of the mattress. The test begins by indenting the dome into the mattress to a specific predefined depth. This is done at a relatively high speed, and then quickly stopped. The test then measures the pressure drop over time, which is then used to determine the visco-elastic constant of the mattress. The visco-elastic properties of a mattress are a very important factor in pressure relieving mattress design. These properties allow mattresses to correctly adjust to the form of a patient while providing the most pressure relief possible.

The final goal for this project was to increase the communication between the Danish Center and those involved with pressure ulcer care and prevention at the Bispebjerg Hospital. Through this interaction, the Danish Center and the Bispebjerg Hospital hoped to improve their level of interaction by creating personal contacts as well as possibilities for future professional collaboration.

The project began with a preliminary evaluation of the domed indenter, which was recently designed and built at the Danish Center. During the initial testing period it was found that the domed indenter did not record data in a reproducible or precise manner. In the weeks following these initial tests, many experiments and alterations were made to the equipment. The main joints and collar suspending the domed indenter were replaced, computer data collection was added, and the primary point pressure sensor was replaced.

Initially the domed indenter had severe offset problems, in some cases accounting for more than 20 percent of the recorded maximum force. This offset was caused by friction in both the joints and collar that suspended the domed indenter. The original parts were poorly machined, and were not intended for use in a precision instrument. After replacement, there was a significant improvement in the results from the domed indenter, and nearly all offset problems were corrected.

After correcting the suspension system for the domed indenter, it became apparent that there were other problems relating to the point pressure sensor. If operating correctly the point sensor was expected to read the pressure at the bottom of the dome, which should be the highest-pressure area of the domed indenter. However, during preliminary testing it was apparent that the sensor was malfunctioning. The ability to read the pressure at the bottom of the domed indenter is required for the indenter to provide the most meaningful data possible. A new sensor was purchased. Once these modifications were complete, we were able to analyze the important variables involved in testing with the domed indenter.

In establishing an effective protocol for the Danish Center's domed indenter, consideration had to be given to the effects of time, temperature and mattress indentation depth on mattress properties. Many simple and complex foam mattresses, such as the tempur-pedic brand mattresses, are very sensitive to heat, and react differently at different times and indentations, in some cases drastically changing their properties. We extensively researched the issue, and conducted exploratory testing on various mattresses using both human subjects and the domed indenter.

In order to accurately analyze mattress properties, a system that could input sensor data quickly and accurately was needed. This system ideally would also be able to export any data collected into excel or access for analysis. The choice was based on these factors, and the cost and availability of each solution. The Danish Center already owned copies of LabVIEW and uLog, two popular data recording software products. LabVIEW was chosen for its higher sampling rate, superior data export options, and better software filtering of the voltage data. This software allowed the team to export the data to excel for analysis, and was already familiar to the scientist at the Danish Center.

In order to increase communication between the Danish Center and Bispebjerg Hospital, the team conducted a series of meetings between engineers at the Danish Center and the clinicians at the hospital. The goal of the meetings was to coordinate the efforts of the Center and hospital, and to allow for communication of ideas. Both organizations benefited, where the Danish Center got new ideas for a seminar they have planned for November, and the hospital has planned to test mattresses at the Danish Center as soon as the service available.

Although the mattress team made significant accomplishments during the time available in Denmark, there are many improvements that could be implemented by the Center in the future. Further visco-elastic testing should be conducted, along with testing for the effects of shear on mattress properties. To accomplish this a more effective software or hardware solution must be found to eliminate the noise currently in the voltage output of the domed indenter. Secondly the controls of the domed indenter must be upgraded to digital signal, and digital stepper motors need to replace the current analog motors to allow for more precise control of the domed indenter.

Testing for shear properties was impossible using the domed indenter in its current state. The motors are not accurate enough to handle the precise movements needed to conduct a shear test. Although the current indenter is incapable of these tests, shear forces are important in the development of pressure ulcers. Shear forces have been known to have significant effects on the development of pressure ulcers, but little is know about the direct correlation between the two. If the domed indenter was capable of testing for the effects of these forces on mattresses, a more definitive answer might be available.

Furthermore, an upgrade needs to be made to the domed indenter hardware. Currently the voltage from the indenter suffers from the effects of noise from an unknown source. This noise severely interferes with many tests and must be removed before the results of the tests can be considered truly valuable. We were able to reduce the noise significantly for our testing, but a more effective solution must be found.

Adding computer controls to the domed indenter would also be required to effectively test mattresses in the future. To upgrade the current indenter to computer controls requires both hardware and software solutions. Digital stepper motors would be needed to provide the vertical and horizontal movements of the domed indenter, since the current analogue solution does not have the required accuracy. These motors would then be controlled digitally through LabVIEW, allowing the software to independently operate the entire test.

Through the results achieved during the teams stay in Denmark, and the recommendations provided to the Danish Center for future work, the mattress testing team is confident that the Danish Center will soon be able to achieve their goal of testing mattresses for their ability to prevent pressure ulcers. The interaction with the Bispebjerg Hospital has also been improved, and will result in a better working relationship between the two professional groups. With a functioning domed indenter, solid relations with the hospital staff, and effective protocols, the team has left the Danish Center with an significant base to begin mattress testing.

Abstract

With the help of the Danish Center and the Bispebjerg Hospital a domed indenter was prepared for testing mattress properties that are important to pressure ulcer prevention. Protocols for the device were written based on research in this field, and testing was conducted on hospital mattresses using these protocols. The indenter was found to have the ability to accurately test the mattress properties and the results were given to the Bispebjerg Hospital, starting a growing relationship between the two organizations.

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1 Introduction

Each year the U.S. health care industry spends 1.6 billion U.S. dollars (11 milliard DKK) in prevention and treatment of pressure ulcers (Whittington et al., 2001). Many different approaches have been put forward to treat this affliction, from traditional surgical approaches to inventive mattress solutions and wheelchair support surfaces. Yet even with such a strong focus on the problem, many still suffer the effects of pressure ulcers. Approximately 40% of paraplegics will develop pressure ulcers at some point in their life, and 7% of intensive care unit (ICU) patients will incur some stage of pressure ulcer development during their average five day stay (Ducker, 2002). The cost of treatment can be enormous; the two most severe levels of pressure ulcers averaging 40,000 to 70,000 US dollars to treat. There is an obvious need for prevention methods that are both cost efficient and clinically effective.

Current methods to prevent and treat pressure ulcers are costly. The average hospital stay for pressure ulcer treatment costs between 20,000 and 30,000 U.S. dollars, with more severe cases escalating to almost twice that amount (Ducker, 2002). Much of this cost is incurred in the extensive hospital stay, which can last months in some cases. The care needed during this stay is also exhaustive for the caretaker. This treatment can involve manually moving the patient on a two hour schedule, 24 hours a day, for the duration of their hospital stay. Extensive research has gone into identifying mattress properties and materials that help prevent pressure ulcers from developing. These testing procedures aim to simulate the human interaction with the mattress through a variety of means. The first and least complex method is to have human volunteers lie on mattresses, taking pressure measurements from various points of contact with the mattress. Another test model employed is human mannequins. Human mannequins have pressure sensors placed at certain points where measurements are taken. The final method is to utilize indenters, shaped liked parts of the thighs and buttocks, which are indented into a mattress.

The Danish Center for Technical Aids for Rehabilitation and Education has developed a domed indenter, modeled after a half buttocks and the side of a thigh. This device measures both interface pressure and indentation hardness. These measurements are critical to understanding the relationship between mattresses and pressure ulcer development, and the data taken from the tester will offer the Danish Center and its customers insight into what properties of mattresses are important for preventing pressure ulcers. This project focuses on the new technology developed by the center, its optimization, and its applications in testing patient support surfaces for properties that prevent pressure ulcers. This project also considers the course of the Danish Center's relationship with local hospitals, and what can be done to facilitate collaborative efforts to prevent pressure ulcers.

The objectives for the project were threefold. First, the team optimized the Domed Indenter so that it gave accurate, reproducible data. Initially our goal was to become familiar with the use of the domed indenter and the general testing environment at the Danish Center. Secondly, the goal was to optimize the Domed Indenter for reproducible data with low errors. After this phase was completed, more extensive testing was conducted using a variety of mattresses, some of which came from the Bispebjerg Hospital. These data were collected and entered into a database, which may be then used to provide insights into the link between mattress properties and pressure ulcer development.

The second objective was to provide recommendations on testing protocols to the Danish Center. Initially this focused on analyzing protocols currently used, both by mattress testers and other patient support testing centers. Later, the project team developed a set of recommendations on the most effective protocols for the domed indenter.

The third objective was to strengthen communication and interaction between the Danish Center and area hospitals. This focused on meetings to determine important properties staff have seen to be important in pressure relief. A set of recommendations was written up for the Bispebjerg Hospital on ways to have their mattresses tested on a yearly basis to determine which mattresses have the overall best qualities over time, so that a cost benefit analysis can be run to help in future mattress selections.

Our project focused on collecting technical data on mattress properties from the Danish Center's Domed Indenter and optimizing the domed indenter so that the data were more reliable and reproducible. The project team provided both recommendations to the Danish Center about their testing approaches, and information to the hospital on methods to determine proper mattress selection for their needs. The connection between hospital mattress usage and the properties of mattresses that cause pressure ulcers is important, and this project provides the Danish Center, those in the health care industry, and manufacturers of mattresses insight into a future with better mattresses to help decrease the problem of pressure ulcers.

1.1 Reading Guide

In the following sections of the project report, there will be further discussion on the topics outlined above. These include background on pressure ulcer development, treatment, and current mattress testing methods, goals for the project and our methods for reaching them, our results and discussion of them, and finally the recommendations the project team made from the information they have gathered throughout this project.

2 Literature Review

This chapter provides background information for our project. Major topics include defining what pressure ulcers are, how they are caused and how they can be prevented; identifying the population that suffers from pressure ulcers, and hence those that would benefit from the new testing methods; describing current trends for testing mattresses for pressure distribution and hardness; information about our sponsor; methods used by scientists to rate mattresses for hospital use, and information about different types of pressure relieving mattresses. These areas are included to give a well-rounded understanding of the knowledge surrounding our project.

2.1 Pressure Ulcers

As the current population ages, more elderly people will become bedridden, creating a large population that will be susceptible to pressure ulcers. It is estimated that in the United States in 2000 pressure ulcers cost the health care industry over 1.6 billion U.S. dollars (11 milliard DKK) (Whittington et al. 2001). Not only do pressure wounds cost health care providers and patients money, they are a significant source of preventable human suffering (Freeman et al. 2001). With aggressive prevention methods, along with thorough risk assessment of patients, much can be done to prevent pressure ulcers. To develop successful prevention routines and effective mattress designs, a thorough understanding of the causes of pressure ulcers is needed.

Pressure ulcers develop when the soft tissues of the body are compressed between an external surface, like a mattress or seat, and a harder tissue in the body, like bone or cartilage. This pressure, over time, reduces the blood flow to the area by stopping the blood's movement through capillary networks. These networks supply the soft tissues of the body with the nutrients and oxygen critical to cellular function. As these nutrients are withheld from the site, the layers of skin begin to weaken. If the pressure is not lessened over time, the underlying skin begins to disintegrate and eventually opens the underlying structure of bone and muscle to infection (Ducker, 2002).

Pressure ulcers are grouped by the medical field into four levels, level one being minor and level four being the most severe. Level one pressure ulcers involve slight abrasions to the skin, where only minor care is needed. On the other end of the spectrum, level four contains ulcers with extensive destruction of the skin layers, along with possible damage to the underlying structures of bones or joints. Any level of pressure ulcer is a serious condition that may take months of hospital stay to treat, and many level 3 and 4 pressure ulcers result in the death of the patient (Ducker, 2002). These deaths are usually caused by complications due to infections, which are difficult to treat in many 3rd and 4th level pressure ulcer victims.

Pressure ulcers in the body do not follow a reverse staging process. As the external skin begins to heal, the body tissues, mainly muscles and fatty tissues, do not immediately regenerate into the area. This slow process of healing also contributes to the lengthy hospital stays that many patients face. This lack of quick regeneration of the skin area involved also leads to a very high re-admittance rate for pressure ulcer sufferers (Ducker, 2002).

The causes of pressure wounds are complex, but can be grouped into two major categories, intrinsic and external factors. Intrinsic factors are factors that come from the patient's health, gender, age, weight, and other internal factors. External factors, also known as extrinsic factors, are issues outside of the body that increase the risk of developing a pressure ulcer, like mattresses (Theaker, 2002).

Extrinsic factors have been divided into three major factors: pressure forces, shear forces, and friction forces. The most understandable factor is pressure, which is normally associated with pressure wounds. The pressure of the body weight compresses an area of skin for an extended period of time against some external surface. This pressure results in loss of blood circulation, leading in most cases to a pressure ulcer. Much of the data on the exact amount of pressure needed to significantly limit the blood flow is based on poorly designed models. Studies indicate though, that the figure of 32mmHg is commonly used (Theaker, 2002). This figure is of little value because it is based on the pressure to stop blood flow in the finger of a healthy adult subject. Many studies have show that this value can be as low as 11mmHg for some patients, which can place them at significant and immediate risk for pressure ulcers (Theaker, 2002). Many of the current prevention methods aim to effectively lower pressure on the body, and many of the more complex mattress designs either reduce pressures or rotate areas subject to high pressure loads. Although pressure forces are a major component in the development of pressure ulcers, other factors also play a substantial role.

Friction and shear forces, though not as significant as pressure forces, do play an important part in the development of pressure ulcers. Friction damage to the skin usually occurs when the patient is being moved or repositioned, an event that occurs frequently in patients who are bedridden. Although all pressure ulcers are directly caused by pressure, friction and shear forces often further the severity of the injury. Often friction from moving the patient causes the bone structure underneath to lacerate the weakened skin, drastically increasing the severity of the injury. Friction and shear forces can also expose pressure wounds to the open air, introducing bacteria to the wound site (Theaker, 2002). Research has been conducted to determine the effects of shear on mattress properties, but there is no clear picture of shear's effects on human skin (Buchanan, 2000).

Intrinsic factors are those that are internal to the patient; their general health, nutrition, age, weight, and consciousness all are factors that can greatly influence their risk of suffering pressure ulcers (Theaker, 2002). Scales like the Norton scale and the Braden scale have been used by health care professionals to evaluate an individual's susceptibility to pressure wounds in the past, and measurements like the Fragment Scale have further refined the factors that go into evaluating a patient's risk (see Appendix 2, 3). Yet these measurements are uncertain at best; they aim only to sort patients into two groups, those who are susceptible and those who are not. They do not provide a real analysis of an individual patient's potential for pressure ulcer development (Perneger et al., 2001). Research is currently being conducted to find better methods to evaluate the potential for pressure wound development. In the Netherlands, a recent study found that measuring the ability of the patient's skin to reheat after a short induced cooling period could be a reliable indicator of the patient's susceptibility to pressure wounds (Marum, 2001). As more is understood of the risk factors that lead to pressure wounds, valuable health care resources can be targeted to those who will benefit the most from the most aggressive prevention techniques.

Although intrinsic risk factors do allow health care professionals to gauge a person's general susceptibility to pressure ulcers, all groups of bedridden people can be affected. In the Whittington et al. (2001) study, one hundred sixteen facilities were surveyed, which provided care for over 17,000 people. All of the surveyed establishments were acute care facilities, also known also as intensive care units, where the average the length of a patient's stay was only five days. Of these 17,000 patients, over seven percent suffered pressure ulcers of some kind. This represents over one thousand patients suffering some form of pressure ulcer, and at an average cost of twenty to thirty thousand U.S. dollars (140.000 to 200.000 DKK) to treat, places a huge burden on health care providers (Ducker, 2002). The study also shows that although age and health are risk factors for pressure wounds, they simply are not accurate enough. For instance, 72% of the population was over 65, and they accounted for 73% of the pressure wound occurrences; a value the researchers thought would have been much higher (Whittington et al. 2001). Intrinsic and extrinsic factors play an important role in the evaluation of a patient's susceptibility to pressure ulcers, but the importance of prevention for all bedridden patients is equally important.

Many properties of a complete pressure ulcer prevention plan simply involve regular maintenance of the patient. Frequent inspection, a thorough cleaning schedule, and special seating and bedding are all components to an effective prevention routine (Ducker, 2002). If problems do develop, a more aggressive approach may be warranted. Over two hundred overlay and bedding products currently exist to alleviate specific forms of pressure ulcers; these options can compliment the efforts of the health care provider.

An important prevention method is analyzing the nutritional intake of the patient. In the study conducted by Benati, Delvecchio, Cilla and Perdone (2001), it was shown that an aggressive plan of a nutrient and vitamin rich diet, including arginine, could greatly decrease the chances of developing pressure ulcers (Benati et al, 2001). Not only was it effective in the prevention, but also sped up recovery rates drastically. Studies like this indicate that a more rounded approach to pressure wounds would be beneficial, and that surgical options for treatment are not the only options. The study conducted by Quaglini et al. (2000) provides an excellent decision tree based on the recommendations from many scales, including Norton, in the decision process for patient care. This approach focuses on all issues involved in the patient's care, and aims to provide an on-the-spot analysis of appropriate action (Quaglini, 2000).

The impact of pressure ulcers is large in both economic and social scales. Ducker (2002) estimates that a severe pressure wound can cost between forty to seventy thousand U.S. dollars (250.000 – 480.000 DKK) to treat, and minor pressure wounds can cost between twenty and thirty thousand U.S. dollars (140,000 – 200,000 DKK) to treat (Ducker, 2002). The majority of this cost lies in the extensive hospital stay, and the twenty-four hour care that is needed. What presents an even greater challenge is that the recurrence rate for even younger patients is near forty percent (Ducker, 2002). Prevention and risk analysis are important tools that must be incorporated into any acute care facility. Pressure ulcers are a large issue in health care, and as the population ages in first world countries, it will grow into an even larger issue.

2.2 Populations at Risk to Develop Pressure Ulcers

Throughout this project it is important to keep in mind that the information we are providing the Danish Center will be used to help people who are suffering from pressure ulcers. It is a crucial step to view the general trends and patterns of this population, which can help identify ways to prevent and treat pressure ulcers. However, each of these sufferers is an individual and as such, their data must be reviewed individually as well. Every person's needs differ and thus we will be studying pressure ulcers through a few case studies, as well as in terms of general trends. This will allow us to make thorough and accurate recommendations to the Danish Center that are based on a complete perspective of pressure ulcers. In order to do this it is necessary to first gain a general background to those who are afflicted by pressure ulcers, and what puts them at risk.

Those who are prone to developing pressure ulcers are those patients who stay in one position for an extended period of time. This encompasses many different groups of patients who have different needs concerning treatment, prevention, and lifestyle. Patients who have suffered a spinal cord injury make up one specific group. This set of patients has usually lost the ability to move parts of their body and thus, especially in the case of quadriplegics, cannot move themselves. They also have lost sensation in parts of their body. This means they do not know when they must shift their body positions and this puts them at a higher risk for forming pressure ulcers. Comatose patients, patients with severe mental illness, and patients with severe malnutrition will be at similar risk as those with spinal cord injuries, in that they are bedridden and unable to move themselves (Ayello & Braden, 2002).

Another group of patients who are at risk are the elderly. This group is more likely to spend long spans of time sitting in a wheelchair or lying on a bed. Reasons for this can range from a broken hip to the onset of Alzheimer's disease. The elderly are also at a higher risk than younger patients because they are more likely to be nutrient deficient and have poor blood circulation (Torpy, 2003).

Nutrient deficiency and poor blood circulation put obese people who are bedridden at risk. When someone becomes too obese to properly move themselves on a regular basis they are at very high risk of developing pressure ulcers. This category of patient is also known for having excess moisture on their skin, putting them at increased risk. This can be caused by poor hygiene concerning bowel movements and urination, or by excessive perspiration (Ivory, 1999).

The last group of people who have recently been targeted as high risk for pressure ulcer development are those patients who are going through surgery. Anyone who must undergo an operation lasting in excess of three hours becomes at risk for a pressure ulcer because they will be paralyzed and anesthetized and thus unable to reposition themselves. In addition, patients recovering from surgery often cannot move from a specified position and thus are at risk (Ivory 1999).

The majority of research for this project will be concerning mattresses. However, there are many other factors that need to be considered when dealing with pressure ulcers. Nutrition, hygiene, and hydration all play significant roles in the development of pressure ulcers because these factors contribute to a patient's ability to fight off infection, promote good blood circulation, and maintain resilient healthy skin and muscles.

2.3 Pressure Ulcer Prevention

Pressure ulcers affect a large population of patients, and each ulcer costs health care facilities a large amount of money and staff time. The recurrence rate of pressure ulcers in these patients is very high, meaning that even more money must be spent to heal these patients. This is why prevention of pressure ulcers is so important and has become a major concern of hospitals and industry.

The most important treatment used to prevent pressure ulcers is the regular rotation of patients. However, this method of prevention is also the most expensive. Take the rotation of a paraplegic burn victim as an example. It may take two to three nurses 15 minutes to correctly rotate this patient. This kind of intensive care is costly to hospitals because of the wages of nurses and the time that it requires. Most patients that are at risk for pressure ulcers must be rotated every two hours. This rotation usually occurs in three stages, where the patient lies first on their side, then on their back, and finally on their other side. Depending on the susceptibility to pressure ulcers, some patients must be rotated more often. For example, new spinal cord injury patients need to by rotated once every half hour in the first weeks following their injury. Also, wheelchair patients often need to shift their weight every hour to every 15 minutes (European Pressure Ulcer Advisory Panel, 2002).

Hygiene also plays an important role in the prevention of pressure ulcers. When any excess of moisture forms on the body the risk of pressure ulcer development is increased. This is why it is important to wipe off any excess perspiration from the patients, and thoroughly clean any excrement from the body. It is also helpful to avoid using materials on the patient such as rubber, which may cause moisture formation on the skin. However, it is also important to maintain skin that is not dry and flaking. If dryness occurs, lotions or oils are used to relieve the patient's dry skin (Ivory, 1999).

A key factor in the prevention of pressure ulcers is to promote circulation to all areas of the patient's body. If more blood reaches the skin and muscles then it will be healthier, and have less chance of tissue death or infection. In order to optimize blood flow it is important not to place pillows under the knees of a patient. This is common practice in heath care facilities, but often causes loss of circulation to the lower legs. Doughnut shaped pillows should also be avoided because they diminish blood flow to areas of the body where the pillow is placed, especially the buttocks. A good way, though, to improve a patient's circulation, and to help relieve muscular discomfort, is to provide them with whirlpool or hot tub with stimulation (EPUAP, 2002).

Another method of improving circulation is electrical stimulus. This new method arose from the hypothesis that since pressure ulcers are caused by pressure, the best way to prevent them is to increase a patient's resistance to pressure. In order to do this, doctors send pulses of high voltage electricity through a patient's skin and muscle. It is done mostly in patients who have lost feeling in their tissue or cannot send signals to their body to move themselves. This treatment not only helps prevent pressure ulcers from forming by increasing the patient's resistance to pressure, but also can help heal existing pressure ulcers by stimulating growth of necrotic tissue. A stimulation of any kind to these patient's tissues has been shown to increase the oxygen levels in the tissues and thus cause skin and muscle to be better nourished and therefore healthier. This is an important recent discovery because it allows for patients to be rotated less frequently which reduces the cost and effort of pressure ulcer prevention (Biundo, Mawsom, and Siddiqui, 1993).

Nutrition is a prevention factor that can be applied to every person susceptible to pressure ulcers. A balanced and healthy diet can help provide the nutrients the skin and muscles need in order to prevent irritation and death of the tissue. This diet should include a daily multi-vitamin that contains plenty of vitamins A, C, and E. It is also important for the patient to eat plenty of calories, especially proteins that are essential for tissue cell reproduction (Ayello & Braden, 2002).

Besides specific treatments, the general care of patients makes a significant difference in their resistance against pressure ulcers. General instructions for caring for a patient at risk for developing pressure ulcers should include not massaging over boney areas of the patient, which can increase existing skin aggravation; lifting patients when rotating them, because any drag or shear force on the skin can cause irritation; and elevating the head of the patient as little as possible, especially not over 30 degrees. A slant in bedding can cause a patient to slowly slide down the bed, causing great irritation from shear forces (EPUPA, 2003). The bedding should also be kept clean and smooth in order to prevent moisture or folds in the material which can aggravate the skin. Finally, the patient's joints and harder areas should be kept from coming in contact with other parts of their body. A good strategy for this is to place pillows in between, not under, the patient's knees and ankles (Ivory, 1999).

Finally, it is important to remember that helping a patient gain their own movement can be the best way to prevent pressure ulcers from forming. Rehabilitation programs are the key to a patient's independence and permanent evasion from pressure ulcers.

2.4 Current Testing Methods

There are three main types of testing methods currently being used to test mattresses for pressure on a human body. These three types are human volunteers, a mannequin and a domed indenter (Bain, Scales & Nicholson, 1999). Each of these testing methods has advantages and disadvantages. It is beneficial to understand all testing methods, so as to better understand the mechanics behind pressure testing.

2.4.1 Human

The first type of testing method commonly used involves the use of human volunteers. In these clinical trials, subjects are usually those who are 55 or more years of age (Nixon, McElvenny, Mason, Brown, & Bond, 1998). The interface pressure on the heels, buttocks, sacrum (portion of the pelvis above the tailbone), and the tailbone is measured. These are the sites where pressure ulcers are most often seen (Wang & Lakes, 2002). Nixon et al. (1998) used human subjects, but did not measure the pressure on the different types of mattresses, and just looked for the prevalence of pressure ulcers developing.

The use of human subjects has some benefits and disadvantages, although many of the disadvantages prevent widespread use. One benefit of this method of testing is a decrease in need for engineering expertise. Engineering issues include the design and construction of a machine to gather the pressure data that currently are being gathered using human subjects. Another engineering issue that does not have to be addressed using this method is the ability to explore the effect of interface pressure on soft tissue blood flow. A third and final benefit is that scientists do not have to re-create the influence of layers of skin, muscle and fat on pressure measurements, because human volunteers have real layers of skin, muscle and fat.

There are many drawbacks as well (EPUAP, 2002). The most prevalent disadvantage is that tests cannot be reproduced, even with the same patient. Reproducible data is important, it provides a basis for measuring precise information, and gives a means to compare data (EPUAP, 2002; Bain et al., 1999; Shelton, Barnett & Meyer, 1998). A second drawback is that in order to test numerous human patients in different positions, it takes more time than using a mechanical device (Bain et al., 1999; Nixon et al., 1998). Another disadvantage is that the use of human subjects does not allow for a standardized product ranking, because the data can not be reproduced and hence any data gathered has much uncertainty and little reliability. Finally, a problem occurs from the placement of sensors on a subject's skin. The sensor is not natural, and hence increases the pressure on the skin (EPUAP, 2002; Bain et al., 1999). In spite of these difficulties, human testing is still occurring because of the advantages related to a less complex technology when compared to other methods, but the field is shrinking and there is an ever growing field using mannequins.

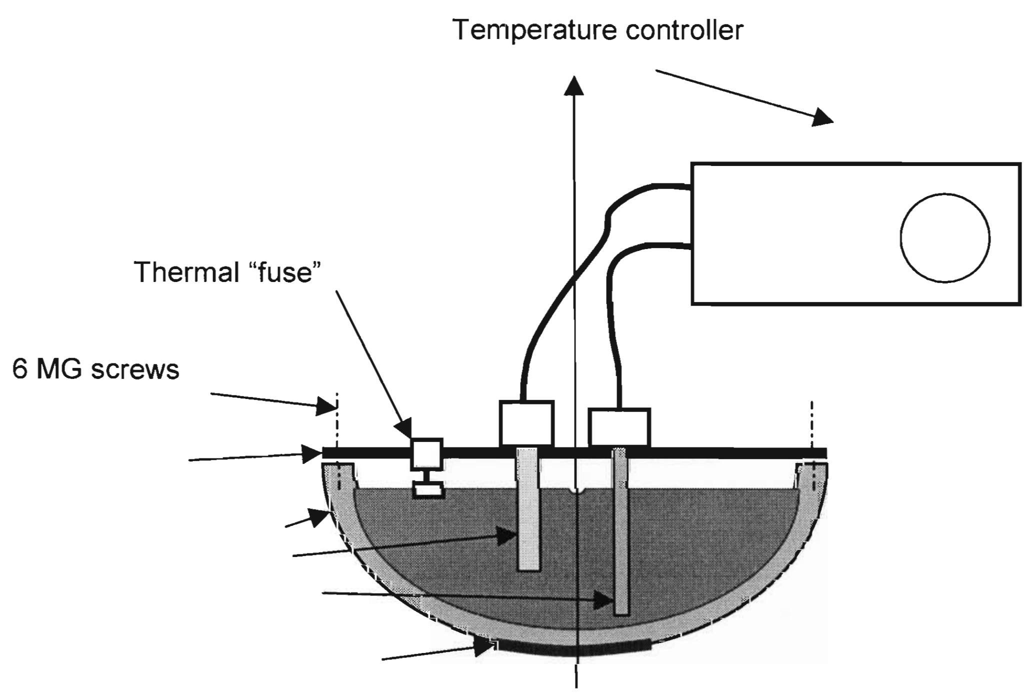
2.4.2 Mannequins

Human-like mannequins are slowly becoming the dominant type of pressure tester used in studies. The European Pressure Ulcer Advisory Panel (EPUAP) recommends the use of these mannequin types for a better comparative ranking of support surfaces (2002). The mannequin test is usually performed in three positions, with three different body sizes, one representing the 95th percentile, one representing the 50th percentile and one representing the 5th percentile of body types of elderly Americans (EPUAP, 2002; Shelton et al., 1998; Goossens & Snijders, 1995; Bain et al., 1999). The mannequin developed by Shelton, Barnett and Meyer uses latex foam and polyurethane coated fabric to simulate human muscle, fat and skin layers (1998). The mannequin developed by Bain, Scales and Nicholson, known as the phantom, uses a soft elastic silicone polymer compound (1999). Both these devices follow the preliminary guidelines of the EPUAP with joints at the hips, knees, shoulders and neck (2002). There are three different arrangements of pressure sensors currently used. In the first possible array, the sensors are placed on the bed or backrest the mannequin is laying on, the second is where the sensors are integrated onto the mannequin's body; and the third is a full body sensor system (Shelton et al., 1998; Goossens & Snijders, 1995; Bain et al, 1999).

The human-type mannequin is used for a variety of reasons. First, the results are reproducible, and reliable (EPUAP, 2002; Bain et al., 1999; Shelton et al., 1998; Goossens & Snijders, 1995). This method of testing also allows for an accurate representation of how pressure is distributed over the surface of a body (Bain et al., 1999). There are disadvantages with this system too. The use of this type of mechanical device can not measure factors such as heat and water vapor transfer, and effects on the circulation of blood (EPUAP, 2002; Bain et al., 1999). The EPUAP has no definite opinion on whether or not the mannequin should be heated to achieve skin temperatures (2002).

2.4.3 Domed Indenter

The third type of measuring device used is a domed indenter. It can measure not only interface pressure, but also the indentation hardness (Bain et al., 1999). The domed indenter measures quite accurately the reaction of the mattress to human buttocks, which is the site on the body where pressure ulcers most often occur (Bain et al., 1999). The domed indenter, adapted from a testing center in Sweden by the Danish Center, measures both normal pressure (perpendicular to the mattress) and the shear force (by dragging across the surface of the mattress) (Wolff, 2002). This domed indenter also measures the temperature of the indenter surface (see Figure #1 below). The thermostat, which measures temperature, is located in a body of water, which is surrounded by the aluminum shell of the domed body (Wolff, 2002). The indenter body is normally kept at human body temperature (37^{O}C) but the scientist does have control over the temperature, and therefore can increase or decrease the temperature if so desired (Wolff, 2002). A sensor at the bottom of the domed indenter measures the pressure, where the pressure is expected to be highest.



Lid

Indenter body

Heater

Thermal sensor

Force sensor

Figure 2.1- the dome of the domed indenter (Wolff, 2002)

One of the disadvantages of this type of device is that results depend on the geometry of the spherical indenter. Furthermore, if the outer body is distorted from its original shape over time, changes can be seen in data gathered, due to changes in geometry of the body (Bain et al., 1999). The domed indenter used by the Danish Center has a rigid outer shell, however, other designs may have non-rigid materials to simulate tissue.

2.4.4 General Practices

All three of these methods use statistical analysis afterwards to interpret their results. Statistical and computer programs are used for interpreting the data (Bain et al, 1999; Nixon et. al.,1998 ; Shelton et al., 1998; Goossens & Snijders, 1995; Wang & Lakes, 2002). The measured output of typical experiments are the interface pressures, which are the perpendicular forces exerted by a segment of skin on a support surface divided by the skin contact area (Bain et al, 1999; Nixon et al., 1998; Shelton, et al., 1998; Goossens & Snijders, 1995; Wang & Lakes, 2002).

There are a few guidelines and commonly followed procedures for pressure testing on mattresses. If a mattress is not covered when received, a generic hospital sheet is to be draped across the mattress (EPUAP, 2002). When using mannequins, it is standard practice that at least three positions, and at least six trials at each position are measured (EPUAP, 2002). A final common procedure is to have a time delay when measuring, so that the mannequin, domed indenter, or human volunteers can be properly situated before a measurement occurs, this allows for visco-elastic creep, which is a time dependent property of materials (Bain et al., 1999).

2.5 Mattress Types

This section will discuss the different types of mattresses, and mattress types used to prevent pressure ulcers. These types are constant low pressure (both fluid and foam) and pressure alternating (also called dynamic). Each type helps decrease pressure in their separate ways.

2.5.1 Constant Low Pressure

2.5.1.1 Foam

Foam mattresses have many different forms, and are the most prevalent mattresses made (Cook & Hussey, 1995; Australian Wound Management Association (AWMA), 2001). There are two different kinds of foam. The first type is closed cell foam. These foams are composed of individual structures encased in membrane. This type is less compliant than open celled foams. They also restrict airflow (Cook & Hussey, 1995). Open cell foams, on the other hand, have interconnected perforated membranes. This structure allows for airflow between cells, and absorption of liquid. The open cell foam's cell size can be controlled, which controls the density of the foam. The change in density changes the amount of air absorbed by the mattress when it is made. Foam mattresses are often a mixture of open and closed cells, so that the advantages of each type of foam can be found in one mattress (Cook & Hussey, 1995).

Some of the advantages of foam mattresses are they are some of the least expensive type of pressure ulcer prevention mattress. Also, because foam compresses when a weight is applied, when a patient lies on a foam mattress, the patient is enveloped by the mattress. Unfortunately envelopment helps to trap heat close to the body, which is an undesired property (Cook & Hussey, 1995). Other advantages are that foam mattresses are lighter, have minimal maintenance associated with them, do not puncture or damage easily, and they are shown to help prevent pressure ulcers with those who have a low to medium risk (AWMA, 2001).

Foam mattresses have a life of only six to twenty-four months, making it imperative to change them often. This means that when testing them, we will need to consider an aged foam mattress as much as a new one. Also, foam should not be too soft or too thin, otherwise a patient would bottom out on it, and it would not relieve pressure. Finally foam traps perspiration, odors and stains easily, causing problems in cleaning (AWMA, 2001).

One type of foam mattress that has gained world-wide fame for its pressure relieving properties is the tempur-pedic foam. The tempur-pedic foam shapes itself to the user's contour, enveloping them in a stable pocket. The tempur-pedic foam is made up of small visco-elastic spherical memory cells, which differ from the conventional foams that are made from elastomeric polymers like polyurethane and latex. The tempur-pedic foam is temperature sensitive so that warm areas are more malleable than cooler areas. Furthermore tempur-pedic foam spreads the pressure out from the hips, arms and shoulders to the rest of the body, creating a much lower pressure over the entire body (Wheeler & Peterson, 1998).

2.5.1.2 Fluids

Fluid mattresses are filled with elastomer gels, water, air, or a viscous liquid (see glossary for viscosity). Elastomer gels are high viscosity fluids, which have basically no flow. They have good dampening and thermal properties (Cook & Hussey, 1995; AWMA, 2001). Short and long term resilience, the ability for a mattress to return to its original properties, are not very good, neither is the envelopment of the patient. The gel is contained in a cushion because it is a liquid, and thus, the properties of this covering cushion too can affect the overall properties of the mattress.

The second type of fluid filled mattresses is filled with water. Water has a low viscosity, so allows for lots of flow of fluid. The flow of fluid allows for a change of pressure, and allows for a swimming type feeling. Good short-term resilience is one of the benefits of this type of mattress. There are several problems though; the water mattress is very easy to puncture, and is heavy which makes it hard to move, transport and set up (Cook & Hussey, 1995; AWMA, 2001). Because of these problems, water mattresses are no longer being produced, and no longer being used in hospitals.

The third type of fluid filled mattresses is air filled. One example of an air filled mattress is the Optima, which has 21 double air bags as a base (Cullum, Deeks, Sheldan, Song, & Fletcher, 2000). Static air mattresses are found to be effective compared to standard mattresses, but they have some problems (Cullum et al., 2000). Air mattresses are easy to puncture, and can increase shear forces on specific patients, mostly those who are petite, as they can be positioned between two air cells (Cook & Hussey, 1995; AWMA, 2001). Air mattresses though are more effective than other fluid filled mattresses (Cullum, et. al., 2000).

The last type of gel mattresses is the viscous fluid filled mattress. This mattress is filled with a less viscous liquid than the elastomer gel. This type of mattress has a slight flow, due to the lower viscosity. These mattresses conduct heat away from the body well, like the other gel mattresses. As well as having a slight flow, these mattresses have good dampening properties. Unfortunately, they also have less resilience than the previous two types. Basically all three types of gel mattresses have good dampening properties, low resilience, and good heat conduction away from the body (Cook & Hussey, 1995).

All types of static pressure relieving mattresses though, do not alleviate pressure enough. There still needs to be a rotation schedule for the patient, so that pressure can be relieved at times from an area, and circulation can return to normal (AWMA, 2001).

2.5.2 Alternating Pressure

Alternating pressure mattresses are the most advanced and technically involved mattresses on the market. Instead of trying to re-distribute pressure over the entire body, these mattresses try to rotate the pressure. The theory behind these types of mattresses is that parts of the body can tolerate high pressures for a certain amount of time (Cook & Hussey, 1995). Alternating pressure mattresses place pressure on some of the weight bearing areas of the body, while relieving pressure from others (Cook & Hussey, 1995). This is the most technologically advanced approach and is most often used for those patients who have conditions where they shouldn't be moved. The AWMA suggests these types of mattresses are best for people at high risk for developing pressure ulcers (2001). Unfortunately, these are also the most expensive beds, costing around 6,000 US dollars (41.500 DKK) (AWMA 2001).

2.5.3 Mattress Covers

Covers to cushions are another aspect besides mattresses that needs to be discussed when talking about prevention of pressure ulcers. Using a cover not suited to one's mattress and problems can cause as many problems as using the wrong type of mattress. According to Cook & Hussey, a cover should contour to the surface of the cushion (1995). If a cover is to big, wrinkles can cause increased shear, and if too small, can cause decreased flexibility in the mattress. Covers should also permit limited air exchange but limit liquid accumulation. The EPUAP recommends that custom covers should be left with their respective mattresses, instead of removing and placing a different cover on them (2002).

2.6 Danish Center for Technical Aids and Rehabilitation

The Danish Center for Technical Aids and Rehabilitation is a Danish organization that oversees the testing of hospital beds, mobile and stationary hoists, and adjustable beds and work chairs for the disabled. They, along with labs in the other Nordic countries, provide certification for all hospital equipment.

Currently the center is looking to extend their testing to mattresses, specifically to address the relationship between mattress properties and the development of pressure ulcers. Our project aims to fill this void, by providing extensive testing of both their tester, and relating those results to the tested mattresses. Our primary contact for the duration of the project was Mr. Bruno Wolff of the Danish Center. The Danish Center provided a workspace environment and a laboratory to conduct the research.

3 Methods and Outcomes

The project involved the collection and analysis of data from the Danish Centers' domed indenter regarding mattresses used in the Bispebjerg Hospital in Copenhagen. To facilitate this our initial methods focused strongly on familiarizing ourselves with the protocols and test procedures relevant to the domed indenter, pressure ulcer prevention and treatment procedures, and mattress policies at the hospital.

At the Danish Center, evaluation of all testing methods and protocols relating to the domed indenter took place. The review of protocols and general literature helped identify important testing variables and their effect on the precision and accuracy of the test output. This review also helped to establish which variables are important to relieving pressure on a patient, and how to test for these variables. The information obtained from this review was then critically analyzed to form the optimum protocol for testing mattresses for their ability to prevent pressure ulcers using the domed indenter. These methods effectively allowed for important mattress properties to be measured accurately on many different types of mattresses.

3.1 Initial Testing of Domed Indenter

The initial phase of data collection focused on the team becoming more familiar with the domed indenter device and its setup. This phase involved researching the technical aspects of the tester's design, observing researchers at the Danish Center as they operated the device, and gathering our own sample data. These preliminary data are not included in the final report, but instead have provided our group with a better understanding of how the domed indenter works, procedures for use, and the output the device is capable of producing.

The testing experience helped to determine a standardized approach to the collection of data from the domed indenter. It also helped identify variables in the testing procedure that caused incorrect results. Previously the Danish Center had not extensively tested the device, therefore this initial testing period was very important step that needed to be performed before writing protocols and gathering of data could take place.

The initial testing led the team to discover that the domed indenter did not produce results that were reproducible or accurate. Therefore, in its initial state the domed indenter could not be used to collect data that could be used to compare mattress properties. To solve this problem, a series of improvements were made to the domed indenter with the help of Bruno Wolff, the original designer of the domed indenter. This period of improvement included the addition of new transducer joints, point sensor adaptation, and an inner tube to outer tube connection collar replacement. The details of these improvements are given in later sections of this report.

3.2 Protocol Development

A major goal for the project was to deliver to our sponsor a recommendation for a final protocol for the Danish Center's domed indenter. The protocol that was provided allows for reproducible, accurate and informative data to be gathered through use of the domed indenter. These protocols also allow for information to be gathered from mattresses, so that mattress's properties may be evaluated and compared. The first step to reach this objective was to research protocols for other testing methods, which can be applied to the domed indenter. The protocols were also investigated to find which properties in a mattress where most important to pressure ulcer prevention.

Danish, European, and American testing procedures for many different testing devices have been investigated in search of the most relevant procedures. These protocols covered all means of testing for pressure ulcer reduction in mattresses. This search has led us to a handful of private testers who devise their own test procedures. Unfortunately, there are no set standards for mattress testing concerning pressure ulcers in North America, Denmark, or the European Union. Thus all testing information we gathered was from private companies who had set their own standards regarding testing of mattresses for pressure ulcer prevention. Most of these standards only require mattresses to reduce pressure on any area of the body to 32 mm of mercury. This requirement dates back to the 1930s, according to Brent Larson of Stork Twin City Testing (2003), and shows insignificant progress towards development of new mattress standards and tests.

The different protocols and testing methods that were considered came from articles that were either found in the United States, or were provided by the Danish Center. The papers come from many different experts in the field of mattress testing and contained numerous methods of testing both mattress and wheelchair cushions, using mannequins, human subjects and indenters. The testing methods and protocols, regardless of testing style, were analyzed in order to apply them to the domed indenter, where possible. For example, some of the testing protocols for mannequins use weights of 30, 60 and 90 kilograms to provide force on the mattresses. The scientists that use this technique feel that these specific weights provide the best data for analysis of different human body types. In similar fashion, our investigation of different values of normal forces on the mattresses were explored in order to find what amount of force accurately represents different parts of a human body, on different size humans. When it was not possible to apply different testing methods to the domed indenter, the researched methods were not forced into the testing procedure, but instead they were utilized as background knowledge to be considered when making further recommendations.

The domed indenter protocols were created using the information gathered from the background material combined with a working knowledge of the domed indenter. The protocols test for point pressure, visco-elastic properties, and pressure/depth relationships in a mattress. These properties were found to be the most important for pressure ulcer reduction and characterization of mattresses.

3.3 Mattress Testing

In total, nine mattresses were tested using the domed indenter. Five of the mattresses were borrowed from the Bispebjerg Hospital and the other four mattresses belonged to the Danish Center. The testing followed the protocols that were created for the Danish Center, and was completed from March 16, 2003 to May 5, 2003.

As the protocol states, the first test run on each mattress was an indentation test. This test indents the dome of the domed indenter into the mattress at a slow rate until bottoming out occurs. The pressure on the dome is recorded and displayed throughout the test so that analysis can be made later.

The second test indents the dome of the domed indenter into the mattress to a specific depth at a relatively high speed and then remains at the given depth for eight minutes. This tests shows how the pressure on the dome drops over time, and is used to find the point pressure on the dome after the mattress has "settled."

The data that were recorded from these tests were stored as text files. The text files were then imported into Microsoft Excel and analyzed using a series of graphs and tables. Finally, the data were stored in a Microsoft Access database that was developed specifically for this purpose.

3.2 Danish Center and Hospital Collaboration

Improvement of the working relationship between the Danish Center and local medical professionals, especially those at Bispebjerg Hospital, was a goal of the Danish Center for this project. In order to accomplish this goal, meetings were held not only at the Danish Center, but also with the staff from the Bispebjerg Hospital's Wound Care Center. Information and ideas that were important to the implementation and development of this project were exchanged. The professionals at the Bispebjerg Hospital included nurses, therapists, and doctors who deal first hand with those affected by pressure ulcers.

An initial meeting was set up with the project team and professionals including Bruno Wolff, Dr. Bo Jorgenson, who treats pressure ulcers at Bispebjerg Hospital, and Tom Jorgenson, a physical therapist who works with patients who develop pressure ulcers. After this meeting, a secondary meeting was arranged between the primary project team and Susan Bermark, a head nurse at the Wound Healing Center, who had recently completed a study on pressure ulcers throughout the entire hospital complex. There were many useful outcomes gained from these meetings. First, future projects and areas of research were identified and discussed. This included the team testing hospital mattresses using the domed indenter, and future testing of hospital mattresses, which could be done by the Danish Center on a yearly basis. Also, new ideas were generated as to what data were available from the hospital. These data came from the prevalence study that will continue in the hospital until the beginning of May 2003. These data could not be given to the team because the study was not finished, but it will help the hospital prevent pressure ulcers in the future and may help link mattress properties to pressure ulcer prevention. Finally, information concerning important qualities in mattresses was also discussed. This included the exchange of ideas regarding static and kinetic shear forces in particular.

Through this interaction, the Danish Center and the Bispebjerg Hospital improved their communication network by creating personal contacts as well as a possibility for future collaboration.

4 Results and Analysis

The following section discusses the results that the project team developed at the Danish Center. The discussion includes information on the initial testing with the domed indenter, modifications to improve the domed indenter, interactions with the Bispebjerg hospital, the development of mattress testing protocols, and collection of mattress test data.

4.1 Basic Domed Indenter Structure

To understand the team's actions taken at the Danish Center, it is important to understand the domed indenter that was used. The indenter is capable of vertical and horizontal movement that is driven by electric, manually activated motors. The speed is set by dials on the device. The total force that is put on the dome head is read by three transducers which connect the dome to the shaft of the domed indenter. This force is displayed on an analogue readout on the device, or on a computer.

The dome has a shaft attached to it that runs to the top of the domed indenter. The weight of the dome and the shafts are supported by the transducers which are attached to an outer shaft that runs parallel to the inner shaft on the dome. The outer shaft is supported by a metal frame attached to the wall at the Danish Center.

The weight of the inner tube and the dome puts the transducers in tension when there is no force on the bottom of the dome. As the dome is indented into a mattress the force on the dome lessens the tension forces on the transducers. This change is measured and given as an output in voltage.

The inner and outer tubes are connected by a frictionless collar at their respective tops. This connection assures that the dome will remain vertical and only move in the vertical direction. For further insight please refer to the diagrams found in Appendix 6.

4.2 Alterations to the Domed Indenter

During the initial testing period it was found that the domed indenter did not record data in a reproducible or accurate manner. In the weeks following this initial testing many experiments and alterations were made to the equipment. These experiments were conducted in order to isolate the components that may have been causing the incorrect data. Alterations were made to the device in order to correct the inaccurate readings. The final product was a reliable and precise domed indenter, which can be used to collect data that may be used as a tool in analysis of mattress properties.

4.2.1 Offset Problems and Testing

The preliminary tests that were run consisted of using the domed indenter to travel into a visco-elastic foam mattress and then exit the mattress. The tests were run at different speeds, temperatures, and depths in order to gain a basic understanding of what the output of the machine would be, and generally how each variable would affect the outcome. When indenting the domed indenter beyond 4cm into the visco-elastic foam mattress the pressure reading exhibited a residual value of 20% of the maximum load. This was seen when the domed indenter was elevated above the mattress after a measurement had been recorded. When the flange (see diagrams of domed indenter appendix D) was moved manually the force readout diminished back to zero, to a higher reading or into the negative range of values. Two hypotheses were considered to explain the residual readings. First, it was possible that at loads in excess of some threshold value, the ball joints might stick, and when the flange was moved the ball joints became free and movable again, decreasing the load on the transducers, and thus the output returned to zero. Second, it was possible that the inner tube shaft had too much friction with the guidance piece at the top of the device (please see appendix D), and when the flange was moved the static friction in the shaft was overcome, and the shaft descended back to its original position. However a significant change in position of the shaft after pulling the domed indenter out of the mattress was not noticed.

The purpose of the next experiment was to investigate if the movement of the indenter into the mattress caused the offsets, or if it was instead the movement of the domed indenter out of the mattress. Initially the indenter was moved from 1cm to 6cm into a mattress. Readouts from the force transducers in millivolts on a digital multimeter at each cm increment, after one minute of settling time for the mattress, were recorded. The domed indenter was then elevated out of the mattress, and the offset on the multimeter was recorded. Next, the indenter was moved into the mattress 1cm, the voltage recorded after one minute, then moved back out of the mattress, then moved in to a 2cm indention and repeating this process until a 6cm indention was reached, where the offset was noted. Finally, a repeat of the second method was done, but not only was the offset noted at each centimeter, but the offset was corrected by moving the flange before a new indentation took place. Results can be seen below in table 4.1, where method 1 is the first experiment described method 2 the second described, and so on.

Table 4.1 – Transducer Readings for Initial Indentation Tests Including Residual Offset				
Depth (cm)	Reading1 (mv)	Reading2 (mv)	Reading3(mv)	Offset3(mv)
0	0	0	0	
1	2,5	2,2	2,6	-0,4
2	5,4	5,2	5,5	0,3
3	9,5	8,9	9,5	0,9
4	14,4	12,8	14	0,9
5	18,7	14,5	19	1,6
6	24,6	18	35	3,3
0	-5.7	3,8		

From these data, it was reasoned that the error was mostly occurring at indentation depths greater than 5 cm. After completing the data taken above, another data set for the third method and the first method were taken. It was decided that the second method was not as accurate. This was because if the person using the device was to take the indenter out of the mattress each time, and not note the offset on the machine, it would not be an accurate recording of the data that is possible to measure, nor would said method optimizing the tester's ability to test for pressure, as error would be increased by not noting it and correcting it. Results can be seen in table 4.2

Table 4.2 – Transducer Readings for Initial Indentation Tests Including Residual Offset (second test)				
Depth (cm)	Reading3 (mv)	Offset3 (mv)	Reading1 (mv)	Offset1 (mv)
1	3,2	-0,4	3	
2	5,8	-0,5	5,5	
3	9	0	11	
4	13	0	14	
5	21	0,9	19	
6	31	1,4	26	0,9

From these data, it was seen that the data are not significantly dependent correcting the offset between each trial. It was concluded that re-zeroing the tester before the start of each indentation test is a more reliable method of testing, because it was noted in the completion of these trials, that the offset went down over time, so if the domed indenter was used again, the offset would then become uncertain. Unfortunately, the experiments did not determine where the problem was occurring, and further testing and adjustment is needed.

In theory, the method of testing with the domed indenter (by indenting a mattress) is appropriate; the problem lays in the construction and manufacturing of the domed indenter and not in the theory and design of it. Also, what was discovered and concluded during this test, re-zeroing the transducer outputs is needed between each indentation depth, is not an accurate way of testing for normal force. The project team decided that the best method to move forward was to try to fix the problem, to get reproducible data, with no offset when an experiment was completed.

The first two ideas tried were to reduce the friction within the ball joints and at the top of the shaft, where the machining is rough, and the inner tube could be catching on the collar of the outer tube. To do this graphite powder and liquid silicon based lubricants were applied to the joints. Even though there was a slight relaxation in the joints, the results continued to be inaccurate and further measures needed to be taken.

4.2.2 Eliminating the Friction

4.2.2.1 Inner Tube Collar

Scientists in the lab of the domed indenter were very concerned with the connection between the inner tube and the collar at the top of the device (see Appendix D). This connects the inner and outer tube of the machine in a theoretically frictionless manner. This connection is made in order to stabilize the dome during normal and shear force testing. It was believed that the joints connecting the two tubes were subject to a great amount of friction, and therefore may be the cause of the inaccurate readings being obtained from the domed indenter. The rough machining of the collar parts, which connect the two tubes, would most likely cause the friction.

The upper joints connecting the tubes were investigated thoroughly by removing all the parts surrounding them. They were then lubricated using a graphite powder. After lubrication, tests were resumed. Unfortunately, the inaccurate readings continued just as before. This led to the conclusion that the connection between inner and outer tubes was only part of the source of distortion, and thus other areas of the tester should be in investigated.

In order to investigate the upper tube connecting joints in a more thorough manner the dome of the indenter was removed. This allowed for a person to manually move the inner tube up and down while it was still in place. This movement allowed the tester to feel in a qualitative manner the amount of friction in the collar. This friction was significant and needed to be relieved. The friction was high enough that lubrication would not be substantial enough.

To relieve this friction the interlocking piece of the outer tube, which was made of plastic, was replaced with a steel version. This new part was made to reduce friction caused by the flexibility of the plastic, and the rough machining of the part to begin with. The new piece was of the same design as the old.

4.2.2.2 Transducer Joints

The three large transducers used to measure shear and normal forces were examined. Each of the three devices is identical, certified, and they have the same properties. Because of this uniformity, only one of the three transducers was sampled for testing.

To test the transducer, it was removed from the ball bearings that attach it to the domed indenter. Then the transducer was hung from one sensing end, perpendicular to the ground. Masses were then hung from the opposite sensing end of the transducer. One, five, and ten kilogram masses were used in the tensile loading because these values generally cover the range of forces put on the transducer during mattress testing. The value produced by the transducer with respect to each different weight is given in figure 4.1. The graph of these points (figure 4.1) shows a linear relationship in the force region of the transducer that was tested. It is also important to note that after each weight was removed the transducer returned to its original no-load value. These data lead to the conclusion that the transducers are accurate devices and are not at fault for producing the inaccurate data.

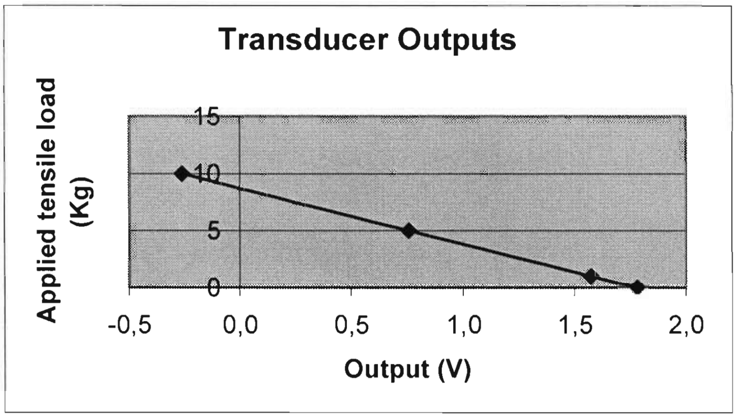


Fig. 4.1

A line graph of the load on a transducer compared to its corresponding voltage output. The result is a line, which shows that the transducer is linear in nature and is correctly calibrated.

The ball joints were the next area of the domed indenter to be investigated. To inspect the joints, they were then removed from the indenter flange and from the transducers. The ball joints were very stiff to the touch, and the force of gravity alone could not rotate the shafts. The joints were also "sticky" meaning that when attempting to manually rotate them, a high amount of force was needed to overcome the static friction in them. The intolerable level of friction in these ball joints led to the conclusion that they were the principal contributor to the inaccurate force readings.

Originally, a layer of machining grease lubricated the ball and socket, but this layer had disappeared. To try and reduce the friction in the ball joints, a lubricant was placed into the space between the ball and socket. First a graphite powder was placed and worked into the ball joint. This did not significantly reduce the joint friction. Next a silicon based liquid lubricant was placed and worked into a different ball joint. The improvement was significant; however the friction that remained in the ball joint was still too high to gather reliable results with. Finally, a combination of the graphite powder and silicon lubricant was placed into a ball joint. This did not cause significant reduction in joint friction. It was reasoned that no matter the amount of lubrication, the ball joints were not an acceptable option. Instead a joint needed to be found with both kinetic and static friction coefficients that were significantly lower than the ball joints.

In selecting a new option for the joints, three factors were deemed the most necessary. First, the joints needed to have a very low coefficient of friction. This was paramount, since the previous joints had led to as much as 20% residual error in force readings. Secondly, the joints needed to have the ability to rotate freely in order to accurately transfer force to the transducers. This rotation needed to be smooth, but did not require the joints to move more than 10 degrees during loading periods. The joint must be able to handle significant loads. The loads placed on the domed indenter consistently exceed 300 Newtons, and the joint needed to be able to handle these forces while maintaining a frictionless interface. Lastly, the joints needed to fit into the space provided on the domed indenter and needed to connect to the transducers and the domed indenter flange.

These criteria led to the selection of universal joints with needle bearings. First, they have very low coefficients of friction through their available range of motion. Secondly the joints could easily accommodate the range of motion that was anticipated. Their effective range for rotational power transfer was 45 degrees of motion, well above the set limits. Finally they were designed for high stress applications, and could handle loads in excess of 500 Newtons.

To accommodate the new joints in the current domed indenter design, a new method of mounting the domed indenter was required. The universal joints could not operate at greater than 45 degrees, so a system needed to be developed to mount them straight while maintaining the transfer of force from the mattress. To resolve this problem, a set of three brackets were manufactured for the lower end of the indenter, along with a socket approach for the upper connections of the transducers.

The lower brackets were manufactured at the Danish Center using steel brackets and welded reinforcements were placed on each side. These brackets were then mounted to the flange of the indenter, as shown in figure 4.2 below. These brackets allowed the joints to rotate with any movement of the indenter, while at all times maintaining an angle of less than 45 degrees. The upper brackets were machined outside of the Danish Center. The design needed to be different than the lower brackets due to space restrictions. They needed to support the force of the domed indenter, while adding no additional length to the transducer and joint unit. The bolt holds the joint inside the block, while securing both to the lip of the outer tube.

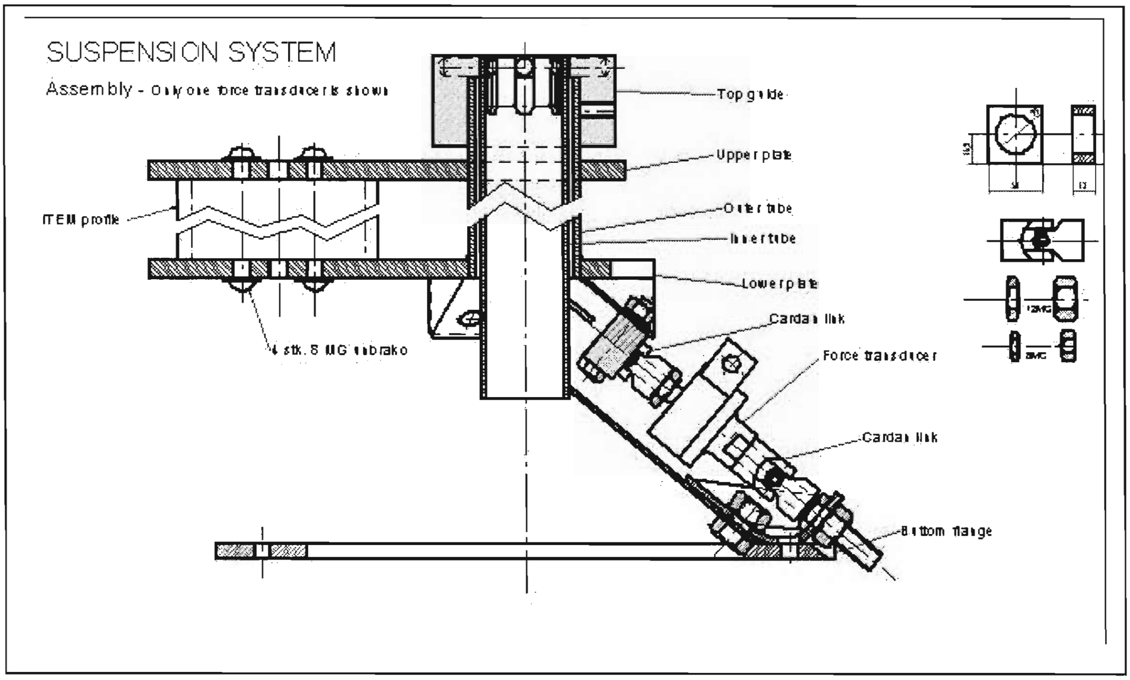


Fig. 4.2

Lower brackets for new joints, in place on domed indenter

After the replacement of the ball joints, the mattress testing team made a series of measurements to determine the reduction of error in the device. After extensive measurements, it was apparent that no load was supported by the joints after the test. The residual error was reduced from 20% to an acceptable level of approximately 0.5% with the new modifications.

4.2.3 Initial Testing and Improvements to the Point Sensor

During the familiarization process with the domed indenter, problems with the point sensor, located at the bottom of the dome, became apparent. If operating correctly the point sensor was expected to read the pressure at the bottom of the dome, which should be the highest pressure area when recording normal forces. However, during preliminary testing the sensor was able to respond only to hard or direct forces given by an object such as a person's hand pressing it, and showed no readings when entered into a mattress.

The ability to read the pressure at the bottom of the domed indenter is required for the domed indenter to provide the most meaningful data possible. Therefore it was decided that the sensor should be fixed before further exploration of the equipment and data gathering could be completed.

Brainstorming took place in order to find the cause of the problems with the point sensor and possible solutions to these problems. Through examination and experimentation it was determined that the lack of response to pressure was due to the arrangement of the sensor and not the actual sensing device, which was found to accurately respond to pressure when directly stimulated. It was then determined that the fault in the sensor could be attributed to a lack of contact being made with the sensing element, and uneven contact through each part of the sensor.

To solve these problems a greater understanding of the sensor was needed. The device was disassembled and each part was investigated for flaws. Through this evaluation it was concluded that the errors were caused by the uneven contact of the larger brass piece with the sensing device.

Brainstorming took place to help conceive ways of solving the problems with the point sensor. Ideas included using a water-filled bag to put pressure on the sensor, allowing the sensor to protrude from the device, creating more direct contact to the sensing mechanism, creating a new and better fitting cover to the sensor, and putting material behind the brass piece to stabilize the sensor.

The solution utilized consisted of placing a washer behind the brass piece going around the sensing area. This allowed for stability of the sensing unit without over-sensitizing the measuring area. Selecting a thin piece of material to push on the sensing area regulated the connection between the entire sensor and the sensing area. The final result was a sensor that kept the curvature of the domed indenter consistent, and accurately measured the point pressure at the bottom of the indenter.

Unfortunately, the tests using the newly rebuilt sensor still contained inconsistencies. Even thought correct data are initially given, the value of the pressure decreases with time. Testing on consistent surfaces such wood and homogeneous foam allow the conclusion to be made that even though the sensor is correctly built the sensing device loses value over time. The sensing device works by changing its conductivity in accordance with the pressure on it. However, due to possible heat transfer from the domed indenter and fault in the sensing material itself, the value the sensing material records diminishes over time and thus causes inaccurate readings.

It is important for testing that the readings of the point sensor be correct over long time periods. This is because many temperature sensitive mattresses will relieve pressure as they heat from a body or heated indenter, and thus continuous and time-dependent data must be obtained.

Further testing to see if the drop from the sensor was consistent and therefore predictable, took place. If this was the case, then readings from the point sensor could still be used to gain accurate data by adjusting the readings with changes in time as needed. However, after very limited testing it was easily seen that the drop of pressure readings decreased in an unpredictable manner. The original point sensor was determined to be unsuitable for this application. Therefore the original point pressure sensor was not used in any of the data collection process.

4.2.4 Replacement of the Point Sensor

The Danish Center purchased a new point sensor to be used with the domed indenter. This sensor is a small foam cushion, surrounded by a sack of air that can be placed anywhere. The sensor has a digital readout that displays the average pressure on the surface of the cushion in millimeters of mercury with an accuracy of +/- one millimeter of mercury.

This sensor does not fit into the housing of the original sensor in the domed indenter. Thus time was spent determining how the new sensor should be used. The two options were to make a new housing for the sensor or place the sensor on the outside of the dome.

Placing the sensor on the dome was the first option considered. The sensor was taped directly onto the bottom of the domed indenter. This allowed for point pressure readings at the bottom of the dome. However, these readings were very inaccurate. One reason for the inaccuracies is the sensor's protrusion from the indenter. This bulge causes not only a deviation from the indenter's spherical structure, but also a hammock effect from the material. The hammock effect is the act of the mattress or mattress covering directly around the protruding sensor not touching the indenter (Figure 4.3). Thus all the pressure from this extended area is placed on the sensor, causing inaccurately high pressure readings (Jay, 1995).

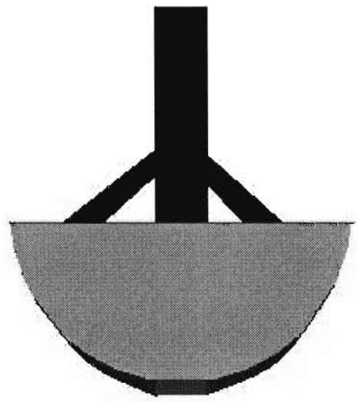


Fig. 4.3 Hammocking effect on point sensor.
The small region at the bottom is the protruding part of the point sensor. The slightly darker area is the "hammocked" area. All the pressure in the hammocked section is being artificially placed on the sensor area, causing falsely high pressure readings.

To solve this problem the second approach was used, in which the domed indenter structure was modified to house the point sensor. To do this the original sensor was removed. This left a 30mm diameter hole in the bottom of the indenter, which was over a centimeter in depth. The cushion on the new point sensor was 40 centimeters wide and stays approximately 4mm in thickness. This meant that in order to keep the spherical shape modification to the sensor area was needed. To create a housing for the new sensor five washers of 30mm in diameter were placed into the hole. This allowed for the cushion sensor to rest partly inside the indenter dome and partly outside the hole. The sensor was made to rest in a position that keeps the spherical nature of the domed indenter by altering the thickness of the washers beneath the sensor to create an ideal platform housing. Inflating or deflating the sensor using the device's stopcock and air syringe can calibrate the sensor.

4.3 Domed Indenter Weighing

The transducers on the domed indenter are in tension initially due to the weight of the dome, the inner tube, and all the equipment on the apparatus. It was important to know with what load on the domed indenter that the transducers would no longer be in tension, but in compression. In order to do this, the domed indenter and all parts connected to the inner tube were weighed.

First the domed of the indenter was weighed. In order to do this, the dome, and its carrying case platform were suspended by a force reading transducer (see figure 4.4 for visual aid). The dome was not lifted out of its carrying platform, because the strings became caught in the wood platform and carrying case due to the lack of clearance at the edges to get the domed indenter. The entire system was then weighed at 21kg.

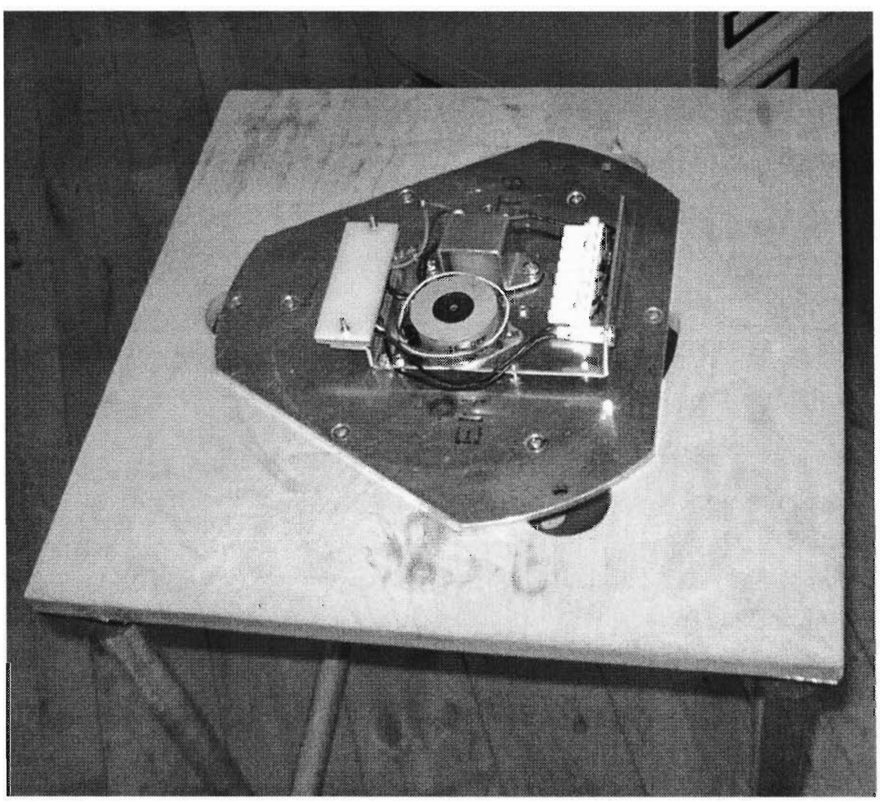


Fig. 4.4

Domed indenter resting in wood platform

The next phase was to measure the inner tube and the three transducers. The new joints and bolts that were placed on later were not measured because they were not a significant addition to the total weight. The inner tube and 3 transducers were weighed to be approximately 26.8 Kg.

The last phase was to measure the wood carrying case so that the weight of just the dome could be found. The carrying case weighed 10.7 Kg. Therefore, the entire inner tube and dome weigh 37.1 Kg, which does not include the weight of nuts, bolts and the new joints. It is estimated that this will add approximately 1 to 2 kg, which leads to an approximate total weight of 39 kg. In order to maintain a tensile load on the transducers during testing, the indention force should not exceed this value.

4.4 Time, Temperature, and Depth Dependence

In establishing an effective protocol for the Danish Center's domed indenter, consideration must be given to the effects of time, temperature and mattress indentation depth on mattress properties. Many simple and complex foam mattresses, such as the tempur-pedic brand mattresses, are very sensitive to heat, and react differently at different times and indentations, in some cases drastically changing their properties. Care must be given to ensure that all tests done using the domed indenter adequately address these issues, and adhere to established standards in mattress and cushion testing. The mattress testing team at the Danish Center extensively researched the issue, and conducted exploratory testing on various mattresses using both human subjects and the domed indenter.

4.4.1 Time Dependence

One of the central goals of the domed indenter is to measure the interface pressure of various mattresses. To successfully do this, the testing must take into account the effects of settling and memory of mattresses, two properties that are time dependent.

In their pilot study, Stinson, Porter, and Eakin (2001) analyzed many of the properties of wheelchair cushions, and established that data sampling taken at eight minutes best characterizes most of the settling exhibited by these cushions. In the period between zero and eight minutes, significant drops in pressure could be seen. After eight minutes they did not find further significant changes in pressure and concluded that mattress settling and changes in pressure due to memory were concluded after eight minutes.

In testing done at the Danish Center data collecting occurred using the domed indenter in a similar fashion as the Stinson paper. The dome was indented into a variety of tempur-pedic and standard foam mattresses. Readings were taken every 30 seconds over a 20 minute period. A slow decay of total force took place, and the decay stopped between six and seven minutes. Therefore, as in the tests conducted by Stinson et al., a constant pressure was maintained after eight minutes. This eight-minute period is used in the protocols for the domed indenter so that the full ranges of mattress properties are investigated during a test, and so that the domed indenter can help predict the effects of a person lying still on a mattress over an extended period of time.

4.4.2 Temperature Dependence

The domed indenter contains a heating control unit that can effectively heat the dome of the indenter to temperatures ranging from room temperature to well above human body temperature. The designers of the device intended that this heating unit could be used to heat the domed indenter to a temperature that would simulate the heat of a human body that was indenting a mattress. In order to create this situation, experiments were performed to find how warm a mattress becomes when in contact with a human.

To test for this mattress warmth, two human subjects were used. The subjects lay on a mattress for a period of five minutes (see table 4.3 for data). The temperature of the mattress was then recorded using an infra-red heat sensor. The testing using the human subjects made the best effort to simulate realistic hospital settings; blankets were placed over subjects with minimal covers between the simulated patient and the mattress surface. The experiment also took place using the domed indenter heated to 37 degrees C, which is the internal human body temperature.

Table 4.3

Test data for 5minute temperature changes on mattress

Test Subject	Initial Temp of Mattress Surface	Final Temp of Mattress Surface	Temperature of the Subject
Human A	22,1	29,6	28
Human A	23,1	29,8	27
Human A	21,8	29,2	28
Human B	21,8	28,4	28
Human B	22,8	28,0	28
Human B	21,0	27,4	28
Domed Indenter	21,8	36,6	37
Domed Indenter	23,6	34,0	37
Domed Indenter	22,2	35,3	37

The data above indicate that setting the domed indenter to 37 degrees does not accurately represent the effects of the human body on a mattress.

Further testing was conducted using a fifteen-minute window for temperature readings so that the mattress would be able to heat to the maximum temperature during the tests. These data are seen in Table 4.4.

Table 4.4

Test data for 15 minute temperature changes on mattress

Subject	Initial Mattress temperature	Final Mattress temperature	Subject temperature
Human A	22	30,5	28,0
Human A	22	31,3	27,5
Human A	22	30,7	28,0
Human B	22	30,9	27,6
Human B	22	32,6	28,3
Human B	22	29,8	28,2
Human B	22	32,5	27,1
DI	22	37,2	37,0

The data indicate that the setting of 37 degrees is not truly representative of human skin, and a different more appropriate value should be set on the domed indenter. From the fifteen-minute samples taken above, it is clear that 31 or 32 degrees would be more characteristic of actual human skin temperature. Susan Bismark, the nurse who provided the team with hospital mattress to test, stated in an interview that standard human skin temperature is 32 degrees C.

A final test was done to prove that setting the dome temperature to 32 degrees C is the correct temperature. This involved setting the domed temperature to 32 degrees C and indenting for a period of 8 minutes, which is the time that will be used in the device's protocols. The mattress was found to consistently heat to 32 degrees C thus proving this to be the correct temperature for the domed indenter.

These findings will be used in further testing with the domed indenter. Previously it was thought that 37 degrees would most accurately represent the human body heating effects on mattresses. After these tests the value of 32 degrees C was shown to accurately reflect the effects of the human body on mattress heating, and will be used in all subsequent tests with the domed indenter.

4.4.3 Depth Dependence

The goal of the domed indenter's tests is to measure the properties of different mattresses so they may be compared. All mattresses are not perfectly homogeneous and have limits to their abilities. A mattress's properties will change depending on how much load is applied to it, or depending on how far an object is indented into the mattress. The two variables of weight and depth are heavily correlated. For example, a heavy object will indent farther into a mattress than a light object if they have the same shape. Also, it takes more applied force to push an object farther into a mattress.

A large majority of expert testing using domed indenters and mannequins utilizes weight as the variable in order to simulate different-sizes of people who are laying on a patient support surface that is being tested. The common weights used are 65, 70, and 95kg, which represent the weights of the 5% 50% and 95% percentile of elderly adults (Bain et al, 1999).

The domed indenter at the Danish Center is not currently designed or built to apply constant weight over time, and thus traditional methods of testing could not be applied. However, the domed indenter is built to accurately indent into a mattress to a particular depth, thus depth of indentation needed to be the variable used to simulate different weights of persons.

In order to use the correct indentation depths, which would differ from mattress to mattress, a strategy was developed. The domed indenter is made to simulate half of a human buttocks. Thus, the team needed to find the weight that each of the three sizes of persons would put on the mattress through half of their buttocks. Two models were used to find these three weights.

The first model, which was suggested by Bruno Wolff, represents the human body as a uniform cylinder. The cylinder dimensions were taken from *The Handbook of Adult Anthropometrics and Strength Measurements* (Peebles & Noris, 1995), using the person's trunk depth as the diameter, the total length as the cylinder length, and the sectional area of the buttock as the buttock volume.

Radius of cylinder = 110 mm

Length = 1700 mm

Buttocks length = 672mm

Total volume of cylinder= Pi*r^2*h = Pi*110^2*1700 = 64.589.800 mm^3 (Eqn 4.1)

Buttocks volume = Pi*110^2*672 = 25.531.968 mm^3

Proportion of volume to weight yields the weight of the buttocks.

Total volume / Buttock volume = 70 kg / ? kg

This calculation shows that approximately 27.67kg press on a mattress thru the buttocks area. This value should be cut in half because the indenter simulates only half of the buttocks.

The second test looked to find the percentage of body weight that the buttocks represented. It is estimated that 75% of the body's weight is contained in and above the bottom of the buttocks and is pressed into a patient support surface when the person is seated (Buchanan, 2000). From this and the previous taken dimensions, a similar result was found.

The proportion of body weight to body length is used below to find the weight of the buttocks.

Total percent / Buttocks Percent = Total length / Buttocks length (Eqn. 4.2)

75% / x? = 1300mm / 672mm

Buttocks Percent = 38.77%

38.77% * 70 kg = 27.14 kg

This calculation supports the previous conclusion.

Next the weight of the buttocks needed to be correlated to the depth of penetration into a mattress. To do this a mock indenter was used. The mock indenter is a hemisphere that can be loaded and then placed onto a mattress. The indentation depth a 70kg person creates can be found by loading the mock indenter to 13.5 kg, which correlates to that person's buttocks weight, and then simply measuring the depth of the mock indenter after

8 minutes. The depth found using this test is referred to as the test indentation depth or TID. Using these tests and calculations the TID can be found for any size person, and can be used with any mattress. It is important to remember that the calculations used to gain these values are approximates and values such as 13.5 kg rounded values that are used for convenience. However, the weights used are consistent for every mattress and thus can be used to effectively compare mattresses.

It was decided to use masses of 12.5, 15 and 20Kg for the masses for indentation. The reasoning behind said decision was for simplified loading of the mock indenter. The Danish center has one 1kg, one 1,5Kg, two 5kg, and two 10kg weights for use. Therefore for the best representation of different weight classes, the weights of 12.5, 15, and 20Kg were selected. Using the second arithmetic method above, these three weights correspond to a body mass of 64.5, 77.4, and 103 Kg respectively. This closely represents the three weight percentiles of people (65, 70, and 95 kg).

In order to stabilize the mock indenter, a method was devised to allow for it to move as frictionless as possible, while staying upright. Figure 4.5 shows the setup, including the stabilization mechanism, for the mock indenter. A board is attached to a part on the mock indenter that guides the mock indenter's rod. This allows the board, which is nailed into the guidance ring, to direct the rod in a straight vertical position, while not applying a vertical force on the mock indenter.

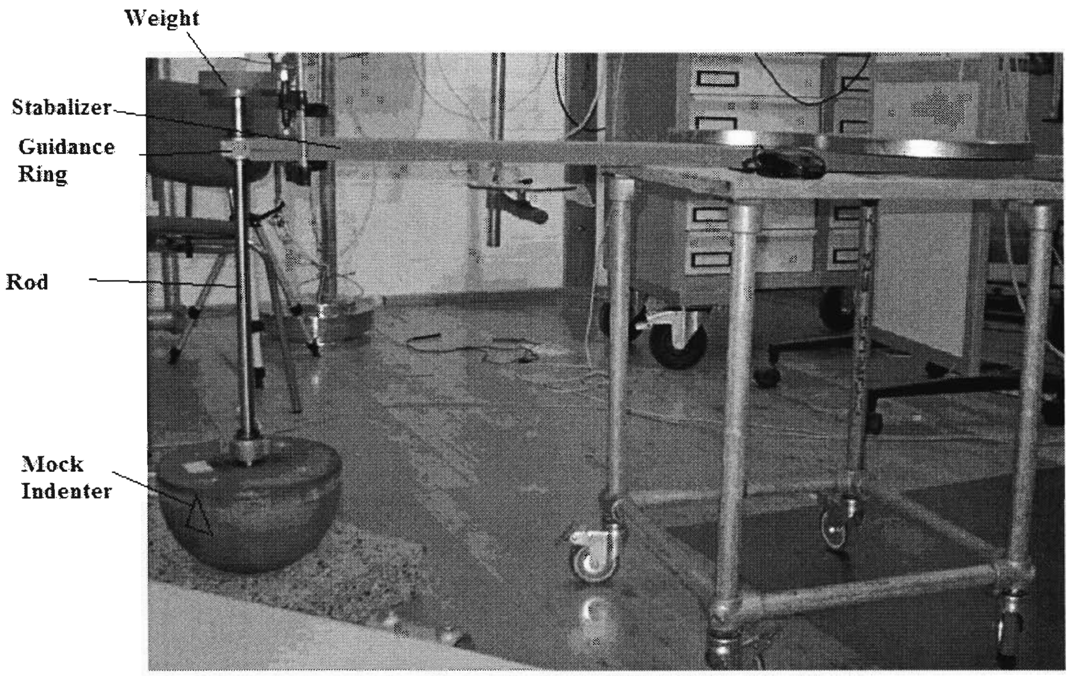


Fig. 4.5

Mock indenter with stabilizing device

In order to most accurately represent indentation with a heated domed indenter, the mattress is pre-heated using a heating pad. The mock indenter and additional mass are then indented into the mattress for a period of 8 minutes. The indentation depth is measured for future tests.

4.5 Computer data system

In order to accurately analyze mattress properties, a system that could input sensor data quickly and accurately was needed. This system ideally would also be able to export any data collected into Microsoft Excel or Access for analysis. The choice was based on these factors, and the cost and availability of each solution.

Much of the initial testing was conducted using a multimeter, which had poor voltage accuracy and had no ability to store the results of a mattress test. All data collected during this period was done on paper using a stopwatch taken at 30 second to one-minute intervals. This system was unacceptable for any later testing, and could not be used by the Danish Center to certify mattresses in the future. A new system was needed that could be reused later by the Danish Center in their testing.

4.5.1 Data Collection Software

After looking at a variety of options, the team selected LabVIEW software from National Instruments. This software allows for accurate collection of voltages from the transducers on the domed indenter at rates greater than 100 times a second. This high sampling rate was needed to satisfy Shannon's principle. Since the machine is powered using 220 volt 50 hertz electricity, sampling must be conducted at least 100 samples per second, which is twice the 50 hertz noise frequency (Smith, 2003).

LabVIEW also provided real-time graphing of the results, something very helpful in monitoring the domed indenter's current force and pressure reading. Since determining when the mattress bottoms out is important, this real-time monitoring is critical to preventing damage to the indenter when this threshold is met.

LabVIEW allowed the user to create a custom interface, designed specifically for this application, which was useful for the mattress testing team. Graphs, sampling rates, and voltage ranges could all be viewed and set from a virtual panel on the computer. This interface is easy to operate, even for those inexperienced in LabVIEW. This interface also allowed the team to make any changes needed to the interface quickly.

Lastly all data points collected could be outputted to a variety of database and spreadsheet products. During the project period Microsoft Excel was used, but in the future any database or spreadsheet product could be selected by the Danish Center. Excel allowed the project team to easily store the results of mattress tests and allowed curve fitting of the data points to a variety of mathematical functions to be graphed along with the data points.

The hardware used to collect these data was a custom analog input box and pc card supplied by National Instruments. The card allows for both the input and output of digital and analog data on up to 32 channels. This allowed the project team to analyze both the individual transducer outputs and the total force readouts. The project team could then analyze and diagnose any irregularities in the data, and the Danish Center has greater flexibility in setting up future testing.

4.5.2 Noise Reduction

Data collection using the computer led the mattress testing team to discover some minor problems with the device, from interference on a small scale to large-scale voltage fluctuations. These problems were addressed through a range of hardware and software solutions.

As initial readings were taken using LabVIEW, a noticeable noise was present on the voltage readings. Although in many cases this noise was not significant, it prevented the readings from being precise at many points. Discovering the source of such interference was important, along with finding an adequate solution.

Initial efforts were placed on finding where in the data acquisition chain the noise was generated. It was determined that the noise was not coming from the computer data collection board or hardware box. Instead the noise was generated somewhere between the transducers on the domed indenter and the connection leads to the computer. Many parts of the domed indenter could be at fault; the wiring for the 220-volt power to the heating element ran up the inner shaft with the transducer outputs, and there were a series of operational amplifiers in the device to ramp up the voltage and provide the matrices math that is used in finding the total force on the domed indenter from the three transducers.

The signals that were originally taken from the domed indenter and displayed using the LabVIEW software contained too much electrical noise for any conclusions to be drawn from them. The problem was unexpected since the multimeter readings that were recorded during pre-testing were very stable. There are differences between the multimeter and the LabVIEW data collection system that may cause this discrepancy. For example, the multimeter only samples data once per second, and thus would not see the same noise as Lab VIEW.

To solve the noise problem tests were done to find where the noise originated. The problem could be in three sections of the testing setup, which are the domed indenter circuitry, the computer software, and the wire leads connecting the two devices. A 1.5 volt battery was used to supply constant inputs thru each part of the testing setup. The computer displayed a constant 1.5 volts when the battery replaced the domed indenter as the input source. This led to the conclusion that the source of the noise originates from the internal circuitry of the domed indenter.

The team was not prepared to investigate the internal workings of the indenter and thus decided to filter the noise that was being produced. In LabVIEW 4 there are no filters that can be added to virtual circuits (this is an option in LabVIEW 6 which is recommended). Thus, the only option was to build external filters that could help pass clear information from the indenter to the computer.

With the help of Bruno Wolff, a low pass filter with amplification was built and set to connect the domed indenter and computer input. The circuit (see figure 4.6) was made from components that were available in the Danish Center's lab and were chosen to create a cutoff frequency that would block out 50 Hz noise as well as other lower frequency noises that were believed to be coming from the physical movements of the domed indenter. The time constant (τ) is 1,47 seconds, which creates a cutoff frequency of 0,68 Hz. The LabVIEW software recorded more accurate results when reading a larger input, thus the team designed amplification into the circuit. For the tests run on the Bisbebjerg Hospital mattresses an amplification gain of 3 was used.

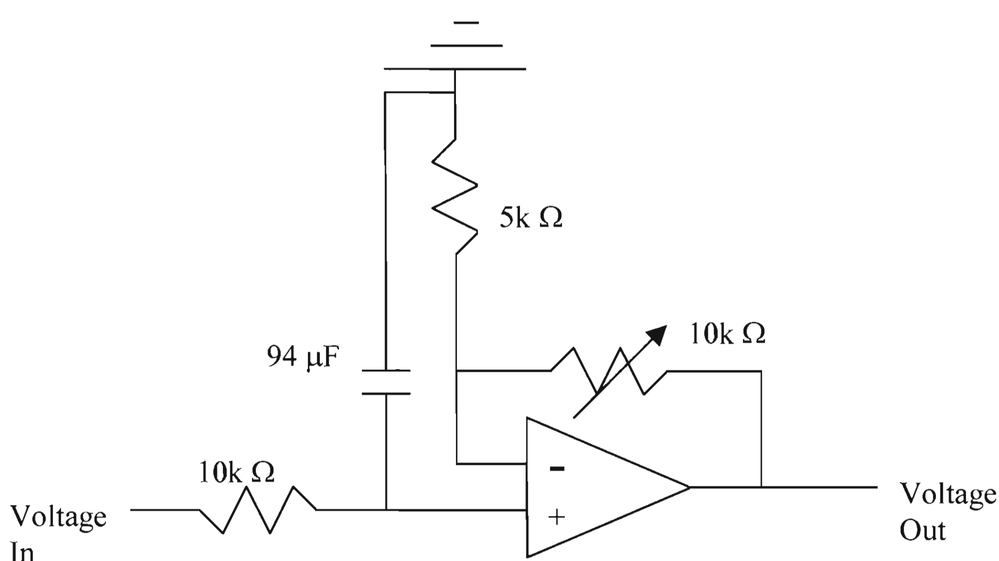


Fig. 4.6

Circuit used to decrease noise in electronics system

The result was a clean signal, which can be easily analyzed. A small amount of noise is still present in the raw data. This does not affect mattress comparison because the noise is not significant and is masked when finding the best-fit lines of the data.

4.5.3 Calibration

The calibration of the domed indenter was completed when the domed indenter was functioning properly. With calibration, millivolts readout on the computer can be converted into Newtons. In order to do this the calibration device seen in figure 4.8 was used. The round end of the board was placed on the center of the domed indenter. At the 45 cm mark, there is a slight indentation in the board that balances the board. The board is 95.7 cm long. A weight of either 5kg or 10kg is placed on the end of the board, and the computer took data for 100seconds. The mean value of the data is calculated for each load. The setup can be seen in Figure 4.7 and Figure 4.8.

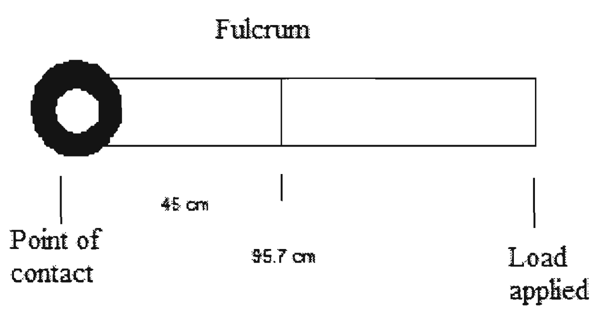


Fig. 4.7 domed indenter calibration-sketch

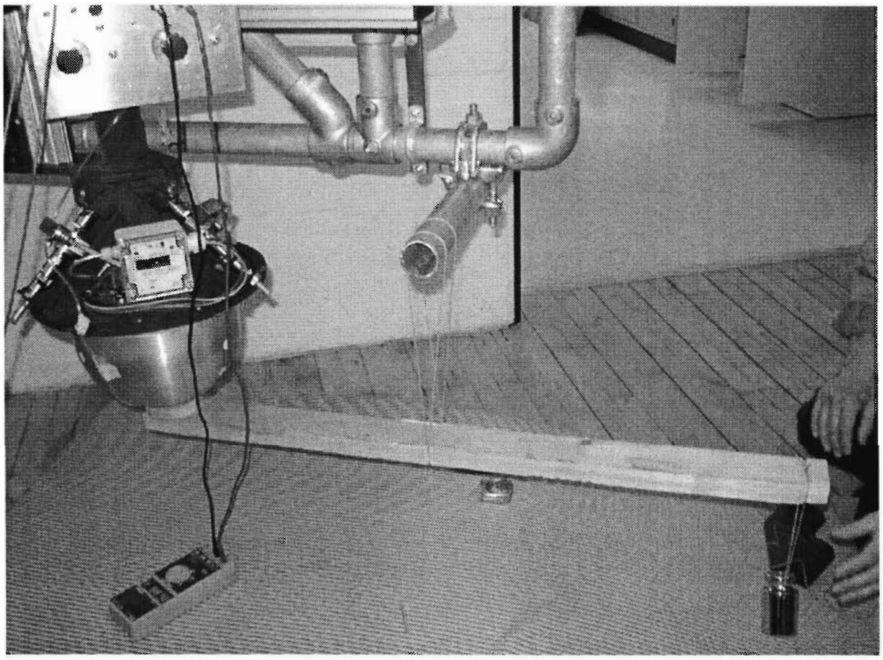


Fig 4.8
Calibration device used to calibrate domed indenter

Once the constants were found, they were averaged to find the most consistent value, and a standard deviation was taken. The values were then converted into a force. This was done using the torque equation of physics. The process can be seen in appendix 10 along with the graphs of the data, equation 4.3 was used to find the force acting on the domed indenter.

T=FD (Eqn. 4.3 torque=force*distance)

The data for the 10kg and 5kg tests were then compared to determine the relationship between force on the domed indenter and the voltage reading from the transducers. These data were then used to convert the voltage readings on the indentation depth test into force. The results for the conversion from Volts to Newtons was 1V = 446 ± 46 N.

4.6 Hospital Collaboration

One of the three major goals for this project was to increase the communication network and interaction between the Bispebjerg Hospital, and the Danish Center. There are two main areas it is felt that the communication and interaction has been increased and improved. These two areas are through seminars, and through future project ideas.

4.6.1 Seminars

When meetings were held with both people at the Danish Canter, like Else Marie, and hospital personal at the Bispebjerg Hospital, like Dr. Jorgenson, one topic came up numerous times. This topic was seminars. Seminars in this chapter mean classes, workshops, and informative meetings.

The first place the hospital and the Danish Center collaborated on the issue of seminars was between Else Marie and Tom Jorgenson. It was mentioned at the meeting the project team conducted with Else Marie, that the Danish Group to Prevent Pressure Sores was looking for someone to speak at the yearly seminar. The topic for 2003 is on seating positions. After our meeting with Tom Jorgenson a day earlier, the project team felt that he was at least someone to contact on the issue. Even if Tom Jorgenson does not accept, this at least is someone the Else Marie can contact in the future on the issues of pressure ulcer prevention. This is important because Else Marie puts together classes and seminars on the topic, which she then teaches to nurses around the country.

The second meeting that seminars where the Danish Center and the Bispebjerg Hospital could exchange information was discussed during the meeting conducted with Susan Bermark and Britt Wahlers. The team was informed that a seminar would be happening soon at the Bispebjerg Hospital when the prevalence study was completed.

Susan and Britt requested an update on the domed indenter, so that they can inform nurses, doctors, therapists and aids, what is currently being done with mattresses at the Danish Center, and what it may mean for prevention of pressure ulcers in the future.

These are the two seminars that are planned. These seminars allow for the Danish Center to share knowledge with the hospital community. Also, because the Danish Center is sharing knowledge, the hospitals will need to talk to them, and communicate information that they have and what they are looking for. This will help to breach the gap between clinician and engineer.

4.6.2 Current and Future Project Ideas

After meeting with the staff at the Bispebjerg Wound Care Center it was evident that the testing of hospital mattress would benefit both the Bispebjerg Hospital and the Danish Center. The team organized the testing of a series of mattress from the hospital in order to begin a testing relationship between these two organizations. The results and methods of these tests were the culmination of the team's work, and are described in previous sections.

Through the meetings the project team had involving staff from the Bispebjerg Wound Care Center, testing of hospital mattresses was needed, and asked for. The project team had two ideas for organizing and completing the goals of the hospital. First the project team tested mattresses that the hospital currently uses. Information concerning testing of mattresses can be found in Chapter 5.

The second idea for mattress testing on the hospital's mattresses was to complete a test over time. This recommended test would result in yearly tests for 5 years. This would mean that the hospital and Danish Center would have to communicate at least on a yearly basis. Also, both organizations will find it easier to communicate with one another on other projects and ideas if they are already collaborating on mattress testing.

4.6.3 Current Communication Level

The current level of communication between the Danish Center and the Bispebjerg Hospital has improved. Through the meetings the project team participated in, the two organizations have found commonalities they did not know existed, like teaching goals, and projects to work on in the future. While these are small steps for the Danish Center and the Bispebjerg Hospital towards working together, they do represent a positive outlook for the future.

4.7 Protocol development

Data concerning mattresses properties is needed in order to compare mattresses. The protocols that were developed for the Danish Center are instructions on how to collect this data using the domed indenter.

4.7.1 Normal Force

The domed indenter was developed so that mattresses could be tested and compared against each other in order to find the most suitable mattresses for different situations. The Danish Center is only a testing site, and is not responsible for drawing conclusions regarding the suitability of mattresses for pressure reduction. Instead, their goal is simply to provide information to experts in the medical field so that they may choose mattresses that best support their patients. With this in mind the team wrote a protocol for a series of tests and analysis that would be able to provide insight about mattress properties.

Research was done in the United States as well as in Denmark with the help of Bruno Wolff. The research focused on finding what mattress properties are important to test, and how to test for these properties. Some of the most useful articles that were read and referenced throughout this paper are summarized below so that background can be provided to the reader.

"Guidelines For The Measurement and Presentation of Interface Pressure Data On Support Surfaces", (EPUAP 2002), is a document that recommends general practices to use when measuring interface pressure between two objects. The recommendations apply to the use of mannequins, instrumentation calibration, data analysis, and data presentation. It also provides definitions for terms used to describe testing methods or mattress properties. The goal of the document is to take an initial step towards the standardization of interface pressure testing. This paper was very useful in deciding how the domed indenter should be run, and what to include into its testing methods.

"Measuring Change in Interface pressure: effect of repositioning and time" (Stinson, Porter and Eakin, 2001), measured the effect of repositioning on interface pressure over an extended period of time. Pressure was measured in one-minute intervals for first one minute, then twenty. In the twenty-minute study, it was noticed that the pressure did not change significantly after eight minutes. Results of this study suggest that the optimum waiting time before measurement is eight minutes. The team's time dependence tests were modeled after the test in this paper. The results that the team received were analogous to Stinson's thus assuring that the eight minute settling time was correct.

"Comparative Evaluation Of Pressure Mapping Systems: Cushion Testing" is a study done by Ferguson-Pell, Nicholson, Lennon, and Bain (no date). In this study a domed indenter made of urethane gel called the Gelbutt is used in correlation with three different pressure mapping systems. Different seating cushions were tested by indenting them with a load of 570 N for 60 seconds. The results show that the system worked well and results could be easily gathered and displayed in a graph. While the data gathered in this study was not useful for this project, the methods used were important to study. There are a very limited number of domed indenters that have been put into use, and therefore it was helpful to review a study before the team conducted its own.

The information gathered from these and other articles was combined with the team's experience with the domed indenter to form a set of protocols. These protocols, which are described below, can be used to find mattress properties that will help experts decide which mattresses suit their patient's needs best.

4.7.2 Shear

Due to the configuration of the there force transducers, the domed indenter has the ability to test for the kinetic friction force as well as normal forces. As the dome moves across a mattress in the horizontal direction the kinetic friction force is measured and readout as a corresponding voltage at the domed indenter output. This voltage readout can be used to determine the coefficient of kinetic friction. Kinetic friction is an aspect of pressure ulcer prevention, but only occurs when a patient is sliding down or moving along a pressure support surface. This is not a common occurrence and thus kinetic friction is not a main factor in the development of pressure ulcers. A patient who is at risk of developing a pressure ulcer is likely to remain stationary on the pressure support surface. At this point there are no kinetic friction forces, but there are static friction forces. Static friction, or how much force it takes to start an object moving with a specific surface below, is thus the more important factor in pressure relieving mattresses.

Static friction can be found by measuring the maximum amount of force that can be applied across the interface of two surfaces before impeding motion occurs. Unfortunately, the domed indenter is too powerful for this measurement to be made. The domed indenter does not have a low enough setting to measure the force required to initiate motion of the dome across a mattress. In Buchanan (2000), a block of 50 pounds was moved 3/8ths of an inch (0.95 cm), back and forth, to measure the shear force. A similar test cannot be done with the domed indenter at this time. This is because the domed indenter has manual controls and a person is not capable of creating precise movements as in the Buchanan study. Also, the project team was unsure if the readout from the three transducers could be directly correlated to shear force. Due to the issues with measuring the shear force, the project team focused its development of the domed indenter on the normal force, and made recommendations to the Danish Center on future development of a shear measurement.

5 Testing Results and Analysis

A great deal of data was collected using the protocols written for the domed indenter, and the nine test mattresses located at the Danish Center. These data were analyzed using Microsoft Excel and stored in a Microsoft Access database. The Danish Center and Bispebjerg Hospital will be given these data so they may review how each mattress performed. This information may lead to improved mattress policies at the hospital, and improved testing abilities at the Danish Center. The following is a guide as to why these tests were run and their relationship to mattress properties they have.

5.1 Test Protocols

These protocols are written for use with the domed indenter. The goal of these protocols is to make testing simple and reproducible, while gathering the largest amount of useful data.

5.1.1 Preparation steps

1. Unpack mattress into environment going to be tested at least 12hours prior to testing it, so it is conditioned to its surroundings (surrounding temperature and humidity noted, and does not change by 2° C and 5% (humidity) (EPUAP Working Group II, 2002; Working Document, 2001; Research Institute).
2. After unpacking, place approximately 800N or 80kg on mattress for approximately 30 minutes to pre-condition it. Should be done before the 12 hours of waiting time in number 1 (Working Document, 2001)
3. Calibrate sensors before each test

4. Cover mattress with covering provided by manufacturer. If specialized cover is not provided drape a clean hospital sheet over mattress (EPUAP Working Group II, 2002; Working Document, 2001; Research Institute).
5. Using mock domed indenter, measure testing indentation depth (TID) for the mattress for weights correlating to 65, 72 and 95 Kg persons, by using the steps described below.

    I. Choose the weight needed to simulate a particular person's weight and apply it to the mock domed indenter. The reason behind the mock indenter weights can be found on page 19.

Person Weight	Mock Indenter Weight
65 kg	12.5
77 kg	15
103 kg	20

    II. Rest the mock domed indenter on the mattress for 8 minutes (Sinson, Porter, & Eakin, 2001).

    III. At the end of 8 minutes measure the depth of the mock domed indenter to find the TID.

5.1.2 Pressure Versus Indentation

Bottoming out of mattresses is of significant concern to pressure ulcer development. No matter the ability of the mattress to absorb pressure, if the mattress bottoms out, pressure reading will increase to many times the unsafe level (Jay 1995). This event occurs when the mattress becomes compressed to the point where the patient is resting on the underlying surface. The pressure dispersion properties at this point are not dictated by the mattress, but instead come from the bed or other underlying surface (Jay, 1995).

The test below will provide a graphical readout, showing the point at which any tested mattress begins to bottom out. The test will also show how the overall force on the indenter increases as a function of depth into the mattress.

The recording of data at 100 points per second is based on the Shannon Sampling Frequency which states that to overcome interference the sampling rate must be at least twice as high as the interference frequency, which is 50 Hz in the domed indenter (Shelton et al, 1998). A speed of 1 or 2 mm per second is a good general speed for this procedure in order to allow for 100-200 data points to be collected every second. This large quantity of data allows for an analysis that characterizes the information gathered and displays the information in an easy to comprehend graphic interface. The speed of 1-2/3 mm/sec is used below, because the mark of 2.5 on the domed indenter motor speed control can easily identified and thus reproducibility of the experiment can be maintained.

1. Place indenter head on the surface of the mattress
2. Indent into the mattress at a constant speed of 1 2/3 millimeters/second (this corresponds to 2.5 on the domed indenter scale)
3. Record a data point for the total force on the dome 100 times every second during the indention
4. Stop indention when bottoming out occurs. This can be seen when there is a sharp increase in pressure or, when the slope of the pressure curve approaches infinity. To protect the domed indenter one may consider bottoming out to

have occurred when the point pressure at the bottom of the dome reaches 100mmHg. This is a very unacceptable pressure that represents the end of pressure relief from a mattress.

5. Remove dome from the mattress and analyze data

5.1.3 Test for Visco-elastic and Point Pressure Properties

Testing for visco-elastic properties is important to understanding how much the mattress redistributes the load. Visco-elastic properties dictate how a material will react to stress and strain over time. This test measures how the stress of a mattress changes over time, when under a constant strain. The relaxation modulus (E(t)) is given by the equation below:

$$E(t)= (\sigma(t)/\varepsilon_o) \quad \text{(Eqn. 5.1)}$$

Sigma (σ) is the stress in the visco-elastic material (which may change over time). Epsilon (ε_o) is the initial strain, which stays constant.

Providing pressure relief to the patient as a whole is the most critical aspect of mattress design. 32mmHg has been established as the pressure limit where capillary collapse occurs. This collapse is the primary cause of pressure ulcer development (Theaker, 2002). If a mattress is able to distribute pressure evenly on the entire body surface, then it is more likely to reduce point pressures to under 32mmHg. On the domed indenter, a spherical object, the highest point pressure will occur at the lowest point on the sphere (Kalpen, Bochdansky, and Seitz, June 1995). The point sensor, located at the bottom of the domed indenter, will be used to conduct these tests.

The speed of 1.1 centimeters/second was used because it was the fastest indentation speed that the domed indenter could move, while being under control enough to stop at the required depth. The fastest speed was used in order to best emulate a step function. A step function is an instantaneous displacement and is used with mathematical models. It is also important to note that at this speed the domed indenter is not moving too slowly, which would cause the mattress to relax around it, while indentation is taking place. A recording rate of 100 times per second was chosen for the same reasons as in the preceding test. The eight-minute mark was set because it was found that after 8 minutes, readings of pressure did not change (Stinson, Porter, Easkin, 2001). This 8 minute waiting period was confirmed through separate experiments performed with the domed indenter (see section 4.4.2).

1. Place indenter head on the surface of the mattress
2. Indent the dome at a speed of 1.1 centimeters/second until the desired Test Indentation Depth (TID) is achieved
3. Record the values of total pressure and bottom point pressure for eight minutes, at a rate of 100 samples every second
4. Remove dome from mattress and analyze data
5. Repeat steps 1-4 for all three TIDs

5.1.4 Mattress Selection

At the Danish Center nine mattresses in total were tested. Three tests were used in order to find the mattress properties that are important to pressure ulcer prevention. Five of these mattresses came from the Bispebjerg Hospital, and the four remaining mattresses were taken from the supply room at the Danish Center. Five of the mattresses were found to have visco-elastic properties and were tested using the visco-elastic test as well as the indentation test. One regular spring mattress was tested, and one air overlay was tested. The nine mattresses represented almost all areas of static mattress development, and form a basis for examining mattress properties between types and brands of mattresses.

The Pentaflex mattress is made by Huntleigh Healthcare. Bispebjerg Hospital loaned the mattress to the Danish Center for testing. Pentaflex mattresses are semi-visco-elastic foam and are specifically designed for pressure relief and pressure ulcer prevention. The mattress is 17.5 cm in thickness, and is composed of a series of cells arranged in a repeating pattern. The cell structure of the mattress made it very difficult to test for point pressure. The point pressure sensor would record very different pressures at the same indentation depth depending on what portion of a cell was pressing on it. The point pressure given in the final data is an averaged value from multiple readings.

The Apollo mattress is made by Inter Care, which is a Scandinavian company. It was loaned to the Danish Center by the Bispebjerg Hospital. The Apollo is a visco-elastic foam mattress that was designed to help prevent the formation of pressure ulcers. It has a thickness of 13.5 cm. All tests were successfully run on this mattress.

The Spring mattress used in testing at the Danish Center is a regular spring mattress that has been housed at the Danish Center for quite some time. The mattress was not made to prevent pressure ulcers and has a thickness of 18.5 cm. All tests were successfully run on this mattress.

The Salus mattress was in the mattress supply of the Danish Center. It is a visco-elastic mattress designed to help in pressure ulcer prevention. The mattress is made of a very resilient material and is 15 cm thick. All tests were successfully run on this mattress.

The Tempur-Med mattress is made by Trykaflastende Products. The Bispebjerg Hospital loaned this mattress to the Danish Center for testing. The Tempur-Med is a visco-elastic mattress that is designed for pressure ulcer prevention. It is also a very temperature sensitive mattress. All tests were successfully run on this mattress.

The Beige mattress used in the testing at the Danish Center was loaned by the Bispebjerg Hospital. There were no manufacturer markings on the mattress and thus it was referred to as the "Beige" mattress because of its distinguishing color. The mattress is a homogeneous elastic foam mattress, and is 12 cm thick. The visco-elastic test was not run on this mattress because it does not have significant visco-elastic properties.

The Air overlay was tested in the same manner as a mattress, and is called a Carebed from Care Products AS in Norway. The Bispebjerg Hospital loaned this product to the Danish Center for testing. It was designed to be placed over another mattress in order to relieve pressure on a patient; however during testing the overlay was tested by itself. The mattress had to be inflated before its testing could begin. The instructions on how to inflate the item were on the side of the mattress and were followed exactly. The final thickness of the product was 9 cm. The product did not contain visco-elastic properties and thus the visco-elastic test was not run on it.

The Tempur-pedic mattress that was tested came from the Danish Center's supply. It is a temperature sensitive and visco-elastic mattress, which was designed for pressure relief and pressure ulcer prevention. The thickness of the mattress is 14 cm. All tests were successfully run on this mattress.

The "Dizzy" mattress came from the mattress supply at the Danish Center. The mattress had no name or manufacturer information, but had a series of stripes on it that made one dizzy when looking at it for an extended testing period. Thus the mattress is referred to as the Dizzy mattress. The mattress is made of homogeneous foam. It is unclear if it was designed for pressure ulcer prevention. The Dizzy mattress has no significant visco-elastic properties, and thus the visco-elastic test was not run on it.

5.1.5 Force-Depth Dependence

The total force reading of a mattress and the point pressure measured are related according to the volume of displaced material in the mattress at each indention depth, if the material is homogeneous and elastic. Using trigonometry and calculus, an equation can be found for force in terms of depth of a mattress. The derivation of the equation can be seen in Appendix 11.

$$\mathbf{F*a = 4\pi\,[((-R^3+R^2d)/3 - 1) + ((R-d)/6)\,\sin(\cos^{-1}(R-d)/R)^2]} \qquad \textbf{(Eqn. 5.1)}$$

F is the force at the point with depth d, *a* is the proportionality factor, R is the radius of the sphere. In order to find the proportionality constant, the mock indenter was used. The force placed on it is known, the depth is measured, and the radius is known. Using this information the proportionality constant *a*, was calculated. Table 5.1 gives the solutions for *a* for all the tests done with the mock indenter (6 mattresses), along with the average and standard deviation. The proportionality constant is different for every mattress, which is why on some mattresses the mock sinks lower than on others. Note: names of the visco-elastic mattresses are italicized.

Table 5.1- Proportionality constants

Force (N)	12.5 Kg	15Kg	20Kg	**Average**	**S.D.**
	122.5N	147N	196N		
		Tempur-med			
d (cm)	6.5	7.3	7.7		
A	0.383143	0.37403	0.300936	0.352703	0.045063

Dizzy Foam					
d (cm)	3.1	4.4	5.2		
A	0.098351	0.173601	0.17208	0.148011	0.043013
Tempur 1					
d (cm)	6.6	7.4	8.4		
A	0.391382	0.380844	0.336474	0.369567	0.02914
Apollo					
d (cm)	6.7	6.9	8.1		
A	0.399613	0.34671	0.321272	0.355865	0.039965
Pentaflex					
d (cm)	4.9	5.6	8		
A	0.25026	0.257202	0.316195	0.274552	0.03623
Beige					
d (cm)	3.7	5	6.5		
A	0.149274	0.21552	0.239464	0.201419	0.046719
Salus					
d (cm)	6	6.7	8		
A	0.341832	0.333011	0.316195	0.330346	0.013025
Spring					
d (cm)	6.1	6.8	8.2		
A	0.35011	0.339864	0.326344	0.338772	0.011921

The average value of *a* for every mattress can then be used to calculate pressure at specific depths of a mattress. This can be used to check the pressure measured using the depth the indenter was indented. Looking at the table, it can be seen that the visco-elastic mattresses have larger *a* values, and lower standard deviations, while the elastic mattresses have lower a values. Some inaccuracies in the measurement of indentation depths may have resulted in the high standard deviations, and it is recommended that the test be repeated to verify the results.

5.2 Indention testing

A mattress's response to normal force is an important factor in the development of pressure ulcers. To gauge its ability to disperse this force, the mattress team developed a protocol to test for the indention at certain weights. This protocol allowed the team to collect data concerning indention characteristics, and analyze and compare the various mattress properties that were affected by indention. The indention test was completed using the domed indenter, and was conducted using a constant speed until the mattress bottomed out. These data points are then graphed and compared to data collected from other mattresses.

The indention test was conducted in the following manner. The mattress was prepared according to the preparatory protocol outlined in the appendices, after which the follow test was conducted:

6. Place indenter head on the surface of the mattress
7. Indent into the mattress at a constant speed of 1 2/3 millimeters/second (this corresponds to 2.5 on the domed indenter scale)
8. Record a data point for the total force on the dome at a frequency of 100 Hz during the indention
9. Stop indention when bottoming out occurs. This can be seen when there is a sharp increase in force or when the slope of the force vs. indentation curve approaches infinity. To protect the domed indenter one may consider bottoming out to have occurred when the point pressure at the bottom of the dome reaches 100mmHg. This is a very unacceptable pressure that represents the end of pressure relief from a mattress.
10. Remove dome from the mattress and analyze data

The test was designed to find both the force vs. indentation curve for the particular mattress, along with determining the point at which the mattress bottoms out. This allows us to compare multiple properties in a single graph, effectively cutting down on the number of tests needed. The data from these tests were collected using the LabVIEW data collection systems, and then stored and analyzed in Excel.

The test is conducted until the mattress passes the bottoming out point. To determine this point, the team measured the output of the point sensor mounted at the bottom of the domed indenter. The value of 100 mm Hg was chosen as an indicator of bottoming out, since this value is more than three times the acceptable pressure reading for a mattress. This value was also chosen since it was easy to read from the pressure point at the bottom of the domed indenter. After initial data analysis, this value was further supported by the fact that all initial test curves became non-linear before the 100 mm Hg level.

The tests were conducted using LabVIEW, with a sampling rate of 100 Hz. This value was used to overcome the Shannon's sampling principle, which states anything less than a value twice the interference rate will produce inaccurate results. The data were collected from the domed indenter through our operational amplifier and high and low pass filters, into the LabVIEW virtual instrument, and saved to the spreadsheet file form, in the tab delimited format. The data could then be imported directly into Excel or Access for data analysis. During the team's time at the Danish Center, the group chose to use Excel to graph all results.

Comparing graphs can be done impartially by ensuring the axis of each is on the same scale. The importance of the graphs is the slope, and the point at which the graph becomes exponential. This point is where the mattress begins to bottom out, where the pressure increases exponentially due to the indenter compressing the mattress between it and the supporting surface below. These values are important to the mattress's performance as they represent the maximum pressure a patient can place on the mattress before it becomes ineffective in the prevention of pressure ulcers. Finding the best fit curve for the graph allows each to be compared both mathematically and visually. The derivative of each can also be graphed and compared, illustrating differences between the rate of change of each mattress.

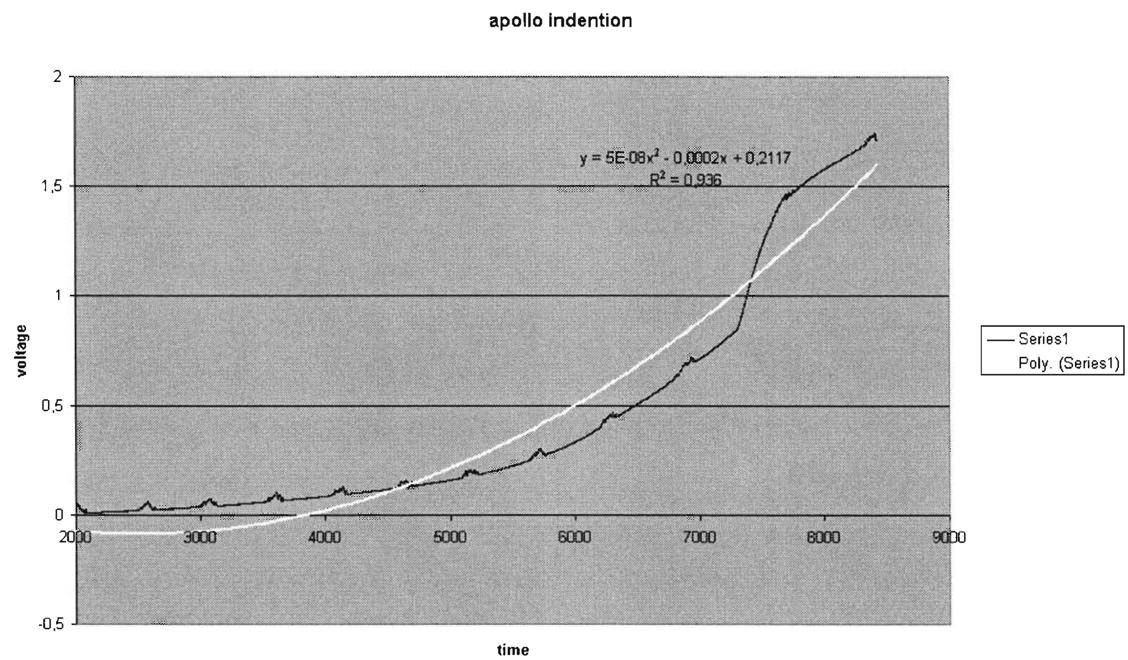


Fig. 5.1 Apollo mattress indentation graph

Figure 5.1 is from testing done on an Apollo mattress, a mattress intended for hospital use. The mattress exhibits visco-elastic properties, and is intended for the treatment of pressure ulcers. It's constructed of non-uniform foam layers with an outer cover to protect it from water and fluid damage. The above graph shows the effect of the domed indenter at a constant movement rate though the mattress. As the time approaches 1 minute and 10 seconds (around 7000 on the graph) the mattress begins to approach the bottoming out point, and the higher rate of increase can be seen. A quadratic curve fit is also graphed, which allows the general properties of the data to be compared between mattresses more readily. The Apollo mattress was loaned to the Danish Center from Bispebjerg Hospital for the purpose of testing for its ability to prevent pressure ulcers.

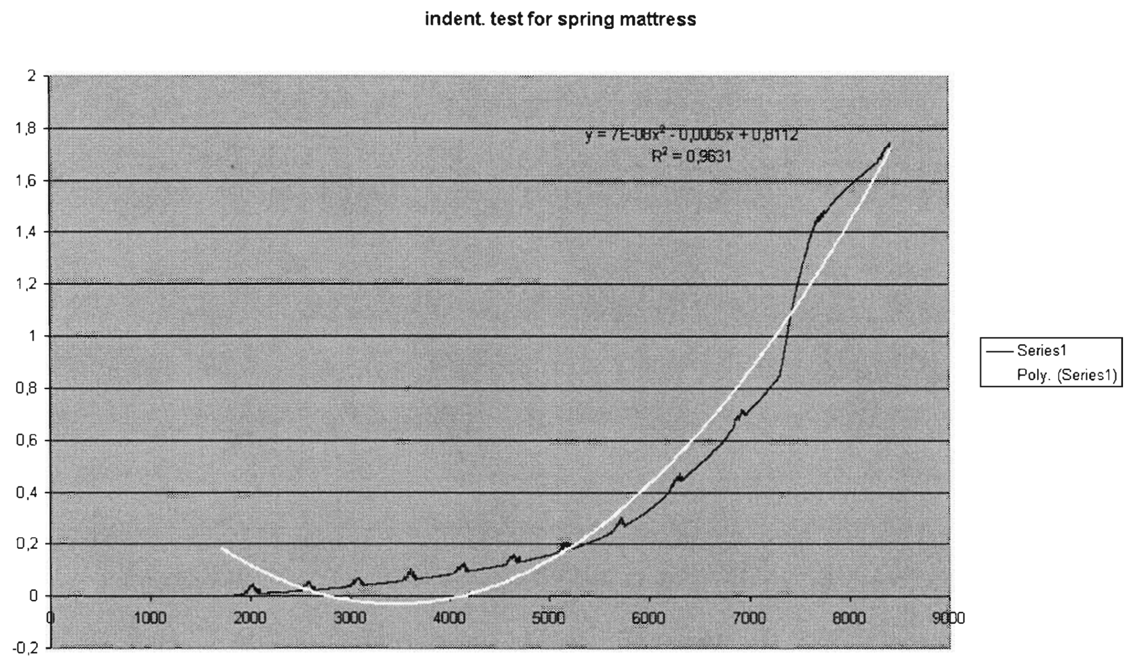


Fig. 5.2 Spring mattress indentation graph

The second mattress is a simple spring mattress. These mattresses are commonly sold for home use, and are not intended for the prevention of pressure ulcers. The graph above shows the results of the indention test of over a period of 1 minute and 20 seconds, which differs slightly from the Apollo graph. The mattress was taken from the stock at the Danish Center, and from its general appearance the team concluded that it has had excessive use over its lifetime.

A comparison of the two graphs can be conducted visually and mathematically. First from a visual inspection it's clear that the spring mattress curve begins to increase at a later point on the graph. This can be attributed to the mattress's excessive wear, which would have reduced the individual spring's stiffness. At the same time the equations indicate that the spring mattress's slope is greater. This would mean that as depth or weight increases, the mattress can not disperse this force and the patient experiences an increase in pressure.

There are various problems that need to be corrected in the future. First the domed indenter is not truly friction free; it requires an initial loading into a mattress to preload any joints that may change later. This is mostly a function of the connection between the inner and outer tubes of the domed indenter, a point which was problematic throughout our testing period. Initially attempts were made to lower the friction of the existing joint, and then the joint was completely replaced. This problem is addressed in the recommendations section. Secondly the tester produces excessive noise in the results; this noise can easily skew data taken from a mattress. The team implemented a filter to attempt to remove the noise from the data, with moderate success. The recommendation to upgrade to LabVIEW 6 includes this factor.

5.3 Visco-elastic tests

The visco-elastic test is used to measure the relaxation properties of a mattress. The relaxation property that was tested in this project was the relaxation modulus. The relaxation modulus, E(t), is the change in stress of a material over time, divided by a constant strain. The relaxation modulus is important in understanding the ability of a mattress to relieve pressure over time.

The test was run by indenting a heated domed indenter into the mattress until the test indentation depth, determined in the preliminary protocols (please see section 5. 1 for how this was found) was reached. The indentation is stopped, and data are recorded using the computer software set up earlier, for eight minutes. Six mattresses were tested using this method. The protocol used for this test is below.

1. Heat domed indenter head to 32°C
2. Place indenter head on the surface of the mattress
3. Indent the dome at a speed of 1.1 centimeters/second, or faster if control can be kept, until the desired Test Indentation Depth (TID) is achieved
4. Record the values of total pressure and bottom point pressure for eight minutes, at a rate of 100 samples every second, using LabView
5. Remove dome from mattress and save data
6. Allow the mattress to rest for at least 8 minutes between tests
7. Repeat steps 1-4 for all three TIDs
8. Analyze data using excel
    a. Truncate first 10seconds of data to account for moving indenter into the mattress and to make sure mattress stabilized
    b. Truncate data after values fall below 10% of original value recorded at 10 sec.

5.3.1 Time and Temperature Effects

It was noted after the tests were completed, that using a heated domed indenter on a room temperature mattress was not an accurate measurement of visco-elastic properties. This is because the heat sensitive mattresses, like the tempur-pedic mattresses, change their material properties with changes in temperature. This means that until the mattress reaches a temperature in the area of the mattress that is affected by the test, and hence affects the test, that is the same temperature as the domed indenter, the properties being measured were not only visco-elastic, but also temperature dependent. Below the updated protocols to eliminate this problem are presented.

1. Place indenter head (non-heated) on the surface of the mattress
2. Indent the dome at a speed of 1.1 centimeters/second, or faster if control can be kept, until the desired Test Indentation Depth (TID) is achieved
3. Record the values of total pressure and bottom point pressure for eight minutes, at a rate of 100 samples every second, using LabView
4. Remove dome from mattress and save data
5. Allow the mattress to rest for at least 8 minutes between tests
6. Repeat steps 1-4 for all three TIDs
7. Analyze data using excel
    a. Truncate first 10seconds of data to account for moving indenter into the mattress and to make sure mattress stabilized
    b. Truncate data after values fall below 10% of original value recorded at 10 sec.

If possible, it would be beneficial to measure the modulus with the mattress and the domed indenter heated to 32°C. This way the modulus that is more important to the conditions the mattress will be under can be measured. A heating pad could be used to preheat the mattress; heating time will depend on the thermal properties of the mattress material. These properties were not investigated in this study, so a preheating time cannot be recommended. Further study in this area is recommended.

The data presented in the next section should be used as a reference for analysis of the data collected in the updated protocols. The following data are not to be used to calculate a relaxation modulus because it will not give an accurate value, due to the combined visco-elastic and thermal effects.

5.3.2 Visco-elastic Test Data and Analysis

After the data were collected, the analysis process started. There are 48,000 data points for every test taken. There are three tests taken for each mattress, for the three test indentation depths (TID). The first ten seconds of data are truncated in order to eliminate possible human error in starting of the test, and also to eliminate the possibility of some motion of the domed indenter from zero to TID. When graphing using Microsoft Excel, only 32,000 points can be used. By eliminating the fist ten seconds of data, which are the least important to finding the relaxation modulus, the remaining data points can be graphed together. Using a Weichert model for visco-elasticity as described by Berthelot (2002) the relationship between time and the relaxation modulus is exponential. Therefore, a plot of $\log_{10}$ force (voltage) versus $\log_{10}$ depth (time) was created. All the graphs of the data for each test, with the best fit line graphed, and the equation alongside, and also with their respective R^2 value (correlation factor) can be seen in Appendix 8.

The visco-elasticity test is a useful tool for mattress designers and developers. This test gives a measure of how well a mattress redistributes pressure over time. This property can be used to investigate how much a pressure-relieving mattress can distribute pressure across the body of a patient. This is a critical property to explore when investigating important mattresses properties, and eventually, how the properties may prevent the occurrence of pressure ulcers.

5.4 Point Pressure Test

Providing pressure relief to the patient as a whole is the most critical aspect of mattress design. 32mmHg has been established as the pressure limit where capillary collapse occurs. This collapse is the primary cause of pressure ulcer development (Theaker, 2002). If a mattress is able to distribute pressure evenly on the entire body surface, then it is more likely to reduce point pressures to under 32mmHg. On the domed indenter, a spherical object, the highest point pressure will occur at the lowest point on the sphere (Kalpen, Bochdansky, and Seitz, June 1995). The point sensor, located at the bottom of the domed indenter, is used to measure this point pressure.

The point pressure test coincides with the visco-elastic test. The dome of the domed indenter is indented into the mattress to a given testing indentation depth and held for eight minutes. At the end of the eight minutes the point pressure value is recorded. The value is taken from the point sensor readout manually in mm Hg with an accuracy of +/- one mm Hg.

The point pressure is recorded using all three testing indentation depths on each mattress. Comparing the point pressures can be used as a tool in comparing the pressure relieving properties of mattresses. By comparing mattress by depth it is easier to identify the most appropriate mattresses for patients who greatly differ in size. The data collected from the mattresses tested at the Danish Center can be seen in table 5.1 below. Italicized mattresses are visco-elastic.

	Dizzy	*Tempur*	*Apollo*	*Pentaflex*	*Temper-med*	Beige	*Salus*	Spring
103 kg	58	40	56	43	51	55	55	99
77.5 kg	54	36	43	40	50	51	50	93
64.5 kg	42	33	41	37	49	45	36	50

Table 5.1

Mattress point pressures in mmHg when indenting different simulated patient weights.

Not all of the mattresses could be tested for point pressure. The inflatable overlay, which was provided by the Bispebjerg Hospital, did not support the pressure of the domed indenter. When simulating the lightest person (65 kg) the domed indenter penetrated through the overlay and rested on the underlying support surface.

The point sensor also encountered problems when testing mattresses that were made with large cells (one cm or more). When testing these mattresses the point sensor at the bottom of the dome could be placed in different locations on the mattresses. The sensor could be positioned in between two cells. This could cause a significant drop in point pressure because of a lack of surface area pushing on the sensor. If the sensor rested on the edge of a cell then the pressure reading would increase artificially. This was found because the very edge of cells is often very stiff and did not conform to the domed indenter as well as the rest of the mattress. If the sensor rested directly on a cell then an expected point pressure would be recorded. To solve this problem, the point sensor was placed in many different locations and the average of the values was given as the final data point, this problem was noticed with the Pentaflex mattress.

6 Recommendations

The following section contains the recommendations the project team has written over the course of the project.

6.1.1 Future Visco-elastic Testing

The visco-elastic testing that is described in the protocol in Section 4.6.3 provides data that can be used to find a relaxation modulus that is not independent of temperature. One way of eliminating this variable of temperature would be to run a test in which the domed indenter's heated domed is indented into a mattress for eight minutes. After the eight-minute period the dome would be lifted from the mattress and held for a period of time. Finally, the dome would be indented back into the already heated mattress and left for another eight-minute period. Data would be recorded during the second time period to find the relaxation of pressure.

This test would represent a patient being lifted from a mattress and then lowered back into the mattress. This event happens very often in patients who are unable to move, as it is currently recommended that a patient who is at risk of developing pressure ulcers be rotated at least once every two hours.

The elastic modulus found using the data gathered from this test would be independent of temperature. However, a mattress may not return back to its original shape when the indenter is lifted. Thus, the modulus found would be influenced by some form of memory that is present in the mattress. Different mattresses would exhibit different memory characteristics, so the waiting time in between indentions would vary the test results greatly. Thus a waiting time that accurately represents the time it takes a patient to rotate should be used.

Another test could be run that would allow for the elimination of temperature and memory variables. This test would require the user to heat a given mattress to 32 degrees C without indenting it. At this point the dome could be indented into the heated mattress and held at a testing indentation depth for eight minutes. Data could be gathered over the eight-minute relaxation period. These data would be sufficient to find the true relaxation modulus of the given mattress. This test does not represent a real life movement of a patient, but would provide comparable data for all mattresses and would be a useful tool when analyzing a mattress's ability to prevent pressure ulcers.

6.2 Critique of the Domed Indenter

The domed indenter is capable of producing reliable and reproducible data on different kinds of static mattresses. There is very little friction throughout the machine and the electrical signals can be modified to have a clean data output.

The strength of the domed indenter is its ability to measure normal forces. Normal indentation into a mattress is very easy to create and manipulate. The indenter is also capable of at indenting to particular depths during a normal test. The point pressure sensor at the bottom of the dome is an excellent way to measure the maximum pressure on the dome during a normal indentation test. This setup allows for a wealth of mattress property information to be gathered through very simple testing.

The ability of the domed indenter to gather data and store data in a computer is an excellent feature. For manufacturer testing, such as the testing done at the Danish Center, this is a necessity. Controlling the domed indenter through a computer is also a necessary application. Currently the device is not arranged in this way, however, it is a possibility for the future.

The domed indenter also has strength in its possibilities for future expansion. Over the course of two months the team made a series of major alterations to the domed indenter. These alterations were made with few difficulties and greatly improved the testing ability of the device. In the future the domed indenter will most likely need further improvements so more advanced testing can occur. These future alterations will be possible because of the expandability of the device.

There is also a great possibility for the domed indenter to measure kinetic friction. The indenter also can include different overlays and hospital sheets with these tests. However, currently it would be impossible to measure static friction with the device. The motors are too powerful to measure this important mattress property.

The speed and accuracy of the motors of the domed indenter may limit its abilities in the future. Testing for properties that would require intricate motions by the motors would not be possible due to their powerful nature.

Geometry of the dome is also a limiting factor. The dome is designed to represent half of a buttock, or more generally, the curves of the lower portion of a human. In the future different curvature could be useful for testing different sizes of people. The indenter also cannot represent an emaciated buttock. A geometry representing this could be useful in the future when testing mattresses that are designed for people who have already developed pressure ulcers.

The final limiting factor of the domed indenter is its lack of point sensors. Much information could be derived from an array of point sensors placed around the entire dome. This could help to describe pressure distribution of a mattress and to verify the mathematical model used to calculate proportionality constants in the indention test.

In conclusion, the domed indenter is a device that will adequately meet the needs of the Danish Center. It is superior to mannequin testing or pressure map testing, which will not be able to measure mattress properties in as objective a manner as a domed indenter. For providing mattress properties concerning pressure ulcer prevention to a manufacturer or hospital the domed indenter is an acceptable device.

6.3 Mattress Collection and Testing Information for Bispebjerg Hospital

The Bispebjerg Hospital is interested in running a study with the Danish Center (the Hjælpemiddelinstituttet) where mattresses that are used in their hospital are tested to see how their properties change over time. The following is a recommendation about how to proceed with the testing so that the optimal data are recorded for all parties involved.

The mattresses should be numbered, or have some means of tracking them for the duration of the study. There should be at least three of each mattress type to be tested, so that the average state and life of the mattresses type can be investigated. Also, each mattress must be tracked. This will allow for testers to see a detailed history of the mattress in the future. Items that may be important for comparing mattresses and results from the tester include: how many patients were on the mattress, for how long, how much did they weigh, how mobile were they, and how often the bed was cleaned. This information is important to track because it helps characterize the lifespan of the mattress. The number of patients on a mattress, their time of stay, mobility, and their weight, helps to give some idea of what sort of strain and pressure the mattress was under. The number of mattress cleanings that take place will help characterize how well the mattress was cared for. While each mattress will not have experienced the same loads, it is inconsistent to directly compare two mattresses that have had vastly different use.

The hospital mattresses should be tested on an annual basis, so that the trend of the mattress properties can be seen to change over time. This information will allow the hospital to see if specific mattresses perform better over time. Also, these tests may allow the hospital staff to predict life expectancies of mattresses, and see how mattress properties degrade over time. This gives them enough information to run a cost benefit analysis, and decide which mattress or mattresses are overall the best for their use.

A test that compares mattresses that have uniform histories would be more useful than tests that compare mattresses with different histories. In order to accomplish this, a testing site that uses the methods described in the European Standard #1957 could be used. This method uses a roller to age a mattress to a specific point, by constantly rolling and pressing down on the mattress. This would give a standard "aging" to a mattress, so that changes in properties could be compared, as each mattress will have gone through an identical process.

6.4 Instrumentation and Data Collection Recommendation

Several important changes to the software and hardware systems would make data collection and analysis more efficient and effective. Most importantly the Danish Center's version of LabVIEW should be upgraded to version 6. There are also many improvements that could be made to the controls and motors of the domed indenter that would improve its ability to conduct controlled, repeatable testing.

6.4.1 LabVIEW

LabVIEW software is currently used to record the data taken from the domed indenter at the rate of a hundred samples a second. These data samples are then graphed on the fly to the screen so that the operator can see the current pressure outputs. The data are also recorded to the hard drive at the end of the test, which can later be imported into spreadsheet or database software like Access and Excel. In the future using LabVIEW 6, these reports could be generated inside LabVIEW. LabVIEW 6 allows for report generation, including graphs and trend lines. This would be highly beneficial to the Danish Center, allowing the whole process to become automated, in conjunction with the development of digital controls and stepper motors. LabVIEW 6 would also allow software filters to be developed that would further eliminate any noise in the system.

Currently the voltage from the domed indenter is filtered through hardware low and high pass filters. This filtering is explained in our results section, but was caused by alternating current noise interfering with our data. LabVIEW 6 contains software filters, including band pass filters. This would allow the operator to eliminate any noise without significant changes. The levels on this filtering could also be adjusted from the front panel of the virtual instrument, allowing those without in-depth knowledge of the LabVIEW VI system to make changes to these values. These changes could then be used in the computer control of the system.

6.4.2 Control System

Developing a control system for the domed indenter will be an important step in testing mattresses. Having a system that can move the domed indenter according to mattress depth and pressure will allow for many new tests that the current indenter cannot perform. Tests for shear could be incorporated, along with tests that maintain a constant force on the mattress while recording change in indention depth (creep), which is more indicative of mattress use than the currently prescribed stress relaxation test. These tests are impossible with the current tester design but would be beneficial in developing a complete view of the mattress. Note that position sensors are also needed to facilitate this test (see below).

To control the movements of the domed indenter many improvements to the system need to be made. One of the most important will be to add stepper motors to the domed indenter's vertical and horizontal movements. Stepper motors, which can control movements to one degree of motion, would allow the movement of the domed indenter to be controlled precisely. The controllers for such motors can also be commanded digitally; a strong advantage over the current analog control signal. Currently the motor's movement when starting up and stopping is uncontrolled and is not linear compared to the normal speed. In a stepper motor all movements are based upon a set degree of movement, which allows for very precise measurements.

Replacing these motors on the domed indenter will require significant work. Currently the control cards and analog motors are heavily integrated into the design of the domed indenter. Both motors are detachable from the movement track though, and as long as a motor can be found to fit this joint it will not be a significant problem to replace them.

The control cards for such motors would ideally have digital inputs to control the motors movements. The control signal could then be generated from LabVIEW, allowing LabVIEW to dynamically control the tests.

With digital stepper motors in place, LabVIEW could dynamically control the testing process. Tests that were previously impossible could be conducted; mainly the shear and constant force tests. Both these tests require precise movements that can be controlled in real time by the computer.

LabVIEW 6 can produce both analog and digital outputs needed for stepper motors. These movements can be programmed dynamically to the reading off of the analog input lines. This ability would ideally be used in the constant force tests. In such a test the goal is to simulate the impact of a human body on a mattress. When a human is placed on a mattress, a constant weight is applied to the surface of the mattress, and the human sinks according to the properties of the mattress. With the current setup of the domed indenter this is impossible, since the indenter can only travel to a specified depth and record pressure. If this pressure changes the indenter only records this change, and cannot change the indention depth dynamically to maintain a constant pressure.

While recording the change in pressure at a specific depth is very useful in characterizing mattresses properties, it does not simulate identically the effects of a human on a mattress, a goal in the design of the domed indenter. Adding stepper motors with digital control units and position sensors would allow the constant pressure tests to be conducted.

A similar problem prevented the domed indenter from being used to test for shear forces. The current motors cannot be controlled dynamically by LabVIEW. Shear tests require small precise movements, something that cannot be accomplished by a human operator using analog control switches. In a shear test the movement of the domed indenter must be controlled very precisely over a very small movement period to be able to calculate the static friction coefficient. Since any movement larger than approximately 10 mm will introduce the effects of kinetic friction, this test could not be accomplished with the current setup.

6.5 Circuit Recommendations

Currently the filter and amplification circuit allows for meaningful data to be gathered which can be used to compare mattress properties. However, the circuit can be improved in order to allow for a cleaner and more accurate data signal to be recorded by the computer. This may allow for a more accurate comparison of mattresses.

The electronic noise caused by the domed indenter is currently filtered by only one low pass filter. It is possible that a larger percentage of the remaining noise could be removed if other filters were added to the circuit, or if the order or cutoff frequency of the filter is altered. An analysis of the frequencies that need to be blocked is required before the addition of component to the circuit can take place. The frequency analysis can be accomplished by examining the noise from the domed indenter with a Fourier Transform. The Fourier Transform would allow the user to identify the range of frequencies that make up the electronic noise, and thus the filter could be redesigned to specifically block the noise frequencies. The team did not attempt to do this because a Fourier Transform program was not available.

Currently the circuit contains an operational amplifier, which is powered by a voltage source chip of +/- 15 volts. A large generator that gives off 24 volts powers this voltage source chip. In the future this 24-voltage source should be taken out and instead be replaced with the voltage flowing into the domed indenter circuits, which is 24 volts as well. This will help to simplify the filtering setup and remove the bulky external second power source.

Further aesthetic maintenance of the circuit will also improve testing. Currently the circuit must be connected to power supplies, inputs, and outputs by a series of alligator clips. By placing the circuit into an electrical box with orderly input and output plugs the cosmetics of the system will be enhanced greatly. This will also serve a good function. The leads that run from the computer to the domed indenter will be shortened and thus there is less area for noise to enter the data. Connecting the computer to the domed indenter will be simplified as well, and confusion between leads will be eliminated. This has not currently been accomplished due to a lack of materials and time constraints.

The final recommended improvement to the circuit is to increase the number of circuit inputs and outputs so that the computer can monitor all aspects of the domed indenter. Currently only the total transducer output is fed to the computer. The Lab VIEW and PC card setup will support up to 16 analogue inputs to be recorded. By utilizing this setup, all outputs for the domed indenter including the point sensor, and separate transducers can be monitored simultaneously throughout any testing period. This includes the horizontal and vertical positions of the domed indenter.

7 Conclusion

Pressure ulcers continue to afflict thousands of hospital patients every year. The prevention of these ulcers is not a simple task, and will require many more years of equipment and mattress advances. Fortunately, organizations such as the Danish Center will remain dedicated to the continued efforts of pressure ulcer prevention. The teams work with Danish Center has contributed greatly to their pressure ulcer prevention efforts by accomplishing the goals set for the project.

The goals of the project were threefold; to foster increased relations between the Danish Center and Bispebjerg Hospital, to develop reusable testing protocols for mattress evaluation, and to provide feedback to the Danish Center on the effectiveness of their indenter. During the team's time in Denmark, all three objectives were accomplished, along with providing the Danish Center with concrete recommendations for future expansion and opportunities in testing mattresses for pressure ulcer prevention.

8 Appendices

A1 Glossary

Creep: a time dependent change in pressure data position to sensor position (EUPAP, 2002)

Elastic: ability to change back to original shape after a force is applied, and a change has take place (Tempur-Pedic Inc)

Hardness: total force required to indent the test surface a designated amount (Bain et al, 1999)

Interface Pressure: Perpendicular force exerted by a part of the skin resting on a surface divided by the contact area of that part of the skin (EUPAP, 2002)

Poisson's Ratio: How much a material distorts in the opposite direction as compressed. An example is clay, you make a block, and push in on one pair of sides, on the other sides it expands, that is a positive Poisson's ratio.

Resilience: the ability of a mattress to return to its normal properties, without wearing out.

Visco- Resistant to change of shape (Tempur-Pedic)

Viscosity: Analogous to friction in solids, degree fluid molecules move across one another, more movement correlates to large friction

A2. Norton Scale

Overview:

The Norton scale can be used to predict if a patient is at risk for development of pressure ulceration.

Parameter	**Finding**	**Points**
physical condition	Good	4
	Fair	3
	Poor	2
	very bad	1
Mental condition	Alert	4
	Apathetic	3
	Confused	2
	Stupor	1
Activity	Ambulant	4
	walk with help	3
	Chairbound	2
	Bedbound	1
mobility	Full	4
	slightly limited	3
	very limited	2
	Immobile	1
incontinent	None	4
	Occasional	3
	usually urine	2
	urine and feces	1

The maximum score from the Norton Scale is 20, and the minimum score is a 5. A score equal or greater to 14 indicates a strong prevalence to pressure ulcer development.

Taken from The Medical Algorithms Project (2003)

A3: Braden Scale

Overview:

The Braden scale can be used to identify those patients at risk for development of pressure ulcerations.

Parameters evaluated (6):

- sensory perception
- moisture
- activity
- mobility
- nutrition
- friction and shear

Parameter	**Finding**	**Description**	**Points**
sensory perception (able to respond meaningfully to pressure related discomfort)	no impairment	responds to verbal commands. Has no sensory deficit that would limit ability to feel or voice pain or discomfort	4
	slightly limited	responds to verbal commands but cannot always communicate discomfort or need to be turned. Also may have some sensory impairment which limits ability to feel pain or discomfort in 1-2 extremities.	3
	very limited	responds only to painful stimuli and cannot communicate discomfort except by moaning or restlessness. Also may have sensory impairment that limits the ability to feel pain or discomfort over half of the body	2
	Completely	unresponsive to painful stimuli.	1

	limited	Also may have limited ability to feel pain over most of body surface	
moisture (degree to which skin is exposed to moisture)	rarely moist	skin is usually dry and linen only requires changing at routine intervals	4
	Occasionally moist	Skin is occasionally moist requiring an extra linen change about once a day	3
	very moist	skin is often but not always moist.	2
	Constantly moist	skin is kept moist almost constantly	1
Activity (degree of physical activity)	Walks frequently	walks outside of room at least twice a day and inside room	4
	Walks occasionally	walks occasionally during day but for very short distances with or without assistance	3
	Chairfast	ability to walk severely limited or nonexistent	2
	Bedfast	confined to bed	1
mobility (ability to change and control body position)	no limitations	makes major and frequent changes in position without assistance	4
	slightly limited	makes frequent though slight changes in body or extremity position independently	3
	very limited	makes occasional slight changes in body or extremity but unable to make significant changes independently	2
	Completely immobile	does not make even slight changes in body or extremity position without assistance	1
nutrition (usual food intake pattern)	Excellent	eats most of every meal and never refuses a meal	4
	Adequate	eats over half of most meals and may occasionally refuse a meal	3
	Probably inadequate	rarely eats a complete meal and has decreased protein intake	2
	very poor	never eats a complete meal and rarely eats more than a third of food offered. Also if NPO or on clear fluid or IVs for more than 5 days	1
shear & friction	no problem	moves in bed and in chair	3

	apparent	independently and has sufficient muscle strength to lift up completely during move.	
	Potential problem	moves feebly or requires minimum assistance	2
	Problem present	requires moderate to maximum assistance in moving; complete lifting without sliding against sheets is impossible.	1

Interpretation

• maximum score 23 (best prognosis)

• minimum score 6 (worst prognosis)

• at risk for pressure ulcer if score <= 16

• the breakpoint for determining risk for pressure ulcer may vary with patient population; in an ICU trauma population the breakpoint was found to be 11 rather than 16 (Jiricka 1995)

Taken from The Medical Algorithms Project (2003)

A4: Gosnell Scale

Overview:

The Gosnell scale is used to assess the risk of pressure sore development.

Parameters evaluated (5):

• mental status: an assessment of one's level of response to his/her environment

• continenence: the amount of bodily control of urination and defecation

• mobility: the amount and control of movement of one's body

• activity: the ability of an individual to ambulate

• nutrition: the process of food intake

In addition evaluation includes recording of

• vital signs: temperature pulse respirations and blood pressure

• skin appearance: color moisture temperature and texture

• diet

• 24-hour fluid balance: daily fluid intake and output

• interventions: all devices measures and/or nursing care activity being used for the purpose of pressure sore prevention

• medications

• comments

Parameter	Finding	Description	Points
Mental status	Alert	Oriented to time place and person. Responsive to all stimuli and understands explanations.	1
	Apathetic	Lethargic forgetful drowsy passive and dull. Sluggish depressed. Able to obey simple commands. Possibly disoriented to time.	2

	Confused	Partial and/or intermittent disorientation to time person and place. Purposeless response to stimuli. Restless aggressive irritable anxious and may require tranquilizers or sedatives.	3
	Stuporous	Total disorientation. Does not respond to name simple commands or verbal stimuli.	4
	Unconscious	Non-responsive to painful stimuli.	5
continence	fully controlled	Total control of urine and feces.	1
	usually controlled	Incontinence of urine and/or of feces not more often than once every 2 days. Or has Foley catheter and is incontinent of feces.	2
	Minimally controlled	Incontinent of urine or feces at least once in 24 hours.	3
	absence of control	Consistently incontent of both urine and feces.	4
mobility	Full	Able to control and move all extremities at will. May require the use of a device but turns lifts pulls balances and attains sitting position at will.	1
	slightly limited	Able to control and move all extremities but a degree of limitation is present. Requires assistance of another person to turn pull balance and/or attain a sitting position at will but self-initiates movement or request for help to move.	2
	very limited	Can assist another person who must initiate movement via turning lifting pulling balancing and/or attaining a sitting position (contractures paralysis may be present).	3
	Immobile	Does not assist self in any way to change position. Is unable to change position without assistance. Is completely dependent on others for movement.	4
Activity	Ambulatory	Is able to walk unassisted. Rises	1

		from bed unassisted. With the use of a device such as a cane or walker is able to ambulate without the assistance of another person.	
	walks with help	Able to ambulate with assistance of another person braces or crutches. May have limitation of stairs.	2
	Chairfast	Ambulates only to chair requires assistance to do so. Or is a confined to a wheelchair.	3
	Bedfast	Is confined to bed during entire 24 hours of the day.	4
nutrition	regular food intake	Eats some food from each basic food category every day and the majority of each meal served. Or is on tube feeding.	1
	occasionally misses food intake	Occasionally refuses a meal or frequently leaves at least half of a meal.	2
	seldom intakes food	Seldom eats a complete meal and only a few bites of food at a meal.	3

Interpretation

• minimum score 5

• maximum score 20

• score 5: very low risk of pressure ulcer

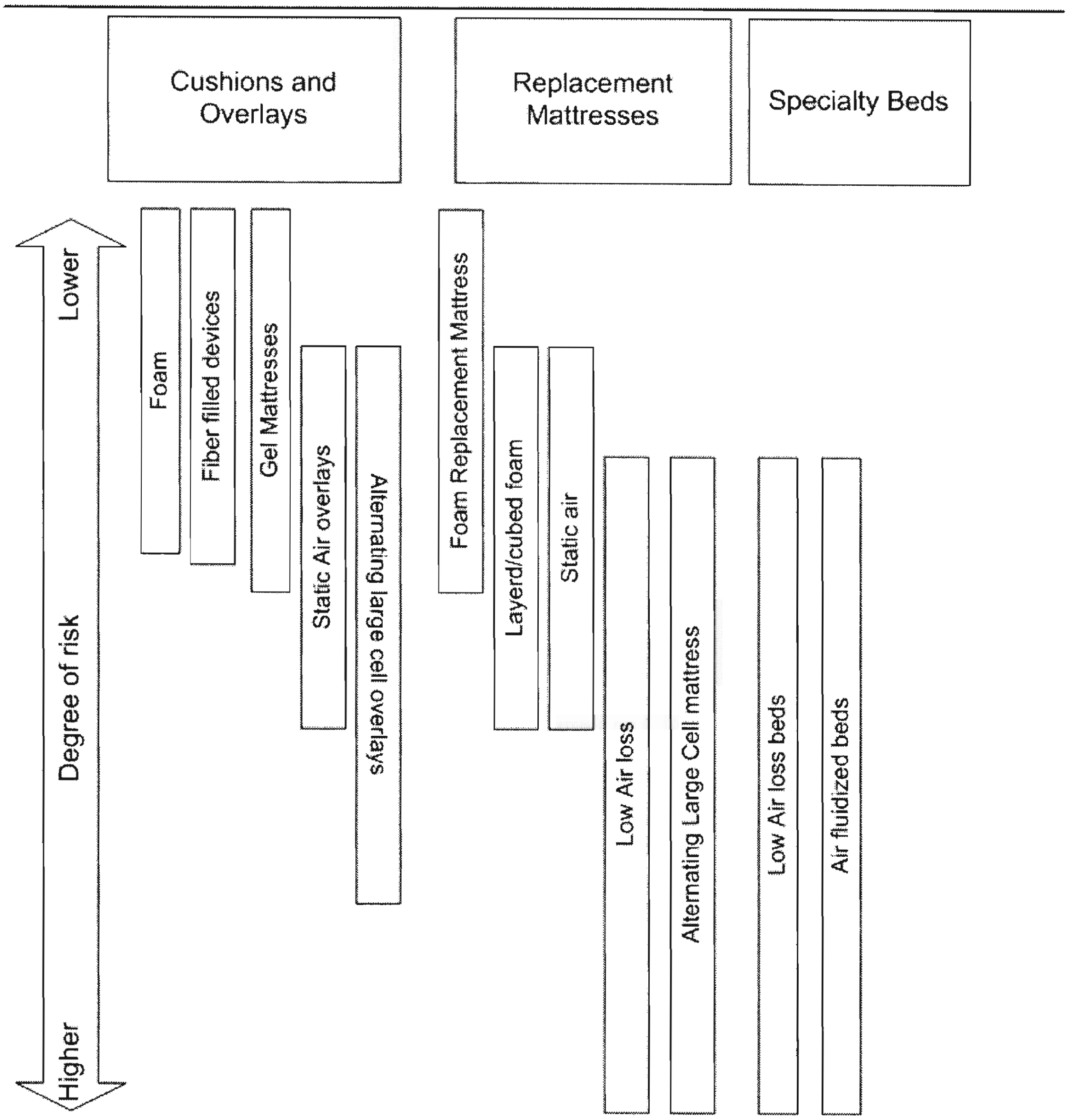
• score 20: very high risk of pressure ulcer

Taken from The Medical Algorithms Project (2003)

A5: AWMA Graphic

From AWMA, graphic demonstrating best types of beds for increasing risk of pressure ulcers.

Recommended use of Support Surfaces depending on degree of risk



Adapted from Australian Wound Management Association's *Clinical Practice Guidelines for Prevention of Pressure Ulcers*, figure 5

A6: Domed Indenter Diagrams

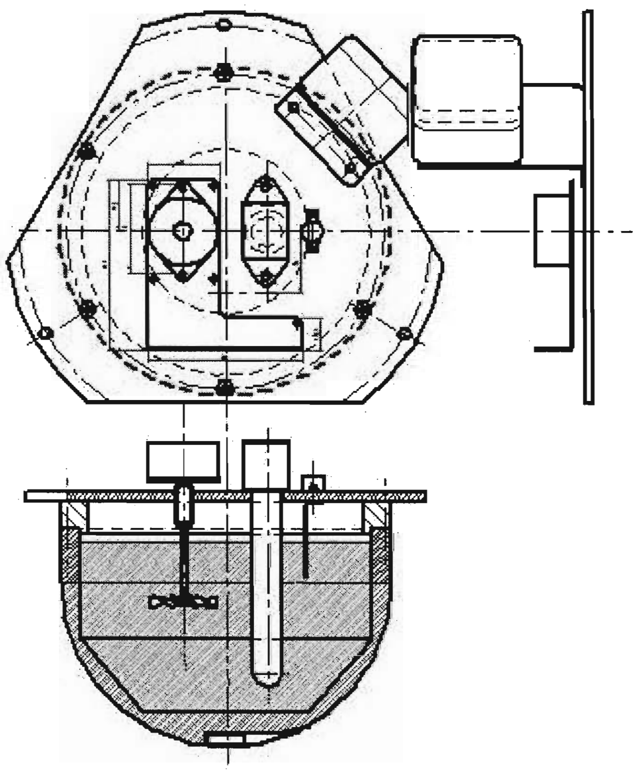


Fig. A6.1 Schematic of Dome of Indenter

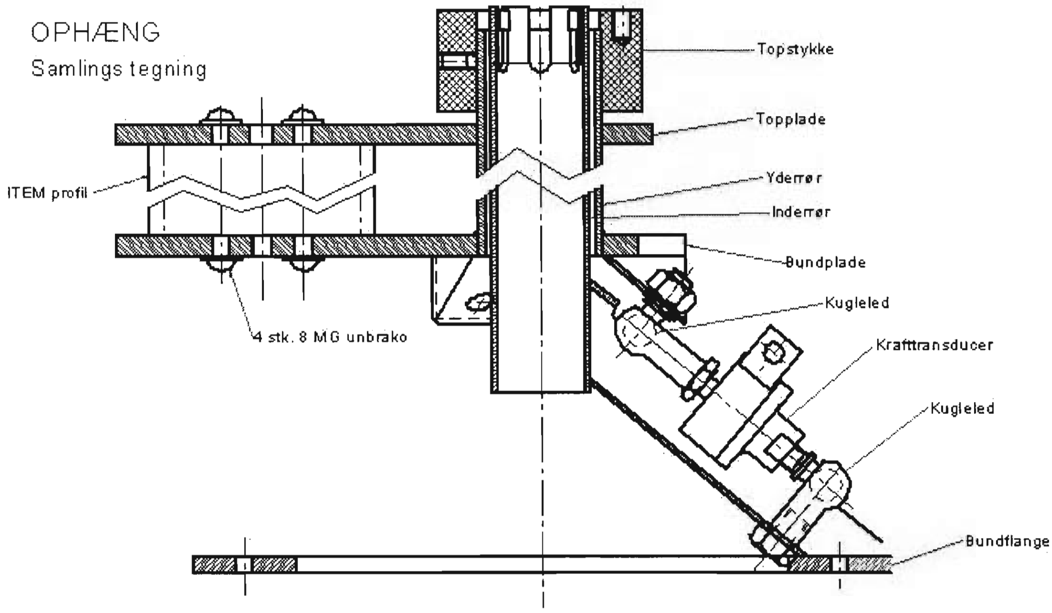


Fig. A6.2 Schematic of suspension system (old)

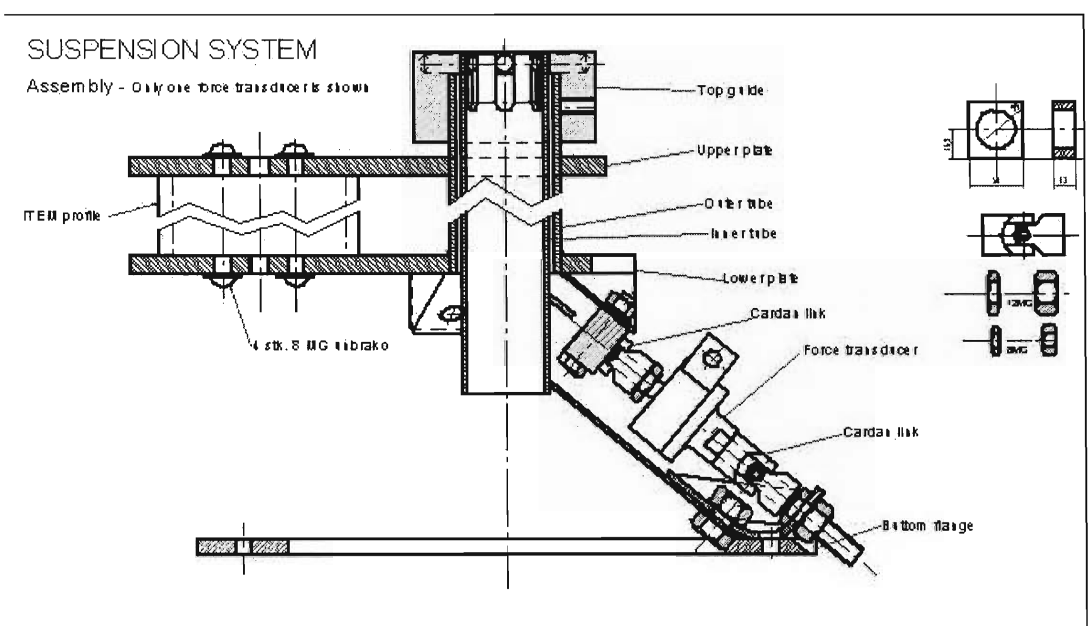
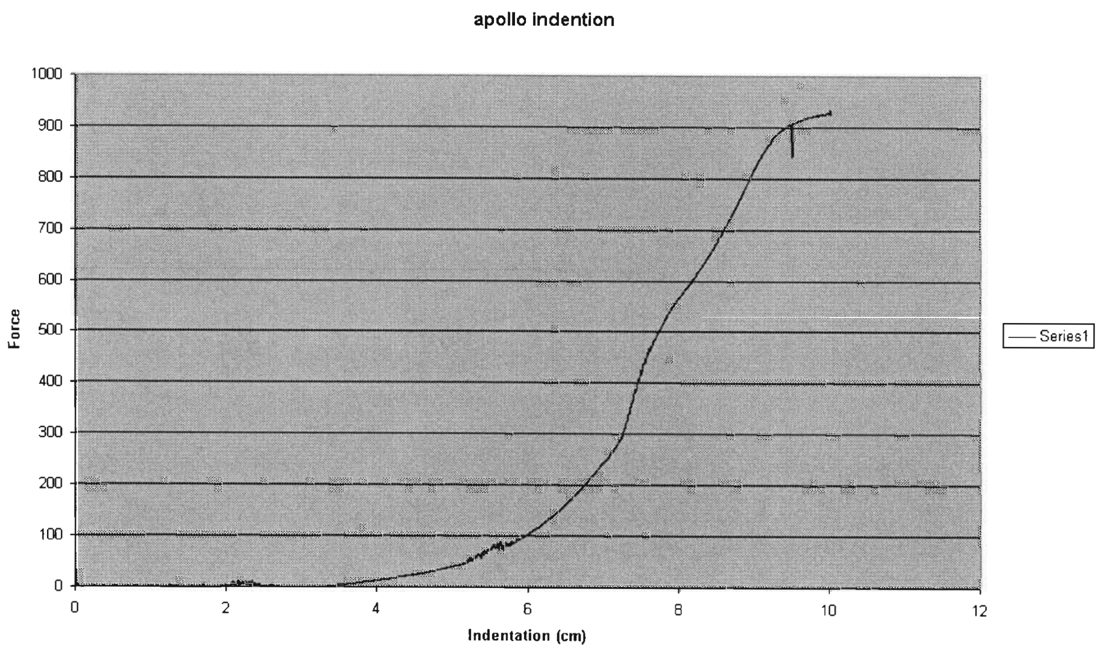
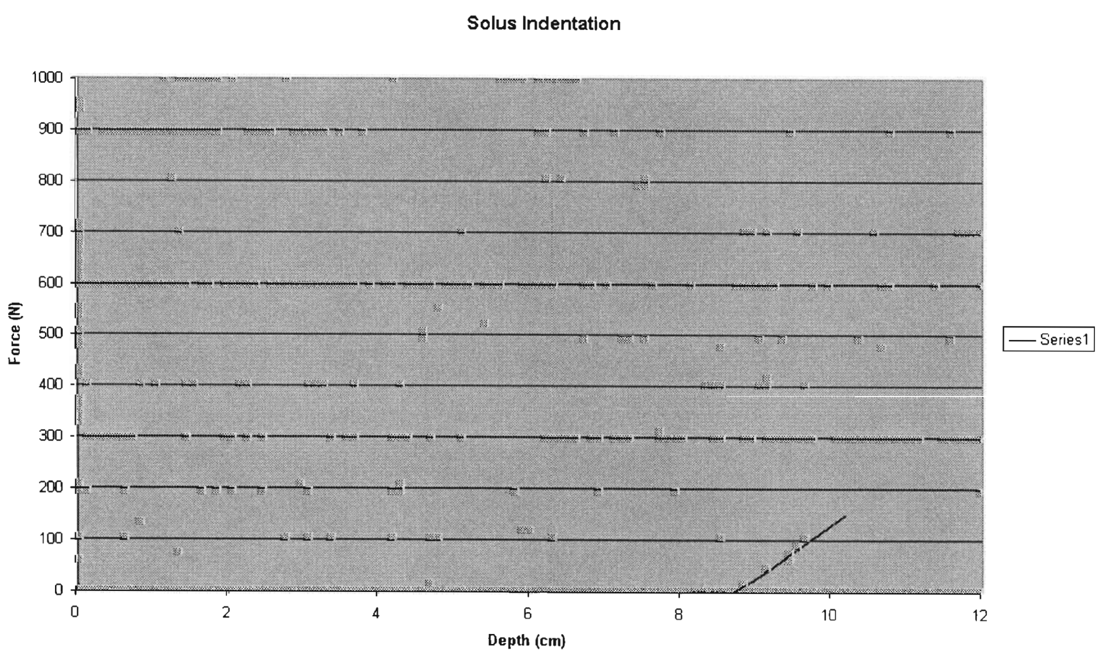
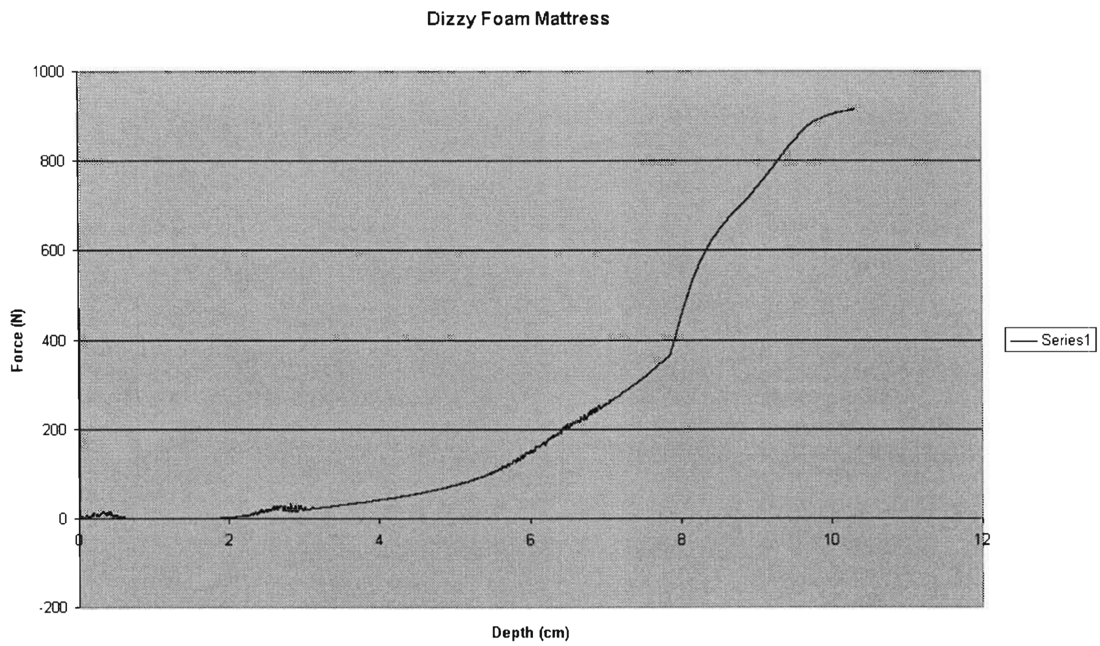


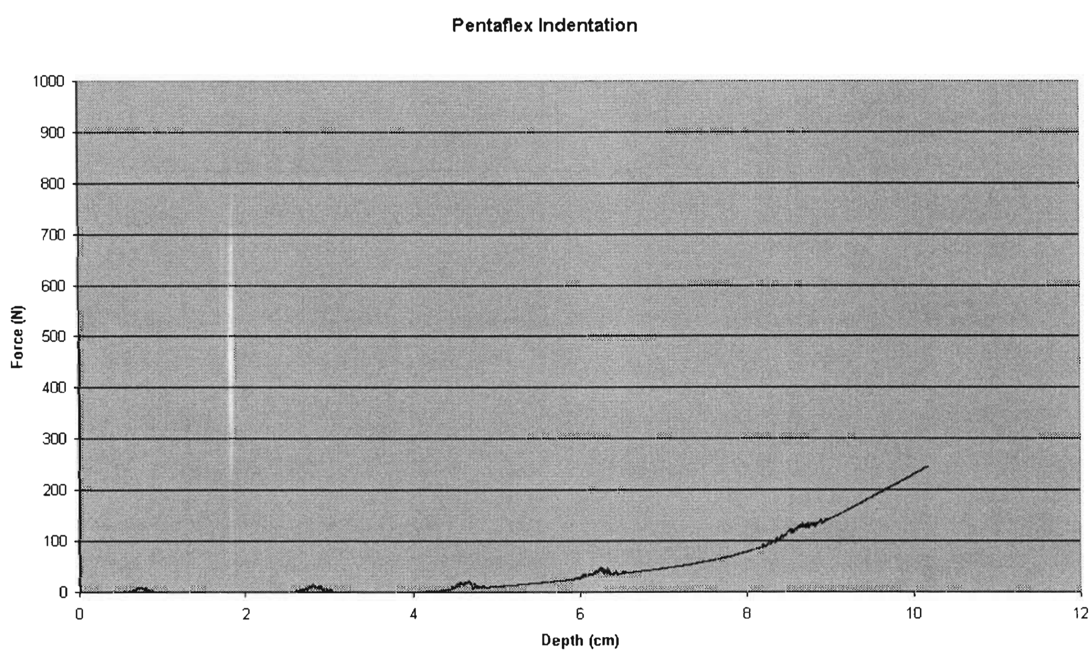
Fig. A6.3 Schematic of suspension system (new)

A7: Indentation test graphs

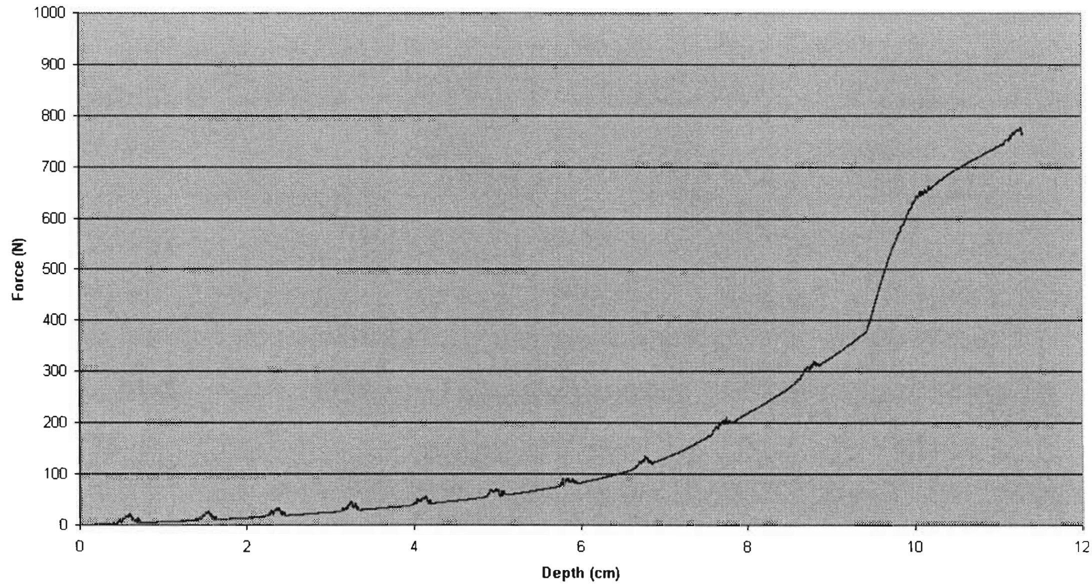




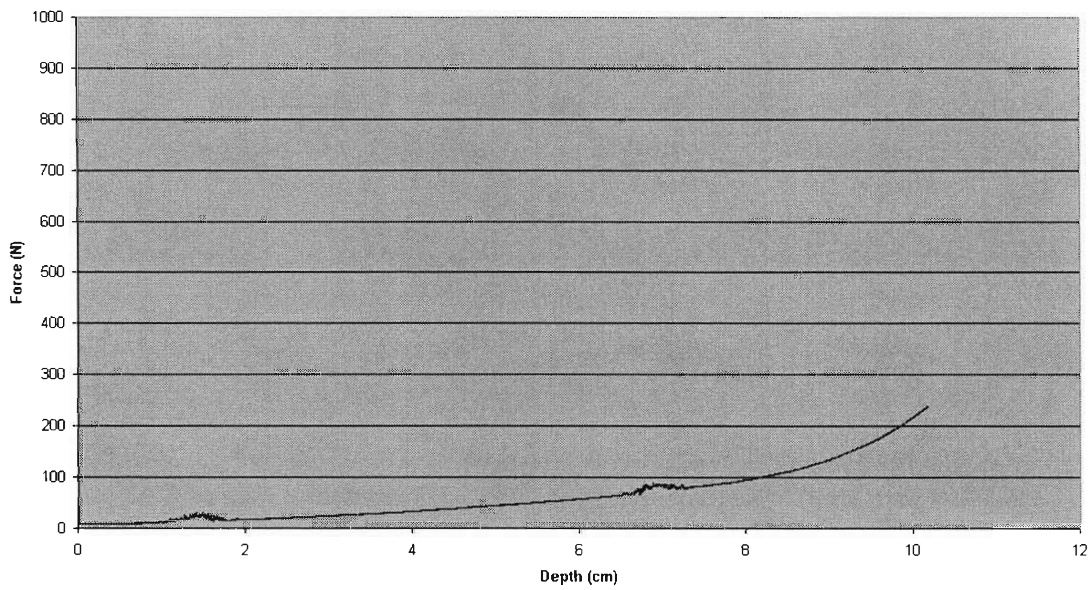

Dizzy Foam Mattress
1000
800
600
400
200
0
-200
Force (N)
0
2
4
6
8
10
12
Depth (cm)
Series1

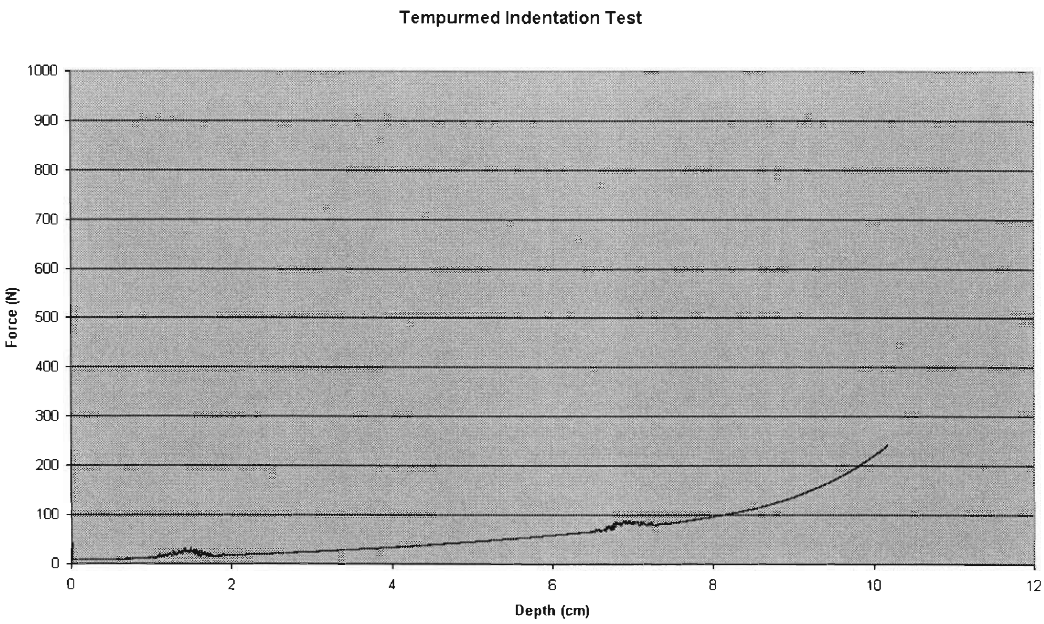

Pentaflex Indentation
1000
900
800
700
600
500
400
300
200
100
0
Force (N)
0
2
4
6
8
10
12
Depth (cm)

Spring mattress indentation test



Tempur Indentation




Tempurmed Indentation Test
Force (N)
1000
900
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
Depth (cm)

A8: Visco-elastic test graphs

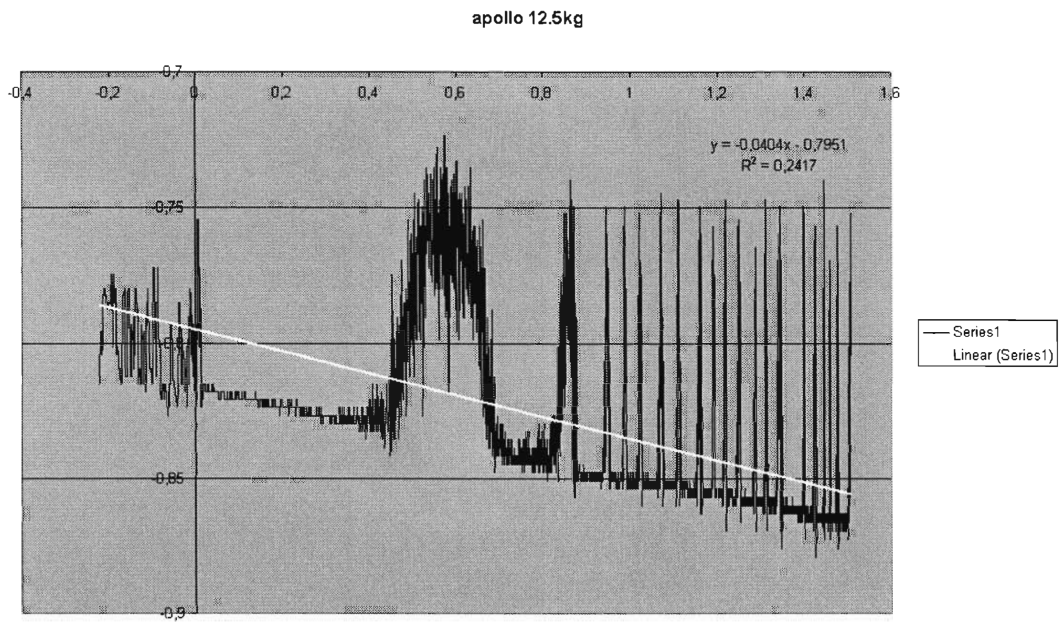


Fig A8.1 Apollo 12.5Kg

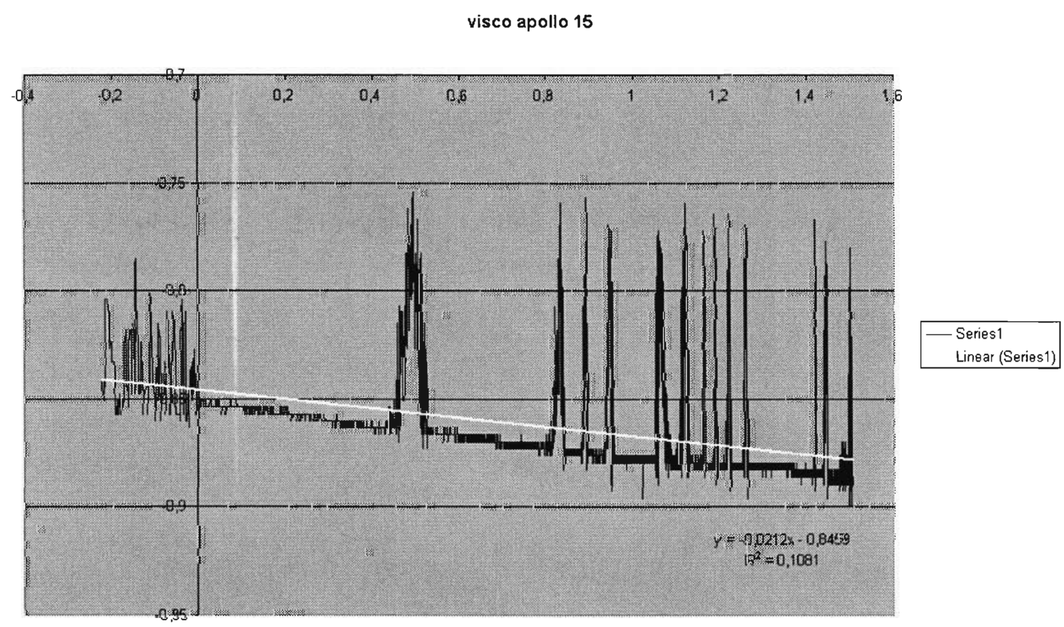


Fig A8.2 Apollo 15Kg

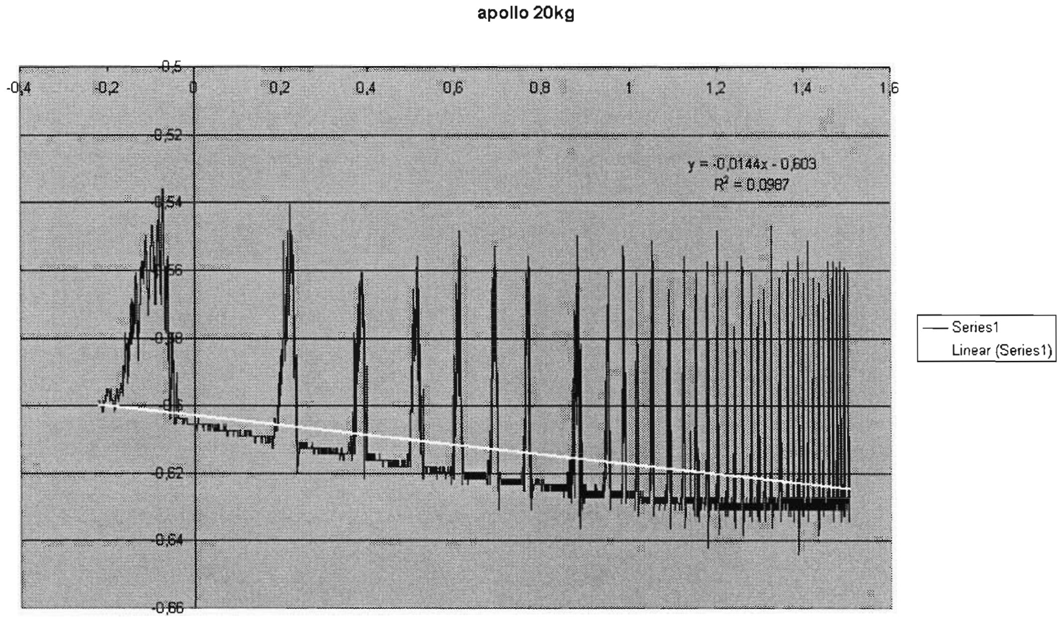


Fig A8.3 Apollo 20Kg

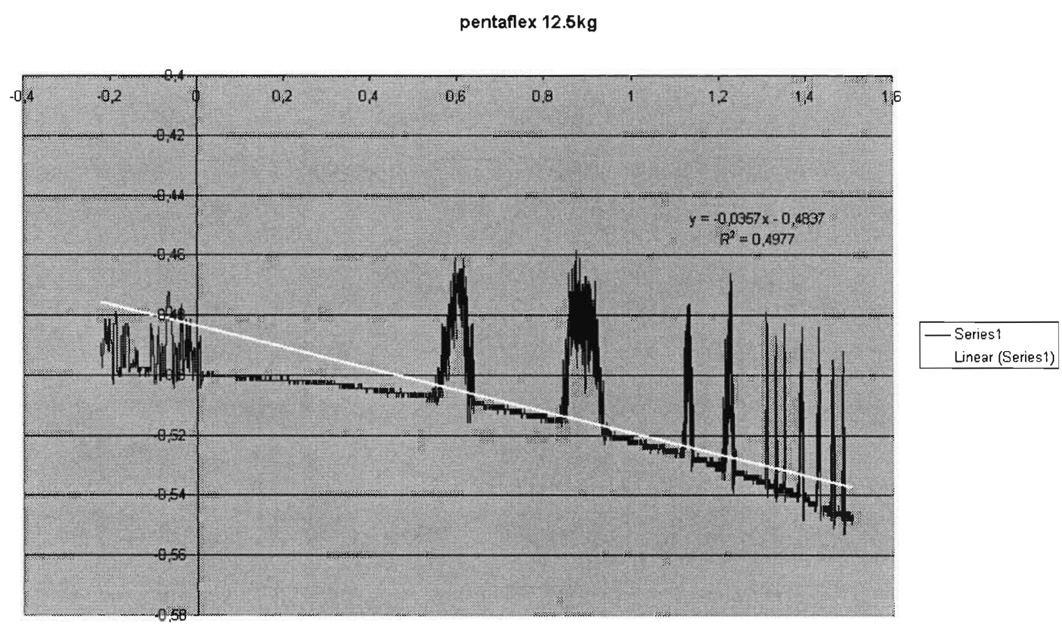


Fig A8.4 Pentaflex 12.5Kg

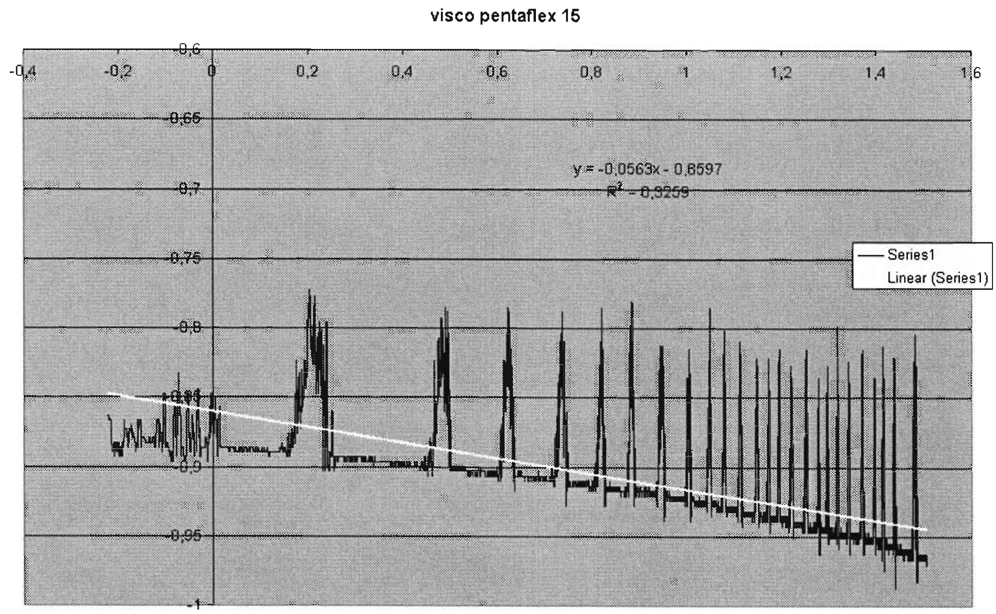


Fig A8.5 Pentaflex 15Kg

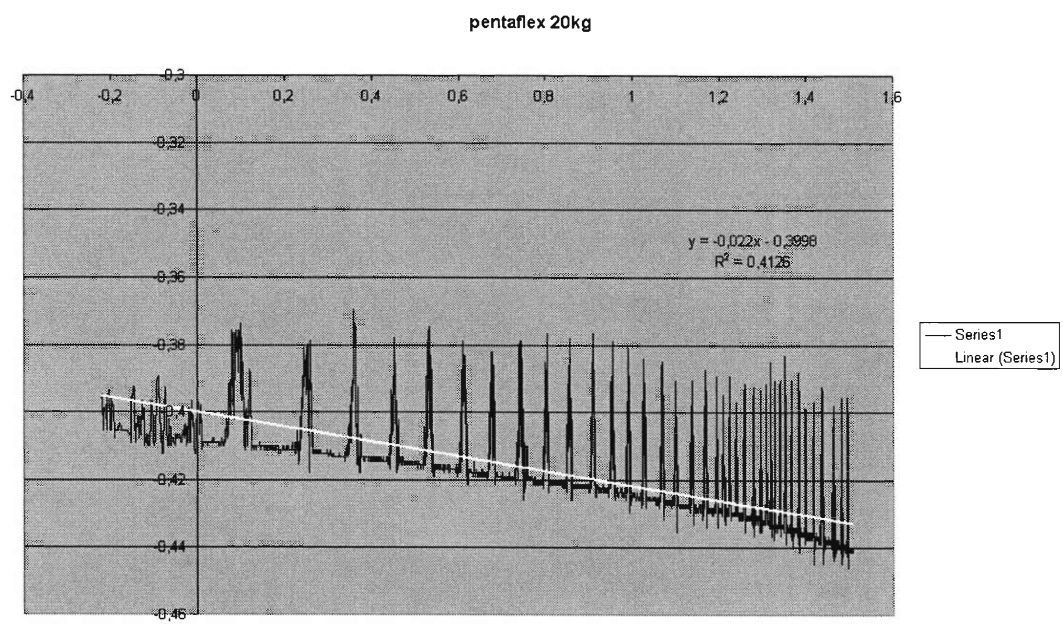


Fig A8.6 Pentaflex 20Kg

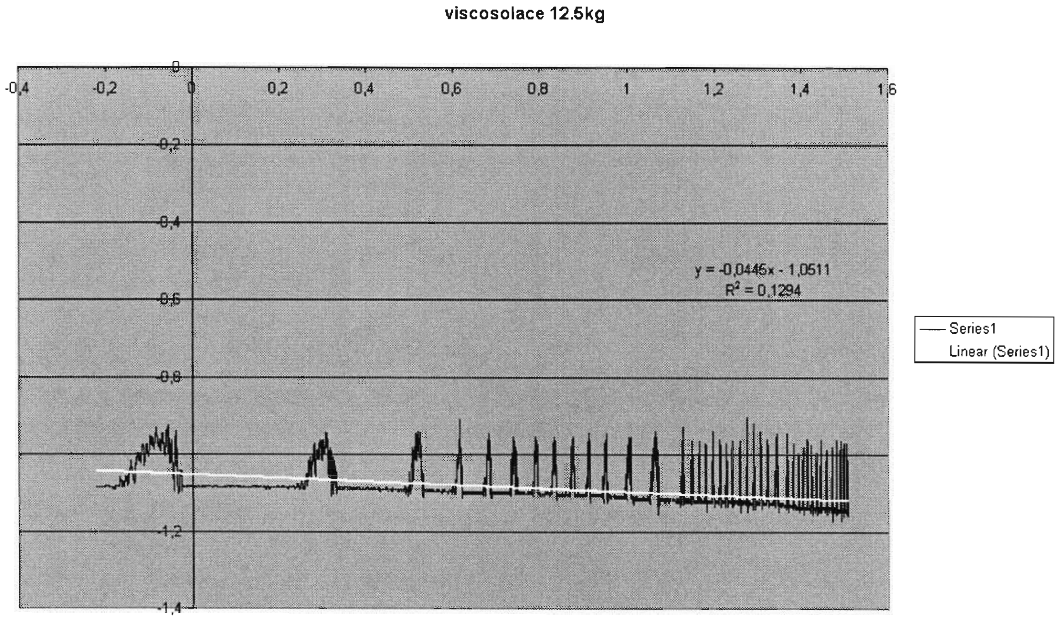


Fig A8.7 Solcae 12.5 Kg

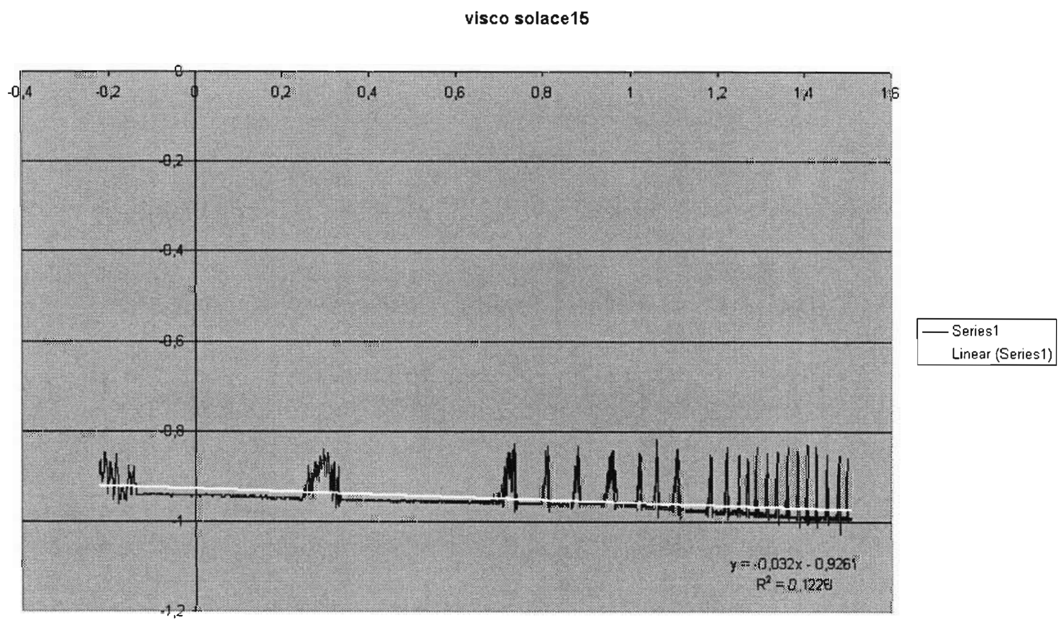


Fig A8.8 Solace 15Kg

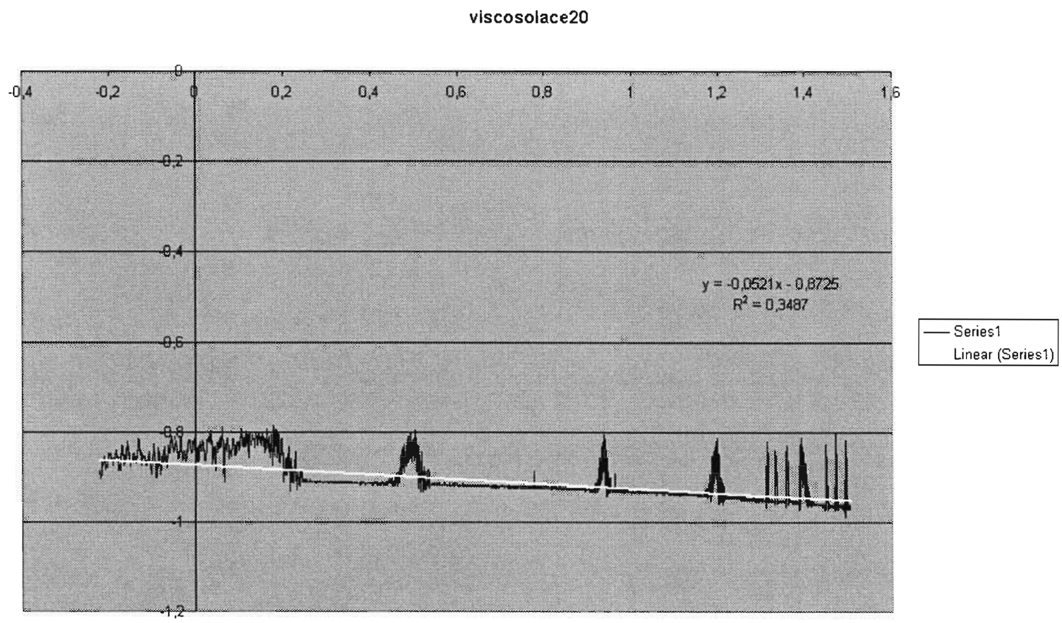


Fig. A8.9 Solace20Kg

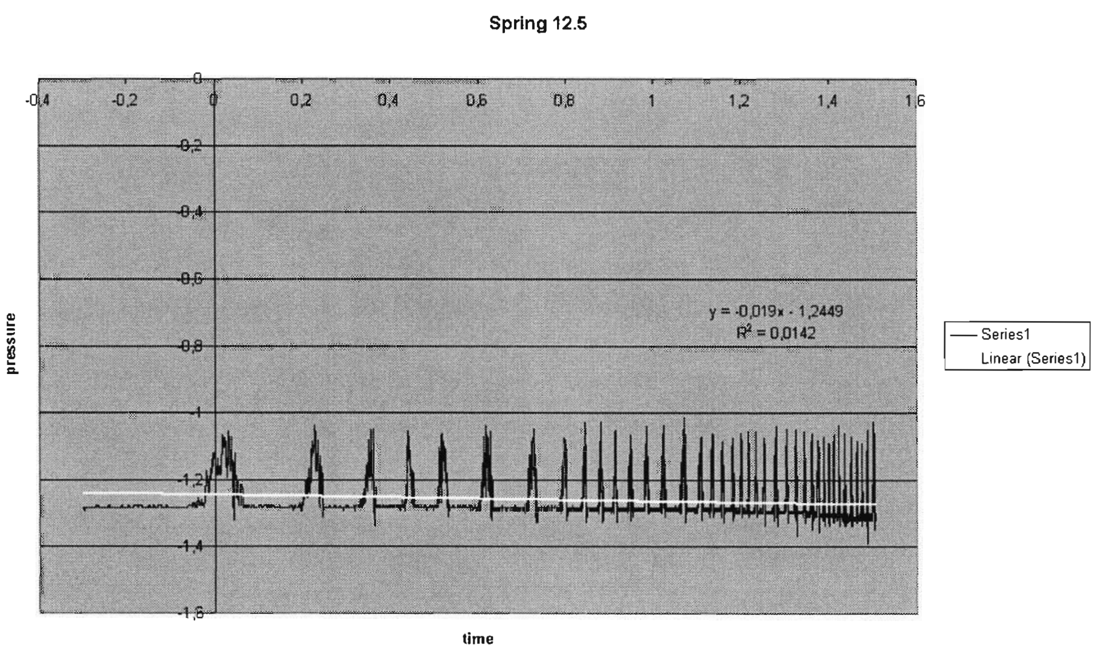


Fig. A8.10 Spring 12.5 Kg

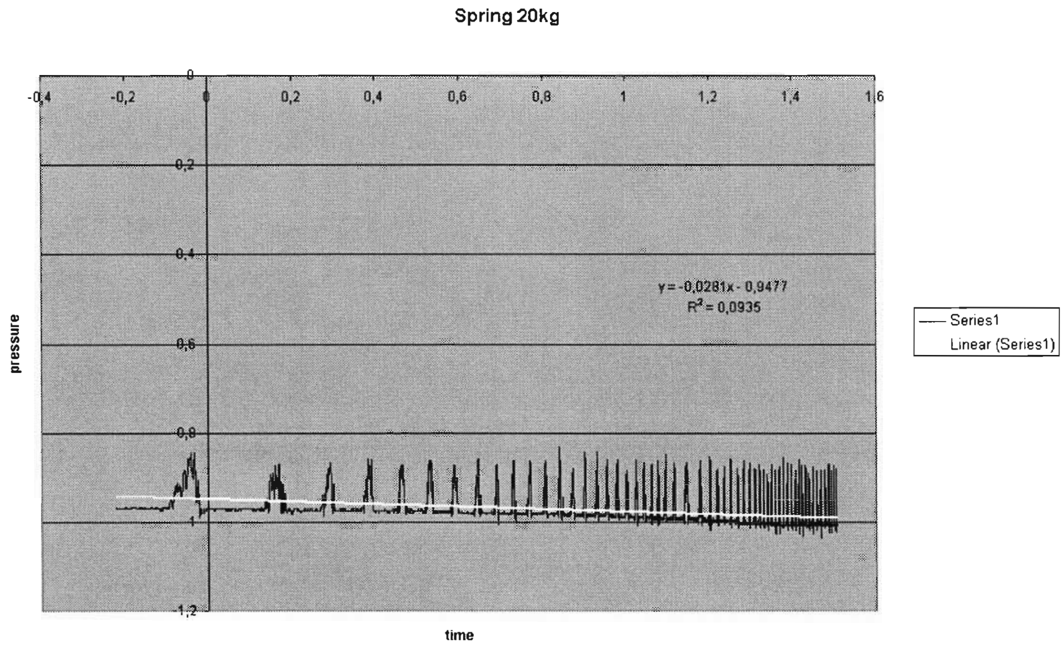


Fig. A8.11 Spring 20Kg

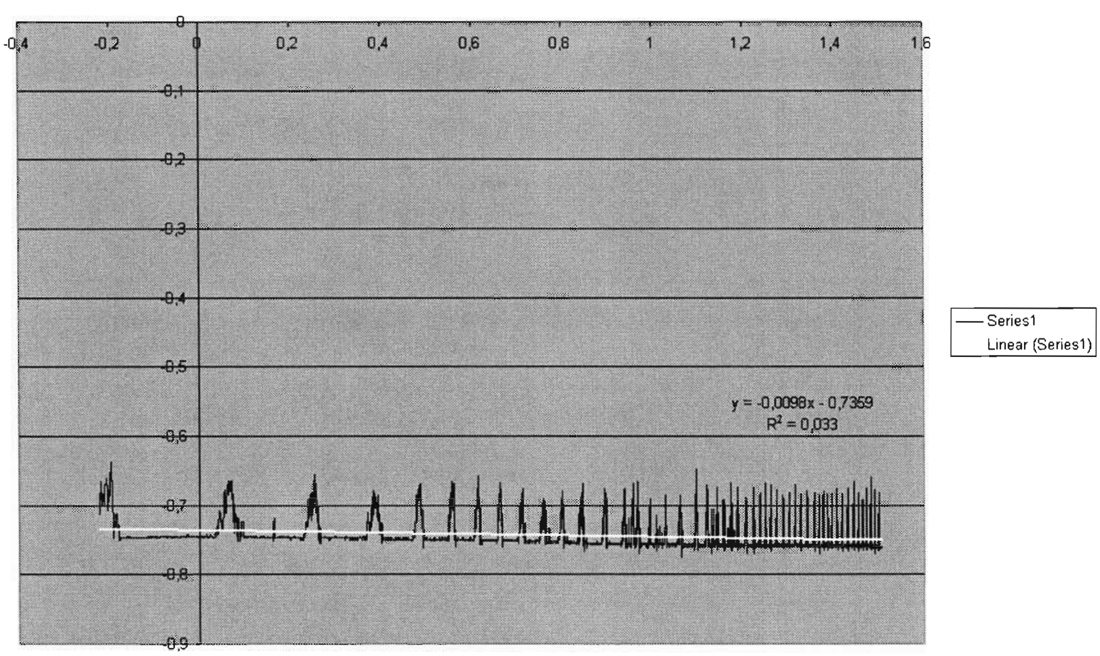


Fig A8.12 Spring 15Kg

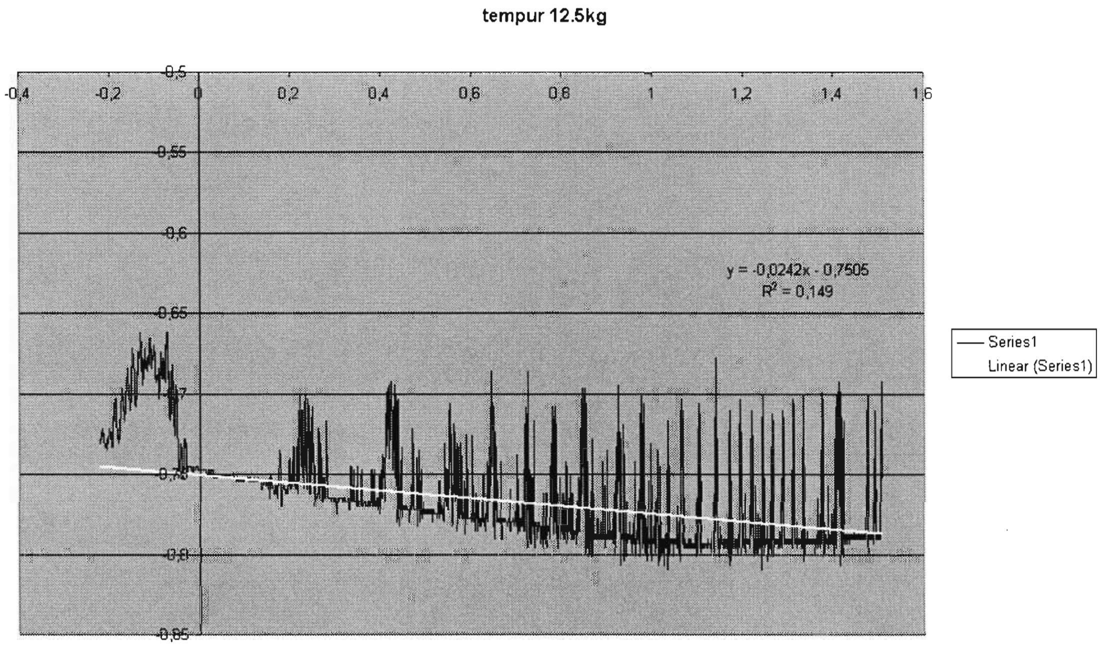


Fig. A8.13 Tempur 12.5 Kg

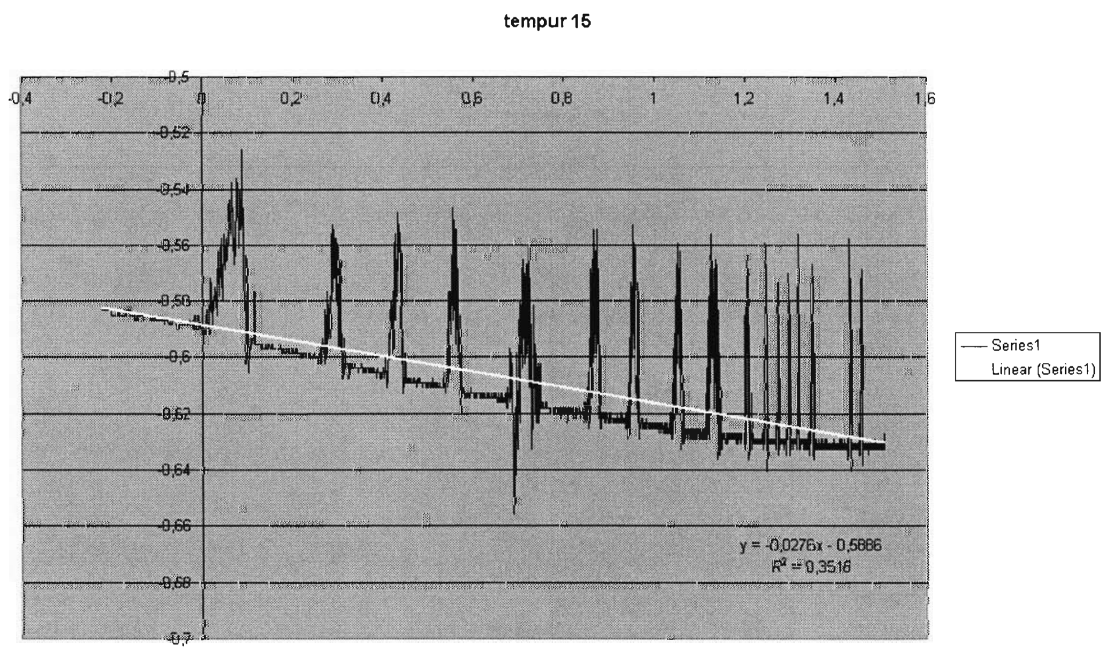


Fig. A8.14 Tempur 15Kg

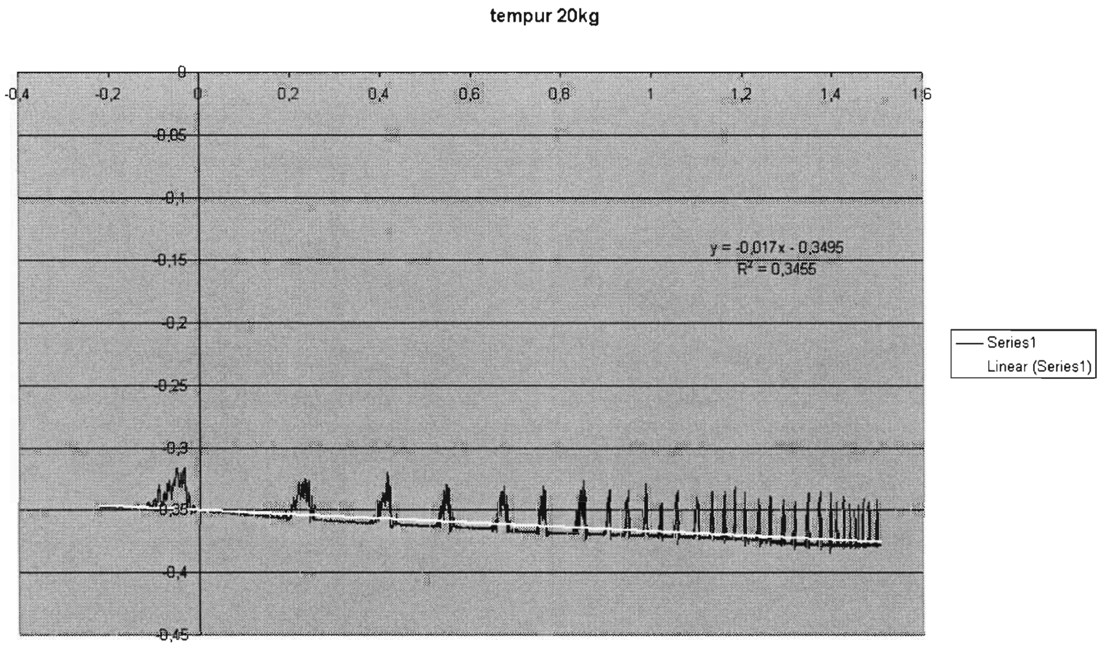


Fig. A8.15 Tempur 20Kg

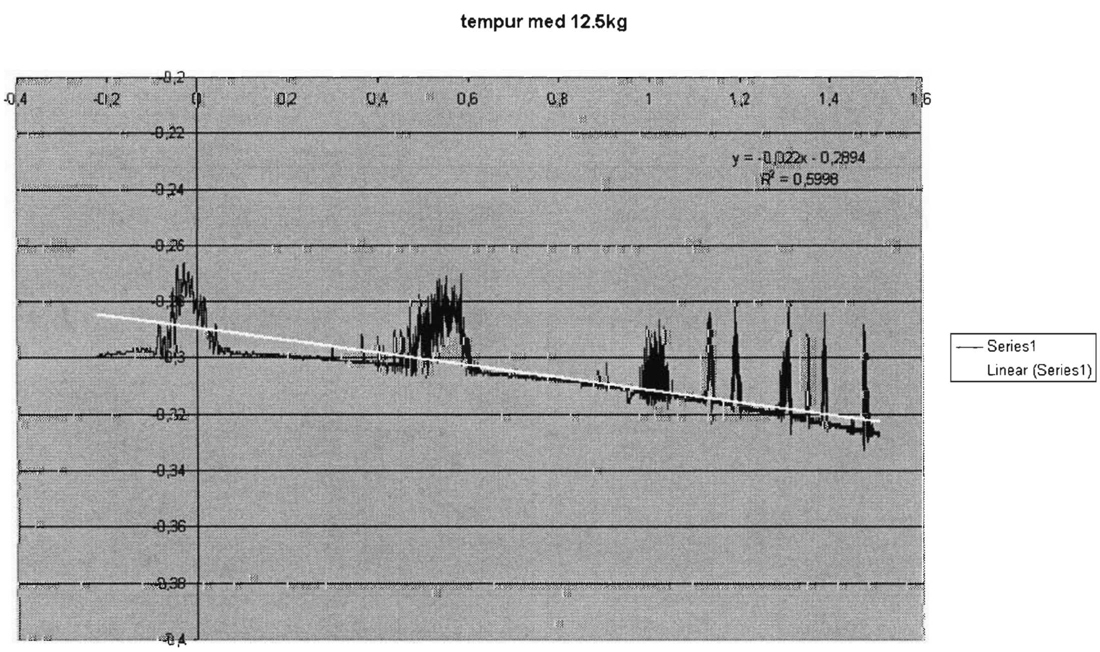


Fig. A8.16 Tempurmed 12.5Kg

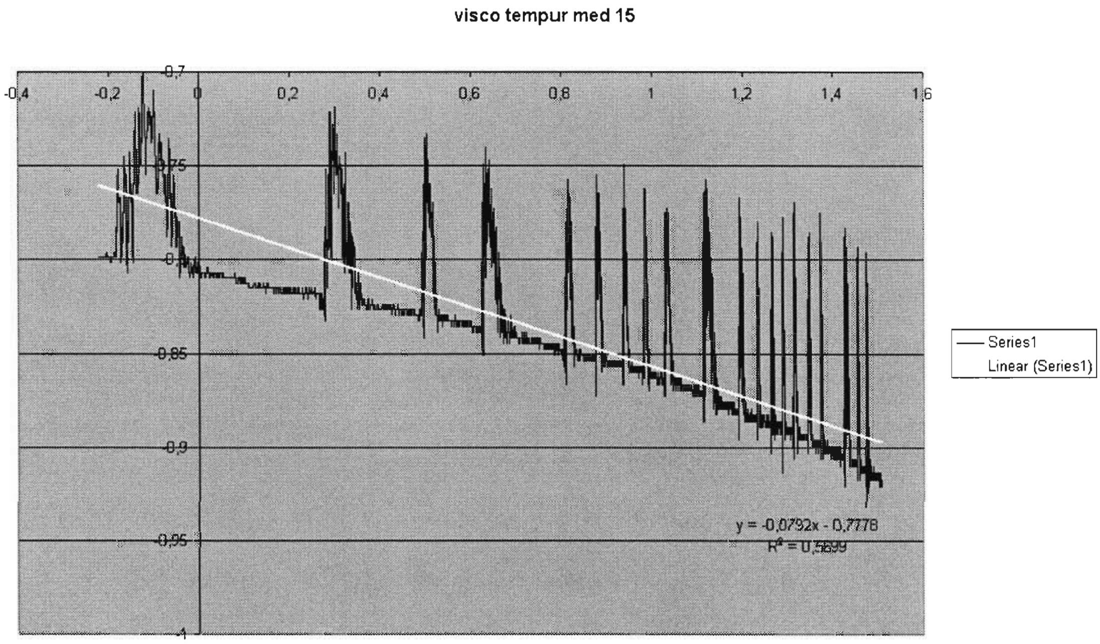


Fig A8.17 Tempurmed 15kg

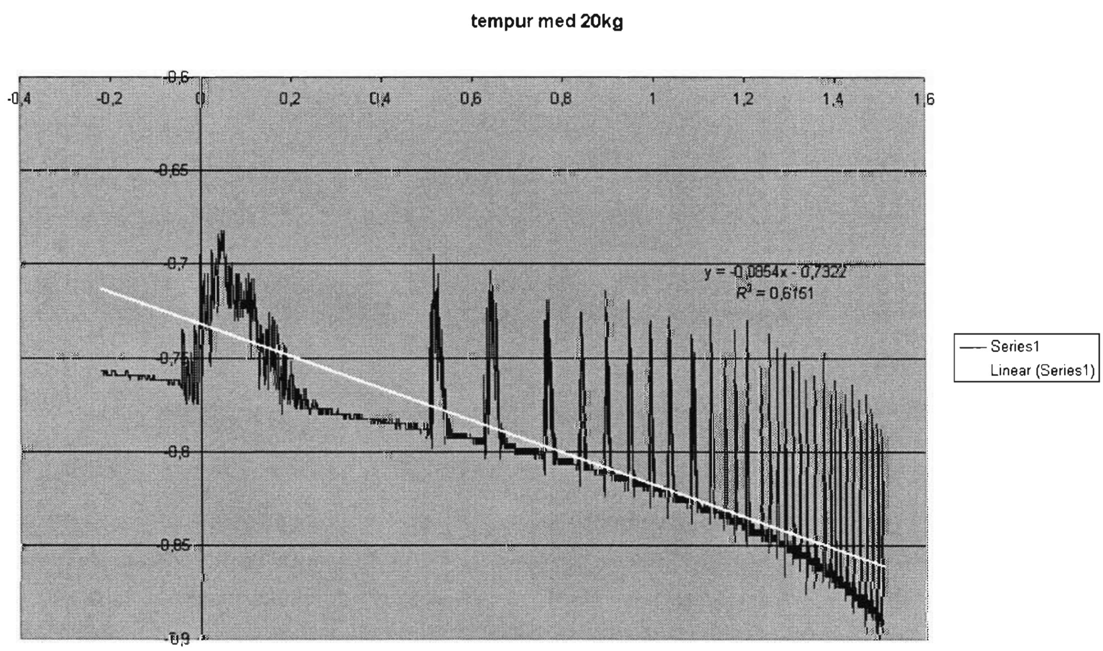


Fig A8.18 Tempur Med 20kg

A9: Point Sensor Data

	Depth 64.5 kg	Point pressure	Depth 77.4 kg	Point Pressure	Depth 103 kg	Point Pressure
Dizzy	3.1 mm	42mmHg	4.4	54	5.2	58
Tempur	6.6	33	7.4	36	8.4	40
Apollo	6.7	43	6.9	41	8.1	56
Pentaflex	4.9	37	5.6	40	8.0	43
Tempermed	6.5	49	7.3	50	7.7	51
Beige	3.7	45	5.0	51	6.5	55
Salus	6.0	36	6.7	50	8.0	55
Spring	6.1	50	6.8	93	8.2	99

Table A9.1 point sensor data

A10: Calibration data and graphs

Fig. A10.2
5kg Calibration 2

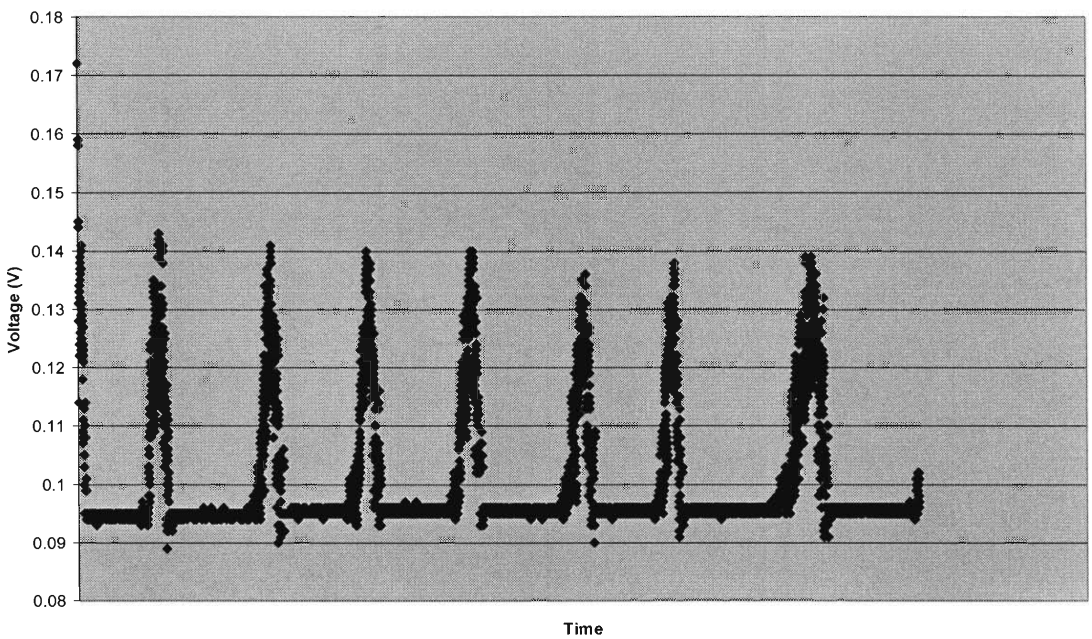


Fig. A9.2
5kg Calibration 2

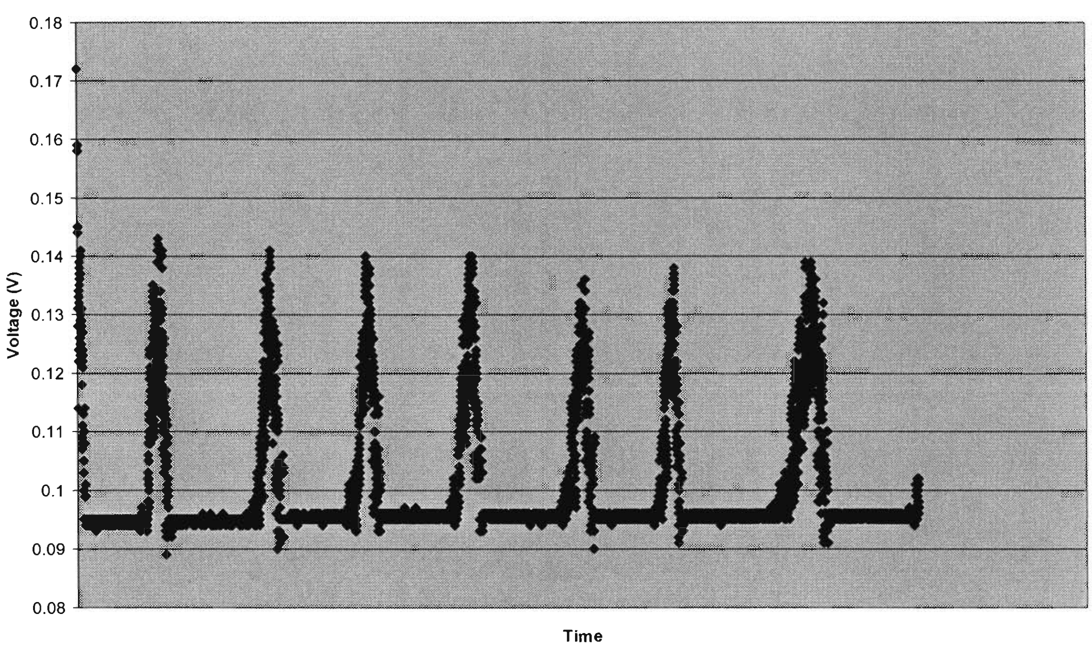


Fig. A10.3
10 Kg calibration 1

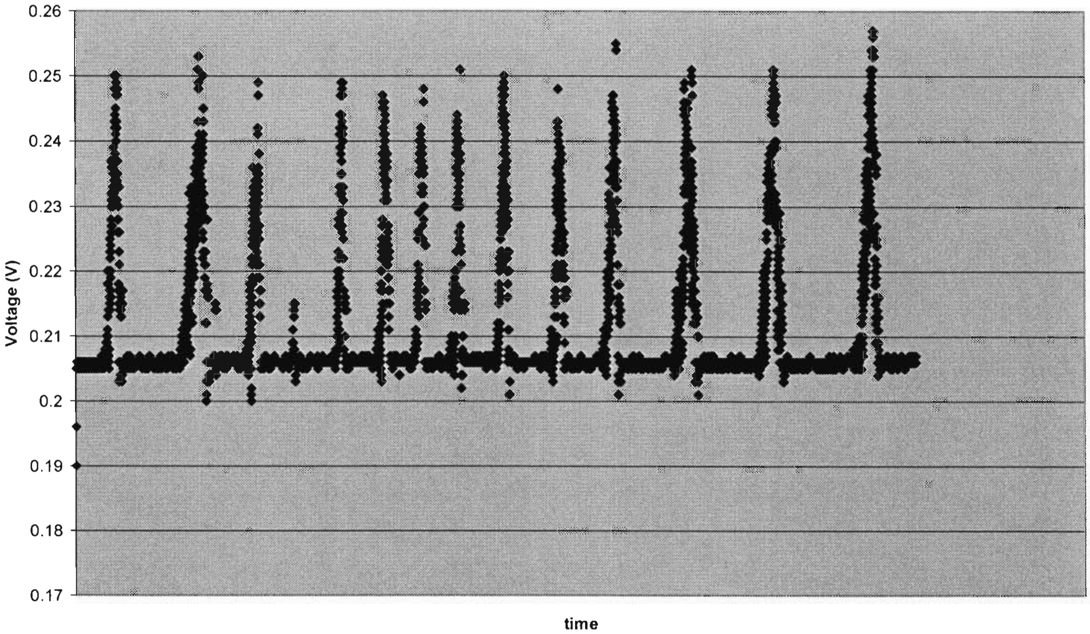
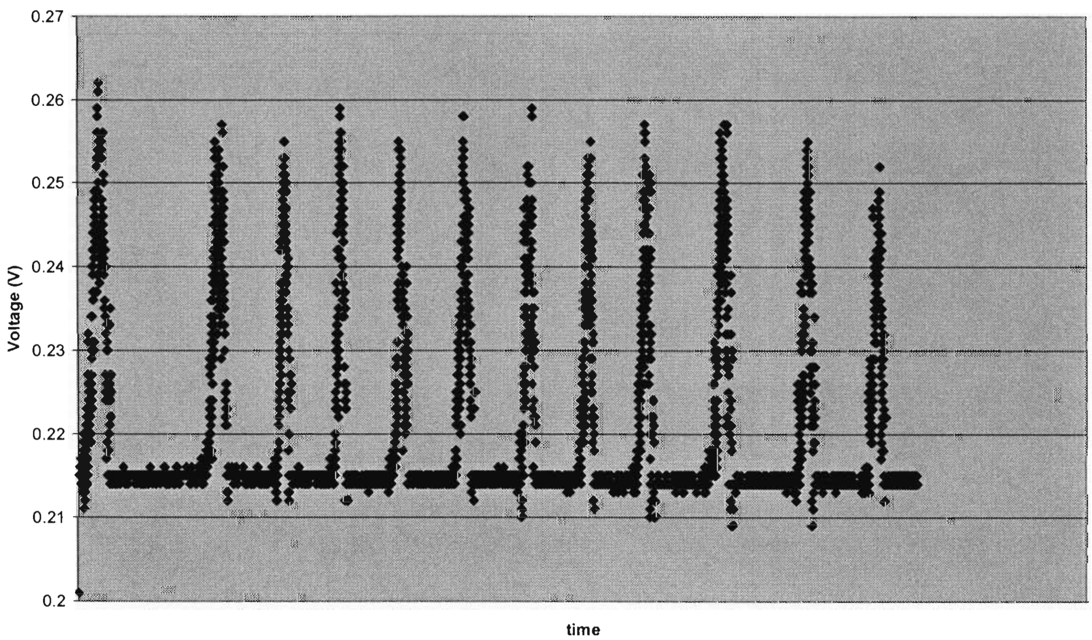


Fig A10.4
10 Kg calibration 2



Mathematical Calculations:

Know that T=F*D, also know the sum of the torques must equal zero (Newton's second law of motion). Therefore, from the measurements done,

$5kg*9.8m/s^2*43.4cm=45cm*F_{di5}$

The 43.4 cm factors in the length to the center of the mass placed on the board, as that is where the torque is acting.

$F_{di5}= 47.26N$

For the 10kg mass:

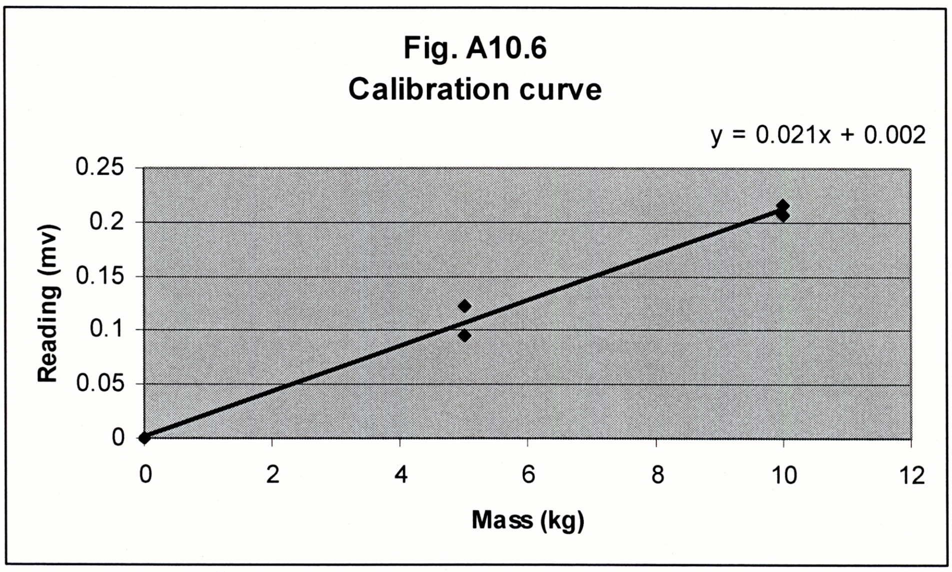
$10kg*9.8m/s^2*41.55cm=45cm*F_{di10}$

$F_{di10}=90.49N$

From these equations, the data are then compared to the outputs from the voltage (seen in Figure A10.5). The test data is converted into how many Newtons for 1mv, in order to provide comparable data. In the third column, the individual mv readings for each test can be found. Figure A10.6 is a graphical result for the data, based on mass and mv readout.

Fig. A10.5
calibration values

Data type	Newtons	mv
5kg,test1	384.23	0.123
5kg,test 2	497.48	0.095
10kg,test1	441.41	0.207
10kg,test 2	439.27	0.215
Average	440.5975	
Standard Deviation	46.24332844	



From these data, the calibration point of 1mv = 446 Newtons was calculated.

A11: Depth Force integral

In order to determine the integral in order to find the dependences between force and depth, the integral was taken between ½ of the dome, and then multiplied by 2 for the entire dome. In order to simplify the integral, it was noted that the surface area could be found, via integrals, and then multiplied by two pi. The integral is found below in Eqn. A11.1, along with the sketch for the equations found in Figure A11.1.

$1/3\int$ r2sintdrdθ, (Eqn A11.1) where the limits of integration are for r, (R-d)/cosθ to R, and for dθ, 0 to $\cos^{-1}((R-d)/R)$.

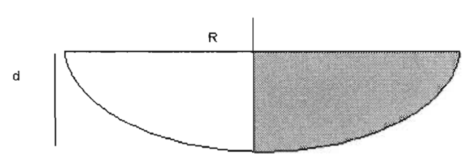


Fig. A11.1
Sketch of depth dependant surface area

Using U substitution and by first integrating the r^2 term, one arrives at the formula given earlier in the report, for the dependence of force on depth.

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