DEVELOPMENT OF THREE-DIMENSIONAL SPACER FABRICS AS ABSORBENT AND CUSHIONING LAYER FOR ADVANCED COMPOSITE WOUND DRESSING

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TONG Shuk Fan (Name of Student)

ABSTRACT

Wound management has become more sophisticated and modern wound dressings now focus more on providing an optimal microclimate for wound healing. There are various types of wound dressings on the current market designed for different types of wounds. Pressure sores are one of the most prevalent types of chronic wounds that can be difficult to heal once they have developed and thus become the burden of caretakers, hospitals and the government. An ideal wound dressing for pressure ulcers should allow the transmission of liquid and gas, absorb exudates, provide cushioning and help to relieve pressure all at the same time. However, there are few wound dressings available in the market that are designed to manage pressure ulcers and their absorbency and cushioning performance are questionable. The heels are one of the most common sites for pressure ulcer development. However, there are a lack of suitable wound dressings for pressure ulcers, especially for those that would accommodate the 3-dimensional (3D) shape of the heel region. The answer could be to use spacer fabrics, which are 3D knitted fabrics that have been recently used as cushioning material in protective work clothing, such as for medical personnel, due to their excellent compression, moisture-wicking, and temperature-controlling properties. Furthermore, the properties of 3D knitted spacer fabrics are versatile by changing the knitting parameters. Therefore, the aim of the study is to develop 3D knitted spacer fabrics as a substitute material for the absorbent layers of wound dressings which will provide both absorbency and cushioning effects.

This study consists of different parts including (a) a clinical study which involves heel interface pressure measurements of elderly individuals and an assessment of their skin conditions, (b) an evaluation of spacer fabrics as a cushioning and absorbent layer in wound dressings for pressure ulcers, (c) the formulation of a pressure simulation model

for a wound dressing for pressure ulcers, and (d) the development of wound dressing composite with spacer fabrics as the absorbent layer and evaluation of the wound dressing composite.

Thirty percent of pressure ulcers occur in the heel region. Therefore, the bedridden and elderly are at high risk for pressure ulcer development. In response, a thorough 6-month clinical study at an elderly home is first carried out. The development of the heel pressure ulcer and the wound management process are monitored and recorded. Due to the low metabolism and different kinds of chronic illnesses of the elderly, their heel ulcer requires more than 6 months to heal. It is found that apart from pressure relief, the key contributing factors are also proper wound care, nutrition and daily care for the healing of ulcer wounds. Interviews and surveys with caretakers and wound nurses are conducted to solicit their opinions on existing wound dressings and their priorities for choosing wound dressings. Based on their feedback and raised concerns, it is found that the critical physical requirements are breathability, cushioning effect and absorbency for wound dressings to treat pressure ulcers. They also point out that existing wound dressings cannot adequately absorb exudates, provide a cushioning effect or allow breathability. The conformity of the wound dressings is yet another one of their concerns.

Pressure is one of the most important factors in the development of pressure ulcers and interface pressure is one of the most commonly used non-invasive methods to predict the risk of their development. To determine the heel interface pressure of the elderly and the effects of heel position and mattress type on the heel interface pressure, an evaluation of the heel interface pressure is conducted on both the bedridden and healthy elderly. The results show that the neutral position of their feet is when they place their heel in the neutral external rotation and upright positions in a relaxed supine position.

However, the upright position may place the bedridden elderly at a higher risk of developing a heel ulcer as opposed to the neutral external rotation position. It is also found that some of the elderly are still at high risk for developing pressure ulcers even with the use of a pressure relieving mattress. Assessments of their skin conditions are also carried out, and the results show that the skin of their heels is considered to be very dehydrated and lack sebum content which may increase skin abrasion and friction as well as the chances of developing a heel ulcer.

Taking the feedback and comments of the nurses into consideration, it is found that the breathability, absorption and cushioning of pressure wound dressings are critical factors. To understand the physical properties of existing wound dressings designed for pressure ulcer wounds and the possibility of using 3D knitted spacer fabrics as the material for the absorbent and cushioning layer, several physical experiments have been carried out, such as testing the compression, absorbency, wettability, water vapor and air permeabilities, thermal conductivity and extensibility. The results indicate that the compression resistance of weft knitted spacer fabrics is higher than pressure ulcer wound dressings which proves that spacer fabrics can provide a good cushioning effect to protect the wound and relieve pressure to prevent further ulceration. The absorbency of spacer fabric which has polyester falls short of wound dressings made of highly absorbent materials, however, it is comparable to those with an adhesive layer. The weft knitted spacer fabrics also have better wettability than most of the wound dressings. The water vapor permeability of both the warp and weft knitted spacer fabrics is better than that of the wound dressings. In terms of the breathability, both the warp and weft knitted spacer fabrics have a better performance than that of the wound dressings. The thermal conductivity and extensibility of the spacer fabrics are comparable to or even excel some of the existing wound dressings. Therefore, based on the results, the overall physical properties of the 3D knitted spacer fabrics are comparable to or even better than most of the existing wound dressings. This indicates that spacer fabrics meet the criteria of existing wound dressings and it is possible to use them as the substrate for the absorbent and cushioning layer of wound dressings.

By changing the knitting parameters of the 3D knitted spacer fabrics, such as type of yarn, and yarn angle and density, their physical properties are changed. In this study, the finite element model (FEM) is adopted to simulate the pressure onto the skin in relation to the contours of the heels and properties of the spacer fabrics, in other words, to simulate the heel-spacer fabric interface pressure. Furthermore, by simply changing the material properties of the spacer fabrics, the FEM can be used to predict their compressional behaviour. The simulation modelling can show the trend of pressure distribution with good accuracy. In addition, the FEM shows the compression behaviour of spacer yarns under pressure. It is found that there is shearing movement in the outer layers of the spacer fabrics under loading.

After an evaluation of the physical properties of the 3D knitted spacer fabrics and their cushioning performance, wound dressing composites are fabricated with three layers, including (a) a layer that is in direct contact with the wound to protect the wound bed during changing of the wound dressing, (b) 3D knitted spacer fabric as the absorbent layer that provides cushioning, and (c) an adhesive coversheet for the outermost layer of the dressing for fixation purposes. Laboratory tests are carried out to evaluate the performance of the newly developed wound dressing composites, especially its absorbency and cushioning properties. The bacterial barrier properties are also evaluated. It is found that the compression resistance of the newly developed wound dressing composites higher than most of the existing wound dressings. The 3 layers of the wound dressing composite have comparable or even excel the performance of current wound dressings. The 3 layers are also more water vapor and air permeable than most of the existing wound dressings. Furthermore, their thermal conductivity is comparable to the existing wound dressings. The extensibility of the newly developed wound dressing composites is comparable to or even better than existing wound dressings. The wound dressings composites demonstrate comparable results to wound dressings that do not have an adhesive layer. The bacterial barrier properties are excellent and the results indicate that the new wound composites are able to protect the wound against bacteria. The study results prove that the newly developed wound dressing composites have a good physical performance and meet the requirements of wound dressings.

The research results and the input from the nurses on the wound dressings available in the market provide useful information on the effects of intrinsic and extrinsic factors on pressure ulcer wound healing. In addition, the neutral heel positions and the effectiveness of pressure relieving mattresses to alleviate the pressure induced onto the heel of elderly individuals have been identified which may advance current knowledge towards new developments in preventive treatments and devices for heel ulcers. The relationship between the knitting parameters and different physical properties of the 3D knitted spacer fabrics is useful for further development of spacer fabrics. The simulation model can also be used to predict the pressure distribution of spacer fabrics. Finally, the outputs of this project can extend to the development of spacer fabrics for different cushioning purposes and help to reduce the production costs of textile medical devices.

PUBLICATIONS ARISING FROM THE THESIS

Journal Articles

Tong, S. F., Yip, J., Yick, K. L., & Yuen, C. W. M. (2016). Pressure Ulcer Wound Care for Elderly in Home: A Case Report. *Journal of Dermatology Research and Therapy*. 2(3):1-5. ISSN:2469-5750

Tong, S. F., & Yip, J. (2016). Reply to Letter to the Editor:" Effects of Different Heel Angles in Sleep Mode on Heel Interface Pressure in the Elderly". *Clinical biomechanics (Bristol, Avon)*, *33*, 32-33.

Tong, S. F., Yip, J., Yick, K. L., & Yuen, M. C. W. (2016). Effects of different heel angles in sleep mode on heel interface pressure in the elderly. *Clinical Biomechanics*, *32*, 229-235.

Tong, S. F., Yip, J., Yick, K. L., & Yuen, C. W. M. (2015). Exploring use of warp-knitted spacer fabric as a substitute for the absorbent layer for advanced wound dressing. *Textile Research Journal*, *85*(12), 1258-1268.

Conference Paper

Tong, S. F., Yip, J., Yick, K. L., & Yuen, C. W. M. (2017). Investigation of pressure redistribution ability of three-dimensional weft knitted spacer fabric and different wound dressings. 14th Asian Textile Conference, June 27-30, 2017, Hong Kong.

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Tong, S. F., Yip, J., Yick, K. L., & Yuen, C. W. M. (2016). A review of three dimensional knitted spacer fabrics for medicine and healthcare and recent developments. CPCE HEALTH CONFERENCE 2016 AGING, HEALTH AND LONG TERM CARE - Integrity, Innovation and Sustainability, January 11, 2016, Hong Kong.

Tong, S. F., Yip, J., Yick, K. L., & Yuen, C. W. M. (2014). Evaluation of pressure relieving mattress for bedridden elderly for pressure sore prevention. BME 2014 Biomedical Engineering International Conference, December 4-6, 2014, Hong Kong.

Tong, S. F., Yip, J., Yick, K. L., & Yuen, C. W. M. (2014). Exploring use of warp knitted spacer fabrics as substitute of absorbent layer for advanced wound dressing. Textile Bioengineering and Information Society 2014, August 6-8, 2014 Hong Kong.

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List of Abbreviations

A	
AATCC	American Association of Textile Chemists and Colorists
ANOVA	Analysis of variance
ASTM	American Society for Testing and Materials
B	
BS	British Standards
C	
CFU	Colony forming unit
CT	Computer tomography
E	
ELF	Economical Load and Force
EN	European Standards
F	
FEA	Finite element analysis
FEM	Finite element method
FSA	Force Sensitive Applications
K	
KES	Kawabata Evaluation System
M	
MEMS	Microelectromechanical Systems
MIU	Surface coefficient of friction
MMD	Mean deviation of coefficient of friction
MRI	Magnetic resonance imaging
N	
NCHS	National Center of Health Statistics
NPUAP	National Pressure Ulcer Advisory Panel
P	
PSST	Pressure Sore Status Tool
PUSH	Pressure Ulcer Scale for Healing
R	
R	Air resistance
S	
SD	Standard deviation
SMD	Mean deviation of surface contour
SPSS	Statistical Package for the Social Sciences
SS	Sessing Scale

SWHT	Sussman Wound Healing Tool

W

WVP	Water vapor permeability
2D	Two-dimensional
3D	Three-dimensional

Chapter 1 Introduction

1.1 Background of Research

Pressure sores, also known as decubitus ulcers or bedsores (Basal & Ilgaz, 2009), are a prevalent type of chronic wound among the elderly, bed-ridden and wheelchair-bound patients, and individuals in long term care facilities (Ostadabbas, Yousefi, Faezipour, Nourani, & Pompeo, 2011). According to literature pressure sores occur due to two factors: 1) the extrinsic mechanical forces that act on skin and soft tissue that cover bony areas, and 2) intrinsic susceptibility to tissue breakdown due to poor blood circulation and inadequate oxygen supplement (Versluysen, 1985). Areas that overlie bony prominences, such as the heels, legs and knees, which have little padding and smaller surface areas, are the weight-bearing points, and therefore, pressure sores frequently develop in these areas (Tymec, Pieper, & Vollman, 1997). According to previous research, the heels are one of the most frequent sites of pressure sores for about 30% of those who suffer from pressure sores (Pearson, Francis, Hodgkinson, & Curry, 2000; Versluysen, 1985).

Researchers have proven that it is difficult for pressure sores to heal once they have developed (Thomas, 2001). Pressure ulcers cause mental anguish and pain, thus restricting normal activities and even causing death (Lyder, 2003). Apart from individual suffering, the costly treatment and extended hospital stays constitute a burden to caretakers, hospitals and governments (Reddy, Gill, & Rochon, 2006). Therefore, there are several strategies for preventing pressure ulcers and facilitating wound healing in the different stages of pressure sores. They target those who are at high risk. Regular repositioning is one of the most common methods for pressure ulcer prevention (Ostadabbas et al., 2011). However, because of the limitations and cost of turning patients frequently, a number of devices have been developed that are used to prevent pressure injuries (Thomas, 2001). In considering that heels are one of the most common sites of ulcers, pressure relieving mattresses, heel protectors, cushions and pillows are widely used devices in hospitals and elderly centres (Murray, Magazinovic, & Stacey, 2001). However, the fit of the products is complicated due to the movement of patients and the shape of the heel. Furthermore, the air permeability and cushioning performance of the products are uncertain. There are special types of wound dressings that are designed for pressure ulcer wounds. However, it is difficult to find a wound dressing that can allow the transmission of liquid and gas, but also absorb exudates, provide cushioning and help to relieve pressure at the same time. In addition, it is difficult to obtain a precisely fitting wound dressing (Weller & Sussman, 2006). Although there is work published in the literature on heel interface pressure, there is little information or studies on heel interface pressure in the elderly population and the effects of foot position on heel interface pressure in real life practices. Therefore, a study on pressure ulcer prevention devices and wound dressings with different fabrications and properties is essential for optimising the absorbent layers of wound dressings in order to improve the healing process and also protect wounds from further ulceration.

Spacer fabrics are three-dimensional (3D) knitted fabrics with two distinctive textile layers that are connected together or kept apart by spacer threads (Abounaim, Hoffmann, Diestel, & Cherif, 2010; Bagherzadeh, Montazer, Latifi, Sheikhzadeh, & Sattari, 2007). According to the literature, the market demand for 3D knitted spacer fabrics has increased in a wide range of industries, including the automotive and geotextile industries, as well as the civil engineering, sports and leisure fields, due to their unique attributes (Abounaim et al., 2010; Ye, Fangueiro, Hu, & Araújo, 2007; Yip & Ng, 2008). Also, 3D spacer fabrics have been recently used as cushioning material in protective clothing for medical personnel and as medical textiles, such as alternative materials in orthopaedic shoes and insert materials of pressure therapy garments due to their excellent compression, moisture-wicking, and temperature-controlling properties (Heide, Möhring, Schürer, Hänsel, & Richter, 2005a; Luximon, 2013; Yick et al., 2014; Yu, Yick, Ng, & Yip, 2015). Researchers have also recommended the use of spacer fabrics as alternative material for absorbent medical applications (Davies & Williams, 2009b). Although there is work in the literature on 3D knitted spacer fabrics, there are few studies that investigate their applications in wound dressings and as the absorbent and cushioning layer of wound dressings. In addition, the effects of the knitting parameters on the physical performance of 3D knitted spacer fabrics are still unclear. Therefore, a study on the effects of changing the knitting parameters on the physical performance of 3D knitted spacer fabrics and the possibility of using them as the substrate for the absorbent layer of wound dressings which can provide a cushioning effect is essential for addressing the knowledge gap in the literature and facilitating the development of wound dressing composites with the use of spacer fabrics as the absorbent and cushioning layer.

The main purpose of the study is to therefore develop a wound dressing composite which uses 3D knitted spacer fabrics as the absorbent and cushioning layer, which not only enhances the wound healing progress, but also protects the wound from further ulceration. Furthermore, the use of 3D knitted spacer fabrics can reduce the financial burden of the patients and their family as opposed to the use of currently available special wound dressings designed for pressure ulcers on the market.

1.2 Problem Statements

Wound dressings are a crucial item used in the treatment of patients with heel ulceration. Nevertheless, there are two main problems associated with wound dressings that affect the healing process of heel ulcerations. They are the uncertainty of the pressure threshold which may cause heel pressure ulcers, type of wound dressing that can be used to treat pressure ulcers as well as the conformity between the 3D shape of the heel and 2D shape of the wound dressing.

i. Uncertainty of pressure threshold and type of wound dressing used to treat pressure ulcer wounds

Due to the lack of research on the effects of heel position on the heel interface pressure especially in the elderly population, the effectiveness of wound dressings is ambiguous. The performance of these products in preventing the development or improving the healing process of heel ulcers is questionable. It is generally accepted that the pressure redistribution and the micro-environment for wound healing vary with the composition and structure of materials used and the design of the products. Although there are some guidelines for pressure ulcer prevention and wound healing treatment, the application of wound dressings still depends on the available types of products and the experience of the caretakers. Therefore, it is difficult to ensure the effectiveness of these products for pressure sore prevention and healing.

ii. 3D geometric shape of heel and fit of wound dressings

Pressure ulcer wound dressings are widely used in hospitals and elderly homes. However, due to patient movement, it is not easy to ensure that they are in the right position. Moreover, because of the 3D geometric shape of the heel, the fit of the wound dressing poses a difficult problem. Sometimes, the dressing may not be able to cover the entire wound on the heel which may lead to infection. Moreover, some dressings may fold on the wound region. This increases the friction between the fragile wound and wound dressing, and even leads to further ulceration of the wound. Therefore, the optimal fit of a wound dressing to the 3D geometric shape of the heel is by no means easily achieved, yet it is critical as the fit may greatly affect the performance of the wound dressing and the healing time.

1.3 Research Objectives

Given the problems that are found in the treatment of patients with heel ulceration, the research objectives of this study are as follows:

i. to review the pathophysiology for developing pressure ulcers, features and properties of wound dressings for patients with pressure ulcers, and current structure and properties of 3D spacer fabrics available in the market;

ii. to analyse the functional requirements of wound dressings, including absorbency, moisture management, air permeability, elasticity, as well as their antimicrobial properties, comfort, cushioning and pressure relief, particularly for the pressure ulcerations of the legs;

iii. to evaluate the interface pressure of the heels and contact conditions of wound dressings and their relation to the 3D knitted geometries of spacer fabrics and their mechanical and stress-strain properties which influence the absorbency, cushioning and comfort of the wound dressing;

iv. to design and develop, on the basis of materials and textile science analyses, the most desirable absorbent and cushioning wound dressing with the following characteristics: (a) incorporates liquid and gas permeable exudate and fluid absorbing pad made of 3D spacer fabrics that comes into contact with the wound, (b) has a plurality of impermeability mechanisms that protect against liquid penetration and microorganisms, and a gas and vapour permeable cover sheet as the outer layer of the textile materials, (c) an elastic adhesive bond that allows application of the pad and cover sheet, and (d) an impervious cover sheet for the outermost layer of the dressing; and

v. to perform laboratory tests that evaluate whether the newly developed wound dressing can fulfil the stated objectives.

1.4 Project Originality and Significance

Although wound dressings have been in use for many years, wound management is becoming more and more complicated. The aim of modern wound dressings is to improve the healing of wounds. Moreover, the prevention and treatment of pressure sores need a significant amount of time and care. This not only greatly affects the lives of patients and their caretakers, but also the hospital services and costs of government as prolonged and expensive hospitalizations are required. Previous research has proven that the health costs of pressure ulcers are undoubtedly high. It is difficult for pressure ulcers to heal, and wound dressings that provide both good absorption and a cushioning effect are rare. Due to the geometric shape of the heel, the fit of wound dressings for heel ulcers is problematic. Therefore, the originality of this project is to address the knowledge gap by evaluating the heel interface pressure of the elderly and determining the physical properties of existing wound dressings for pressure ulcers, which not only will improve the fit of the dressing to the heel, but also optimise the performance of wound dressings for heel ulcers, particularly in pressure reduction and absorption.

In this project, flexible sensors will be used as an effective means to evaluate the heel interface pressure of the elderly for different heel positions. They will provide useful information for the cushioning requirement of the wound dressing. In addition, different physical experiments will be performed in order to gain a better understanding on existing wound dressings and 3D spacer fabrics. This will contribute to further developments in advanced wound dressings.

In this research, 3D spacer fabrics will be used as the absorbent layer of wound dressings, and these fabrics are suitable for treating the wounds of patients with heel pressure sores. The multi layered composite wound dressing composed of 3D spacer fabrics as the absorbent and cushioning layers which will be developed in this project has significant potential. By changing the knitting methods and patterns, materials, thicknesses and densities, the properties of the 3D spacer fabrics can be varied, and thus the properties of the multi layered composite wound dressing. As a result, this new multi layered composite wound dressing combines both the functional properties of wound dressings and pressure relief properties required by patients for foot pressure sores so that the cost and hardships for the patients and their families are reduced, and this also applies to the costs to the government as well.

1.5 Outline of the thesis

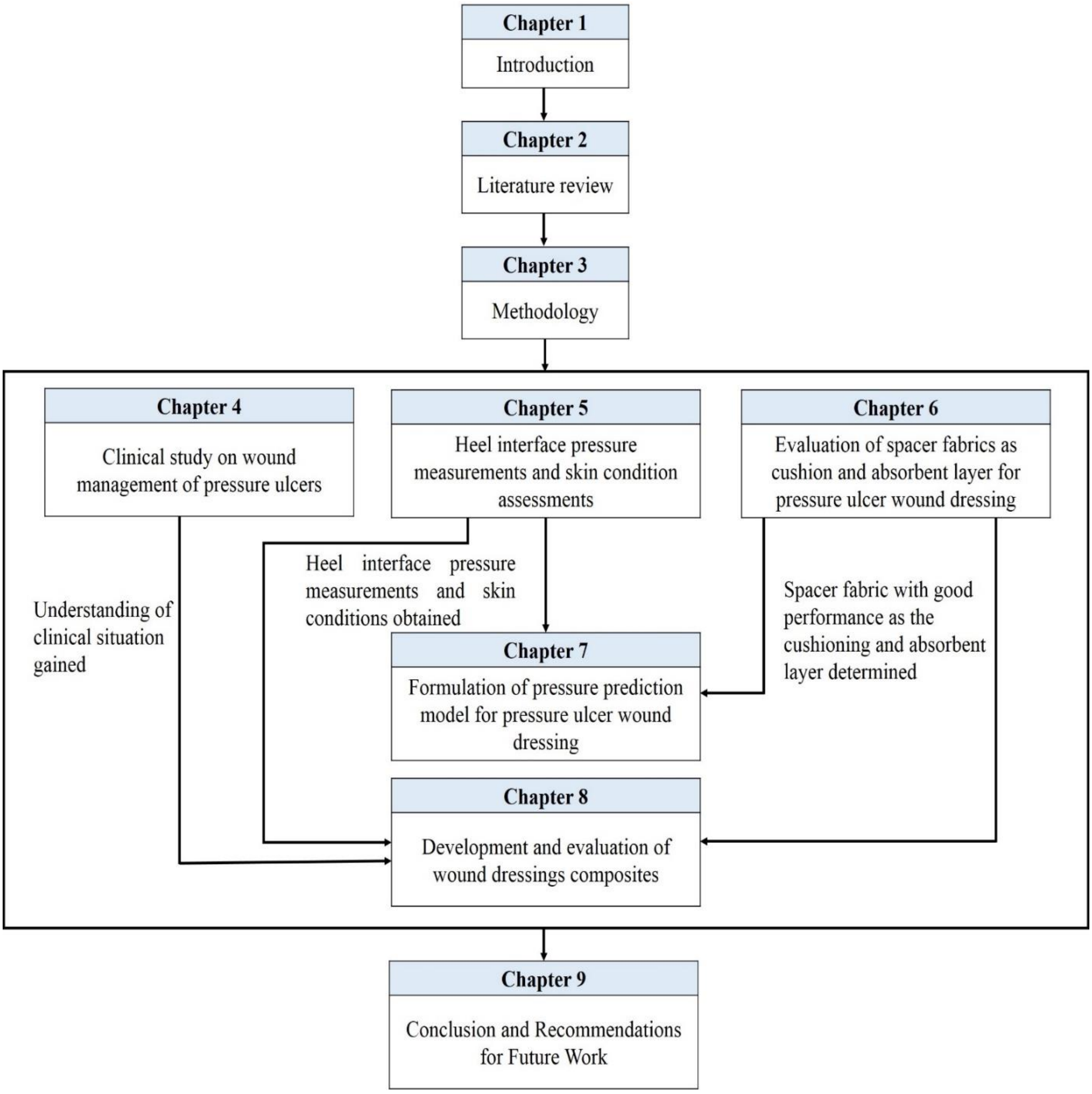


Figure 1.1 Flow diagram of research methodology

There are a total of nine chapters in this thesis as shown in Figure 1.1. Chapter 1 provides the background information of the research, as well as the concept and rationale and the aims of this study.

Chapter 2 is the literature review which includes a review of the factors and impacts of pressure ulcers, their designated wound dressings and interface pressure. A review of

3D spacer fabrics, their applications and the biomechanical models are also included in this chapter.

In Chapter 3, a summary of the overall research plan and methodology adopted are provided. The objectives of each method and experiment are reported. The methods and standards adopted and the machinery used in this study are listed and explained in detail in this chapter.

Chapter 4 reports the results of the interviews and surveys with caretakers and wound nurses which have been conducted to collect their opinions on existing wound dressings and their priorities in choosing wound dressings. A thorough 6-month clinical study in an elderly home is reported. The pressure ulcer development process and wound management are also recorded. A fundamental understanding of the considerations of the nurses and their priority for choosing wound dressings provides direction and form the basis of this study. Pressure ulcer wound management and the factors that affect wound healing in real situations also provide direction for the development of a new wound dressing composite.

Chapter 5 presents the evaluation results of heel interface pressure and skin conditions. The neutral heel position and its effects on the heel interface pressure are studied. The effectiveness of pressure relieving mattresses for pressure relief is discussed. The results of heel interface pressure measurements obtained can act as a useful reference for the formulation of a prediction model for interface pressure between spacer and heel and the development of the absorbent layer of wound dressings as well as the wound dressing composite.

Chapter 6 contains the results and discussions on the physical properties of 3D knitted fabrics and existing wound dressings. These allow a more in-depth understanding of the effects of changing the knitting parameters of 3D knitted spacer fabrics, such as yarn type and spacer yarn angle, on the physical properties of 3D knitted spacer fabrics. The aim of carrying out these physical experiments is to determine whether 3D knitted spacer fabrics have a comparable physical performance as existing wound dressings. The findings will act as a reference source for fabric selection and design of wound dressing composites with the ultimate goal of developing a wound dressing composite for pressure ulcer wounds with 3D knitted spacer fabrics as the absorbent and cushioning layer. The material properties measured by standard tests are useful information for formulating a prediction model of interface pressure between spacer and heel.

Based on the findings discussed in the previous chapters, a pressure prediction model for 3D knitted spacer fabrics is presented in Chapter 7. The 3D heel images obtained are used for the formulation of a prediction model to examine interface pressure between spacer and heel. A biomechanical model is established to simulate the interface pressure distributed over the spacer fabric when heel is loaded onto the fabric. The development of the model is based on the mechanical properties of the fabrics, contour of the heel and contact interaction between the heel and spacer fabric by using finite element modelling. The finite element model (FEM) is adopted to simulate the skin pressure in relation to the contours of the human heel and fabric properties of the spacer fabrics. It is useful for the simulation of the pressure distribution properties of spacer fabrics. By simply changing the material properties or the density of spacer fabrics with the program, the FEM can be used to predict their compressional behavior. With the use of the simulation model and heel geometry, the pressure distribution on the spacer fabrics can be precisely and objectively quantified.

After the evaluation of the physical properties of the 3D knitted spacer fabrics and their performance in cushioning are provided in Chapter 6, the wound dressing composite is presented in Chapter 8. The wound dressing composite is composed of three layers, including: (a) a layer that is in direct contact with the wound to protect the wound bed during changing of the wound dressing, (b) 3D knitted spacer fabric as the absorbent layer that provides cushioning, and (c) an adhesive coversheet for the outermost layer of the dressing for fixation purposes. The laboratory tests for evaluating the performance of the newly developed wound dressing, especially its absorbency and cushioning properties, are reported.

The last chapter is Chapter 9, which provides a general conclusion on the thesis work and recommendations for future works.

Chapter 2 Literature Review

2.1 Introduction

Pressure ulcers on bedridden patients are a common and serious problem, as they cause pain and wound infections, and sometimes severe and extensive wound infections can lead to serious health problems. Several types of treatments have been widely adopted to prevent and enhance healing. In this chapter, an overview on pressure ulcers and the available treatments is presented. Additionally, existing types of wound dressings for pressure ulcers are discussed. In order to develop an advanced absorbent layer of wound dressing for pressure ulcer wounds, three-dimensional spacer fabric and its applications are also reviewed. Finally, as the heels are prone to pressure ulcers, an instrument for internal pressure measurement of the heel is also presented.

2.2 Pressure Ulcers

2.2.1 Etiology of Pressure Ulcers

According to the National Pressure Ulcer Advisory Panel (NPUAP) in the United States (US), pressure ulcers are localized damage to the skin and underlying tissue, which are usually caused by pressure, shear or friction National Pressure Ulcer Advisory Panel (2014). The term ‘pressure sores’ is also commonly known as bedsores and decubitus ulcers, in which decubitus means “to lie down” in Latin (Bass & Phillips, 2007).

2.2.2 Classification of Pressure Ulcers

In general, the staging system of the NPUAP is one of the most commonly used systems for pressure ulcer classification (Bass & Phillips, 2007; Black et al., 2007; National Pressure Ulcer Advisory Panel, 2014; Pearson et al., 2000; Thomas, 2001). According to their staging system, pressure ulcers can be divided into four stages. Stage I is exemplified by continued erythema of the skin that is non-blanchable even with pressure onto the area from a gloved finger. The skin is still intact and no ulceration is yet evident. Stage II involves damage to the skin via ulceration, blistering, or abrasion. Often, Stages I and II are indicators of deeper necrosis. They may also occur independently as sheer injuries, caused by sliding against sheets or support surfaces. In Stage III, there are lesions that represent the full-thickness destruction of the skin. Although the ulcer may not visibly extend into the muscles, pressure itself usually causes necrosis of the underlying muscles as previously discussed. In Stage IV, the lesions extend into the muscles, tendons, joints, nerves, and even bone. Lesions in Stages III and IV require surgical intervention because they are often large and infected, and require sharp debridement. Figure 2.1 illustrates the four stages of a pressure ulcer. Based on the literature, the majority of pressure ulcers are usually those of Stage I or II, or 92% and 64% of the cases, respectively (Pearson et al., 2000).

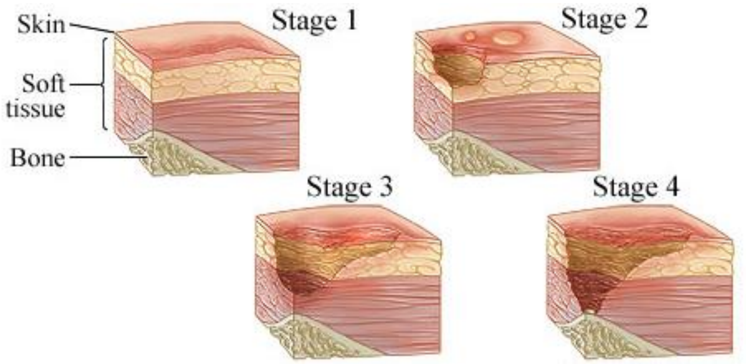


Figure 2.1 Four stages of a pressure ulcer (Myers, 2004)

2.2.3 Incidence and Prevalence of Pressure Ulcers

Pressure ulcers are a significant health problem worldwide. Apart from bedridden and wheelchair bound patients, diabetics and the elderly are also at high risk for pressure ulcer development (Ostadabbas et al., 2011; Pearson et al., 2000). In research work by Myers (2004), the incidence rate of pressure ulcers for patients with spinal cord injuries ranges from 7% to 39% and then increases to 30% five years after injury to the spinal cord. Researchers have reported that the incidence of pressure sores in the elderly is 10-25% and about 70% of them are older than 65 years old (Landi, Onder, Russo, & Bernabei, 2007; K. Liu & Dai, 2011; Thomas, 2001), while nearly 57% of adult patients with a principal diagnosis of pressure ulcers are older than 65 years old (Russo, Steiner, & Spector, 2008). Landi et al. (2007) demonstrated that two thirds of pressure ulcers occur in patients who are over 70 years old and the prevalence is 17-28% for those in nursing homes. There is also consensus that pressure ulcers are common in bedridden elderly patients who are in the community, nursing homes or hospitals. The prevalence of pressure ulcers in general is 4-30% for those in hospitals, 2.4-23% for those in long term care facilities and 4% for in home care patients. Previous work by Jaul and Menzel (2014) provided evidence that the prevalence of pressure ulcers has recently doubled while the percentage incidence of pressure ulcers has increased 80% from 1995 to 2008. Park-Lee (2009) reported that 159,000 nursing home residents (11%) in the US had a pressure ulcer in 2004. Based on the results of a study by Jaul and Menzel (2014) in Sweden, 97.7% of the patients who are over the age of 65 years old have a pressure ulcer. The percentage of those who are over 65 years old with a pre-existing pressure ulcer at the time of hospital entry from nursing homes and other living situations is 26.2% and 4.8% respectively (Keelaghan, Margolis, Zhan, & Baumgarten, 2008). The incidence of pressure ulcers in those who are hospitalized ranges from 4% to 38% while that for individuals in long term care facilities is 10% to 17% and can be as high as 38%. Myers (2004) also concluded that 66% of the elderly who have acute femoral fractures will develop pressure sores. The NPUAP estimated that 1 to 3 million people develop pressure sores every year, and more than 2.5 million patients in acute care facilities are suffering from pressure sores in the US (Dorner, Posthauer, & Thomas, 2009). Lyder and Ayello (2008) showed that the number of pressure ulcers for hospital stays was

280,000 in 1993, but increased to 455,000 in 2003. The National Center of Health Statistics (NCHS) reported that more than 10% of nursing home residents develop pressure ulcers (Ostadabbas et al., 2011). From 2007 to 2008, the Queen Mary Hospital in Hong Kong reported 34 cases of pressure ulcers and from 2009 to 2010, the number of cases reported increased to 70 (Yim, 2011). For the hospitalized elderly and those in outpatient settings, the percentage incidence of pressure sores is 8.8% and 1.61% respectively, and 25.16% in Hong Kong nursing homes (K. Liu & Dai, 2011; Russo & Elixhauser, 2006).

2.2.4 Impact of Pressure Ulcers

The quality of the life of patients is greatly affected by the presence of pressure ulcers as they are painful and difficult to heal. The lengthy treatment and hospitalization periods are not only difficult on the pressure ulcer patients but also cause significant distress to their family members. Previous researchers have proven that the complete healing rate of pressure ulcers is as low as 10% and less than 13% are healed in two weeks in acute hospital settings. Although 59% of Stage III ulcers will heal after 6 months of therapy, the rest require up to one year of treatment. For patients with a Stage IV ulcer, only one third of them will heal after 6 months of therapy while the others who are admitted with a pressure ulcer pass away during the healing period (Thomas, 2001). In addition, pressure sores may give rise to multiple and life threatening medical complications (Pearson et al., 2000). According to the Agency for Healthcare Research and Quality in the US, 1 out of 25 hospitalized patients with pressure ulcers as a primary diagnosis end up dying (Ostadabbas et al., 2011). The NPUAP also mentioned that 60,000 people die from pressure ulcer complications in the US each year (Dorner et al., 2009).

2.2.5 Factors of Pressure Ulcer Development

Pressure ulcers are complex chronic wounds which originate from one or more contributing factors. As they are difficult to heal and greatly affect the patients and their family, researchers have carried out much research to investigate the risk factors for pressure ulcer development. In general, the contributors of pressure ulcers can be divided into two types, including extrinsic and intrinsic factors. Extrinsic factors are mechanical force on skin and soft tissue over the bones while intrinsic factors are those that affect the supporting structure of the skin and the vascular and lymphatic systems (Jaul, 2010; Murray et al., 2001; Myers, 2004; Somerset, 2007; Versluysen, 1985).

One of the major factors of pressure sore development is due to shear stress. The effect of gravity forces on the body means there will be contact with the bed, wheelchair and other hard surfaces (Bass & Phillips, 2007; Murray et al., 2001; Ostadabbas et al., 2011). Murray et al. (2001) found an inverse parabolic relationship between time and pressure in which higher shear stresses can induce pressure sores in a shorter period of time while lower shear stresses require a longer time to cause tissue damage. Maklebust and Sieggreen (2001) pointed out that a normal capillary filling pressure is around 32 mm Hg at the arteriolar end of the capillary and around 12 mmHg at the venous end of the capillary. Therefore, if the external pressure is greater than 32 mmHg, the blood flow might be restricted to that particular area (Davies & Williams, 2009b; Jaul, 2010; Maklebust & Sieggreen, 2001; Myers, 2004; Somerset, 2007; Tymec et al., 1997). Apart from gravity force, shearing force and friction are also contributors to pressure ulcer development. Shearing force is the parallel load that causes the bones to slide against resistance between the skin and its contact surface. The blood vessels between the dermis and deep fascia are distorted as the epidermis and dermis remain still with the contact surface, but the deep fascia moves with the bones (Bass & Phillips, 2007;

Murray et al., 2001; Somerset, 2007). Besides, friction is created between the skin and contact surface that are moving across each other and leads to the initial breakdown of the skin. Moisture, which originates from urine, faeces, perspiration and drainage from wounds, is also regarded as one of the extrinsic factors as prolonged exposure to moisture may cause epidermis maceration and render the skin susceptible to injury (Bass & Phillips, 2007; Maklebust & Sieggreen, 2001; Murray et al., 2001).

Intrinsic factors include age, nutrition, chronic illnesses, skin conditions and oxygen delivery. Pressure ulcers often occur in those who have impaired mobility or are seriously ill, and particularly affect older people as their metabolic rate and skin become more delicate (Ostadabbas et al., 2011; Reenalda, Jannink, Nederhand, & IJzerman, 2009). Malnutrition is also one of the critical contributors of pressure sore development. Researchers have proven that insufficient protein and energy intake are independent risk factors. In addition, deficiency of vitamin C or minerals such as zinc and other trace elements may lead to the breakdown of tissues (Murray et al., 2001). Moreover, people who have arterial disease, hypotension and diabetes are at high risk (Healthwise, 2015; Murray et al., 2001; Thomas, 2001). Previous research has identified that increasing skin and body temperatures contribute to increased perspiration and increase oxygen demand, thus making the skin more susceptible to erosion and infection. Dry and scaling skin also reduces the resistance of tissue to mechanical forces (Murray et al., 2001). On the other hand, the chances that pressure ulcers will form on moist skin are greater than on dry skin. The maceration of the epidermis easily causes disintegration of the skin and tissue sloughs, and there is an increase in friction (Maklebust & Sieggreen, 2001). Oxygen and nutrition delivery are important factors in pressure ulcer development. If oxygen and nutrition cannot be transmitted to certain areas, at the same time, toxic metabolic waste would accumulate in these areas, and the capillaries there will collapse and a thrombus wound will form (Reuler & Cooney, 1981).

2.2.6 Sites of Pressure Ulcers

As pressure ulcers are defined as the localized areas of tissue damage deprived of nutrition when prolonged pressure is applied onto patients, areas that overlie bony prominences, such as the heels, legs and knees, which have little padding and smaller surface areas, are less likely to attenuate pressure successfully and more likely to develop ulcerations (Basal & Ilgaz, 2009; Bass & Phillips, 2007; Ostadabbas et al., 2011; Pearson et al., 2000; Somerset, 2007; Thomas, 2001). The heels are most frequently the site of pressure ulcers, such that the incidence of heel ulcers is about 30% (Pearson et al., 2000; Sopher, Nixon, McGinnis, & Gefen, 2011; Versluysen, 1985). The general consensus is that the anatomy of the heel contributes to pressure ulcer development. In considering that only a thin layer of fat covers the heel, protection against pressure exerted onto the heel by the weight of the foot is minimal (Cancer Research UK, 2012). Figure 2.2 shows the areas at risk of pressure ulcers and Figure 2.3 illustrates an example of a heel pressure ulcer.

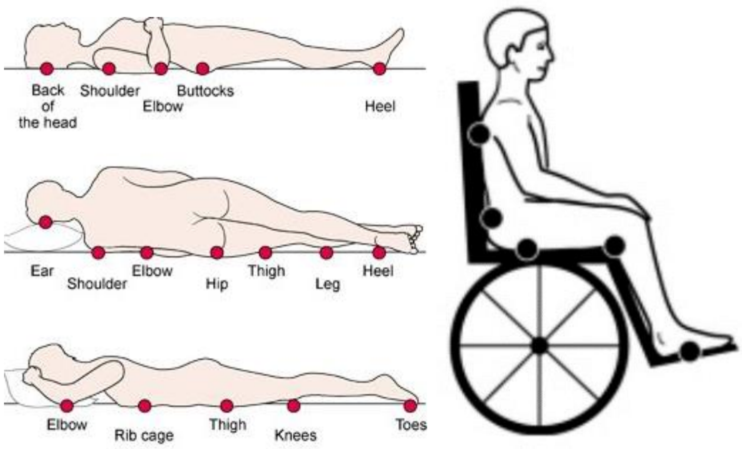


Figure 2.2 Areas where pressure ulcers will occur

Sources: left: http://www.cancerresearchuk.org/cancer-help/coping-with-cancer/coping-physically/skin/managing/dealing-with-pressure-sores,

right: (Ostadabbas et al., 2011)

Figure 2.3 An example of pressure ulcer on heel

Source: http://www.podiatrytoday.com/current-insights-on-treating-heel-pressure-ulcers

2.2.7 Risk Assessment Tools for Pressure Ulcers

Risk assessment tools are used to predict whether individuals are at risk of pressure ulcer development based on risk factors. In general, risk assessment tools use specific numerical scoring systems to categorize the severity of the risks, including no risk, low, medium and high risk (Murray et al., 2001). Researchers such Tolmie and Smith (2002) reviewed several risk assessment tools and found that the Norton Risk Assessment Score is one of the most widely used assessment tools, especially in Australia. However, it is only suitable for elderly patients in hospital settings and sometimes under-predicts the risk. On the other hand, the Waterlow Risk Assessment Card is a widely used comprehensive tool in the UK which contains 11 main assessment criteria, and each criterion contains a number of sub-scales rated on a scale of 0-8 in accordance with the degree of risk. However, it is complicated and sometimes over-predicts the situation (Murray et al., 2001; Tolmie & Smith, 2002),. Furthermore, the Braden Scale for Prediction of Pressure Sore Risk is widely used in the US. Researchers have proven that this tool is more reliable if it is performed by a registered nurse. Its validity excels the Norton Risk Assessment Score and Waterlow Risk Assessment Card (Murray et al., 2001).

Apart from the risk assessment tools, there are several other tools to track the healing process of pressure ulcers, including the Pressure Sore Status Tool (PSST), Pressure Ulcer Scale for Healing (PUSH), Sussman Wound Healing Tool (SWHT) and Sessing Scale (SS). The PSST is widely used to assess the status of pressure ulcers. This tool is used to examine 13 items that score wound and periwound characteristics, such as size, skin colour and depth, and each item is rated on a 1-5 scale with 1 equal to best and 5 equal to worse. After completing the PSST, the total score will be calculated, which will range from 13 to 65, in which higher scores denote that the pressure ulcer status of a patient is more severe. However, the PSST is commonly used in research rather than in clinical practice (Marreco, Moreira, Genari, & Moraes, 2004; Pillen et al., 2009; Somerset, 2007). The PUSH tool is a simple, quick and easy to scoring resource developed and validated by the NPUAP. It monitors 11 wound parameters of length times width, amount of extrude and types of tissues (Pillen et al., 2009; Somerset, 2007). On the other hand, the SWHT is based on an acute model of wound healing by describing the changes in the status of the tissue and size of the wound. In the SWHT, there are 21 items which include wound attributes, location and extent of tissue damage. The SS is a 7 stage scale used to measure the healing progress and each stage describes wound tissue attributes throughout the wound healing process (Pillen et al., 2009; Thomas, 2001).

2.2.8 Treatments and Devices Available for Pressure Ulcers

Researchers have found that more than 90% of pressure ulcers are preventable (Myers, 2004; Reddy et al., 2006; Simpson, Bowers, & Weir-Hughes, 1997). The main purpose of pressure sore prevention strategies is to reduce either the magnitude or duration of the interface pressure between a patient and the support surface (McInnes, Jammali-Blasi, Bell-Syer, Dumville, & Cullum, 2011). In order to prevent and treat pressure ulcers, different methods are adopted to determine the appropriate prevention interventions including facility-specific standardized protocols, individualized care plans and orders from physicians or nurses (Wipke-Tevis et al., 2004). The NPUAP in the US has also published a reference guide for pressure ulcer prevention and treatment, while Canada has its own practice guidelines for clinicians (European Pressure Ulcer Advisory Panel, National Pressure Ulcer Advisory Panel, & Pan Pacific Pressure Injury Alliance, 2014; Houghton, Campbell, & CPG, 2013). In Hong Kong, the Hong Kong Association of Gerontology as well as the Social Welfare Department have also provided some guidelines for nursing homes on pressure ulcer prevention and treatment (Hong Kong Association of Gerontology, n.d.; Social Welfare Department, n.d.). In general, the management of pressure ulcers focuses on avoiding further deterioration of the ulcers by regular repositioning and the use of pressure relief devices, maintaining cleanliness of the wound and balancing the level of moisture of the ulcer, thus preventing the development of infections and minimizing the pain of patients (Lyder & Ayello, 2008). Regular repositioning of patients is one of the most widely used methods for pressure sore prevention (Ostadabbas et al., 2011). However, it is difficult to carry out because of the limitations and costs of turning them frequently (Bass & Phillips, 2007; Thomas, 2001). Therefore, a number of pressure sore preventive devices have been developed, including pressure relief beds, mattresses, overlays and cushions. However, researchers have indicated that pressure relief devices are only able to consistently reduce the interface pressure to under 32 mmHg while pressure reducing devices reduce pressure to under the standard support surfaces, but not under 32 mmHg. So, most devices are regarded as pressure reducing devices (Myers, 2004; Thomas, 2001, 2006).

According to the literature, only a few pressure relieving beds are available in the market that can reduce the pressure under the minimal capillary pressure, such as air-fluidized beds and low-air-loss mattress systems. However, researchers have proven that if the head of bed is elevated to 30 degrees, the benefits of these systems are lost. They are also expensive. In addition, the CircOlectric bed is an equipment with an automatic turning device to provide vertical elevation of the head. However, it is expensive, large and time-consuming to monitor (Bass & Phillips, 2007).

There are also several types of other mattresses and overlays available in the market. They are made of foam, filled with fiber, air or water to maintain the even distribution of pressure (Simpson et al., 1997; Thomas, 2006). Foam mattresses and overlays are relatively lower in cost and suitable for patients with low to medium risk of pressure ulcers. However, they may increase the tissue temperature due to the insulation as well as the metabolic rate and oxygen consumption so that the capillary blood flow will be reduced. Some may even increase tissue maceration due to the excess skin moisture. Fiber-filled overlays are useful for minimizing skin maceration from excess moisture accumulation and reduce shear and friction. However, due to their rapid deterioration, they are only recommended for patients who are at low risk for pressure ulcers or to provide comfort. Low-air loss mattresses, one of the most common types of air mattresses, are tailored so that air can pass over the skin of patients by alternatively inflating and deflating the tubes on the mattress (Thomas, 2006). They are helpful for the even distribution of pressure and promote moisture evaporation which is especially useful when skin maceration takes place. With their excellent pressure reduction property, they are used for patients with a medium risk of pressure ulcers. In terms of water mattresses, they utilize gentle wave motions to maintain the even distribution of pressure (Thomas, 2001).

Fleece is used as the cover in overlays, and commonly made of 100% polyester and 100% wool. They can protect the skin from shear and friction and reduce skin maceration from excess moisture. Researchers (Simpson et al., 1997) have proven that wool fleece is more effective for reducing friction and shear as opposed to synthetic fleece as the natural oils can create a slick surface and moisture absorption property can maintain good hydration of epidermis. However, researchers (Marchand & Lidowski, 1993) have also proven that they can be the potential reservoirs for infection and increase the interface pressure when used on a specialist bed.

Apart from beds, mattresses and mattress overlays, there are different support surfaces, such as cushions, pillows and heel protectors, which can be used to relieve pressure and cushion vulnerable parts of the lower limbs and more evenly distribute surface pressure (Cullum, Nelson, & Flemming, 2001; Somerset, 2007). They are useful because as mentioned earlier, heels are one of the most common sites for pressure ulcers. About 30% of those who suffer from pressure ulcers have an ulcer on the heel as the calcaneum exerts pressure onto a small surface area that only has minimal protection from a thin covering of the subcutaneous fat (Lyder, 2003; Murray et al., 2001; Thomas, 2001).

In general, fiber-filled and foam cushions are the most common types of cushions used for pressure ulcer prevention. The former reduces tissue interface pressure; however, they rapidly deteriorate in effectiveness. On the other hand, the latter can retain their support properties longer, but will cause tissue temperature and metabolic rate to rise if there is no moisture permeable cover (Murray et al., 2001; Ostadabbas et al., 2011). Air-filled cushions are proven to provide good pressure relief if they are appropriately used. However, they can be highly detrimental if the air cells are under- or over-inflated as these will increase the tissue interface pressure (Murray et al., 2001; Pearson et al., 2000). Heel protectors can cause reduced ventilation and, if fitted too tightly, increase the surface-interface pressure (Maklebust & Sieggreen, 2001). In addition, these support surface devices can be difficult to use and require several adjustments to ensure proper positioning (Murray et al., 2001).

Pillows placed under the full length of the lower leg, which suspend the heels, will also assist in relieving pressure onto the heels. Researchers (De Keyser, Dejaeger, De Meyst, & Evers, 1994) have proven that an ordinary head pillow is the most effective heel pressure-reducing device. However, it may increase the tissue temperature and also metabolic rate and oxygen consumption. As a result, the capillary blood flow may be reduced (De Keyser et al., 1994). Moreover, there are three types of heel pressure relief devices that are mentioned and compared in the literature (Gilcreast et al., 2005): a fleece cushion heel protector (the Bunny Boot), the egg-crate heel lift positioner, and the foot waffle air cushion. There are no statistically significant differences between the devices in terms of incidence of pressure ulcers: 3/77 (4%) for the Bunny Boot; 4/87 (4.6%) for the egg crate and 5/76 (6.6%) for the foot waffle (Gilcreast et al., 2005).

After examining the different types of pressure ulcers, incidence and prevalence of pressure ulcers, as well as their impacts, development, sites, risk assessment tools, treatment and devices available, the following knowledge gap is found.

Knowledge Gap 1: Although there are different guidelines for pressure ulcer prevention and treatment for caretakers to follow, the daily care procedures for pressure ulcer prevention and wound treatment are still unclear. In addition, the healing process of pressure ulcer wounds has not been well examined yet.

2.3 Wound Dressings

2.3.1 Background Information on Wound Dressings

Wound dressings were developed thousands of years ago to cover wounds and control bleeding (Augustine, Kalarikkal, & Thomas, 2014; Gilcreast et al., 2005; Weller & Sussman, 2006). However, wound management has recently become more sophisticated as modern wound dressings focus more on promoting wound healing. In general, wound dressings are used to restrict the evaporation of water from the surface of wounds, cushion pain and trauma, manage exudates and protect wounds against bacteria invasion. According to various researchers (Augustine et al., 2014; Gilcreast et al., 2005; Lou et al., 2008; Maklebust & Sieggreen, 2001; Watson & Hodgkin, 2005; Weller & Sussman, 2006), a good wound dressing should not only be permeable to oxygen, but also able to absorb blood and exudates. Also, it should prevent dehydration and the formation of scabs. Finally, a good wound dressing should provide good protection against secondary infections and mechanical damage, and is sterile and non-toxic, has a non-adherent and non-sensitizing adhesive, and does not cause allergy reactions.

In general, a typical composite wound dressing has 3 layers, including a non-adherent, an absorptive and a bacterial barrier layer. Figure 2.4 shows a composite wound dressing commonly found in the market and Figure 2.5 illustrates the structure of a composite wound dressing.

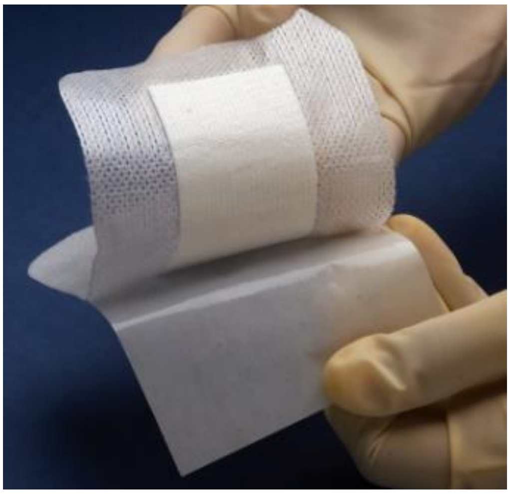


Figure 2.4 Composite wound dressing available in the market

Source: http://www.elderindia.com/contentTemp.php?p=31

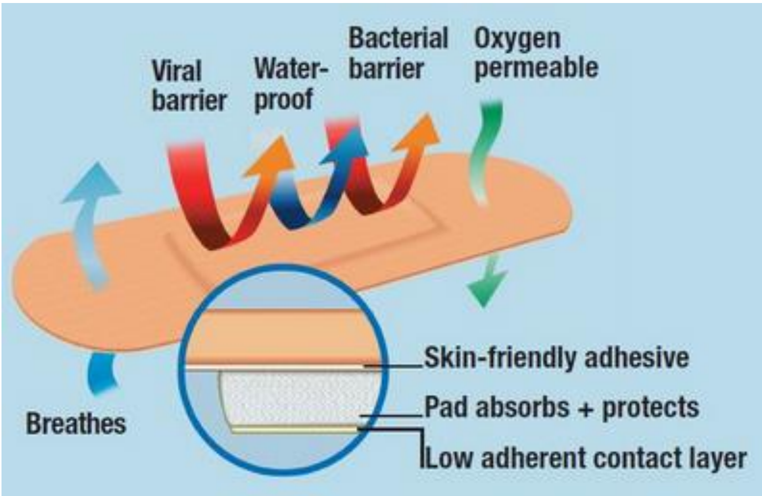


Figure 2.5 Structure of composite wound dressing

Source: http://www.healthandcare.co.uk/wound-dressing/coverplast-barrier-first-aid-dressing.html

Based on clinical perspectives, dressings are classified as film, simple island, non-adherent, moist and absorbent dressings (Beldon, 2010). Film dressings can be used as primary or secondary dressings. They can also be a barrier for the protection of fragile skin that is suffering from friction or shear force. However, simple island dressings can only be used over a suture line and not for open wounds. Their central pad is composed of cellulose material for the absorption of oozing from the suture line during the first 24 hours after surgery. Non-adherent dressings do not stick to the drying secretions of wounds, and as a result, there is less pain and trauma when they are removed. Moist dressings are used to prevent moisture loss of the skin that surrounds the wound or actively transfer moisture to the area while absorbent dressings are used to exudate absorption to prevent skin maceration. It is important to apply dry absorbent dressings to the wound bed and ensure that their size and shape fit the wound site. For some cases, antimicrobial dressings will be adopted to protect the skin against infection and provide a moist environment for wound healing. They are used as a primary or secondary dressing for infected, draining or non-healing wounds and good at managing minimal to heavy drainage. They can be in different forms including transparent, foam or island. Silver, iodine and polyhexethylene are the most common active ingredients of antimicrobial dressings (Beldon, 2010; Gilcreast et al., 2005; Somerset, 2007; Weller & Sussman, 2006).

2.3.2 Wound Dressings for Pressure Ulcers

Lyder and Ayello (2008) reported that there may be more than 300 different types of dressings available in the market for pressure ulcers. In accordance with their different properties, they have different strengths and limitations which may suit different stages of pressure ulcers (Lyder, 2003; Weller & Sussman, 2006). Transparent films, hydrocollids, hydrogels, foams, alginates and hydrofibers are widely used in wound dressings for different stages of pressure ulcers.

Transparent film dressings are impermeable to liquid but permeable to gas and moisture vapour. Although transparent films can facilitate adhesion and extend the wear time of dressings, they do not absorb exudates and dehydrate the wound. Therefore, they are not suitable for wounds that are highly exudative as there may be leakage (Hom, Adams, Kories, & Masiel, 1999; Maklebust & Sieggreen, 2001; Thomas, 2001; Weller & Sussman, 2006).

Hydrocolloid dressings differ from transparent film dressings as they are impermeable to moisture and gases. Although they are highly adhesive on the surrounding skin, they do not adhere to the wound tissue and damage the epithelisation of the wound. Furthermore, they can absorb exudates and facilitate superficial necrotic tissue removal by autolysis of the pressure sore. They are more cost-effective as the frequency for changing the dressing is reduced. However, they cannot be used over tendons or on wounds with eschar formation (Beldon, 2010; Hom et al., 1999; Thomas, 2001; Weller & Sussman, 2006).

Hydrogel-impregnated gauze dressings area made of three layers of hydrophilic polymers, which can interact with aqueous solutions but are insoluble in water. They are used for pain control and reduction of inflammation. They help to maintain a moist wound environment and promote debridement, granulation and reepithelialisation. They are good for granular and necrotic wounds. As the hydrogel is non-adherent, a secondary dressing is used to cover the hydrogel and secure onto the wound (Beldon, 2010; Hom et al., 1999; Maklebust & Sieggreen, 2001; Thomas, 2001; Weller & Sussman, 2006).

Foam dressings, which use a kind of sponge like polymer, absorb exudates, prevent skin maceration and facilitate superficial necrotic tissue removal by autolysis. The exudates can pass through the non-adherent, semi permeable surface into the insulating foam. Foam dressings are highly absorbent with good cushioning and protection. For wounds with a large necrotic area or are heavily draining, the dressing needs to be changed more frequently in order to prevent leakage of the exudates. If the foam dressing is covered with occlusive film or tape, the water vapor transmission is affected which also affects its effectiveness. Polyurethane foam, one of the most widely used foams in foam dressings, has good cushioning effect. However, its moisture transmission property is low and it is non-recyclable (Beldon, 2010; Hom et al., 1999; Maklebust & Sieggreen, 2001; Thomas, 2001; Weller & Sussman, 2006).

Alginate dressings, composed of material derived from seaweed, are highly absorbent and particularly suitable for exudative and infected wounds. When they absorb drainage, they turn into a gel form in order to maintain a moist environment for wound healing. Although they are not adherent to wounds, the epithelial tissue may be damaged during removal if the wound is allowed to dry. Therefore, they are not suitable for pressure ulcers with dry eschar or clean granulating wound beds (Beldon, 2010; Hom et al., 1999; Maklebust & Sieggreen, 2001; Thomas, 2001; Weller & Sussman, 2006).

Hydrofiber dressings, made with non-woven sodium carboxymethyl cellulose fibres, are used for wounds with moderate to heavy exudates. They form a gel-like cover on the wound in the absorbing of exudates. Hydrofiber dressings need to be changed once they are fully saturated with exudate in order to prevent leakage (Beldon, 2010; Weller & Sussman, 2006).

2.3.3 Conformability of Wound Dressings to Heel Ulcers

According to the literature (Cichowitz, Pan, & Ashton, 2009; Murray et al., 2001; Sopher et al., 2011; Thomas, 2001), heels are the second most common ulcer site. The posterior heels have a unique anatomy in which the calcaneus bone is covered by a layer of subcutaneous tissue including fat padding and skin (Cichowitz et al., 2009; Gu, Li, Ren, Lake, & Zeng, 2010). For those who need to lie in bed for a long period of time, the posterior heel comes into contact with the supporting surface. However, the posterior heel lacks fat filled fascial interstices, which can provide a cushioning effect and redistribute the pressure of tissue loads. Therefore, all of the weight of the foot and lower limb are applied onto the calcaneus bone of the posterior heel thus causing more vulnerability for pressure ulcer development (Campanelli et al., 2011; De Keyser et al., 1994; Fowler, Scott-Williams, & McGuire, 2008; Sopher et al., 2011). Boateng, Matthews, Stevens, and Eccleston (2008) and Seaman (2002) noted that ideal wound dressings should be able to cover the whole wound and prevent bacterial infections. Researchers such as Balakrishnan, Mohanty, Umashankar, and Jayakrishnan (2005) stated that poor conformability of wound dressings means that they wrinkle or flute in the wound bed. Therefore, conformability of wound dressings is critical for an optimum wound healing environment. However, due to the three dimensional shape of the heel, it is difficult to fit dressings onto the three dimensional contours of the heel to treat the ulcer wounds (Zahedi, Rezaeian, Ranaei-Siadat, Jafari, & Supaphol, 2010). Weller and Sussman (2006) concluded that innovative wound dressings are necessary for wounds on the face or areas which are difficult to fix the dressings. Other researchers, such as Queen, Evans, Gaylor, Courtney, and Reid (1987), assessed the conformability of wound dressings by using an in vitro technique. They proved that their conformability test is a useful tool to evaluate how wound dressings meet the requirements of conformability by applying wound dressings at a transmural pressure to conformational surfaces to investigate whether wrinkles will occur at the edges of the dressings.

After reviewing the different kinds of wound dressings in the market, the following knowledge gap is found.

Knowledge Gap 2: Although there are different kinds of wound dressings in the market which claim that they are designed for pressure ulcer wounds, their pressure relief and cushioning performance are ambiguous. There is therefore a lack of suitable wound dressings for pressure ulcers, especially those on the 3D shape of the heel region.

2.4 Interface Pressure

2.4.1 Basic Information on Interface Pressure

Interface pressure is the pressure induced between the skin and a support surface, and a good indicator of pressure ulcer development as it is easy to measure and non-invasive (Phillips, 2007; Reenalda et al., 2009). Thomas (2001) indicated that pressure applied onto susceptible tissues is the main cause of pressure sores. Sprigle and Sonenblum (2011) also indicated that interface pressure measurement is an effective method to assess the effect of pressure distribution with the changing of positions. Apart from pressure ulcers, measurement of interface pressure can be helpful in many situations and there are many applications, such as determining the effect of pressure garments on burn scars (Partsch et al., 2006; Yu, Yick, Ng, & Yip, 2013), and assessing the effect of compression bandages (Al Khaburi, Dehghani-Sanij, Nelson, & Hutchinson, 2012; Kumar, Das, & Alagirusamy, 2014), compression stockings (Lurie & Kistner, 2014), girdles (P. Y. Liu et al., 2014) and footwear (Lo, Wong, Yick, Ng, & Yip, 2016; Shu et al., 2010; Wang, Wang, Zheng, Wei, & Wang, 2013). Interface pressure measurement is also helpful for assessing the comfort of car and aircraft seats and also correcting the posture of car drivers (Andreoni, Santambrogio, Rabuffetti, & Pedotti, 2002; Ciaccia & Sznelwar, 2012; Gyi & Porter, 1999; Kyung & Nussbaum, 2008; S. H. Lee, Park, Jung, & Lee, 2016; Paul, Pendlebury, & Miller, 2012). Apart from determining the effectiveness and comfort of various products, researchers have also studied the effects of interface pressure distribution on the quality of sleep (Chen et al., 2014).

2.4.2 Interface Pressure and Pressure Ulcers

Phillips (2007) carried out work to disprove the general belief that an interface pressure of 32 mmHg is considered to be safe and the subject is not at risk for pressure ulcer development because 32 mmHg is greater than the normal capillary filling pressure.

Nevertheless, she still considered interface pressure to be an important measurement for developing and selecting support surfaces (Phillips, 2007). Furthermore, Bass and Phillips (2007) indicated that higher interface pressure causes pressure ulcers in a shorter period of time compared to lower interface pressure. Therefore, researchers have studied the relationship between the support surface and area of body that comes into contact with the support surface in terms of interface pressure (Reenalda et al., 2009; Thompson-Bishop & Mottola, 1992). Defloor (2000) investigated the effect of position and mattress on interface pressure while Stinson, Porter-Armstrong, and Eakin (2003) examined the relationship between interface pressure and gender, body mass index and seating position. Brienza, Karg, Geyer, Kelsey, and Trefler (2001) studied the relationship between pressure ulcer incidence and interface pressure in terms of seat cushions for the wheelchair bound elderly while Gravenstein, van Oostrom PhD, and Caruso (2013) studied the effectiveness of regular repositioning of high risk patients. The effectiveness of wheelchair cushions and pressure relief manoeuvres have been investigated with the use of interface pressure (S. H. Lee et al., 2016; Sonenblum, Vonk, Janssen, & Sprigle, 2014; Wininger, 2015).

2.4.3 Heel Interface Pressure

There are many researchers who have carried out investigations on the effects of pressure reducing support surfaces and standard hospital mattresses on heel interface pressure (Flemister, 1991; Guin, Hudson, & Gallo, 1991; R. Liu, Kwok, Li, Lao, & Zhang, 2007; Masaki et al., 2013; Phillips, 2007; Ragan, Kernozek, Bidar, & Matheson, 2002; Shelton, Barnett, & Meyer, 1998; Sprigle & Sonenblum, 2011; Thompson-Bishop & Mottola, 1992; Tymec et al., 1997; Wang et al., 2013; Whittemore, 1998). In the literature, the range of heel interface pressures is different from study to study. For instance, Wang et al. (2013) indicated that the interface pressure of the heels, sacrum and scapula when lying in bed should be between 50-94 mmHg. Thompson-Bishop and Mottola (1992) indicated that the average heel pressure ranges from 28.1 to 62.1 mmHg while lying on pressure reducing support surfaces while the average heel pressure of those who laid on standard hospital mattresses is 93.9 mmHg. However, Sopher et al. (2011) found a heel interface pressure of 68 mmHg for those who used standard hospital mattresses and 44.7 to 103.2 mmHg on specialty mattresses. Guin et al. (1991) also evaluated the heel interface pressure with different heel pressure reducing devices and found that the heel pressure ranges from 22.9 to 51.2 mmHg on different heel pressure reducing devices at elevated and supine positions while Masaki et al. (2013) found that the heel pressure without the use of any device is 50.1 to 51.3 mmHg. Flemister (1991) found that the heel pressure ranges from 28.4 to 42.7 mmHg on different support surfaces and with the use of different heel protectors.

2.4.4 Instruments for Interface Pressure Measurement

Interface pressure can be measured by using pressure sensors. There are different kinds of pressure sensors available in the market, from single cell pressure transducers to pressure mapping mats depending on the usage. According to the literature, single cell transducers are adopted to measure the interface pressure of the sacrum and heels while lying down, and ischial tuberosities and trochanters during sitting. On the other hand, pressure mapping maps are used to measure the sitting surface (Reenalda et al., 2009). There are many different types of pressure measuring systems available, such as the Ergocheck® measuring system (Wilkinson & Raburn, 1996), Pliance X System (Goske, Erdemir, Petre, Budhabhatti, & Cavanagh, 2006; Lai & Li-Tsang, 2009) , ELITE system (Andreoni et al., 2002) and Tekscan system (Feng, Ge, & Song, 2011; Linder-Ganz, Yarnitzky, Portnoy, Yizhar, & Gefen, 2005; R. Liu et al., 2007; Shelton et al., 1998; Wang et al., 2013). Apart from these widely used measuring systems, other researchers have adopted the FSA (Force Sensitive Applications) torso pressure mapping system and MEMS pressure sensing technology (Best, Desharnais, Boily, Miller, & Camp, 2012; Brienza et al., 2001; Casey, Clarke-Moloney, & Grace, 2011). Figure 2.6 shows the Pliance X system while Figure 2.7 presents the design of a pressure mapping sensor. Figure 2.8 shows the FlexiForce sensor and Tekscan system.

Figure 2.6 Pliance X system
Source: http://www.novel.de/novelcontent/pliance

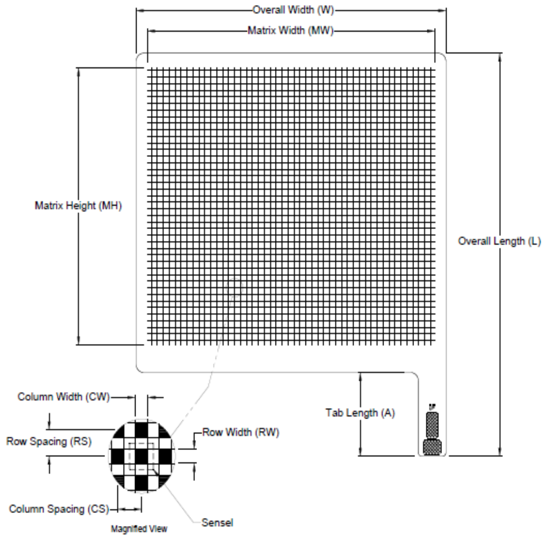


Figure 2.7 Design of pressure mapping sensor (Tekscan 5315-A)
Source: https://www.tekscan.com/products-solutions/pressure-mapping-sensors/5315

Figure 2.8 Example of Flexiforce sensor with Tekscan system
Source: https://www.tekscan.com/product-group/test-measurement/force-measurement

After discussing and reviewing the literature on basic information on interface pressure, interface pressure and pressure ulcers, heel interface pressure and instruments for interface pressure measurement the following knowledge gap is found.

Knowledge Gap 3: Although interface pressure is regarded as one of the most common methods for predicting the risk of pressure ulcer development, information on the heel interface pressure especially that of the elderly is not yet well examined. The effects of foot posture on heel interface pressure are still uncertain.

2.5 Spacer Fabrics

2.5.1 Basic Information on Spacer Fabrics

Spacer fabrics are a kind of 3-dimensional knitted fabrics with two distinctive textile layers connected together or kept apart by spacer threads with particular spacings (Bagherzadeh et al., 2007). In general, spacer fabrics are produced through either warp or weft knitting. Warp knitted spacer fabrics are made by using a Raschel machine which has two needle bars and six yarn guides. By using a Raschel machine, two layers are knitted on their own needle beds and pile yarns are interknitted from one needle bar to another in order to connect the two separate fabrics together (Abounaim et al., 2010). On the other hand, weft knitted spacer fabrics are produced with the use of a double jersey circular knitting machine which has a rotatable needle cylinder and needle dial. Moreover, by changing the dial height, the thickness and spacing of spacer fabrics can be easily changed by different amounts of pile yarns placed between two fabrics (Abounaim et al., 2010; Bruer & Smith, 2005; Davies & Williams, 2009b). Figure 2.9 shows an example of the structure of a 3-D spacer fabric and Figures 2.10 and 2.11 are a double needle bar Raschel machine and a double jersey circular knitting machine used to produce warp and weft knitted spacer fabrics, respectively.

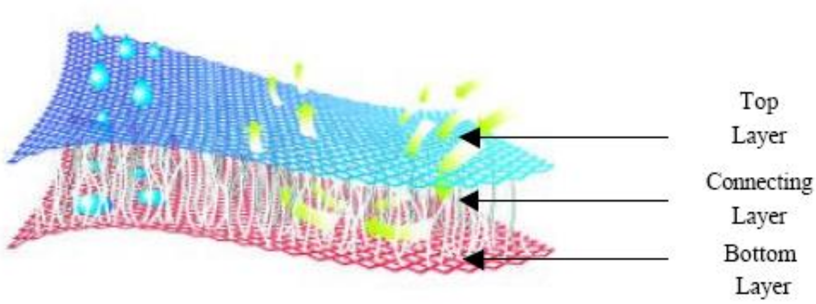


Figure 2.9 Structure of 3-D spacer fabric (Abdelrahman & Newton, 2011)

Figure 2.10 Double needle bar Raschel machine (Armakan & Roye, 2009)

Figure 2.11 Double jersey circular knitting machine (EC21 Inc, 2013)

2.5.2 Performance of Spacer Fabrics

Yip and Ng (2008) found that fabric density greatly affects both the air permeability and thermal conductivity of spacer fabrics while the type of spacer yarn and its arrangement are closely related to the compression properties of spacer fabrics. In addition, the bending properties depend much on the type of fabric and spacer yarn selected while fabric type, structure, type of spacer yarn and density are closely related to the bending properties (Armakan & Roye, 2009; Yip & Ng, 2008). Different types of spacer fabrics can be produced based on the properties required by using different fabric types, fabric densities, thicknesses, spacer yarns, etc. Therefore, spacer fabrics have various fabric properties. In general, the structure of spacer fabrics provides tortuous spaces, thus making spacer fabrics highly breathable, excellent in compression elasticity, insulated, and adjustable for vapor transport. Moreover, spacer fabrics have good bending performance and drapability.

2.5.3 Applications of Spacer Fabrics

According to the literature, the market demand for knitted spacer fabrics has increased because of their unique attributes, and the demand is found in a wide range of industries, such as automotive, medical textile, geotextile, civil engineering, sports and leisure, and environmental protection (Abounaim et al., 2010; Ye et al., 2007; Yip & Ng, 2008). They have been recently used more and more as cushioning material in personnel protective clothing and equipment against impact due to their excellent compression and moisture-wicking properties, and temperature-controlling characteristics (Y. Liu, Hu, Long, & Zhao, 2012; Y. Liu, Hu, Zhao, & Long, 2011b). Furthermore, they are widely used in shoes or insoles, face fabrics for sports, moulded cups for intimate apparel and other types of bandages (Bagherzadeh, Gorji, Latifi, Payvandy, & Kong, 2012; Bruer & Smith, 2005; Chellamani, Vittopa, & Arumugam). Finally, Yip and Ng (2007) proved that knitted spacer fabrics are becoming more popular in the cushion market which has been dominated by polyurethane foam and could be widely used in furniture in the future (Yip & Ng, 2007) see Figures 2.12 to 2.17 for examples of commercial products that use knitted spacer fabrics.

Figure 2.12 Cooling ballistics vest (Knitting Industry, 2012)

Figure 2.13 Helmet (Endura Limited, 2017)

Figure 2.14 Fabric of sports shoes (Jinjiang Huayu weaving co. Ltd., 2014)

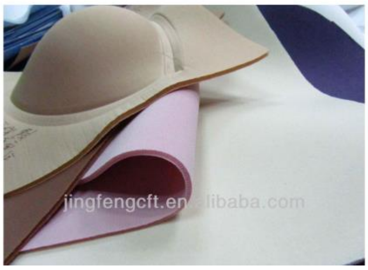


Figure 2.15 Bra cup (Alibaba.com, 2008)

Figure 2.16 Cushions (Changshu DongTao Home Textile Co. Ltd., 2013)

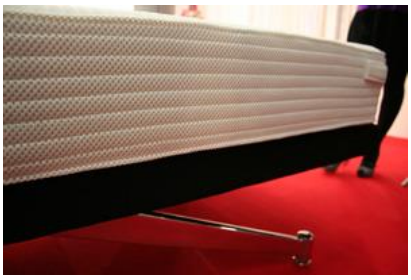


Figure 2.17 Mattress (Fujian Jinjiand Hau Yu Weaving Co. Ltd., 2014)

According to the literature, 3D knitted spacer fabrics play an important role in the medical field and healthcare industries, and their importance has been growing rapidly in the past ten years. Both 3D warp and weft knitted spacer fabrics have been widely investigated and used for different medical and healthcare purposes. Due of their excellent heat and moisture regulation properties, researchers have started to investigate the possibility of using them in bandages (Bartels, 2011; Heide, Möhring, & Schwabe, 2004; Heide, Schwabe, & Möhring, 2005b; Kanakaraj & Anbumani, 2007; Milosavljević & Škundrić, 2007). Not only are they as effective as traditional bandages, but they also provide a more optimum microclimate and distribute pressure more evenly.

Furthermore, S. H. Lee et al. (2016) evaluated the performance of commercially available compression bandages for venous leg ulcers and 3D knitted spacer fabrics. Their results proved that 3D knitted spacer fabrics meet the expected criteria stipulated for compression therapy (G. Lee, Rajendran, & Anand, 2009).

Apart from its excellent flexibility and elasticity, the good breathability of 3D knitted spacer fabrics has also gained a great deal of attention from researchers (Ghorbani, Hasani, Rafeian, & Hashemibeni, 2013). They studied the compression properties of 3D knitted spacer fabrics and the results obtained are comparable with those of traditional and neoprene foams. Traditional and neoprene foams are not washable and recycling them is difficult. However, 3D knitted spacer fabrics are washable, reusable and even biodegradable, depending on the materials used. The breathability of 3D knitted spacer fabrics is also one of the key factors that render them superior to traditional orthopedic insole materials. Therefore, researchers including Heide et al. (2005a); Luximon (2013) and Yick et al. (2014) suggested the use of 3D knitted spacer fabrics as an alternative for orthopedic insoles. Recently, Yu et al. (2015) investigated the possibility of using 3D knitted spacer fabrics as an alternative for existing insert materials in pressure therapy garments, such as thermoplastic and foam, which have poor air permeability, moisture absorbency and wicking properties. Their study proved that the comfort and breathability of 3D knitted spacer fabrics are better, and at the same time, the interface pressure between spacer and heel is comparable with that of conventional materials, and hence the compliance of patients with hypertrophic scars is increased.

3D knitted spacer fabrics are moldable. Therefore, this property means that spacer fabrics can be used in different orthoses including knee braces and hip protectors and as padding materials (Abou-Taleb, 2014; Bartels, 2011; Heide & Moehring, 2003;

Pereira, Anand, Rajendran, & Wood, 2006; Trümper, Sachse, Diestel, & Cherif, 2011; Viju, Parthiban, Srikrishnan, & Thilagavathi, 2012; Ye, Hu, & Feng, 2008). The study results indicated that the air permeability of 3D knitted spacer fabrics can prevent skin maceration and at the same time, compression and warmth in order to enhance healing (Abou-Taleb, 2014; Pereira et al., 2006).

Apart from its excellent compression behavior, some work has been done to examine the absorbency of 3D knitted spacer fabrics. Davies and Williams (2009b) carried out experiments to prove that 3D knitted spacer fabrics have high absorbency and liquid retention. Therefore, they recommended that 3D knitted spacer fabrics can be an alternative for absorbent medical applications (Davies & Williams, 2009b).

Aside from using 3D knitted spacer fabrics alone, they can also be combined with different materials in order to provide a more versatile performance. Möhring and Schwabe (2008) incorporated thermal conductors into the pile zone of 3D warp knitted spacer fabrics to generate and transport heat. The experimental results proved that this lightweight and flexible thermal 3D knitted spacer fabric can be used for hypothermia prevention and for emergency services such as rescuing injured people in cold conditions (Möhring & Schwabe, 2008). Ghorbani et al. (2013) compared the performance of neoprene foam and neoprene-spacer fabric. The results proved that the latter is more tough but also more permeable to moisture than the conventional neoprene foam. Therefore, they suggested that neoprene foam should be used together with 3D knitted spacer fabrics in orthopaedic textiles for better comfort and improved performance (Ghorbani et al., 2013).

Recently, researchers have started to investigate the possibility of using 3D knitted spacer fabrics for implantation. According to Fournier et al. (2014), a novel coating material for orthopaedic implants was developed by knitting super elastic nitinol wire into the structure of 3D knitted spacer fabric for hip and knee replacements. After evaluation of the performance by experiments and implantation test with a rabbit, the performance of the newly developed implant coating material met or exceeded the current coating technologies with reduced micro-motion, improved osseo-integration and stronger implant fixation in vivo (Fournier et al., 2014).

After reviewing information on spacer fabrics, a knowledge gap is found.

Knowledge Gap 4: The effects of the knitting parameters on the physical properties of 3D spacer fabrics are still uncertain and there is a lack of studies on applications of 3D spacer fabrics in wound dressings.

2.6 Computational Modelling and Simulation

2.6.1 Basic Information on Finite Element Analysis (FEA)

The Finite Element Analysis (FEA), which is one of the most common computational simulation method, is a versatile tool used to predict the mechanical properties of composite materials (Hu & Teng, 1996; Tan, Tong, & Steven, 1997). The FEA is a novel numerical method used to solve ordinary and partial differential equations and overwhelmingly dominates nonlinear as well as linear problems. The use of the FEA means that an approximated solution of the distribution of field variables is sought in the problem domain that is often difficult to obtain analytically. It is done by first dividing the problem domain into a number of smaller units of simpler geometry known as elements (Mayr, Weikert, & Wegener, 2007; Rao, 2014). The FEA has been widely used to solve structural, mechanical, heat transfer, and fluid dynamics problems as well as problems of other disciplines (Dhatt, Lefrançois, & Touzot, 2012).

One of the great advantages of using the FEA is that the method provides vivid simulation of in vivo conditions (Cheung & Zhang, 2005). FEA can predict load distribution and deformation of systems, and enable input parameters to be rapidly changed for material modification so as to observe their effects (Goske et al., 2006). The FEA has been commonly adopted with great success in many instances of biomechanical research because of its capability to model structures with asymmetric geometry and complicated material characteristics (Cheung & Zhang, 2005; Peng & Cao, 2002). The FEA is an approach to simulate the performance of a part or system on the computer, and has been most widely used owing to its versatility, with no restrictions on the geometry, material properties, or deformation patterns of contact bodies.

Textiles are commonly used in different fields such as the medical, automatic and furniture industries because of their unique structure and properties. Therefore, many researchers aim to simulate the mechanical properties of textiles in order to predict their performance and eliminate wear trials. Among the different computational methods, the FEA is the most widely used method. There is work in the literature on studying the mechanical properties of textiles for different purposes such as evaluating their wrinkling or draping properties as well as the pressure distribution. For instance, Eischen, Deng, and Clapp (1996) created a Finite Element Model (FEM) to simulate three-dimensional motions related to real fabric manufacturing processes. Boisse, Borr, Buet, and Cherouat (1997) studied the deformation of woven fabric during the forming process as shown in Figure 2.18. In their study, the tensile strength of single fibre yarn and fabrics is tested.

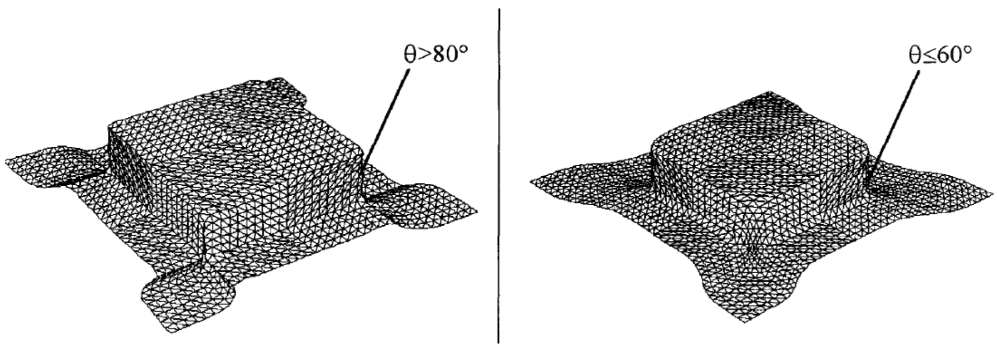


Figure 2.18 Examples of FEM modelling (Boisse et al., 1997)

Durville (2009) created FEM models of textile materials at the fiber scale and simulated their mechanical behavior under different solicitations. Figures 2.19 and 2.20 show the textile composite sample after shearing and bending tests respectively.

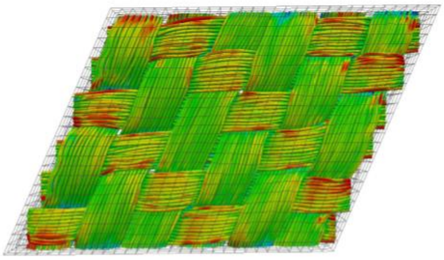


Figure 2.19 View of textile composite sample submitted to shear test (Durville, 2009)

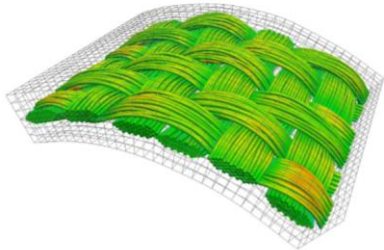


Figure 2.20 Global view of composite sample after bending (Durville, 2009)

Niwaya (1999) developed a basic system to predict the wearing silhouette, garment pressure, and ease looseness of a garment. X. Zhang, Yeung, and Li (2002) simulated dynamic garment pressure and stress distributions on a 3D human body during wear by analyzing the characteristics of the materials and the mechanical properties. Lin et al. (2012) also evaluated the compression performance of fabrics with the FEM. Apart from garments, the relationship between pressure and material properties of socks has also been assessed (Dan, Fan, Shi, & Zhang, 2016; M. Zhang, Dong, Fan, & Dan, 2015). In addition, Yu et al. (2015) adopted the FEM to simulate the effects of fabric properties on the pressure delivery of pressure gloves as shown in Figures 2.21 and 2.22. The simulation model allowed for instant evaluation of the interface pressure between glove and hand skin in response to different materials used (Yu et al., 2015).

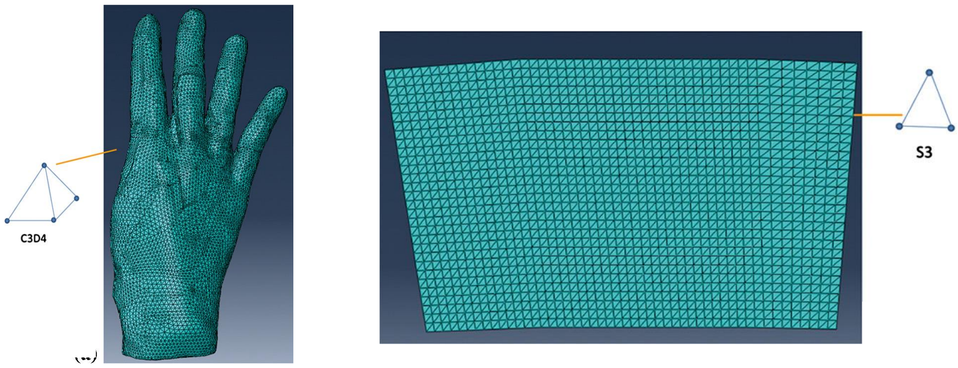


Figure 2.21 Meshed models of hand (left) and glove fabric (right) (Yu et al., 2015)

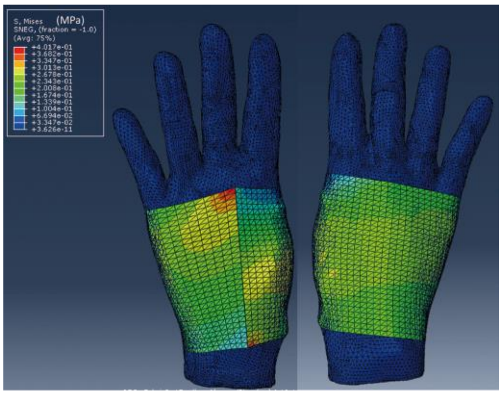


Figure 2.22 Stress distribution of glove fabric after fully encompassing hand (Yu et al., 2015)

2.6.2 Building Finite Element Model (FEM)

In order to produce computational models by using FEM, four major steps are necessary, including geometric modelling, meshing, specification of material properties and specification of boundary, initial and loading conditions (Tan et al., 1997).

2.6.3 Obtaining Geometry for Finite Element Model (FEM)

In order to obtain the geometry for finite element modelling, Computerized Tomography (CT) and Magnetic Resonance Imaging (MRI) are two common methods used to reconstruct the visualized anatomic structure of the human body (Tenenbaum, Shabshin, & Herman, 2013; Zheng, Mak, & Leung, 2001). By using CT or MRI, not only will the contours of the body be shown, but also the tissue structures inside the body and their position identified. However, CT uses computed and processed X-ray slices to obtain the tomographic images. The procedure emits radioactive waves, which may have adverse effects on humans (Zheng et al., 2001). On the other hand, MRI uses strong magnetic fields and radiowaves to generate images, which is less harmful to humans but longer scanning time is required (Zheng et al., 2001). Apart from CT and MRI, three-dimensional body laser scanning is another method to obtain 3D geometric body images. However, it only can capture the body surface contours but not the tissue structure inside (Werghi, 2007; Yu, Yick, Ng, Yip, & Chan, 2016). Figures 2.23 and 2.24 show the heel anatomy modelled with the FEM and captured with MRI.

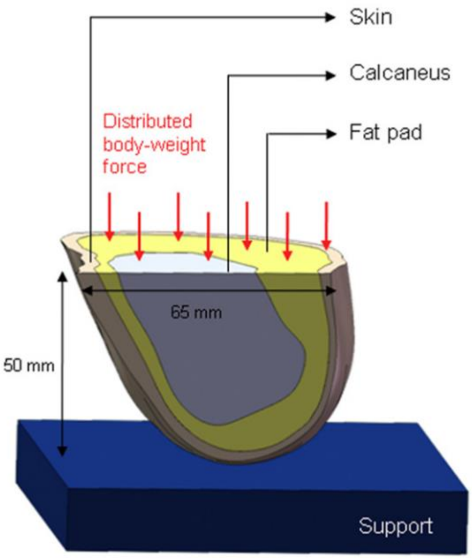


Figure 2.23 Heel anatomy modelled with FEM (Sopher et al., 2011)

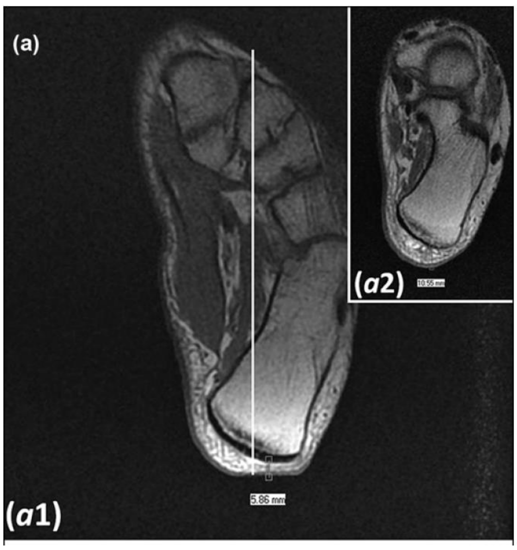
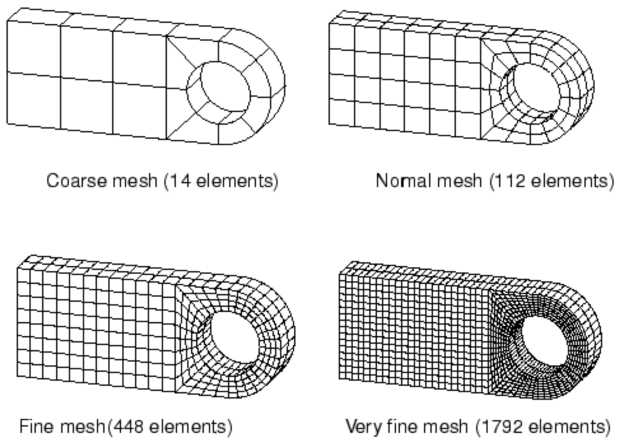


Figure 2.24 Heel anatomy captured by MRI (Tenenbaum et al., 2013)

2.6.4 Modelling of the Geometry

The geometry of an object is represented by a collection of elements in finite element modelling, and curved lines/surfaces may be approximated by using piecewise straight lines or flat surfaces, if these elements are assumed to be flat or straight pieces and segments. During modelling, the accuracy of the representation of the curved parts is controlled by the number of elements used. Therefore, with more elements, the representation of the curved parts with straight edges would be smoother and more accurate. On the other hand, with more elements, a longer computational time is required. As such, compromises are usually made in order to decide on the optimum number of elements used. These compromises usually result in the omission of fine details of the geometry unless very accurate results are required for those regions (Dassault Systèmes, 2009; G. R. Liu & Quek, 2013). Dassault Systèmes (2009) used a connecting lug model to demonstrate the compromisation between accuracy and number of element. Connecting lug is a device welded firmly to a massive structure at one end and contains a hole in another end. When the lug is in use, a bolt will be placed through the lug hole. Due to the presence of the lug hole in the model, a suitable mesh size is important to compromise the accuracy of the results and the computational resources required as shown in Figure 2.25. In Figure 2.26, the peak stress on the bottom of the lug hole reaches the equilibrium much more slowly than the displacements because stress and strain are calculated from the displacement gradients; thus, a much finer mesh is required to accurately predict displacement gradients than needed to calculate accurate displacements. Figure 2.27 shows the mesh refined around the lug hole based on the results of accuracy.



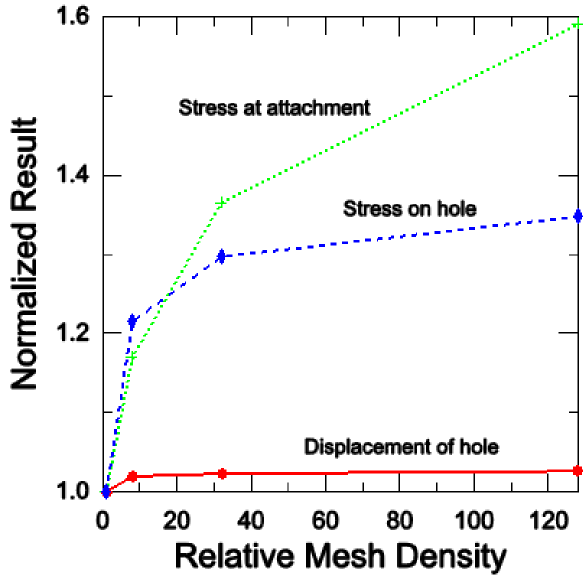


Figure 2.25 Different meshes for connecting lug (Dassault Systèmes, 2009)

Figure 2.26 Convergence of results with mesh refinement (Dassault Systèmes, 2009)

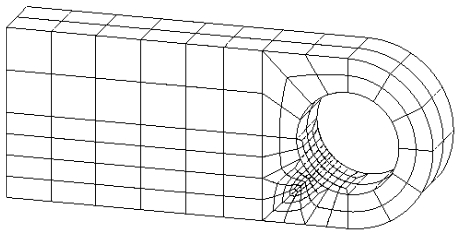


Figure 2.27 Mesh refined around lug hole (Dassault Systèmes, 2009)

2.6.5 Meshing

According to the literature, triangular and quadrilateral elements are commonly used in two-dimensional planes, while tetrahedron and hexahedron elements are widely used in three-dimensional spaces. In general, triangular and tetrahedron elements are the most flexible and well-established elements (Dassault Systèmes, 2009; G. R. Liu & Quek, 2013). Therefore, they are commonly found in most pre-processor software. An additional advantage of using triangular and tetrahedron elements is the flexibility in adapting complex geometry and boundaries. One can easily visualize fitting triangles into an acute grid pattern, but it is less obvious, for instance, with quadrilateral elements without severely distorting the elements. However, the disadvantage of using triangle elements is that the accuracy of the simulation results based on triangular elements is often significantly lower than that obtained using quadrilateral elements. On the other hand, quadrilateral or hexahedron elements are in general more difficult to generate automatically. However, better accuracy can be obtained. Figures 2.28 and 2.29 show the fitting of tetrahedron and hexahedron elements.

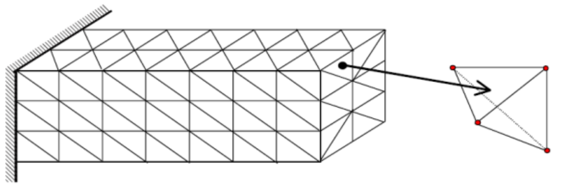


Figure 2.28 Tetrahedron element (G. R. Liu & Quek, 2013)

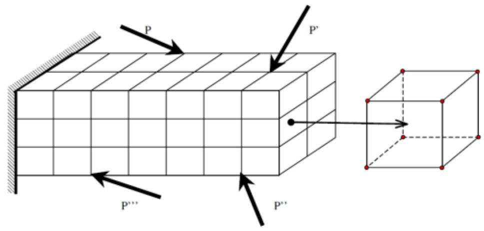


Figure 2.29 Hexahedron element (G. R. Liu & Quek, 2013)

2.6.6 Specification of Material Properties

Materials can be anisotropic, meaning that the material properties vary with direction. Deformation in anisotropic material caused by a force applied in a particular direction may be different from that caused by the same magnitude of force applied in another direction. Composite materials are often anisotropic. A large number of material constants have to be used to define the material property of anisotropic materials. Many engineering materials are, however, isotropic, where their material properties are not direction-dependent. Isotropic materials are a special case of anisotropic material. There are only two independent material constants for isotropic materials: usually the Young's modulus and Poisson's ratio (G. R. Liu & Quek, 2013). Many engineering systems consist of multiple components and each component can be of a different material. In fact, even within a single component, there can be multiple materials, as in the case of a composite material. Properties of materials can therefore be defined for a group of elements or even for individual elements if needed. The FEM can therefore work very conveniently for systems with multiple materials, which is its significant advantage. For different phenomena or physics to be simulated, different sets of material properties are required (G. R. Liu & Quek, 2013). For example, Young's and shear moduli are required for the stress analysis of solids and structures, whereas thermal conductivity coefficients will be required for a thermal analysis.

2.6.7 Specification of Boundary, Initial and Loading Conditions

Boundary, initial, and loading conditions play a decisive role in simulation (G. R. Liu & Quek, 2013). Users can specify these conditions either to the geometrical identities, such as points, lines or curves, surfaces and solids, or the mesh identities, such as nodes, elements, element edges and element surfaces. There are displacement and force boundary conditions for solids and structures. For heat transfer problems, there are temperature, heat flux, and convection boundary conditions.

2.6.8 Finite Element Modeling of Human Body

Many in the literature have examined the prevention and treatment of pressure sores, however, the effectiveness of the related devices has not yet been well evaluated (Pearson et al., 2000). In addition, Thomas (2001) stated that pressure applied to susceptible tissues is the main cause of pressure sores. However, other researchers (Flemister, 1991; Thompson-Bishop & Mottola, 1992; Verver, Van Hoof, Oomens, Wismans, & Baaijens, 2004) demonstrate that it is difficult to perform reproducible and accurate measurements of the interface pressure between the human body and preventive devices. In order to understand the pressure distribution of pressure ulcers and the performance of the prevention methods and pressure ulcer devices, many researchers have adopted finite element analysis. Finite element analysis has also been used, for example, to investigate the influence of the thickness of wheelchair foam cushions on the buttocks (Ragan et al., 2002). The effects of foot posture on support surfaces are also important for examining heel interface pressure and therefore Goske et al. (2006) adopted a finite element analysis to investigate the performance of different insole designs on reducing plantar heel pressure as shown in Figure 2.30.

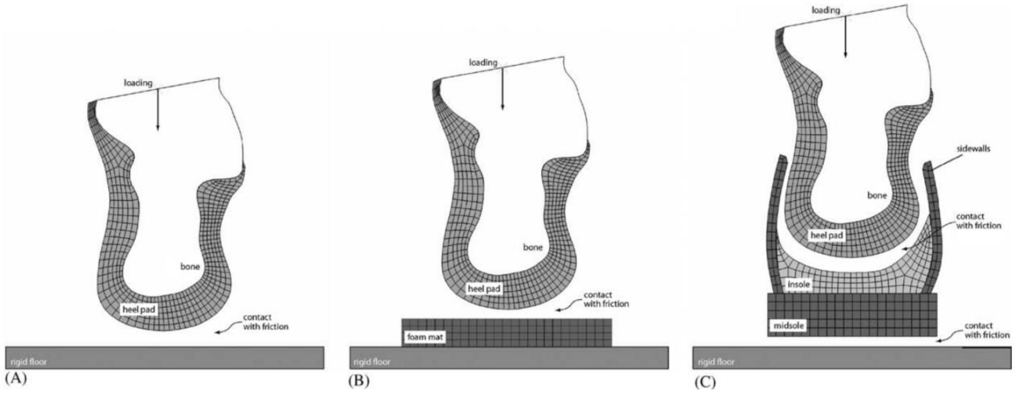


Figure 2.30 Finite element modeling of heels for plane strain: (A) barefoot, (B) foot on foam mat and (C) use of footwear model (Goske et al., 2006)

Sprigle and Sonenblum (2011) also used a finite element analysis to determine if interface pressure measurement is an effective method to assess the effects of changing postures on pressure distribution. Sopher et al. (2011) examined the effects of foot posture and stiffness of support to determine the risk of development of heel ulcers by using a finite element analysis. Figure 2.31 shows an FE model that simulates the foot resting at angles of 60° and 90° to the supporting device (Sopher et al., 2011).

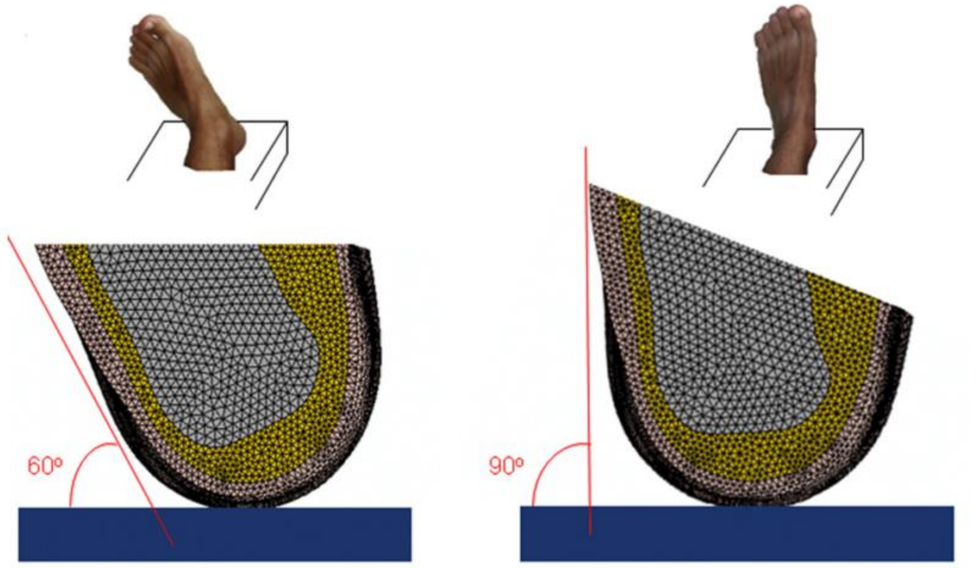


Figure 2.31 FEM of foot resting at 60° and 90° to supporting device (Sopher et al., 2011)

Ragan et al. (2002) used an FE approach to investigate the influence of the thickness of foam wheelchair cushions. In addition, (Kuroda & Akimoto, 2005) adopted two-dimensional FEMs to study the stress distribution of pressure ulcers under different structural conditions. They also used an FE approach to investigate the stress distribution of pressure ulcer as shown in Figures 2.32 to 2.35 (Kuroda & Akimoto, 2005).

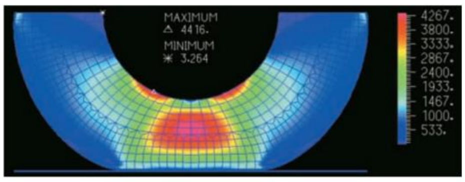


Figure 2.32 Stress distribution for no structural changes (Kuroda & Akimoto, 2005)

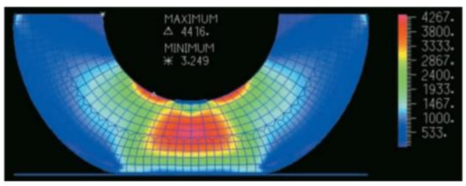


Figure 2.33 Stress distribution for some structural changes (Kuroda & Akimoto, 2005)

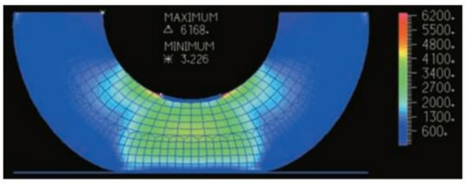


Figure 2.34 Stress distribution for moderate structural changes (Kuroda & Akimoto, 2005)

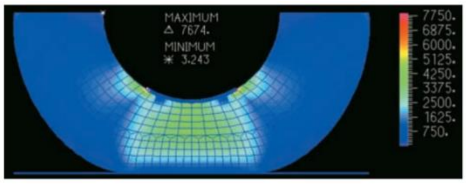


Figure 2.35 Stress distribution for large structural changes (Kuroda & Akimoto, 2005)

2.6.9 Finite Element Modelling of Spacer Fabrics

Apart from the relationship between pressure distribution and foot or preventive devices, many researchers have adopted finite element analysis to predict and demonstrate the compressional behavior of spacer fabrics. Psilla, Provatidis, and Mecit (2009) investigated the compression of warp knitted spacer fabrics at both micro and macro levels of mechanical analysis. In their research, the load-displacement curves obtained by stimulation and experiments were used to evaluate their computational method. Furthermore, they investigated the effects of the structural and physical parameters of the samples on compression resistance. Velosa, Rana, Fangueiro, and Marques (2012a) adopted the FEM to predict the mechanical behavior of sandwich composite panels manufactured based on 3D warp knitted spacer fabrics. Figure 2.36 shows the flatwise tensile strength of spacers in FEM.

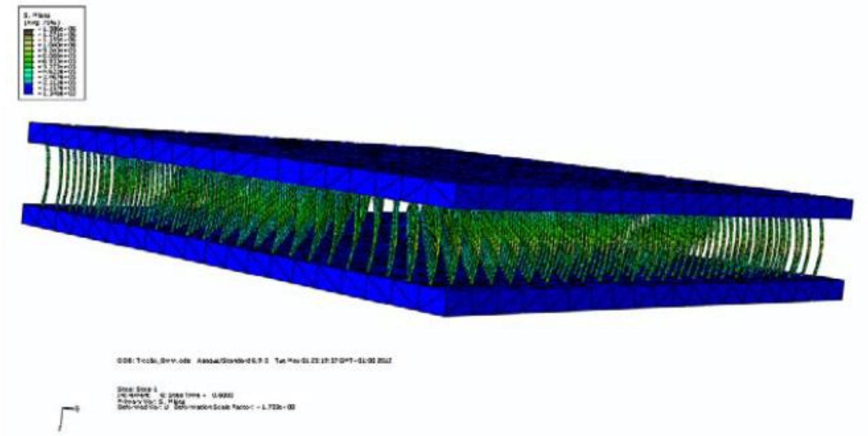


Figure 2.36 Von Mises stress field in flatwise tensile loading (Velosa et al., 2012a)

Apart from warp knitted spacer fabrics, some researchers have investigated the behavior of weft knitted spacer fabrics under impact loading (J. J. Li, Sun, Hu, & Gu, 2010; Sun, Hu, & Gu, 2010; M. Zhang, Sun, Hu, & Gu, 2009). Figure 2.37 show examples of FEMs of weft knitted spacer fabrics.

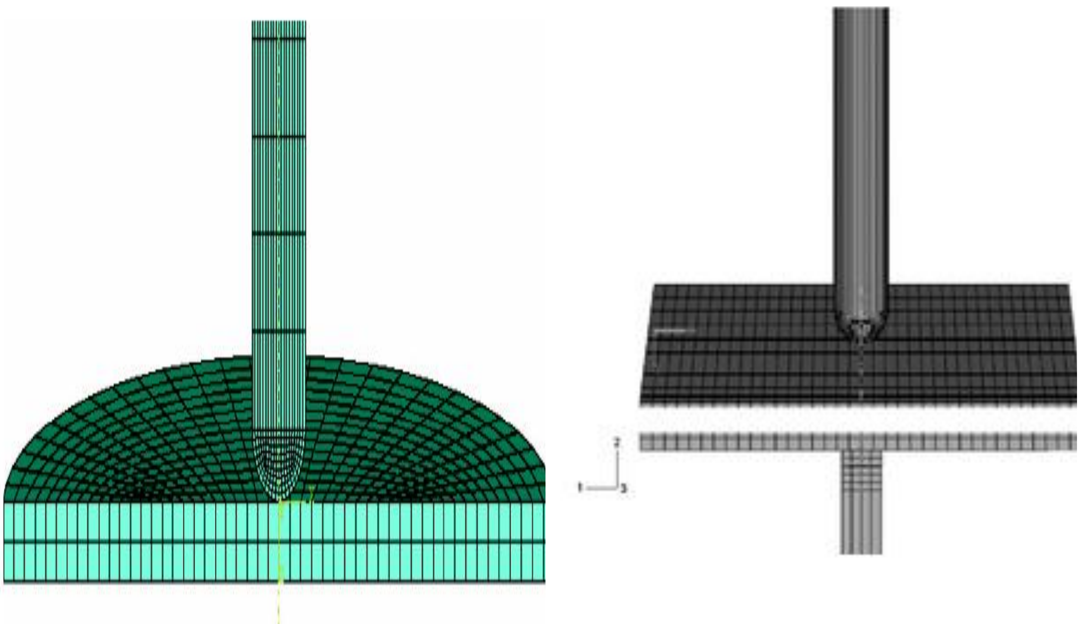


Figure 2.37 FEMs for weft knitted spacer fabrics under point impact (Left: (J. J. Li et al., 2010); right: (M. Zhang et al., 2009))

Apart from the prediction of the mechanical behavior of the entire spacer fabric, (Brisa, Helbig, & Kroll, 2015) studied the influence of the mechanical behavior of a single vertical spacer yarn of a warp knitted spacer fabric under compression loading as shown in Figure 2.38.

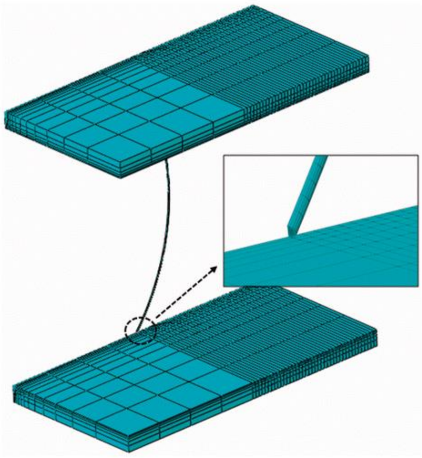


Figure 2.38 Yarn under compression loading and meshed yarn (Brisa et al., 2015)

Not only are the compression properties of knitted spacer fabrics under plane compression studied, but Du and Hu (2012; 2013) also studied their compression behaviour under spherical compression by using an FEM (Du & Hu, 2012, 2013). Recently, Hou, Hu, and Silberschmidt (2012) used the FEM to study the factors that affect the compression deformation of 3D spacer fabrics. In their study, the geometric modelling of a monofilament layer of unit cells was carried out as shown in Figure 2.39.

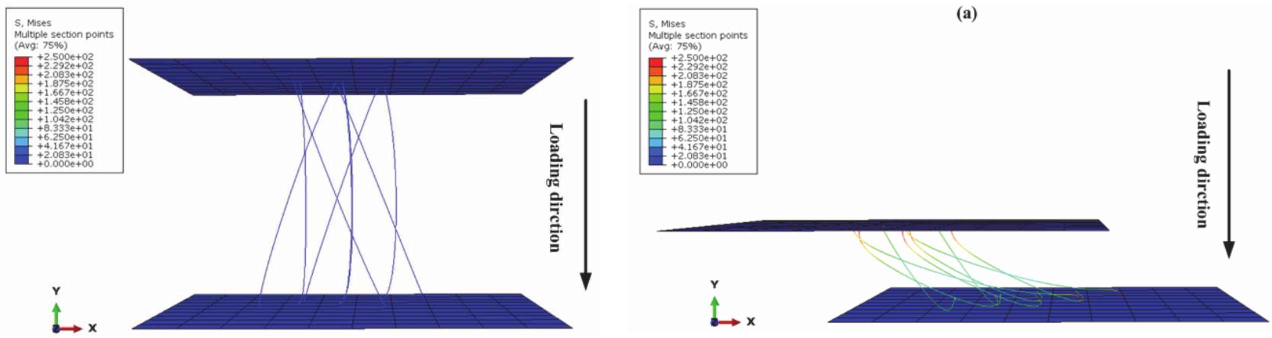


Figure 2.39 Deformed FEMs of 3D spacer fabric: Underformed model (left); Deformed model (right) (Hou et al., 2012)

2.6.10 Knowledge Gaps of Finite Element Model

According to the literature, FEMs are a widely used tool for the prediction of mechanical behaviour of different materials. Although researchers have investigated the mechanical performance of the human body and spacer fabrics with the use of the FEM for simulation, the deformation of the spacer layer between the spacer fabrics is still not clearly understood. Also, no study has simulated and examined the pressure distribution of spacer fabrics from loading due to the 3D shape of the heels.

Therefore, these research gaps have led to the following knowledge gap.

Knowledge Gap 5: FEMs are one of the most widely used tools to predict the mechanical behavior of different materials. However, there is a lack of studies on the simulation of the pressure distribution of 3D spacer fabrics from loading due to the 3D shape of the heels.

2.7 Summary

Pressure ulcers are a kind of chronic wound which is difficult to heal. People who are bedridden, wheelchair bound or diabetic, or the elderly, are at higher risk for pressure ulcer development. The areas that overlie the prominent parts of the body are less able to bear pressure and therefore, those areas may more easily develop ulcerations. The heels are one of the most common sites for pressure ulcer development. Not only is the quality of life of the patients affected, but there are also significant effects on the family and caretakers of the patients as well as financial burden on hospital services and the government. Heel ulcers are a complicated type of wound and many factors contribute to their development, such as pressure, friction, shear, chronic illness, nutrition, age and skin conditions. Although there are different guidelines for pressure ulcer prevention and treatment for the caretakers to follow, the daily care procedures for pressure ulcer prevention and wound treatment are still unclear. Furthermore, the healing process of pressure ulcer wounds is not yet well examined.

There are different kinds of wound dressings available in the commercial market. Some are designed for pressure ulcer wounds and can provide both good absorbency and cushioning effects for pressure relief. However, the effectiveness of existing wound dressings is ambiguous. The fit of wound dressings is another critical problem, especially for the heels, which have a 3D shape, because when they cannot be properly positioned, their effectiveness may be reduced.

Interface pressure is one of best indicators to objectively evaluate the effectiveness of a support surface for heels. Although there is research carried out on heel interface pressure, the interface pressure changes from case to case. Information on the heel interface pressure of the elderly and the influence of the heel posture on the heel interface pressure still need to be examined in-depth.

Spacer fabrics have been proven to have a wide variety of applications, including in medical products, due to their versatile physical, mechanical and thermal properties. Their excellent ventilation and cushioning properties are also important for pressure ulcer prevention and the healing process. In the meantime, spacer fabrics are also mouldable so they can accommodate different shapes. They are also a key item for the optimal fit of heel protectors and wound dressings. Although 3D knitted spacer fabrics are widely used in different medical applications, there is a lack of research on the possibility of using 3D knitted spacer fabrics as the absorbent and cushioning layer for wound dressings.

The FEM is one of the most frequently methods to simulate the mechanical behavior of human body parts and fabrics. With the use of the FEM, researchers can easily simulate and predict the mechanical behavior of human body parts or fabrics by changing the settings and the material properties assigned without carrying out experiments on real human subjects or manufacturing the fabrics themselves. However, there are a lack of studies on the pressure distribution of 3D spacer fabrics from loading due to the 3D shape of the heels.

Chapter 3 Research Methodology

3.1 Introduction

In this chapter, the methods for developing an advanced wound dressing composite for pressure ulcers with three-dimensional (3D) spacer fabric as the absorbent layer will be discussed in detail. The methods take into consideration: (a) a clinical study of elderly subjects, (b) heel interface pressure measurements and skin condition assessment of elderly subjects, (c) evaluation of spacer fabrics as cushioning and absorbent layer for pressure ulcer wound dressings, (d) formulation of a pressure simulation model for pressure ulcer wound dressings, (e) development of wound dressing composites with spacer fabrics as the absorbent layer, and (f) evaluation of the wound dressings composites.

3.2 Experimental Design

Figure 3.1 shows the experimental design for the whole study. A thorough scientific basis will be first provided for a better understanding of the pathophysiology mechanisms and the considerations and problems of caretakers and patients in terms of pressure ulcer development and healing treatment. As interface pressure exerted onto the body and the skin conditions of the subjects are the key factors that affect the development and healing of pressure ulcer wounds, precise interface pressure measurements (specifically on the heels) and skin condition assessments must be made. The physical properties of the available wound dressings for pressure ulcers and 3D knitted spacer fabrics will also be detailed. A biomechanical simulation model for 3D knitted spacer fabrics will be developed to evaluate and optimize their effectiveness as the absorbent and cushioning layer of pressure ulcer wound dressings. Wound dressing composites with 3D knitted spacer fabric as the absorbent and cushioning layer will be developed and their physical properties will be evaluated.

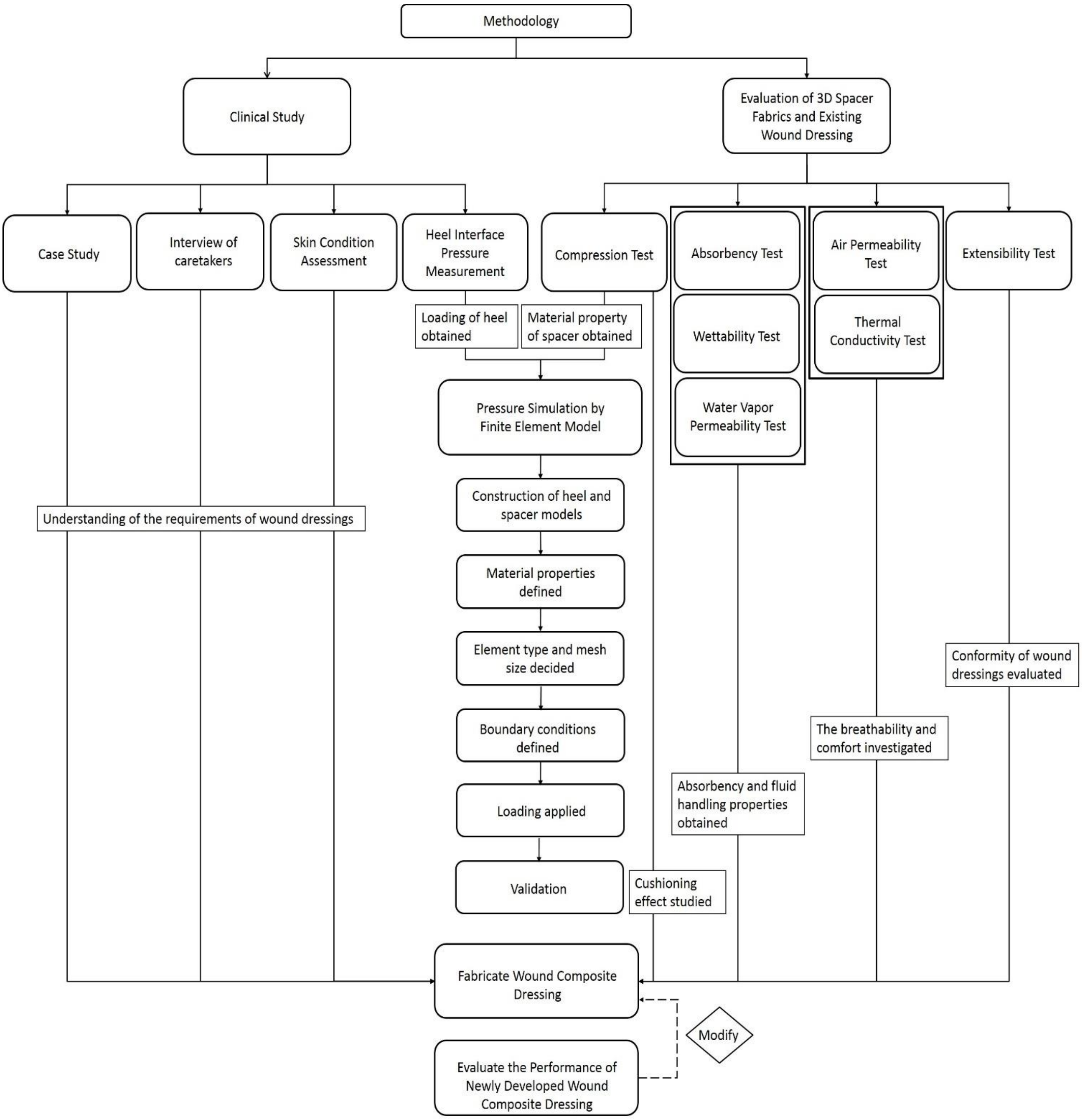


Figure 3.1 Experimental design to study use of 3D knitted spacer fabrics as absorbent and cushioning layer of wound dressings for pressure ulcers

3.3 Clinical Study of Elderly

In the previous literature, Schubert (2001) and Smith (1995) reviewed the literature on the treatment of pressure ulcers in nursing homes while Versluysen (1985) investigated the prevalence of pressure ulcers in the elderly with orthopaedic problems.

Schubert (2001) examined the effects of phototherapy on the healing process of pressure ulcers in elderly patients. Brem et al. (2001) tracked the healing progression of pressure ulcers in elderly patients between the ages of 65 to 102. However, they did not record detailed information about the treatment provided. Liu and Dai (K. Liu & Dai, 2011) studied the effects of medical and nutritional care on the healing of pressure ulcers in the elderly while Cereda, Gini, Pedrolli, and Vanotti (2009) investigated the differences between using a disease-specific and standard dietary approach for pressure ulcer healing in the elderly. Berlowitz, Bezerra, Brandeis, Kader, and Anderson (2000) investigated the quality of nursing home care in terms of treating pressure ulcers. Baumgarten et al. (2006) reported incidents of pressure ulcers in the elderly during the first two days of their hospital stay and the characteristics that may increase the likelihood of pressure development. Belmin, Meaume, Rabus, and Bohbot (2002) and Hopkins, Dealey, Bale, Defloor, and Worboys (2006) examined the effects of applying negative pressure wound therapy to Stage IV pressure ulcers by using different types of wound dressings on the elderly. The latter also studied the experience of elderly individuals with pressure ulcers (Hopkins et al., 2006).

The previous literature shows that there are different contributing factors that influence the healing of pressure ulcers, such as mechanical force, nutrition and skin condition. Although there is numerous research work that investigates the performance of pressure ulcer preventive devices and treatments (Bou et al., 2009; Jaul, 2010; Masaki et al., 2013; Murray et al., 2001; Ostadabbas et al., 2011; Thomas, 2001), detailed clinical case studies of pressure ulcer healing in the elderly have not yet been implemented yet. The purpose of this study is to therefore address this knowledge gap. This study is important as it provides detailed information on real life situations; that is, the type of treatment adopted in nursing homes and the healing progression of heel pressure ulcers in the elderly population, by considering different intrinsic and extrinsic factors.

3.3.1 Case Study

Bedridden or wheelchair-bound elderly individuals are at higher risk of pressure ulcer development. Therefore, in this study, a clinical study is conducted to review the pathophysiology of pressure ulcers which will provide a better understanding of the development and healing process of pressure ulcers and add to the knowledge of the daily care needed for pressure ulcer wounds. An elderly home in Hong Kong took part in a 6-month clinical study that examined the wound healing progress of three elderly individuals with a pressure ulcer. The preventive and healing methods that were used for pressure ulcers and treatment were investigated.

3.3.2 Interviews with Caretakers

The registered nurses at the elderly home were invited to complete a questionnaire on the prevention and treatment of pressure ulcers and possible concerns, problems and opinions around existing wound dressings. After that, the registered nurses and the caretakers in the elderly home were individually interviewed on the daily care and strategies that were adopted for the prevention of pressure ulcers, treatment for patients who already have a pressure ulcer, and the elderly who are potentially at high risk for pressure ulcer development.

3.4 Heel Interface Pressure Measurements and Skin Condition Assessments

According to the literature, heel interface pressure is one of the easiest and most non-invasive methods to determine the risk of pressure ulcer development and also influences the wound healing progress. As well, the percentage of elderly who are at risk of pressure ulcer development is high but the healing process is slow. In the elderly population at the elderly home, mattresses greatly affect heel interface pressure. Therefore, to gain a better understanding of the influence of mattress type and foot posture on the heel interface pressure, it is important to determine the neutral foot position of the elderly, evaluate the differences in their interface heel pressure between standard hospital and pressure-relieving mattresses, and assess the heel interface pressure in various foot positions. Furthermore, the skin conditions, including sebum and moisture contents, and the elasticity of the skin, are key factors associated with the development of pressure ulcers. However, there is lack of information or studies on the skin conditions of the elderly and the effects on pressure ulcer development. Therefore, the skin conditions, including moisture and sebum contents, and elasticity are investigated in this study.

3.4.1 Subject Recruitment Criteria and Demographics

Fifty-one participants were recruited over a 6-month period of time from an elderly home in Hong Kong. The inclusion criteria included those who are aged 70 years old or older, do not have a pressure ulcer, and do not have any previous scars from pressure ulcer lesions. The individuals were not eligible if they have contractures or either one of their legs is missing as this may affect the heel pressure results due to the balance of the body weight. Also, those with a history of leg surgery were not eligible. Individuals with hemiplegia, diabetes, dyspnea, or excessive lymphedema or edema were excluded. Finally, those who require tube feeding were not eligible. All of the participants fully understood the measurement procedures, and consent was obtained from each individual prior to completing any part of the study. During the first visit, the eligibility of the participants was confirmed. Their demographic characteristics, including age, gender, height, and weight, were collected as shown in Table 3.1. Their medical history and current health situation were verified. In this study, 40 out of the 51 patients use a standard hospital mattress (a 30 indentation force deflection at 25% or 30 lbs per square inch to compress the mattress to 25% of its original height) while the rest use a pressure-relieving mattress (18 indentation force deflection at 25% or 18 lbs per square inch to compress the mattress to 25% of its original height) according to the assessment given by the professional nursing staff who used the Norton scale.

Table 3.1 Subject demographics

	Participants who use standard mattress	Participants who use pressure relieving mattress
Number of participants	Female: n=20	Female: n=5
	Male: n=20	Male: n=6
Total no. of participants	N=51	
Age (years old)	83.66±8.07	80.64±7.88
BMI (kg/m²)	22.16±3.49	22.42±5.02

3.4.2 Heel Interface Pressure Measurements

The participants were categorized into groups with one group designated as those who use a standard hospital mattress and the other group as those who use a foam pressure-relieving mattress. The participants were using either one of these two mattresses according to the assessment given by the caretakers who used the Norton scale. In the heel pressure measurement, each participant was lying on his or her back with arms positioned along the sides and head elevated at 30° on either the standard hospital or pressure-relieving mattress. The mattresses were covered with a thin cotton sheet. The interface pressure of their heels was measured by using the Economical Load and Force (ELF) system (Flexiforce) and Flexiforce® sensors as shown in Figure 3.2 placed between the exterior apex of the heel and the support surface. The error of the linearity of the B201-L sensor is less than ±3%, and its hysteresis is less than 4.5%. A measurement range of 4.4 N to 111 N is used in this study. The sensing area of the sensor is a circle that is 9.53 mm in diameter. The thickness is only 0.203 mm.

Figure 3.2 ELF with USB port (single head system) and FlexiForce B201 Sensor

According to previous researchers, the weight distribution of the heels varies with different resting angles to the support surface (Sopher et al., 2011). In this study, three different positions of the heels are evaluated, including a resting state, and angles of 60° and 90° to the support surface. Two acrylic stands were tailor-made in order to ensure that the heel was supported at 60° and 90° to the mattress as shown in Figure 3.3.

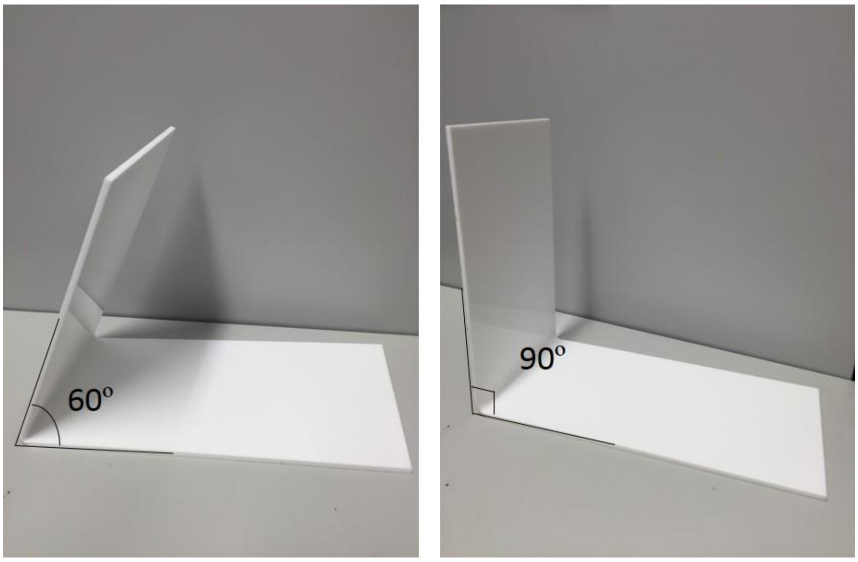


Figure 3.3 Tailor-made acrylic stand to measure heel positioned at 60 and 90 degrees to support surface

Two sets of measurements were taken for each subject. One set of measurements was taken when their heel was directly placed onto the support surface in a relaxed state, and then supported at angles of 60° and 90°, in which the heel in the relaxed state was measured as shown in Figure 3.4. With the participants remaining on the support surface, another set of measurements was carried out with an acrylic stand placed between the heel and the support surface but without giving any support as shown in Figure 3.5. The measurements were recorded at 75 s after loading as the first 30 s were used to stabilize the system to allow better repeatability (Shelton et al., 1998). The exterior apex of the heel was measured, and Figure 3.6 shows the measured points on the heel at 60° and 90°, respectively. Each experiment was repeated three times in succession and the mean of the readings was calculated.

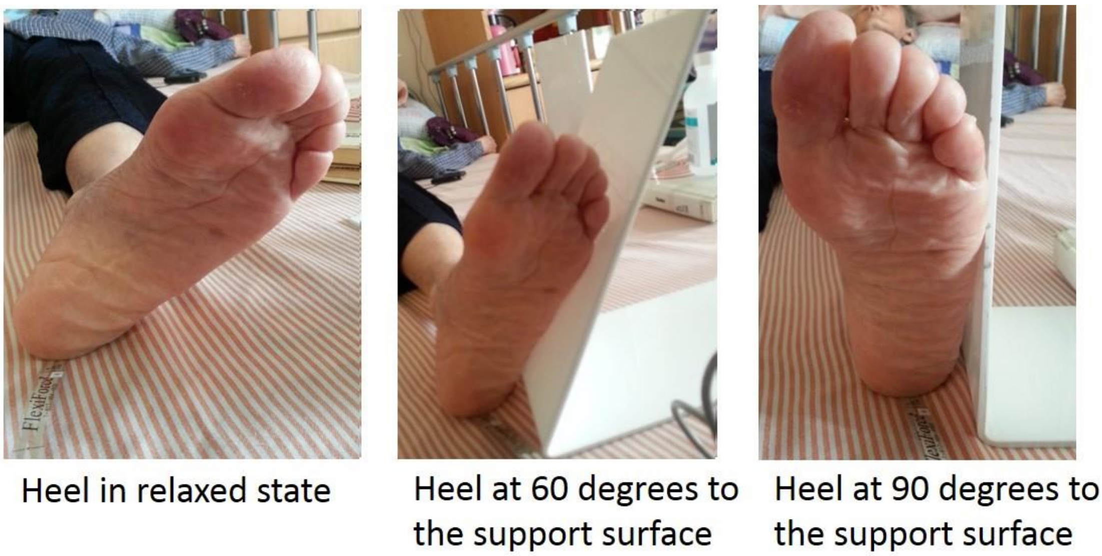


Figure 3.4 Heel in relaxed state and at 60 and 90 degrees to the support surface

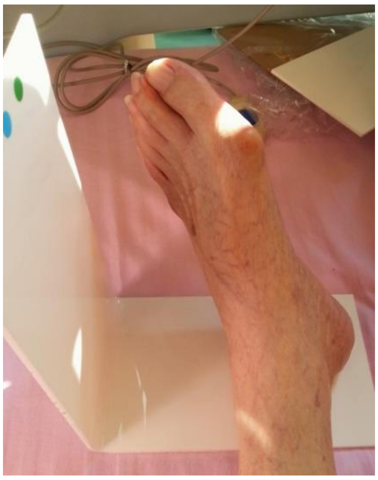


Figure 3.5 Heel in relaxed state with acrylic stand placed between heel and support surface

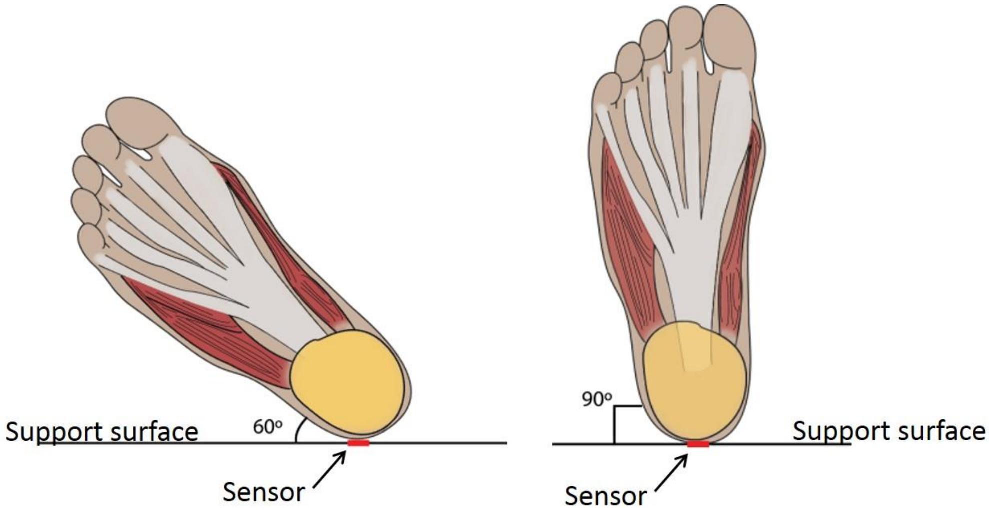


Figure 3.6 Measured points on heel at 60 and 90 degrees to the support surface

3.4.3 Skin Condition Assessments

In the study, the Multi Skin Test Center MC 900 was used for the objective assessment of the heel skin properties. Three probes, including those that measure the moisture, elasticity and sebum content, were used to examine the moisture level, sebum content and elasticity of the heel as shown in Figure 3.7. To ensure reliability, each measurement was repeated 4 times on different positions of the heel and the average was automatically calculated by the system.

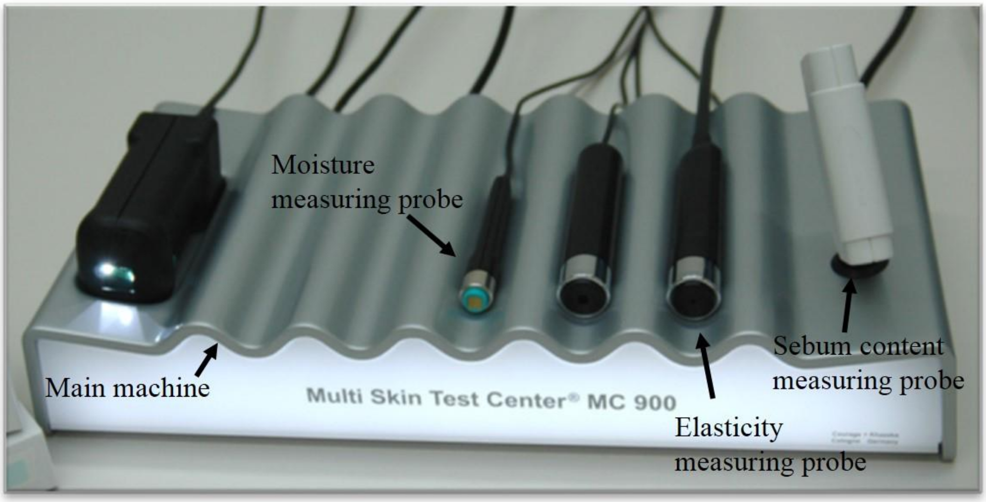


Figure 3.7 Multi Skin Test Center MC 900 machine with three probes for measuring skin conditions

3.4.4 Statistical Analysis

Descriptive statistics were obtained for heel pressures in different heel positions of each subject for both groups of elderly participants, in which either a standard hospital or a pressure-relieving mattress was used. One-way ANOVA was conducted by using SPSS to examine the effects of foot position and mattress and assess whether pressure exerted onto the heel is affected by any of these factors. A p-value < 0.05 was considered statistically significant.

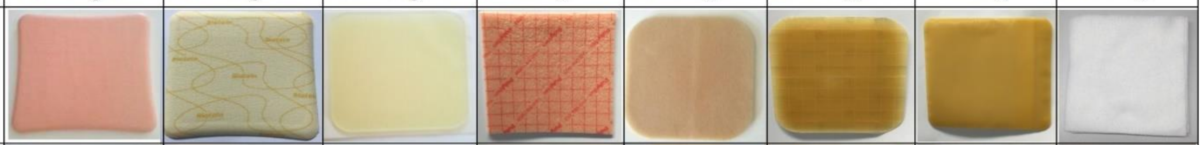
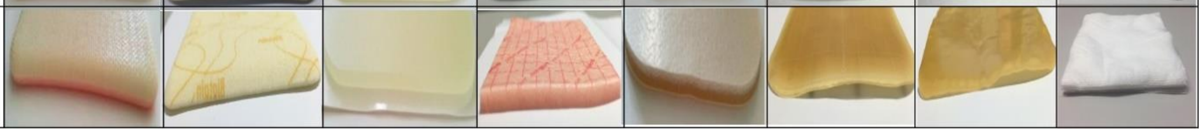
3.5 Evaluation of Spacer Fabrics as Cushioning and Absorbent Layer for Pressure Ulcer Wound Dressing

There are different wound dressings designed for pressure ulcer wounds in the commercial market. Investigating the physical properties of existing wound dressings can provide a thorough understanding of the criteria for wound dressings especially those for pressure ulcer wounds. Therefore, an experimental study on the required physical properties of wound dressings is carried out in this research work. After that, warp and weft knitted spacer fabrics are evaluated with the same experiments and the results are compared with the existing wound dressings to determine whether it is possible to use knitted spacer fabric as the absorbent layer for advanced wound dressings.

3.5.1 Material Selection

Seven different types of wound dressings, which were purchased from local shops, have a cushioning effect, and are especially relevant for the management of extruding wounds, such as burns, ulcers and surgical wounds, and one simple non-woven swab which is commonly used in general wound care were selected for comparison. Table 3.2 shows the different views of the eight types of wound dressings.

Table 3.2 Front, back and side views of different wound dressings

	Dressing 1	Dressing 2	Dressing 3	Dressing 4	Dressing 5	Dressing 6	Dressing 7	Dressing 8
Front view								
Back view								
Side view								

Seven different types of warp knitted spacer fabrics and fifteen different types of weft knitted spacer fabrics which were purchased from local shops are used as the samples in this study. Samples 1 to 4 of the warp knitted spacer fabrics have the same structure (Warp_a) while Samples 5 to 7 of the warp knitted spacer fabrics have a different structure (Warp_b). Furthermore, Samples 1 to 11 of the weft knitted spacer fabrics have the same structure (Weft_a) while Samples 12 to 15 of the weft knitted spacer fabrics have a different structure (Weft_b). Therefore, the letters a and b are used to identify the two different types of structures among the spacer fabrics. Their fabric characteristics, including fabric structure, yarn angle, and areal and bulk densities were determined. Tables 3.3 and 3.4 show the microscopic views of the spacer fabrics. Tables 3.5 and 3.6 provide the chain notations of the warp knitted spacer fabrics while Figures 3.8 and 3.9 are the technical diagrams of the weft knitted spacer fabrics. All of their specifications are listed in Table 3.7.

Table 3.3 Microscopic front, back and side views of warp knitted spacer fabrics

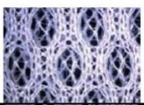
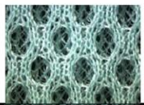
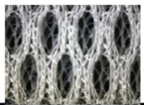
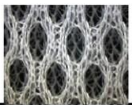
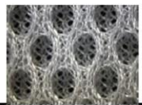
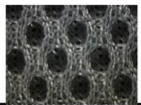
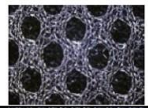
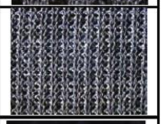
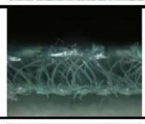
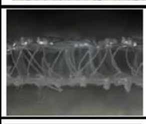
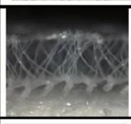
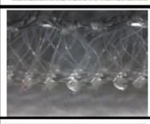
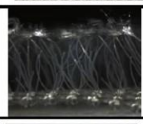
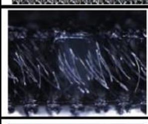
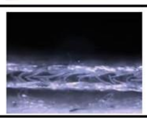
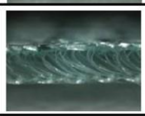
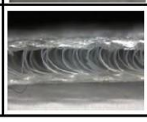
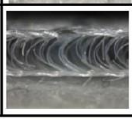
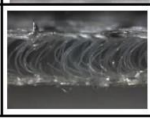
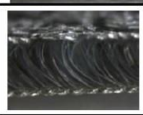
	Warp_a_1	Warp_a_2	Warp_a_3	Warp_a_4	Warp_b_5	Warp_b_6	Warp_b_7
Front view							
Back view							
Side View (coursewise)							
Side View (walewise)							

Table 3.4 Microscopic front, back and side views of weft knitted spacer fabrics

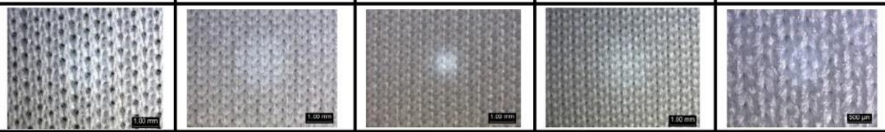
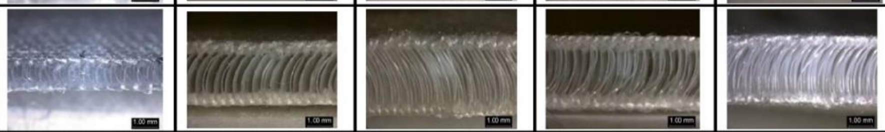
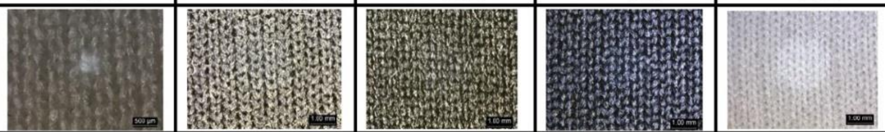
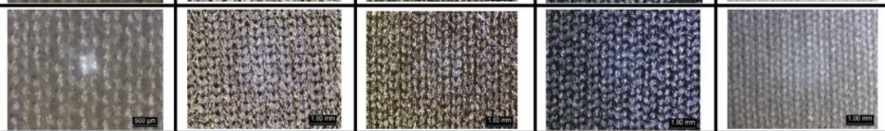
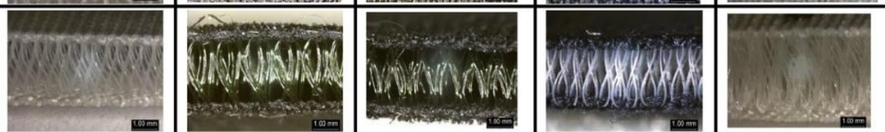
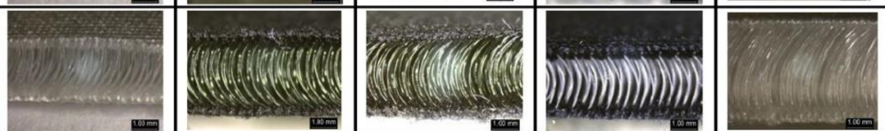
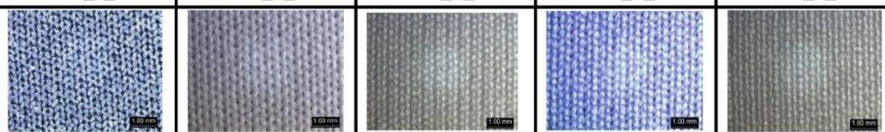
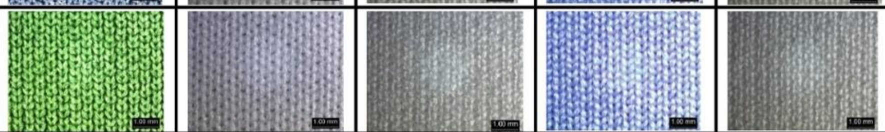
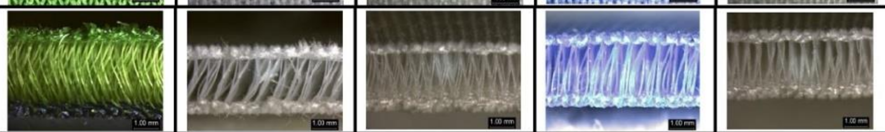
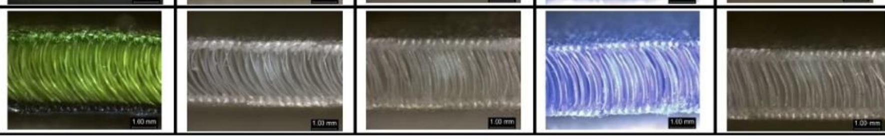
	Weft_a_1	Weft_a_2	Weft_a_3	Weft_a_4	Weft_a_5
Front view					
Back view					
Side View (coursewise)					
Side View (walewise)					
	Weft_a_6	Weft_a_7	Weft_a_8	Weft_a_9	Weft_a_10
Front view					
Back view					
Side View (coursewise)					
Side View (walewise)					
	Weft_a_11	Weft_b_12	Weft_b_13	Weft_b_14	Weft_b_15
Front view					
Back view					
Side View (coursewise)					
Side View (walewise)					

Table 3.5 Chain notations of yarn guide bars for Warp_a_1 to Warp_a_4

Guide bar	Chain notations	Threading
1	(1-0, 0-0/ 1-2, 2-2)x2/ (3-4, 4-4/ 3-2, 2-2)x2//	3 full 1 empty
2	(3-4, 4-4/ 3-2, 2-2)x2/ (1-0, 0-0/ 1-2, 2-2)x2//	3 full 1 empty
3	(1-0, 2-1/ 2-3, 1-2)x4//	full
4	(0-0, 1-2/ 2-2, 1-0)x4//	full

Table 3.6 Chain notations of yarn guide bars for Warp_b_5 to Warp_b_7

Guide bar	Chain notations	Threading
1	(1-0, 0-0/ 1-2, 2-2)x2/ (3-4, 4-4/ 3-2, 2-2)x2//	3 full 1 empty
2	(3-4, 4-4/ 3-2, 2-2)x2/ (1-0, 0-0/ 1-2, 2-2)x2//	3 full 1 empty
3	(1-0, 1-0/ 1-2, 1-2)x4//	full
4	(0-0, 1-2/ 2-2, 1-0)x4//	full
5	(2-2, 1-0/ 0-0, 1-2)x4//	full

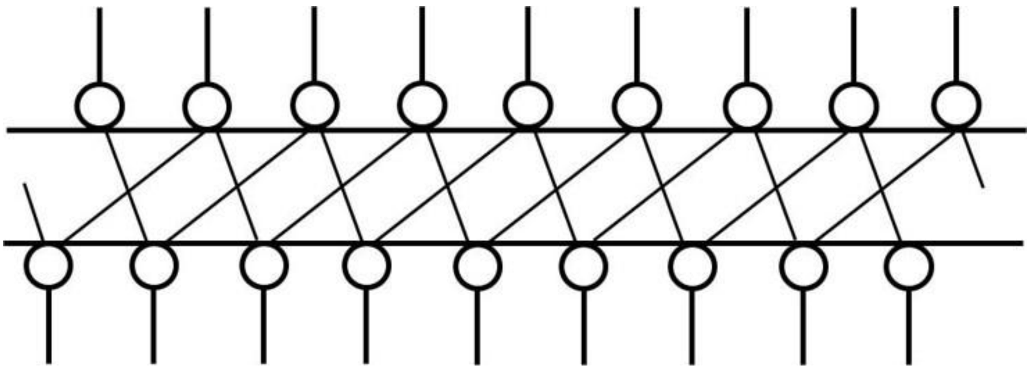


Figure 3.8 Technical diagram of Weft_a_1 to Weft_a_11

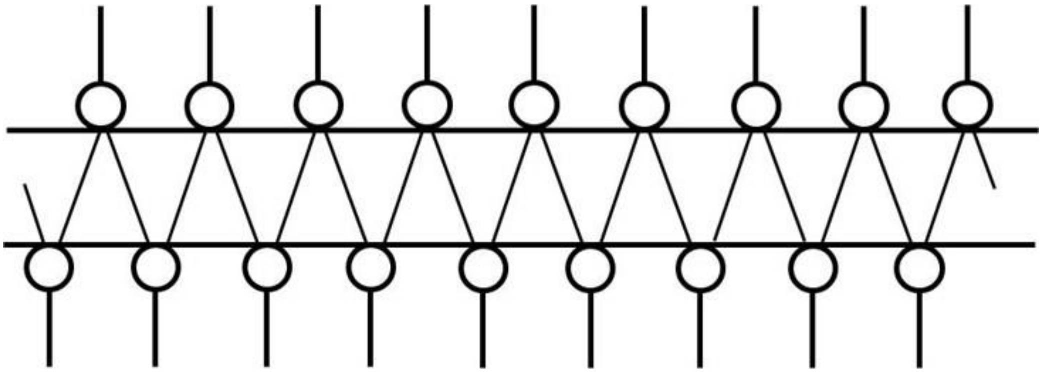


Figure 3.9 Technical diagram of Weft_b_12 to Weft_b_15

Table 3.7 Physical properties of spacer fabrics and wound dressings (including standard deviation)

	Fabric type	Structure	Composition	Thickness (mm)	Spacer yarn type	Areal mass (kg/m^2)	Bulk density (kg/m^3)	Angle of spacer yarn (θ)	
								Course	Wale
Warp_a_1	Warp-knitted	Warp_a	100% Polyester	1. 03±1.49	Monofilament	0.1353±2.16	131.29±2.10	20.15°	19.02°
Warp_a_2	Warp-knitted	Warp_a	100% Polyester	1.76±0.05	Monofilament	0.1729±1.70	98.09±0.96	44.88°	32.06°
Warp_a_3	Warp-knitted	Warp_a	100% Polyester	2.19±0.34	Monofilament	0.1464±1.83	66.77±0.83	51.23°	14.23°
Warp_a_4	Warp-knitted	Warp_a	100% Polyester	2.29±0.11	Monofilament	0.1385±2.52	47.65±0.85	29.11°	26.63°
Warp_b_5	Warp-knitted	Warp_b	100% Polyester	2.48±0.16	Monofilament	0.1990±1.90	80.30±0.77	54.89°	34.25°
Warp_b_6	Warp-knitted	Warp_b	100% Polyester	2.90±0.10	Monofilament	0.2413±1.53	83.28±0.54	50.59°	27.71°
Warp_b_7	Warp-knitted	Warp_b	100% Polyester	3.33±0.08	Monofilament	0.2422±2.01	72.76±0.60	43.23°	40.21°
Weft_a_1	Weft-knitted	Weft_a	100% Polyester	1.23±0.02	Monofilament	0.1795±2.24	146.46±1.83	60.47°	57.37°
Weft_a_2	Weft-knitted	Weft_a	94% Polyester 6% Elastane	2.68±0.04	Monofilament	0.3573±3.55	133.31±1.32	64.27°	52.51°
Weft_a_3	Weft-knitted	Weft_a	93% Polyester 7% Elastane	2.99±0.06	Monofilament	0.4188±5.61	140.06±1.87	75.17°	75.41°
Weft_a_4	Weft-knitted	Weft_a	93% Polyester 7% Elastane	2.62±0.13	Monofilament	0.4204±12.96	159.09±4.91	79.65°	76.96°
Weft_a_5	Weft-knitted	Weft_a	92% Polyester 8% Elastane	2.98±0.05	Monofilament	0.3681±11.07	123.36±3.71	67.31°	74.56°
Weft_a_6	Weft-knitted	Weft_a	91% Polyester 9% Elastane	2.75±0.11	Monofilament	0.4412±10.37	160.73±3.91	62.16°	57.20°
Weft_a_7	Weft-knitted	Weft_a	90% Polyester 10% Elastane	3.36±0.12	Monofilament	0.4604±11.52	137.04±3.43	52.15°	40.94°
Weft_a_8	Weft-knitted	Weft_a	89% Polyester 11% Elastane	3.30±0.12	Monofilament	0.4237±12.38	128.26±3.75	78.19°	68.32°
Weft_a_9	Weft-knitted	Weft_a	89% Polyester 11% Elastane	2.98±0.04	Monofilament	0.4102±4.28	137.65±1.44	69.46°	70.690°
Weft_a_10	Weft-knitted	Weft_a	88% Polyester 12% Elastane	4.29±0.16	Monofilament	0.5535±16.34	128.88±3.80	68.25°	71.52°
Weft_a_11	Weft-knitted	Weft_a	86% Polyester 14% Elastane	3.28±0.05	Monofilament	0.4843±5.23	147.88±1.60	67.49°	46.70°
Weft_b_12	Weft-knitted	Weft_b	93% Polyester 7% Elastane	2.60±0.06	Monofilament	0.3364±6.00	129.24±2.31	55.52°	39.63°
Weft_b_13	Weft-knitted	Weft_b	93% Polyester 7% Elastane	2.90±0.09	Monofilament	0.4370±9.16	150.70±3.16	71.84°	80.19°
Weft_b_14	Weft-knitted	Weft_b	89% Polyester 11% Elastane	2.88±0.04	Monofilament	0.4194±3.77	145.48±1.31	81.13°	76.59°
Weft_b_15	Weft-knitted	Weft_b	87% Polyester 13% Elastane	2.93±0.06	Monofilament	0.5392±6.22	184.35±2.13	77.23°	78.63°
Dressing 1	-	-	Hydrocellular polyurethane foam	6.04±0.06	-	0.7211±10.30	119.32±1.84	-	-
Dressing 2	-	-	Polyurethane foam	4.52±0.06		0.7145±9.75	157.94±2.15	-	-
Dressing 3	-	-	hydro-active polyurethane matrix	1.56±0.03	-	1.8260±17.18	1173.49±11.04	-	-
Dressing 4	-	-	Hydrophilic polyurethane matrix	4.46±0.02	-	0.9461±7.12	212.23±1.60	-	-
Dressing 5	-	-	Hydrocolloid	2.34±0.19	-	1.4348±15.73	614.21±6.73	-	-
Dressing 6	-	-	Hydrocolloid	1.38±0.02	-	1.0480±4.64	1087.14±4.82	-	-
Dressing 7	-	-	Hydrocolloid	0.96±0.03	-	1.3201±20.26	957.09±14.68	-	-
Dressing 8	-	-	Non-woven	6.36±0.11	-	0.5892±12.06	92.72±1.99	-	-

Different experiments were carried out to investigate the physical properties of the wound dressings and knitted spacer fabrics, including testing the compression, absorbency, wettability, water vapor and air permeability, and thermal conductivity. In addition, the elasticity of the wound dressings was examined. All of the tests were conducted in accordance with ASTM D1776, at a temperature of 20ºC and relative humidity of 65%.

3.5.2 Compression Test

In considering that spacer fabrics are expected to provide a cushioning effect as wound dressings for burns, ulcers and surgical wounds, the compressional behaviour of wound dressings is important. The INSTRON 4411 machine was used to test the compression behaviour of the test samples in accordance with ASTM D 575 Standard Test Methods for Rubber Properties in Compression. The machine was set up with two compression platens in which the top platen is a 2 cm x 2 cm square plate while the bottom platen is a circular plate with a diameter of 150 mm. All of the samples were 100 mm x 100 mm in dimension. The smaller top platen with a larger sized sample was used to simulate the loading applied by heel onto the wound dressing or spacer fabric in real life. The sample was placed onto the fixed platen and the compression test was conducted at a speed of 1.2 mm/min up to a deformation of 80% of the initial thickness of each sample. In each case, 5 samples were tested and their experimental results were averaged to plot the compression stress-strain curve.

3.5.3 Absorbency Test

Absorbency is important in pressure ulcer wound dressings as pressure ulcer wounds will produce different amounts of exudate in their different stages. Therefore, the ability to absorb wound fluid is particularly important for wounds with different amounts of exudates. Furthermore, the number of times that a wound dressing needs to be changed depends on its absorbency, as all exudates produced by the wound should be entirely absorbed by the dressing. So, better absorbency can reduce the number of times that a dressing needs to be changed. BS 7959-1:2004 (Materials used for the control of liquid spillages - Determination of sorbency) was adopted to measure the absorbency of the samples. Distilled water and 0.9% saline water were used as the testing liquids and their temperature was controlled at 20 ± 2°C in accordance with BS 7959-1:2004. In each case, 5 samples were measured and the average value was recorded.

By weighing the samples before and after testing, their sorbency after 30 s of draining was calculated by using the following equations.

$$\boldsymbol{S_{30}}(\mathrm{L}/\mathrm{kg}) = \frac{\boldsymbol{V_{30}}}{\boldsymbol{W_{30}}} \;\ldots\ldots\; \text{Equation 3.1}$$

where $\boldsymbol{S_{30}}$= sorbency after 30 s of draining (L/ kg), $\boldsymbol{W_{30}}$= mass of the sample (kg), and $\boldsymbol{V_{30}}$= volume of liquid (L) held by the sample after 30 s of draining.

$$\boldsymbol{V_{30}} = \frac{\boldsymbol{W_{30}}}{\boldsymbol{\rho}} \;\ldots\ldots\; \text{Equation 3.2}$$

where W_{30}= mass of liquid held by the sample after 30 s of draining (kg).

$$\boldsymbol{W_{30}} = \boldsymbol{W_{A2}} - \boldsymbol{W_{A1}} - \boldsymbol{W_{P}} \;\ldots\ldots\; \text{Equation 3.3}$$

where $\boldsymbol{W_{A1}}$= mass of the receptacle + “S” hook (kg), $\boldsymbol{W_{A2}}$= mass of the receptacle + “S” hook+ test sample+ liquid retained after 30 s of draining (kg), and $\boldsymbol{\rho}$= density of the test liquid (kg/L).

3.5.4 Wettability Test

Wettability is one of the critical requirements of wound dressings as it concerns their ability to absorb wound fluid. Wettability depends on the surface energy. If the surface of a dressing has a small surface tension, the adherence of a fluid onto the surface of the dressing would be higher and wound fluids can thus be absorbed easily. The wettability of the samples in this study is examined by using a contact angle goniometer as shown in Figure 3.10. Accurate measurements of the static and dynamic contact angles of liquids on a solid substrate can be obtained by using this apparatus. The goniometer has a light source, image capture, sample stage and lens. The angle formed between the solid substrate and the tangent to the drop surface is measured in order to determine the contact angle.

The sample was placed onto the sample holder and held with clips. After that, a 5 μL droplet was suspended at the end of a syringe needle which prevented the droplet from dripping onto the surface of the sample itself. The surface with the mounted sample was moved upward so that it came into contact with the pendant drop. After that, the surface with the mounted sample was lowered and the droplet transfer was completed as shown in Figure 3.11. A back light drop which is the silhouette was enlarged on a glass screen and each of the two points of contact of the drop was examined by adjusting the goniometer eye piece and the internal measuring mechanism. In each case, 5 samples were measured and the average value was recorded.

Figure 3.10 Contact angle goniometer

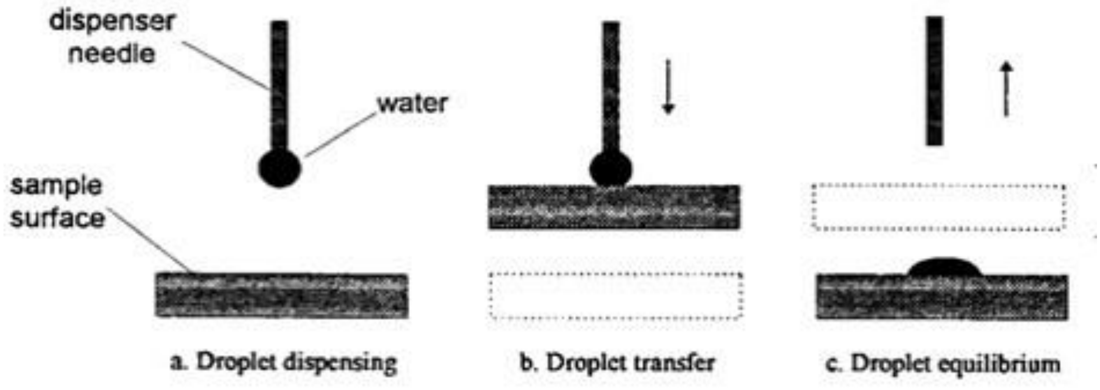


Figure 3.11 Technique for water droplet transfer

3.5.5 Water Vapor Permeability Test

The water vapor permeability (WVP) or moisture transmission is important for wound dressings. In considering that exudates or sweat will be produced in many types of wounds, it is vital that the wound dressing can transfer exudate or sweat away from the surrounding skin in order to maintain ventilation. The WVP is defined as the transmission of moisture or vapour from the skin to the surrounding areas. The WVP was measured by using the cup method in accordance with BS 7209. In each case, 10 samples were measured and the average value was recorded before and after 24 hours. The weight of the samples before and after the experiment was measured, and the WVP was calculated by using the following equations.

$$\boldsymbol{WVP}(\mathrm{g \cdot m^{-2} \cdot hr^{-1}}) = \frac{\boldsymbol{M}}{\boldsymbol{At}} \text{ ...... Equation 3.4}$$

$$A = \pi r^2 \text{ ...... Equation 3.5}$$

where ***WVP***= water vapor permeability $(\mathrm{g \cdot m^{-2} \cdot hr^{-1}})$, ***M***= loss in mass (g), ***t***= time between weighing (hr), ***A***= internal area of the cup (m^2) and ***r***= internal radius of the cup (mm).

3.5.6 Air Permeability Test

Air permeability is another important basic criterion that demonstrates whether a wound dressing has good breathability through the air exchange of a material. The KES-F8 of the Kawabata Evaluation System (KES) was adopted for measuring the air permeability of the wound dressings and 3D spacer fabrics and the KES-F8-AP1 air permeability tester was used to evaluate the resistance of the samples to the passage of air which is related to comfort. The speed of the piston was 2 cm/s and the air flow rate was 8 π cm^3/s. Taking into consideration that the structure of the spacer fabrics and wound dressings is different, different hole sizes were selected. As spacer fabrics have many pores on their surface, the smallest hole of 0.2 π cm^2 was selected for more precise measurements, and the air flow rate per unit area was 0.4 π m/s. On the other hand, as the structure of the dressings is denser, all 3 hole sizes, 0.2, 2 and 20 π, with an air flow per unit area of 0.4, 4 and 40 π m/s, were used. For each sample, 10 readings were taken, and the average value of the air resistance (***R***) was measured as kPa · s/m.

3.5.7 Thermal Conductivity Test

Apart from air permeability, thermal conductivity is also one of the critical properties of a good wound dressing as it helps to promote good thermal regulation of the wound environment and prevent the accumulation of heat building up from underneath. The KES-F7 was adopted to measure the ability of the fabric to conduct heat (thermal properties), and a KES-F Thermo Labo II was used. During the experiment, the sample was placed into a T-box to detect heat and heat retention, and the temperature of the BT-Box, which is the heat plate and water box, was preset to 30℃ and 20℃ respectively. Ten samples were measured for each case and the average value was recorded. By measuring the amount of heat that passes through the sample from the power consumption of the test plate heater, the thermal conductivity value (k) recorded as a unit of *W/mK*, can be calculated by using the following equation:

$$\text{Thermal conductivity } (k) = \frac{\text{Heat flow rate x distance}}{\text{area x temperature difference}} \text{ ...... Equation 3.6}$$

$$\boldsymbol{k} = \frac{\boldsymbol{WD}}{\boldsymbol{Ax\Delta T}} \times \ 100 \text{ ...... Equation 3.7}$$

where $\boldsymbol{W}$= the quantity of heat (watt), $\boldsymbol{D}$ = thickness of the sample (cm), $\boldsymbol{A}$= surface area of the sample (cm^2) and $\boldsymbol{\Delta T}$ = temperature difference between the BT Box and the water box.

3.5.8 Extensibility Test

According to the literature, the conformity of wound dressings is important as it will affect the effectiveness of the wound dressings and the optimum wound healing environment. In addition, wrinkling or fluting may injure the fragile wound bed. In this study, the conformability of the wound dressings is evaluated by its extensibility in accordance with EN 13726-4:2003. The INSTRON 4411 machine was used to test the compression behaviour of the samples. All of the samples were cut into dimensions of 50 mm x 75 mm with a testing area of 50 mm x 50 mm. Two parallel marks, spaced 50 mm apart, were made on each sample. Then, the sample was clamped by the two jaws on the INSTRON 4411 machine outside the markers. The extensibility test was conducted at a speed of 300 mm/min up to an extension of 80% of the initial length of each sample. In each case, 5 samples were tested and their experimental results were averaged to plot the extension stress-strain curve.

3.6 Formulation of Pressure Simulation Model with Finite Element Analysis

3.6.1 Introduction

In this section, a finite element analysis (FEA), which is a computational simulation method, will be used to simulate the interface pressure between spacer and heel and deformation of the spacer fabric under loading. A 3D biomechanical model was developed with a finite element model (FEM). By changing the corresponding material properties of the 3D knitted spacer fabrics, the pressure distribution of different samples of 3D knitted spacer fabrics under heel loading can be predicted.

3.6.2 Finite Element Model Building

A commercial FEA software, ABAQUS/CAE 6.14-4 (Dassault Systémes SA, Frances), was used to carry out the simulation. The interface pressure simulation model mainly consisted of two items; the heel and spacer fabrics, with six steps carried out: 1) geometrical models of the heel and the spacer fabrics were created, 2) the appropriate element type and material properties were then defined, 3) both the models of the heel and spacer fabric were meshed, 4) the initial and boundary conditions were defined, 5) numerical processing of the applied loading on the spacer fabric by the heel was carried out by setting the loading conditions of the heel to the spacer fabric in order to obtain the numerical solution, and 6) the results were post processed and validated.

3.6.2.1 Geometrical Shape of Heel and Spacer Fabrics

3.6.2.1.1 Construction of Heel Contour Model

Three-dimensional geometric models of the heel and spacer fabrics were developed to predict the pressure distribution on the 3D knitted spacer fabrics. A 3D laser scanner was used to obtain the 3D images of the body parts to form the geometric models. The laser scanner is suitable for simulations that require the contour of the body parts but not the cross sections. In this study, the Artec Eva 3D scanner (Artec-Group, Luxembourg) is used to obtain the geometric model of the heel as shown in Figure 3.12. This 3D handheld scanner, which uses structured light scanning, is light, fast and versatile, and weighs only 1.9 lbs. The principle behind the Artec EVA 3D scanner is to project structured light onto the face of objects and capture a multitude of frames. After scanning, the frames are automatically combined into a single 3D mesh in the 3D reconstruction phase (Ciobanu, Xu, & Ciobanu, 2013). With the use of this scanner and

Artec Studio 10 Professional software, precise measurements of the entire foot including the plantar surface can be obtained in high resolution which is up to 0.5 mm and the 3D point accuracy is up to 0.1 mm. Its 3D accuracy over distance is up to 0.03% over 100 cm (Artec Europe, 2017).

Figure 3.12 Artec EVA 3D scanner used to capture images of foot
Source: https://gomeasure3d.com/artec/eva/

In this study, the left foot of a healthy 27 year old Chinese female with a height of 155 cm and weight of 45 kg, is used to develop the heel model. Figure 3.13 shows the original scanned foot image with and without software post processing. After that, the result was imported into another software, SolidWorks 2012 (Dassault Systèmes SOLIDWORKS Corp, USA). By using SolidWorks, the irrelevant parts of the foot image were removed to reduce the image size and convert the heel components into a solid model that meets the requirements of the FEA.

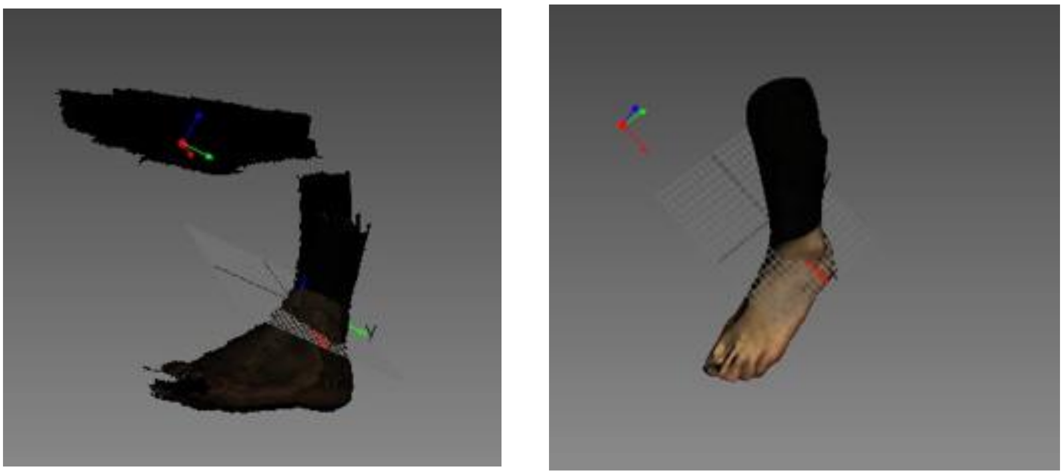


Figure 3.13 Scanned foot (Left: original scanned results; Right: after software post processing)

3.6.2.1.2 Development of Spacer Fabric Model

Based on the physical experiments discussed in Section 3.5, the spacer fabric, Weft_a_8 with a better overall performance, especially compression resistance when compared to others was selected for simulation. The microscopic views of the selected fabrics provided details on the spacer fabric, such as the fabric thickness, yarn angle, fineness of the spacer yarn and spacing between the spacer yarns. The spacer fabric model was developed with the use of SolidWorks with reference to these parameters.

3.6.2.2 Defining Material Properties

In this study, the simulation model comprises two material models of the spacer fabric and heel. In Section 3.5.2, the use of a compression tester (Instron Model 4411, USA) to determine the compression of the spacer fabrics was discussed. The compression behavior of the spacer fabrics was measured in accordance with ASTM D 575 Standard Test Methods for Rubber Properties in Compression. The spacer fabrics were compressed up to 80% of their original thickness. The Young's modulus, which is the material stiffness, is presented as the ratio of the compression stress to the compression strain. The Young's modulus of the spacer fabrics was determined from the stress-strain curve with Equation 3.8.

$$\boldsymbol{E} = \frac{\sigma}{\varepsilon} = \frac{s(1+e)}{ln(1+e)} = \frac{s(1+(\frac{L_i-L_f}{L_i})}{ln(\frac{L_i-L_f}{L_i})} \text{ ...... Equation 3.8}$$

where $\boldsymbol{E}$ = Young's modulus (MPA), $\boldsymbol{\sigma}$ = true stress (N/mm$^{2)}$, $\boldsymbol{\varepsilon}$ = true strain, $\boldsymbol{s}$ = engineering stress, $\boldsymbol{e}$ = engineering strain, $\boldsymbol{L_i}$ = initial thickness (mm), and $\boldsymbol{L_f}$ = final compressed thickness (mm).

The nonlinear elasticity of the spacer fabrics was also determined from the stress-strain curve by using Equation 3.9.

$$\varepsilon_{pl} = \varepsilon - \frac{\sigma}{E} \text{ ...... Equation 3.9}$$

where $\boldsymbol{\varepsilon_{pl}}$ = plastic strain, $\boldsymbol{\varepsilon}$ = true strain, and $\boldsymbol{E}$ = Young's modulus (MPA).

A heel model with human bone and skin properties is developed in this study. As skin and dermis elasticity are different from person to person, the properties of the heel were determined by referring to the heel properties provided in previous research work (See (Goske et al., 2006; Sopher et al., 2011)).

3.6.2.3 Defining Mesh Element Type

There is a trade-off between mesh density, results accuracy and required computational resources with the use of the FEA (Dassault Systèmes, 2009; G. R. Liu & Quek, 2013). The FEMs with a finer mesh provide a highly accurate result, however, more computational resources are needed as the models will be more complex. On the other hand, if a coarser mesh is used, the results may be less accurate but less computational resources are required and a more simplified model will be created. Therefore, it is important to reach a compromise between the desired quality and the computational time by choosing an appropriate element size.

Triangular and quadrilateral elements are commonly used for two dimensional planes, while tetrahedron and hexahedron elements are widely used for 3D shapes. Triangular and tetrahedron elements are more commonly used due to their flexibility in complex geometries (Dassault Systèmes, 2009; G. R. Liu & Quek, 2013).

3.6.2.4 Defining Boundary Conditions

Boundary conditions play a decisive role in simulation. They consider the degree of freedom of the elements during simulation and have significant influence on the simulation results. The boundary conditions can be the geometrical identities, including points, lines and surfaces, or the mesh identities, including nodes, elements and element surfaces. In this study, the boundary or displacement conditions are set by adding the constrains of the heel model and spacer fabric model.

3.6.2.5 Process of Heel Applying Load onto Spacer Fabrics in Simulation Model

Apart from the boundary conditions, the initial and loading conditions are also important for simulation. Two models will be created, one is the spacer fabric model in a micro view while another one is a heel-spacer fabric model for a macro view. The purpose of creating the micro view spacer fabric model is to simulate the behaviour of spacer yarns under loading. The pressure is applied evenly onto the top layer of spacer in order to simulate the real life situations. There are two main objectives for creating this heel-spacer fabric model, which are to 1) simulate the heel-spacer fabric interface pressure and 2) investigate the compression behaviour of spacer fabrics under loading. In real life situations, loading is applied by the heel onto the spacer fabric. To simulate this loading, pressure was applied onto the axial plane of the heel in the modelling. Furthermore, surface-to-surface contact was applied to simulate the inter-surface interaction between the heel and spacer fabric.

3.6.2.6 Validation

To validate the prediction ability of the model, wear trial with real subject were carried out. The same subject for foot scanning was invited for the interface pressure measurement. The left foot of a healthy 27 year old Chinese female with a height of 155 cm and weight of 45 kg was evaluated. A 3 cm x 3cm pressure sensor (Novel Pliance X system, Germany) was used to measure the heel interface pressure exerted on the spacer fabrics. The spacer fabric was placed under the heel of the subject when the subject was lying down on a hard surface. The pressure sensor was placed between the exterior apex of the heel and the spacer fabric as shown in Figure 3.14. The measurements were recorded at 75 s after loading as the first 30 s were used to stabilize the system to allow better repeatability. Each experiment was repeated three times in succession and the mean of the readings was calculated. The measured results obtained from wear trial were compared with the predicted results of the FEM.

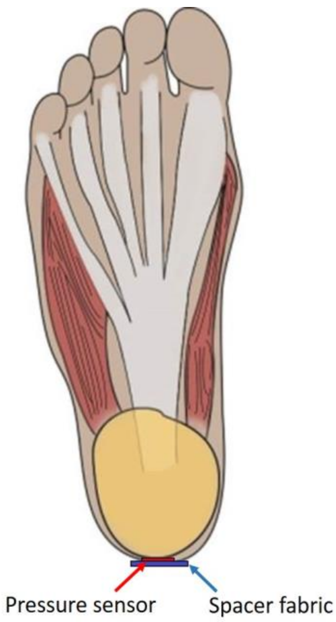


Figure 3-14 Interface pressure measurement between heel and spacer fabric

3.7 Development and Evaluation of Wound Dressing Composites

The objective of this research work is to design and develop a new wound dressing composite for pressure ulcer wounds based on clinical and patient evaluations with spacer fabric used as the absorbent layer. To provide an optimum healing micro environment for pressure ulcer wounds, the use of 3D spacer fabric as the absorbent layer of wound dressings is recommended. According to the literature, modern wound dressings normally consist of three layers including the wound contacting, absorbent and barrier surface layers. The wound contacting layer does not adhere to the wound while the absorbent layer in between the wound contacting and barrier surface layer is used to absorb exudate and blood. The outermost layer, which is the barrier surface layer, protects the wound against microorganisms. The structural design can reduce the time for the wound healing process of pressure ulcer patients so as to minimize the health effects of pressure ulcer treatments on patients and their family.

The new wound dressing composite is designed and developed based on the results collected from a clinical study along with evaluated material properties and biomechanical pressure. Apart from the material property tests, microbiological testing is necessary as the wound dressing composite is meant for medical applications. Microbiological testing is used to determine the barrier properties of the wound dressing composite against bacteria by evaluating the level of antibacterial activity of the finishing on the textile material.

3.7.1 Material Selection

Based on the evaluation of the material properties of the different 3D knitted spacer fabric samples, Weft_a_8 was chosen as the absorbent layer of the wound dressing composite as it has the best performance in the compression, absorbency, wettability, water vapor and air permeability, thermal conductivity and elasticity tests. For the barrier surface and wound contact layers, three samples were chosen for each layer, which are Type 1, Type 2 and Type 3 for the barrier surface layers and Type A, Type B and Type C for the wound contact layers respectively as shown in Table 3.8. Table 3.9 shows the outside, inside and side view of the nine different combinations of three layer wound dressing composites while Table 3.10 provides their physical properties.

Table 3.8 Outside, inside and side view of three adhesive and three barrier surface layers

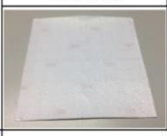
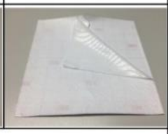
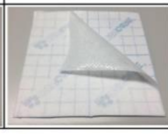
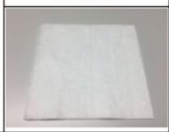
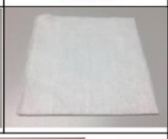
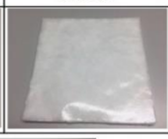
Barrier surface layer	**Type 1**		**Type 2**		**Type 3**	
Composition	Non-woven		Polyurethane film		Non-woven	
Outside and inside view	Outside	Inside	Outside	Inside	Outside	Inside
						
Wound contact layer	**Type A**		**Type B**		**Type C**	
Composition	70% viscose and 30% polyester		① Low adherent perforated polyester film ② Cotton/acrylic fiber pad ③ Hydrophobic outer layer		8-ply 100% cotton	
Outside and inside view	Outside	Inside	Outside	Inside	Outside	Inside
						
Side view						

Table 3.9 Nine different combinations of three layer wound dressing composites

Wound dressing composite	Combination	Outside	Inside	Side view
1A	• Barrier surface layer: Type 1 • Absorbent layer: Weft_a_8 • Wound contact layer: Type A			
1B	• Barrier surface layer: Type 1 • Absorbent layer: Weft_a_8 • Wound contact layer: Type B			
1C	• Barrier surface layer: Type 1 • Absorbent layer: Weft_a_8 • Wound contact layer: Type C			
2A	• Barrier surface layer: Type 2 • Absorbent layer: Weft_a_8 • Wound contact layer: Type A			
2B	• Barrier surface layer: Type 2 • Absorbent layer: Weft_a_8 • Wound contact layer: Type B			
2C	• Barrier surface layer: Type 2 • Absorbent layer: Weft_a_8 • Wound contact layer: Type C			
3A	• Barrier surface layer: Type 3 • Absorbent layer: Weft_a_8 • Wound contact layer: Type A			
3B	• Barrier surface layer: Type 3 • Absorbent layer: Weft_a_8 • Wound contact layer: Type B			
3C	• Barrier surface layer: Type 3 • Absorbent layer: Weft_a_8 • Wound contact layer: Type C			

Table 3.10 Physical properties of nine different combinations of three layer wound dressing composites (including standard deviation)

	Thickness	Areal mass	Bulk density
1A	5.02±0.08	0.6393±0.02	126.87±3.86
1B	6.50±0.14	0.8000±0.00	123.08±0.44
1C	4.91±0.05	0.7123±0.00	145.07±0.92
2A	5.03±0.06	0.6235±0.01	123.95±1.47
2B	6.33±0.10	0.7623±0.01	120.43±1.92
2C	5.23±4.58	0.6994±0.01	133.72±1.85
3A	4.58±.04	0.5893±0.01	128.68±0.02
3B	6.16±0.22	0.7458±0.02	121.07±2.65
3C	4.70±0.15	0.6722±0.01	143.03±2.41

3.7.2 Compression Test

As cushioning is one of the most important properties of the newly developed wound dressing composites, the compressional behavior of the wound dressing composites was tested. The same method and same machine as those for testing the 3D knitted spacer fabrics were used. Details on the testing are provided in Section 3.5.2.

3.7.3 Absorbency Test

Absorbency is one of the most important requirements of wound dressings especially for those that treat wounds with exudates. To evaluate the absorbency of 3D knitted spacer fabrics, the volume of water or saline water that can be absorbed by the fabric was examined in Section 3.5.3. However, in order to investigate the absorbency of the three layer wound dressing composites, a new method was adopted to simulate the absorption of wound exudates by the wound dressing in real life. According to previous researchers, in vitro artificial wound models can be used to assess the absorbency of wound dressings in order to determine wound fluid handling capacity (Casu, Schubert, Tegelkamp, & Loper, 2014; Grande & Sivakumaran, 2016; Holm, Walters, & Zehrer, 2011; Lutz, Zehrer, Solfest, & Walters, 2011). By referring to their models, a vertical absorption model and artificial wound fluid are developed in this study. Based on the artificial wound fluid and composition of typical human extracellular fluid and chronic wound fluid provided in the literature (Lutz et al., 2011), the artificial wound fluid used in this study is modified, which is shown in Table 3.11 in which 10 ml of 1% Acid dye 37 diammonium salt was added to replace 10 ml of deionized water in order to colour the fluid for ease of visualization.

Table 3.11 Artificial wound fluid and composition of typical human extracellular fluid and chronic wound fluid

Ingredient	Amount (g)	Protein (g/L)	Lipids (g/L)	Sugar (g/L)	Sodium (g/L)	Potassium (g/L)	Chloride (g/L)
Phosphate-buffered saline	627.48	0.00	0.00	0.00	1.73	0.07	2.73
Distilled and deionized water	314.80	0.00	0.00	0.00	0.00	0.00	0.00
Whey protein isolate	51.00	40.11	0.40	0.00	0.41	0.66	1.22
Vegetable oil	2.10	0.00	2.10	0.00	0.00	0.00	0.00
Sodium bicarbonate	3.73	0.00	0.00	0.00	1.02	0.00	0.00
Dextrose or sucrose	0.89	0.00	0.00	0.89	0.00	0.00	0.00
Totals	1000.00	40.11	2.50	0.89	3.16	0.73	3.95
Human extracellular fluid (average)		20.30	5.00	0.90	3.30	0.20	3.70
Chronic wound fluid (average, range)		39 (26-51)	2.3 (1.6-7.5)	1.3 (0.60-2.56)	3.24 (3.06-3.36)	0.17 (0.13-0.22)	3.69 (3.4-3.86)

The coloured artificial wound fluid was poured into an infusion bag and an infusion set and a 18G needle were used to maintain a constant flow rate. According to the definitions for quantifying the levels of exudate, minimal exuding produces less than 5 ml of fluid per 24 hours, moderate exuding produces 5-10 ml of fluid every 24 hours while high exuding produces more than 10 ml of fluid every 24 hours (Lutz et al., 2011; Mulder, 1994). Therefore, in order to investigate the fluid handling capacity of the newly developed wound dressing composites and the existing wound dressings, three different volumes were adopted for each sample, including 4 ml, 8 ml and 12 ml of fluid, to evaluate their absorbency for different amounts of exuding.

The test samples were placed onto a transparent plate with a 1 cm x 1 cm checkered pattern and the wound contacting layer was facing up. Coloured fluid was dropped onto the wound contacting side of the samples at a flow rate of 0.5 ml/ min. Cameras on the top and the bottom of the device recorded the spread of the fluid from the top and bottom of the samples over time and the amount of fluid spread on the top and bottom of the test samples were determined.

3.7.4 Water Vapor Permeability Test

WVP, also known as moisture vapor transmission, is important for wound dressings. Due to exudate or sweat that may be produced by some types of wounds, it is vital that the wound dressing can permit water vapor to pass from the skin or wound to the external environment in order to maintain ventilation. The method and machine used are the same as those for the spacer fabrics. The details of the WVP test are provided in Section 3.5.5.

3.7.5 Air Permeability Test

As mentioned before, air permeability shows whether the wound dressing composites have a ventilated environment and therefore good breathability which is critical for wounds to properly heal. The KES-F8 of the KES was adopted for the measurement of the air permeability of the wound dressing composites and the KES-F8-AP1 air permeability tester was used to evaluate the air resistance of the samples. The details of this test have already been discussed in Section 3.5.6.

3.7.6 Thermal Conductivity Test

The thermal conductivity of the newly developed wound dressing composites was evaluated because it shows whether there is good heat regulation for the wound and inhibition of accumulated heat. The method and machine used are the same as the thermal conductivity test for the spacer fabrics. The details of the test have already been discussed in Section 3.5.7.

3.7.7 Extensibility Test

Conformity of wound dressings is important as it will affect the effectiveness of the wound dressings and the optimum wound healing environment. In addition, wrinkling or fluting may injure the fragile wound bed. To evaluate the extensibility of the wound dressing composites, the machine used is the same as that for testing the spacer fabrics. The method is similar except that the deformation was 20% of the initial length of each sample, not 80%. After extension, the distance between the two marks on the samples were re-measured again. Apart from the stress strain curves, the permanent setting, which means the change in length after elongation, was calculated.

$$Extensibility \ \ (N \cdot cm - 1) = \frac{ML}{5.0} \ \ \ldots\ldots \text{ Equation 3.10}$$

where ***ML***= maximum load.

$$Permanent \ \ set \ \ (\%) = \left(\frac{\mathbf{L_2 - L_1}}{\mathbf{L_1}}\right) \times 100 \ \ \ldots\ldots \text{ Equation 3.11}$$

where $\boldsymbol{L_1}$= distance between the two markings before elongation, and $\boldsymbol{L_2}$= distance between the two markings after elongation.

3.7.8 Surface Friction Test

The surface friction of wound dressings is important for the wound bed and the surrounding skin during healing. As wound dressings come into direct contact with the wound bed, further injury to the fragile skin of the wound should be avoided in case of further ulceration. Friction is one of the key contributing factors of pressure ulcer development. Therefore, the surface friction of the wound dressings should be measured, which was done by using the KES-FB4-A automatic surface tester of the KES. This surface tester provides objective numerical values of the fullness, softness, smoothness and crispness of a sample, and simulates the strokes performed by hand that artisans and professionals use to evaluate the texture of a fabric sample. In this part, the surface friction of the currently available wound dressings in the market and the three non-adherent layers which are in direct contact with a wound were evaluated.

3.7.9 Bacteriostatic Test

Use of wound dressings with a bacterial barrier is one of the most common means that wounds are prevented from bacterial colonization (Mikhaylova et al., 2011). Based on the literature (Mikhaylova et al., 2011; Singh, Joyce, Beddow, & Mason, 2012) and the draft BS EN 16756, a direct contact method was adopted to test both the existing wound dressings and newly developed wound dressing composites. The bacterial species used were Escherichia coli (AATCC 25922) and Staphylococcus aureus (AATCC 25923). Nutrient agar or broth was used to inoculate the two species and the inoculation mediums were sterilized at 121℃ and 15 psi for 15-20 minutes. The loopful colonies were transferred to the nutrient broth for 24-hours of inoculation at 37℃. The inoculates were obtained as 1-3 x 10^8 CFU ml^{-1} (colony forming unit) and serial diluted to approximately 200 CFU ml^{-1} for the tests later on bacterial barrier ability. All of the solid inoculations were maintained on nutrient agar at 37℃.

In this test for bacterial barrier ability, the samples were prepared as 5 cm x 5 cm squares and both the inoculated control and test samples were directly inoculated on the sterile nutrient agar. The test evaluates the bacterial barrier property of the wound dressings and their ability to protect a wound against infection from the external environment. Therefore, the barrier layer faced upwards while the wound contacting layer faced downwards in contact with the agar. The bacterial inoculum (0.5 ml of 2 CFU ml^{-1}) was evenly spread over the surface of each test sample. On the other hand, no bacterial inoculum was spread over the control samples. After 24 hours of incubation at 37℃, the dressings were removed and the agar plates were observed for evidence of microbial growth in the areas covered by the dressings. Each sample was tested in triplicate.

3.8 Chapter Summary

In this chapter, the testing methods for the research experiments have been outlined and discussed in detail. In order to obtain better understanding of the pathophysiology mechanisms and take into consideration the issues that caretakers and patients face during treatment for pressure ulcers and healing, a 6-month clinical study at an elderly home along with the implementation of a questionnaire and interviews with registered nurses and caretakers have been carried out. The wound healing progress of three elderly individuals with a pressure ulcer has been examined to investigate the preventive and healing methods that are most optimal for pressure ulcer development and treatment in real practices.

The heel interface pressure of the elderly with the use of different types of mattresses and in different foot positions has been evaluated to obtain a better understanding of the influence of mattress type and foot position on heel interface pressure. Heel skin conditions, including moisture and sebum contents and elasticity have been investigated as skin condition is one of the key factors that contributes to pressure ulcer development.

In order to understand the criteria for existing wound dressings and their performance as well as the possibility of using 3D knitted spacer fabrics as the absorbent and cushioning layer of wound dressings, the physical properties of existing wound dressings in the market and different types of spacer fabrics have been studied. The influence of the knitting parameters on the physical performance of the spacer fabrics have also been investigated. As cushioning and absorbency are the two main factors of advanced wound dressings, compression resistance and absorbency properties are the two main focuses. Furthermore, wettability, water vapor and air permeabilities, and thermal conductivity which are related to breathability and comfort have been tested.

Extensibility which is related to conformity has also been evaluated.

After that, with the results obtained from measuring the heel interface pressure and testing the compressibility of the spacer fabrics, a 3D biomechanical model is developed to simulate the heel-spacer interface pressure with an FEM. After constructing the models of the heel and spacer fabric, defining the material properties, element type and size, and boundary conditions, and applying loading, the pressure distribution results are validated with real life cases.

The results obtained from the clinical study and evaluation of the material properties are used to design and develop the newly developed wound dressing composites. To evaluate the performance of the newly developed wound dressing composites, experiments that tested the material properties, such as compression, absorbency, breathability and surface friction tests, are carried out and the results are then compared to those of the existing wound dressings. In addition, bacterial barrier ability is an important property to avoid wound infection and needs to be examined in the newly developed wound dressings composite. Therefore, a bacterial barrier test is carried out to evaluate the ability of the composite to protect the wound against bacteria.

Chapter 4 Clinical Study on Wound Management of Pressure Ulcers

4.1 Introduction

In this chapter, a qualitative study on the wound management of pressure ulcers is carried out at an elderly centre for more than 6 months. The healing progress of elderly patients with heel ulcers is examined. The registered nurses of this elderly centre are interviewed and have completed questionnaires. These comprise the collected data; that is, information on pressure ulcer wound treatment and preventive methods. Their feedback and recommendations for pressure ulcer prevention and available wound dressings are also collected.

4.2 Clinical Study of Wound Management of Elderly

The healing of pressure ulcer wounds is complicated and involves different extrinsic and intrinsic factors. Although there has been numerous research work on the performance of pressure ulcer preventive devices and treatments, there is still a lack of information or studies on the wound healing progress of heel pressure ulcers in the elderly especially those in regular nursing homes. Therefore, this chapter aims to provide a report on patients who are living at a home for the elderly with a pressure ulcer, and treated through normal wound care practices by using thick gauze instead of specially designed wound dressings.

4.2.1 Case Study

4.2.1.1 Subject Demographics

Two subjects were monitored in the study. Subject A is an eighty-six year old bedridden elderly man with diabetes, hypertension, benign prostatic hyperplasia, heart disease, cataracts, syphilis, history of duodenal ulcers and a right femoral fracture. He was placed into a local home for the elderly in Hong Kong in 2016. With large intestinal haemorrhage due to intestinal cancer, he was admitted to the hospital and underwent colostomy surgery. After surgery, he was placed in the rehabilitation department for recuperation. After approximately one and half months, he was discharged from the hospital but had a Stage III ischemic heel ulcer on his left foot. Initially, the area of his pressure ulcer was 6 cm × 8 cm. The patient was required to undergo regular follow-up consultations at the podiatry department in the hospital. Instructions for wound treatment were given by the podiatry department to the nursing home staff after each consultation session.

Subject B is a seventy-eight year old bedridden elderly woman with a collapsed 12th thoracic vertebra, hypertensive heart disease, diabetes mellitus, low blood pressure, hyperlipidaemia, cataracts, skin allergy, moderate depression, a closed fracture of the clavicle, atrial fibrillation and acute retention of urine. She was placed into a local home for the elderly in Hong Kong in 2016. With low blood pressure and high heart rate, she was lethargic and admitted to the hospital for 4 days. Later, she was discharged from the hospital with a Stage III ischemic heel ulcer on her right foot. Initially, the area of her pressure ulcer was 4 cm × 3.5 cm with necrosis of the subcutaneous tissue and slough at the base, mild maceration at the periphery of the ulcer but no probing to the deep soft tissue or calcaneus of the right heel. Like the male subject, this patient was also required to undergo regular follow-up consultations at the podiatry department in the hospital, at about once every two months. Instructions for the wound treatment were given to the nursing home staff by the podiatry department after each consultation session.

4.2.1.2 Wound Treatment of Subjects

4.2.1.2.1 Subject A with Heel Ulcer

For the first twelve days, the aseptic technique was used and iodosorb paste was applied onto the wound base with thick gauze every day. All of the applied iodosorb paste on the wound base was thoroughly removed by using normal saline water during cleansing and both sides of the white carrier gauze were to be removed before putting on a new application. From the thirteenth day onwards, normal saline water was used to remove the applied iodosorb paste first and then an aqueous betadine solution was applied for disinfection purposes. After cleansing, a thick gauze along with betadine ointment was applied on the wound base once daily and adhered with surgical tape. In addition, thick padded heel protectors were applied both during the day and at night, and the left posterior heel was slightly elevated off the mattress by using a flat pillow. The first visit to see this patient started two months after his discharge from the hospital and continued every week to record his healing progress. In the second follow-up consultation, a professional in the podiatry department at the hospital gave instructions to the nursing home staff for the wound care treatment. The instructions were that the betadine solution would continue to be applied to the heel ulcer but the normal saline water was to be eliminated. After that, thick gauze with betadine ointment would be applied onto the wound base once daily as previously done.

4.2.1.2.2 Subject B with Heel Ulcer

The instructions for treating the heel ulcer wound of Subject B was to clean the ulcer with normal saline water for a few times and then use an aqueous betadine solution. After that, betadine ointment would be applied onto the wound base once daily and at least two thick gauze pads would need to be applied along the right plantar to the posterior heel regions and held with surgical tape. Furthermore, an open toe thickly padded heel protector was used during both day and night, and the right posterior heel was slightly elevated off the mattress by using a flat pillow. In addition, it was suggested that dressing pads were applied onto the right ankle and right foot borders which are at high risk for multiple pressure sore development. It was also suggested that the patient wear loose thick cotton socks in order to protect the foot during cooler weather. The first visit to see this patient started one month after her discharge from the hospital and continued every week to record her healing progress. Almost every two months, Subject B would have a follow-up consultation at the podiatry department. In the second follow-up consultation, a professional in the podiatry department at the hospital gave instructions to the nursing home staff for the wound care treatment. The instructions were that the wound was to be cleaned with Milton sterilizing fluid that contains 1% sodium hypochlorite instead of normal saline water and betadine solution. Gauze was soaked with Milton sterilizing fluid and applied onto the wound base once daily. After two months at the third follow-up consultation, the instructions were that a Unisept solution is to be used for cleansing and betadine solution on Durafiber dressing and gauze applied onto the heel ulcer wound and fixed with Tubifast bandage. At the fourth follow-up consultation, Hibitane solution was recommended for cleansing the wound and betadine solution on Durafiber dressing and gauze were applied onto the wound base once daily as previously done. At the fifth follow-up consultation, the instructions were that the Hibitane solution for wound cleansing and the betadine solution would continue to be applied to the heel ulcer and a thick gauze applied onto the wound base once daily as previously done.

4.2.1.3 Wound Healing Progress

4.2.1.3.1 Subject A

Subject A is a bedridden elderly patient who underwent colostomy surgery at a public hospital and stayed in the hospital for nearly one and half months. During his stay, he developed a pressure ulcer on his heel. Subject A has different chronic illnesses, such as diabetes, hypertension, benign prostatic hyperplasia, and heart disease. He is considered to be at high risk for pressure ulcer development, based on the previous literature that discussed the intrinsic factors for the development of pressure ulcers. In addition, as he underwent colostomy surgery, his appetite was poor which severely affected his nutritional intake. In addition, his mobility was impaired and his body had difficulties in recovering from the surgery. Therefore, he was not able to turn by himself. However, insufficient pressure relief of the bony prominent parts of his body would then likely lead to pressure ulcer development.

At the first visit, the heel ulcer of Subject A was highly exudative and the wound was large and deep. During the first four visits, there was a thick layer of soft white tissue around the wound base which was red in color. The routine of the nursing home was that after bathing with the help of the staff in the morning, the heel ulcer wound was washed with a betadine solution and covered with thick gauze, and betadine ointment was applied onto the wound base. After applying the wound dressing, heel protectors and cushions were used and repositioning was carried out every two hours to avoid prolonged pressure onto the wound and other bony areas to prevent further development of the pressure ulcer. As the individual has diabetes and underwent colostomy surgery, he was given milk (mixed from a powder) to maintain his blood glucose level and receive the required nutrition to facilitate the wound healing process. However, according to the observations of the nursing home staff, his appetite was poor after he was discharged from the hospital. Therefore, the healing progress of his heel ulcer was slower. On the fourth visit, he had a fever in the morning, and the nursing home staff sent him to a public hospital. He was subsequently hospitalized for one night. On the fifth visit, it became obvious that the size of the heel ulcer was becoming smaller and shallower. According to the staff, the amount of exudate was also reduced. Based on their observations, his appetite had also improved and he was able to ingest liquid food. On the seventh visit, a few days after the follow-up consultation, the thick white layer of soft tissue around the wound base had become harder, much like dead skin. There was a significant improvement in the heel ulcer wound on the eighth visit in which a layer of scab had developed which covered the wound base. Afterwards, the scab thickened and hardened, and the amount of exudate greatly decreased. At the last visit, which is the seventeenth visit, his heel ulcer was regarded as healed and our follow up was finished. Figure 4.1 shows the weekly heel ulcer healing progress of Subject A.

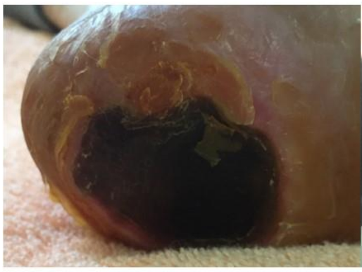
Figure 4.1 Weekly healing progress of heel ulcer: Subject A (Tong et al., 2016)

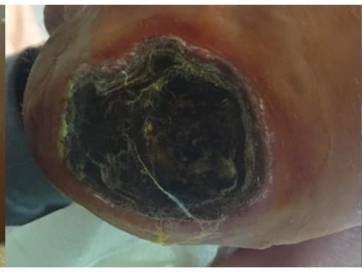
4.2.1.3.2 Subject B

Subject B is a bedridden elderly patient who had to stay in the hospital for 4 days due to atrial fibrillation and acute retention of urine. During her stay, she developed a pressure ulcer on her heel. As mentioned before, she has different chronic illnesses, such as diabetes, hypertensive heart disease and hyperlipidaemia. She is regarded to be at high risk for pressure ulcer development based on the previous literature that discussed the intrinsic factors for the development of pressure ulcers. As her mobility was impaired due to the collapsed 12th thoracic vertebra, she was not able to turn by herself. Therefore, like Subject A, insufficient pressure relief of the bony prominent parts of her body would then likely lead to pressure ulcer development. According to the nursing home staff, she has the habit of sleeping in a position with her right knee flexed so that the right plantar heel is often in direct contact with the mattress.

Similar to Subject A, the routine for Subject B at the nursing home is that after bathing with the help of the staff in the morning, her heel ulcer wound was cleaned with the solution suggested by the podiatry department and covered with thick gauze in accordance with the instructions of the podiatry department. After applying the wound dressing, heel protectors and cushions were used and repositioning was carried out every two hours to avoid prolonged pressure onto the wound and other bony areas to prevent further development of the pressure ulcer. As Subject B has diabetes like Subject A, she was given milk (mixed from a powder) to maintain her blood glucose level and receive the required nutrition to facilitate the wound healing process.

During the first five visits, the heel ulcer wound of Subject B was large with black necrotic eschar. At the sixth visit, the black necrotic tissue debris at the periphery of the heel ulcer started to slough off. Before the eighth visit, Subject B had her second follow-up consultation with the podiatry department at the hospital. The heel ulcer wound was treated by a professional and the black necrotic tissue debris was removed. Therefore, starting from the eighth visit, the black necrotic tissue debris was reduced but yellowish slough developed. In addition, there was newly developed tissue underneath. At the thirteenth visit, the yellowish slough was still thick and covered most of the wound base. One day before the fourteenth visit, Subject B had her follow-up with the podiatry department and the wound was cleaned by a professional and the slough was reduced. Therefore, on the fourteenth visit, most of the thick yellowish slough was removed and the newly developed tissue was exposed. After that, particularly on the seventeenth visit, the wound base of the heel ulcer was reduced in size and became shallower. The amount of exudate and new tissue continuously increased. There was a thick layer of soft white tissue around the wound base. Subject B had another follow-up consultation before the nineteenth visit and the thick layer of white tissue around the wound base was treated by a professional. Therefore, at the nineteenth visit, the wound was clean and the newly grown tissue made the wound seem shallower. After that, the wound size was greatly reduced and became shallower with less exudate. There was a significant improvement in the heel ulcer wound on the twenty-second visit. The wound size was reduced nearly 50% and the wound base was shallower. At the twenty-third visit, a layer of scab had developed which covered the wound base. Afterwards, the scab thickened and hardened, and the amount of exudate was greatly reduced. At the last visit, which is the twenty-sixth visit, her heel ulcer was regarded as healed and the follow up work of this study was finished. Figure 4.2 shows the weekly healing progress of the heel ulcer of Subject B.

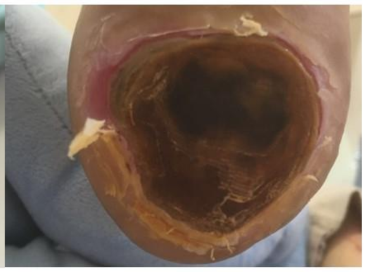

First visit


Second visit

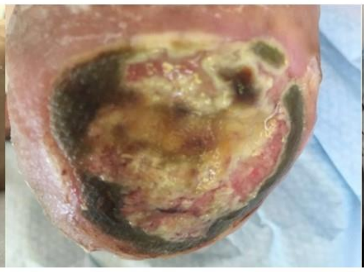

Third visit


Fourth visit


Fifth visit


Sixth visit


Seventh visit


Eighth visit


Ninth visit


Tenth visit


Eleventh visit


Twelfth visit


Thirteenth visit


Fourteenth visit


Fifteenth visit


Sixteenth visit


Seventeenth visit


Eighteenth visit

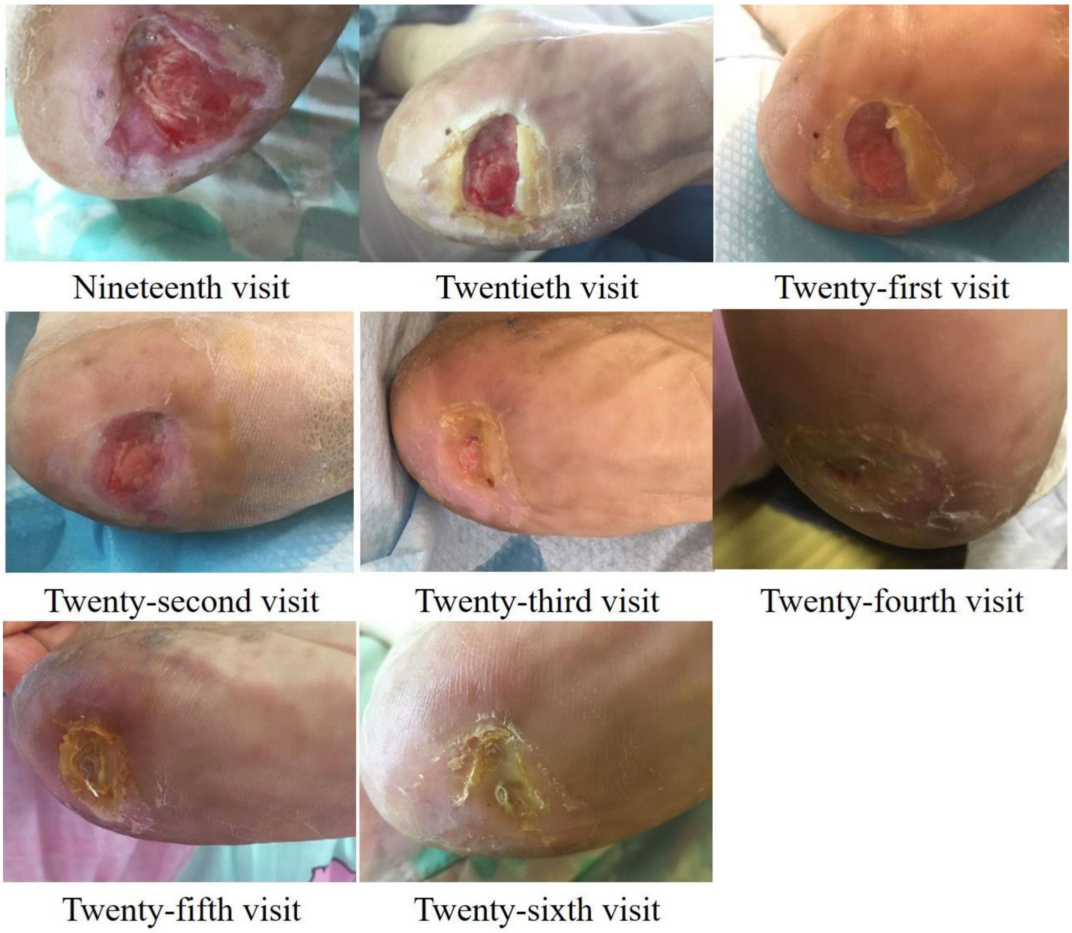


Figure 4.2 Weekly healing progress of heel ulcer: Subject B

Although the two elderly individuals in this study have different chronic illnesses and are immobile with a low metabolism, their heel ulcers gradually healed due to proper wound care. According to an interview with the nursing home staff, a daily shower keeps their skin clean and improves their blood circulation which contribute to improving the wound healing process. Based on the previous literature and reference guidelines published by the NPUAP, keeping skin clean by using warm water and a mild cleansing agent is an important skin care process that helps to minimize the irritation and dryness of the skin so as to prevent further ulceration and enhance wound healing (European Pressure Ulcer Advisory Panel et al., 2014). The betadine solution and ointment, Hibitane solution and Milton sterilizing fluid used have antibiotics which could have slowed down or stopped the growth of bacteria. Cleaning the wound with an antiseptic agent removes the surface debris and remnants of dressing so as to prepare the wound bed for healing. In addition, the wound is covered with thick gauze in the two cases instead of special wound dressings that are designed for pressure ulcers. The cost of gauze is low which reduces the burden of the ulcer treatment on the elderly individuals and their family. The gauze is also good for the absorption of exudates from the wound and provides a ventilated environment for wound healing. Moreover, the thick gauze can protect the wound base and provide a certain cushioning effect.

It is well known that minimizing the mechanical load is regarded as one of the most critical preventive measures to enhance wound healing as mechanical forces may cause further ulceration. Therefore, different pressure relief strategies including regular repositioning every two hours, the use of a pressure relieving mattress, cushions and heel protectors, and elevating the heel are also adopted to redistribute the pressure on the heel and avoid contact of the ulcer wound with the mattress so as to reduce the impacts of the pressure ulcer wound and occurrence of further ulcerations.

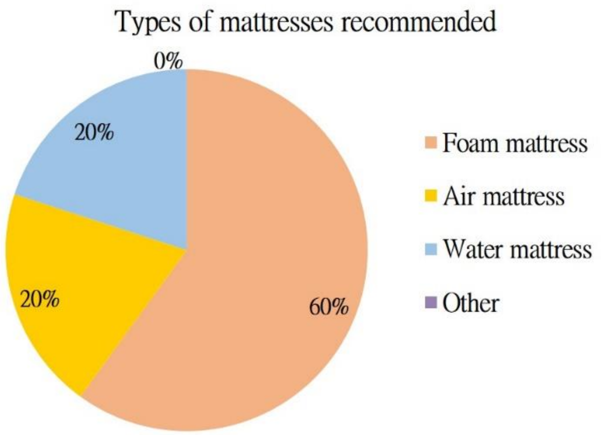
Proper nutrition is also one of the most important factors that enhances the healing of pressure ulcer wounds. Researchers have indicated that patients with a higher protein intake experience more rapid healing of pressure ulcers as opposed to those with insufficient caloric intake of protein (Cereda et al., 2009; Yoshikawa, Livesley, & Chow, 2002). Furthermore, K. Liu and Dai (2011) proved that malnutrition increases the severity of wound infections, and reduces the deposition of collagen and the tensile strength during healing. It is found in this study that dietary intake (particularly that of Subject A) greatly affects the wound healing process. Thus, the healing process is gradually enhanced when elderly individuals have better nutrition, especially in terms of more protein. Based on the healing progress of the elderly individuals here, it was found that different extrinsic and intrinsic factors of pressure ulcers should be avoided or enhanced by adopting appropriate treatment and care. Therefore, this study supports the contribution of pressure, nutrition and skin conditions to the healing of pressure ulcers.

4.2.2 Caretaker Interviews

In order to gain a thorough understanding of the potential problems that may occur in real practices in terms of pressure ulcer prevention and healing, interviews and questionnaires are used in this study for data collection. Seven registered nurses at the studied elderly centre were interviewed. Six of them have more than 20 years of related experience in taking care of the elderly and one of them has 16-20 years of related work experience.

4.2.2.1 Results and Discussion

Based on the questionnaire result, it was found that the elderly are regularly repositioned over 10 times every day. In order to prevent and enhance the healing of pressure ulcers, pressure relief mattresses are used and foam, and air filled and water filled mattresses are recommended while foam mattresses are preferred. Gel overlays and cushions are the most preferred followed by fibre-filled overlays and cushions. Figure 4.3 shows the results of the types of mattresses that are recommended for pressure ulcer patients while Figure 4.4 shows the types of overlays and cushions that are recommended by the nurses. In terms of the preferred types of wound dressings, hydrofiber and foam are the most recommended. However, the preferred types of wound dressings are similar as it highly depends on the cases, which are similar at the elderly home. Figure 4.5 shows the types of wound dressings recommended. In addition, the recommended time for changing a wound dressing is around 24 hours.



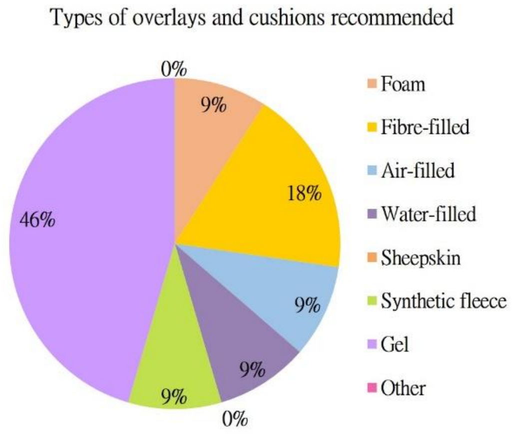


Figure 4.3 Types of mattresses recommended by caretakers

Figure 4.4 Types of overlays and cushions recommended by caretakers

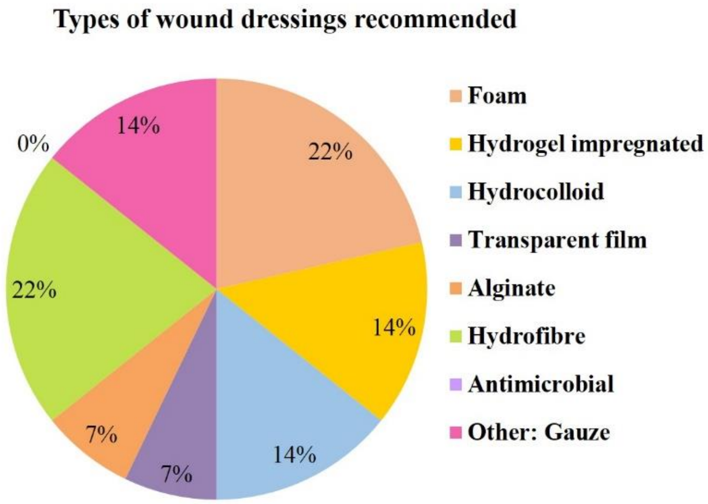


Figure 4.5 Types of wound dressings recommended for pressure ulcers

During the interviews, the registered nurses were asked to provide feedback on the wound dressings that they are currently using for pressure ulcers. There were sixteen statements that were scored in accordance with the physical properties of the wound dressings used and their input towards these wound dressings, as follows: 5 points for strongly agree, 4 for agree, 3 for neutral, 2 for disagree and 1 for strongly disagree. The average score for each question is shown in Table 4.1.

Table 4.1 Mean of each question

Statement	Mean (±SD)
I think that the wound dressing(s) has/have a good thermal feel.	3.57 (±0.53)
I think that the wound dressing(s) is/are breathable.	3.14 (±1.21)
I think that the wound dressing(s) has/have good absorption of wound exudate.	2.86 (±1.35)
I think that the wound dressing(s) become too damp.	1.86 (±0.69)
I think that the wound dressing(s) can relieve pressure.	2.71 (±1.25)
I think that the surface of the wound dressing(s) is/are soft.	4.29 (±0.49)
I think that the wound dressing(s) can reduce pain during the changing of the dressing.	3.57 (±1.27)
I think that the wound dressing(s) reduce the number of times that the dressing(s) need to be changed.	2.71 (±1.38)
I think that the wound dressing(s) fit the size and shape of the wound.	2.57 (±0.79)
I think that the wound dressing(s) can prevent the development of pressure ulcers.	2.43 (±1.13)
I think that the wound dressing(s) can heal pressure ulcer wounds.	4.14 (±0.69)
I think that the wound dressing(s) can improve the quality of life.	2.86 (±1.35)
I think that the wound dressing(s) are convenient to use.	4.71 (±0.49)
I think the wound dressing(s) are good.	4.14 (±0.90)
I am satisfied with the wound dressing(s)	4.29 (±0.76)
I want to try other types of wound dressings.	3.29 (±1.60)

In order to focus on the feedback of the nurses for the physical properties of the wound dressings that they are currently using, five important physical properties were selected, including air permeability, absorbency, cushioning, softness and thermal conductivity. The mean scores of the nurses given in accordance with the following physical properties were plotted (see Figure 4.6). The input of the nurses towards the wound dressings that they are currently using is shown in Figure 4.7.

According to Figure 4.6 the softness of the wound dressings (gauze) is the best among all five physical properties. The participant nurses are satisfied with the softness (4.29) and thermal conductivity (3.58) of the wound dressings that they are currently using. However, they have no particular feelings about the air permeability (3.14) and are dissatisfied with the absorbency (2.86) and cushioning effects (2.71). In addition, Figure 4.7 shows that the nurses are satisfied with the convenience of the wound dressings (4.71) as well as the reduction of pain during changing the dressing (3.57) and the enhancement of healing due to the wound dressings (4.14). However, they are not satisfied with the conformity (2.57) and the frequency of changing the wound dressings (2.71).

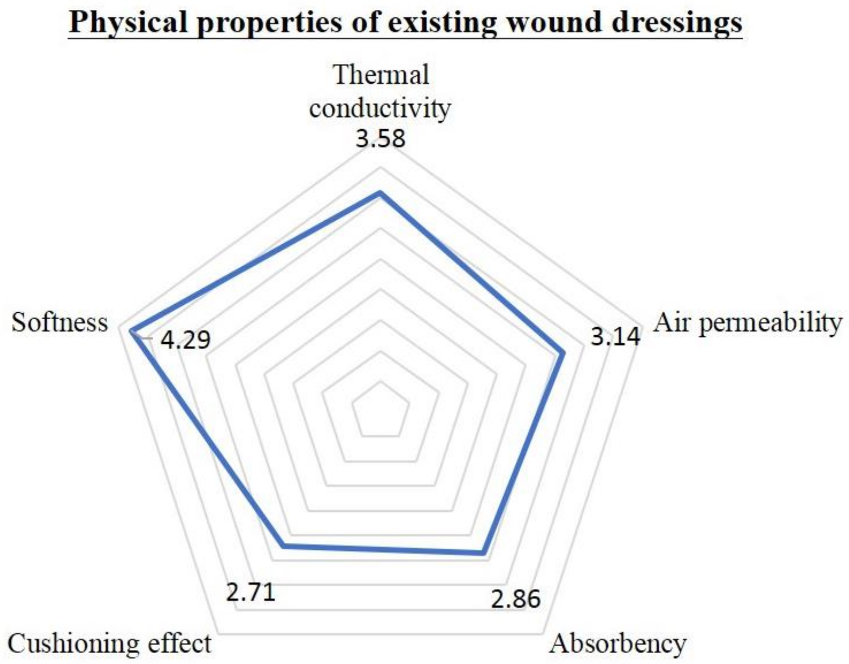


Figure 4.6 Average scores of physical properties of wound dressings used by nurses in study

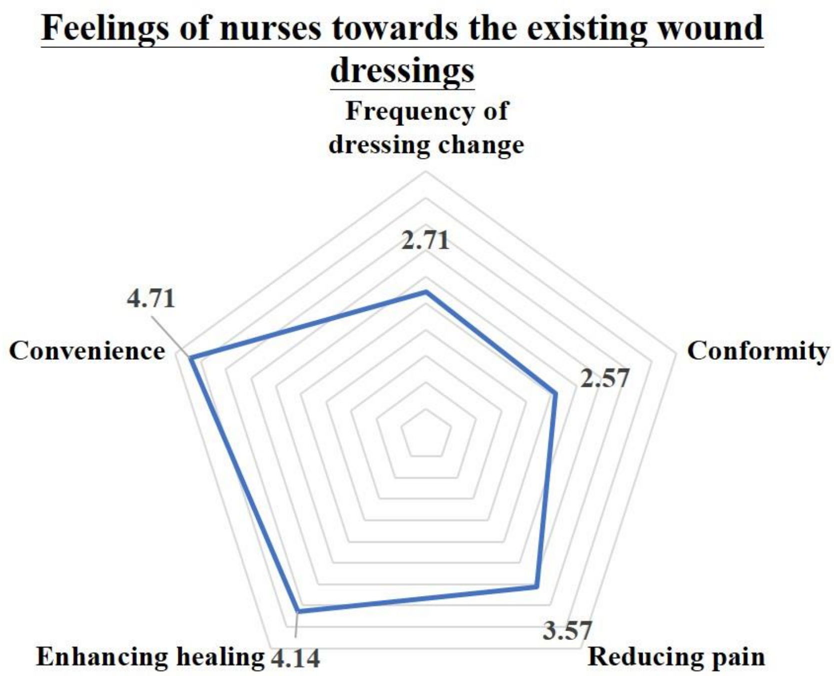


Figure 4.7 Input from nurses about wound dressings that they are currently using

Based on the feedback of the registered nurses, it was found that they are overall satisfied with the wound dressings that they are currently using for pressure ulcer patients in terms of some of the properties, including thermal conductivity, softness and convenience of use, but not with the breathability and absorbency of exudate. Although they feel that the wound dressings can heal pressure ulcers, they do not believe that the wound dressings can relieve pressure or prevent pressure ulcers. Furthermore, they feel that the conformity of the wound dressings and their ability to minimize pain during changing of the dressings are inadequate. Therefore, if there are other potential wound dressings that have been developed for pressure ulcer wounds, they are willing to try them.

In addition, their priorities in selecting wound dressings for pressure ulcer patients are shown in Table 4.2 and Figure 4.8. There are ten requirements for selecting wound dressings, with 10 as the most important property while 1 is the least important one. Based on the scale, a lower score of a factor means higher priority of this factor while a higher score means less importance placed on the factor when choosing the wound dressings. It is obvious that breathability (8.57) and ability to absorb (8.43) are the most critical factors that are considered when the respondents choose a wound dressing for their pressure ulcer patients followed by the amount of pressure relieved (8.14) and comfort (7.86). For wound dressings, softness (6.29) is more important than the other two factors, secondary damages caused by changing dressings (4.14) as well as conformity of the wound size and shape (4.14). On the other hand, convenience of using the wound dressings (2.43) and the number of times that the dressing needs to be changed (1.71) are the least important factors.

Table 4.2 Average scores of priorities in choosing wound dressings for pressure ulcer patients

	Comfort	Breathability	Absorption ability	Pressure relief	Less pain during removal
Mean (±SD)	7.86 (±1.21)	8.57 (±0.79)	8.43 (±1.62)	8.14 (±1.77)	4.14 (±2.91)
	Softness	Dampness	Fits the wound size and shape	Convenient to use	No. of times that dressing needs to be changed
Mean (±SD)	6.29 (0.76)	3.29 (±1.50)	4.14 (±0.90)	2.43 (±1.27)	1.71 (±0.76)

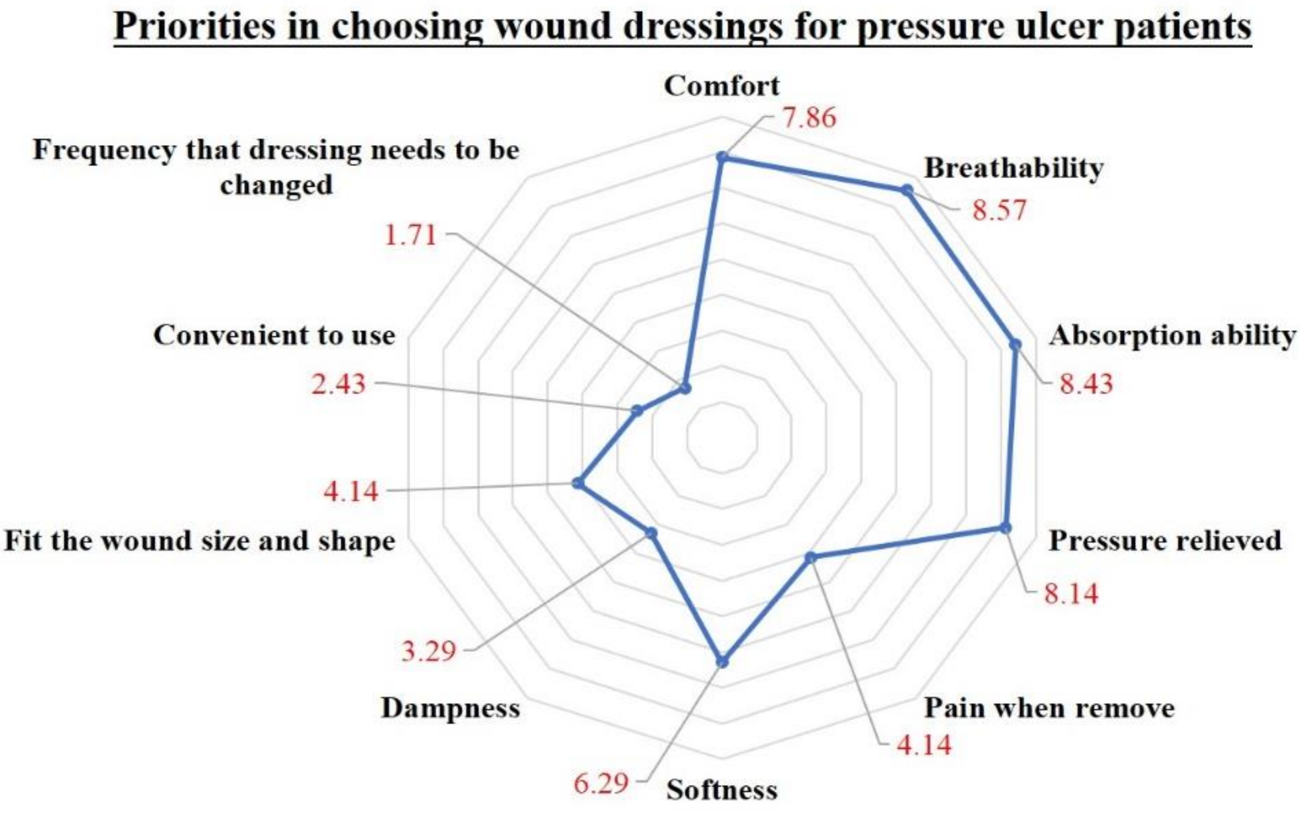


Figure 4.8 Priorities in choosing wound dressings for pressure ulcer patients

4.3 Chapter Summary

According to the literature, 30% of pressure ulcers occur in the heel region and the bedridden and elderly are at high risk for pressure ulcer development. However, wound healing management for pressure ulcers especially in the elderly is still unclear. Therefore, in this chapter, the wound management of heel pressure ulcers has been investigated and the wound healing progress of two elderly patients is examined. Heel ulcers may develop in the immobile elderly during their hospitalization. The results agree with the literature that heel ulcers are one of the most frequent sites of pressure ulcer development. With a low metabolism and different kinds of chronic illnesses, more than six months is required for their heel ulcers to heal. The healing process is long and complicated, as many different contributing factors may affect the healing. However, due to the efforts of the caretakers, it is found that proper wound care, nutrition and daily care contribute to the healing of ulcer wounds, which is entirely possible, even if the individual is an elderly person.

In addition, in order to gain a better understanding on the expectations of wound dressings for pressure ulcers, the general practices of pressure ulcer prevention and wound treatment, the nurses are solicited for their opinion on existing wound dressings as well as the properties of the wound dressings that they prioritize. During the visits to the elderly centre, the methods for pressure ulcer prevention have been investigated which include the use of pressure relief mattresses, cushions and heel protectors, as well as daily care and balanced meals. Although the registered nurses agreed that some of the physical properties of the wound dressings that they currently use are good, they also pointed out that the absorbency of exudate, cushioning effect and breathability are lacking. Furthermore, conformity to the wound, including the size and shape of the dressing, is poor. However, they prefer wound dressings that have breathability and absorbency, which are considered as the most important factors. Therefore, based on the feedback and concerns of the nurses, breathability, cushioning effect and absorbency are the important physical requirements for pressure ulcer wound dressings. The conformity of the wound dressings is also one of their concerns. The above findings provide the critical criteria for the design and development of new wound dressing composites for pressure ulcers.

Chapter 5 Heel Interface Pressure Measurements and Skin Condition Assessments

5.1 Introduction

Pressure ulcers are commonly found in the bedridden and elderly, with extrinsic factors and intrinsic factors as the main contributors to this problem. Extrinsic factors include pressure, shear and friction while intrinsic factors include age, nutrition, chronic illnesses, skin conditions and oxygen delivery. Although the development of pressure ulcers is multifactorial, pressure is one of the most important causal factors. Previous research has pointed out that a pressure greater than 32 mmHg is generally considered as the breakdown pressure and prolonged higher pressure causes pressure ulcers in a shorter period of time compared to lower pressure. In addition, areas that overlie bony prominences, such as the heels, sacrum and knees, are more prone to pressure ulcers. In the previous chapter, the observation results of a follow up case of two subjects who are in an elderly home demonstrate the influence of chronic illnesses, age and nutrition on the development of pressure ulcers and wound healing. In this chapter, the heel interface pressure and skin conditions of the elderly are examined. According to the literature, the neutral heel position causes external rotation. However, this may not be true for the elderly due to muscle contraction and reduced ability of the muscles to stretch. Therefore, in this study, the neutral heel position of the elderly in a relaxed condition is examined when they are lying on a mattress. Previous research has indicated that skin strain is greater when the foot is in an external rotation position as opposed to an upright position. Therefore, in this study, the heel interface pressure of the elderly when placed onto a standard hospital mattress or pressure relief mattress is reported. The influence of foot position on heel interface pressure and the effectiveness of standard hospital mattresses and pressure relief mattresses are investigated and discussed. Skin conditions, including the elasticity, moisture and sebum content of the elderly are reported. In this study, fifty-one elderly individuals who are 70 years old or older have been recruited to participate in heel interface pressure measurements and heel skin assessments.

5.2 Heel Interface Pressure Measurement

Pressure not only affects the chances of pressure ulcer development, but also the healing process of wounds. Several risk assessment tools have been designed to predict the risk for pressure ulcer development. However, since the assessment is performed by registered nurses, it is also subjective. The selection of pressure relief devices and wound dressings for pressure ulcers is also subjective and depends on the availability of the items and experience of the caretakers. However, interface pressure is a good predictor for the objective assessment of the risk for pressure ulcer development and the effectiveness of pressure relief devices and wound dressings. Although previous studies have investigated the effects of heel position on the heel interface pressure, they are predictions made by using finite element modelling or magnetic resonance imaging (Sopher et al., 2011; Tenenbaum et al., 2013). The literature also indicates that patients who are bedridden or over 70 years old are at high risk for pressure ulcer development. Real life information on the heel interface pressure and heel position is therefore important, especially of the elderly. However, such information thus far has been ambiguous. There is also a lack of information on the neutral heel position of the bedridden elderly and the influence of heel position on heel interface pressure. While pressure relieving mattresses are one of the most common items used to relieve pressure in order to reduce the risk of pressure ulcer development and prevent further damage to a pressure ulcer wound, the effectiveness of standard hospital and pressure relieving mattresses is not clear. Therefore, this study aims to study the neutral heel position of the elderly in the relaxed state, effects of heel position on the heel interface pressure as well as effectiveness of standard hospital and pressure relieving mattresses to relieve or redistribute the heel interface pressure of the bedridden elderly.

5.2.1 Neutral Heel Position of the Elderly in Relaxed State

In order to understand the risk that the elderly face in developing a pressure ulcer, it is important to conduct an in-depth study on the resting position of their lower limbs, especially bony parts like the knees and heels. As pressure ulcers on the heels are the main focus in this study, the heel angles of fifty-one subjects were measured.

Among the fifty-one subjects, forty of them were lying on a standard hospital mattress while eleven were lying on a pressure relieving mattress. Figure 5.1 shows the foot of a subject in a relaxed state when lying on a standard hospital mattress and Figure 5.2 shows the foot of a subject in a relaxed state when lying on a pressure relieving mattress.

Figure 5.1 Foot of subject in relaxed state on standard hospital mattress

Figure 5.2 Foot of subject in relaxed state on pressure relieving mattress

The measured heel angles of the subjects who were lying on standard hospital and pressure relieving mattresses are plotted in Figures 5.3 and 5.4, respectively. In **Error! Reference source not found.**, it can be seen that a third of the subjects or 37% and 30%, position their heel at an angle of 60°–69° or 90°–99° on the hospital mattress respectively. In addition, none of those who used a pressure relieving mattress had their heel placed at angles of 40°–49° and 70°–79°. According to Figure 5.4, similar to those who were using a hospital mattress, most of the elderly, or 46% and about one quarter of the elderly or 27%, who are using a pressure relieving mattress have their heel placed at angles of respectively. Some (18%) position their heel at an angle of 50°–59°. According to Sopher et al. (2011), an angle of 60° to a supporting surface is assumed to be the neutral external rotation position. The results of this study are therefore in agreement with Sopher et al. (2011) that the heel of most of the participating elderly is placed at an angle of 60° to the supporting surface when relaxed. However, many of the heel angles are also perpendicular to the supporting surface.

Figure 5.5 shows the heel angles of the subjects to a supporting surface in the relaxed state. According to the pie chart, the trends of the subjects who are using hospital and pressure relieving mattresses are similar. Most of them place their heel in the neutral external rotation and upright positions when they are in a relaxed supine position regardless whether they are using a hospital or pressure relieving mattress. However, only eleven were using a pressure relieving mattress which is fewer than the subjects who were using a hospital mattress (40 subjects). Therefore, the diversity in heel angle is less as opposed to the group of subjects who were using a hospital mattress.

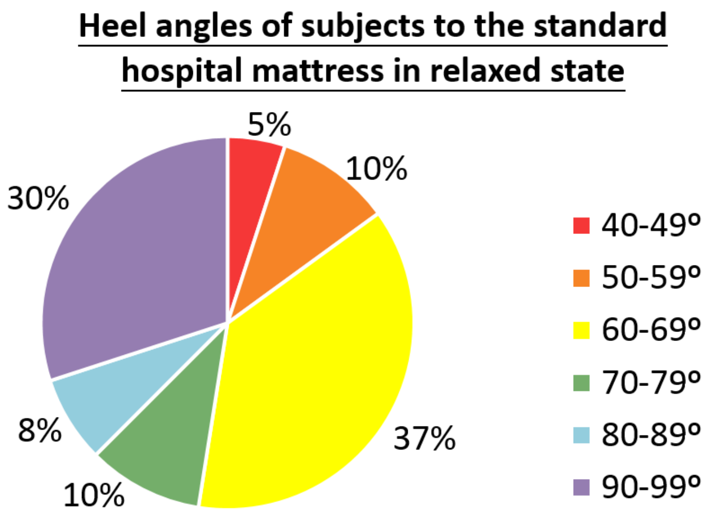


Figure 5.3 Heel angle of subjects to standard hospital mattress in relaxed state (Tong, Yip, Yick, & Yuen, 2016)

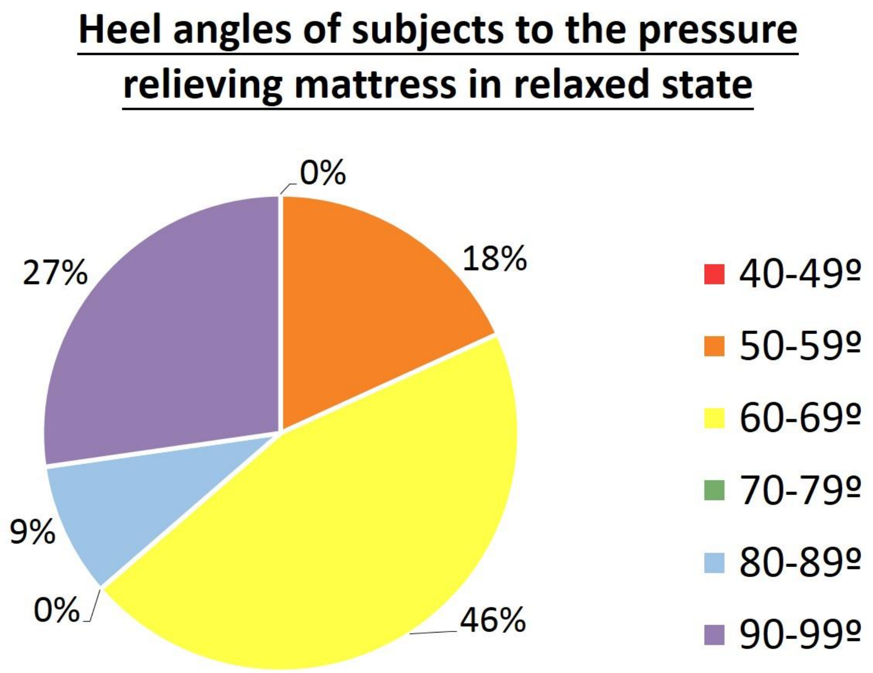


Figure 5.4 Heel angle of subjects to the pressure relieving mattress in relaxed state (Tong, Yip, & Yick, 2016)

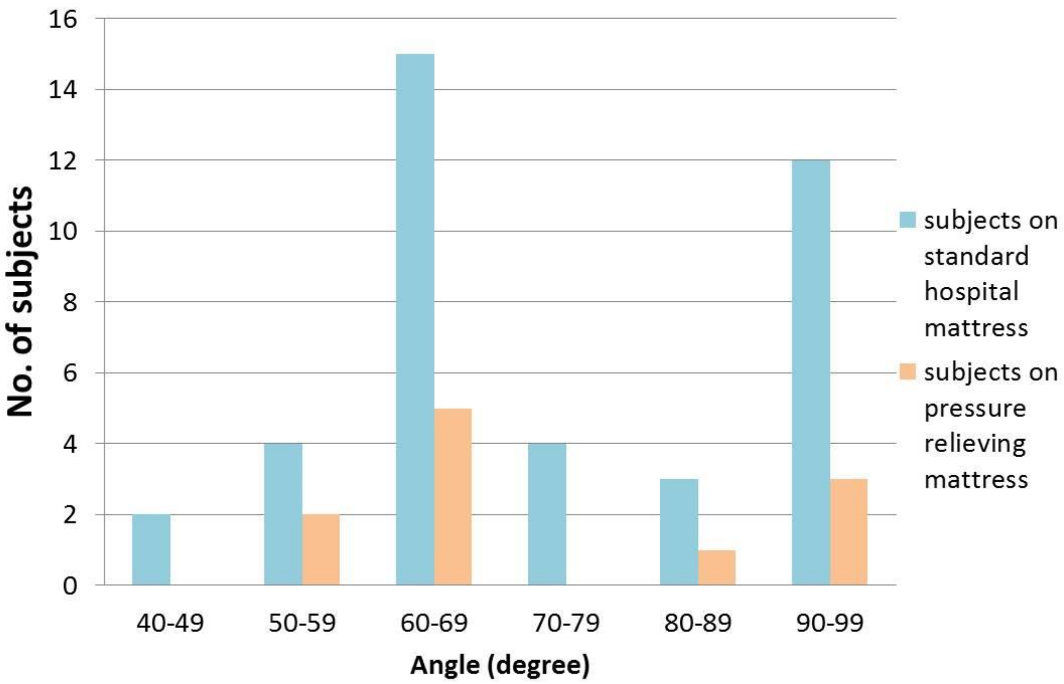


Figure 5.5 Heel angle of subjects to supporting surface in relaxed state (Tong, Yip, Yick, et al., 2016)

5.2.2 Heel Interface Pressure of the Elderly on Different Types of Mattresses

The above results show that the neutral heel positions of the elderly is both the neutral external rotation position and perpendicular to the supporting surface. Therefore, based on the obtained results, the heel angles of the elderly when lying in bed are 60° and 90° to the supporting surfaces. The heel interface pressure of the elderly when lying on different types of mattresses was measured at both 60° and 90°. As there were 40 subjects who used a hospital mattress and 11 who used a pressure relieving mattress, their average heel interface pressure was therefore calculated as shown in Table 5.1 and Figure 5.6. From the results, it can be observed that when the heel is supported at a 90° angle to the surface, the heel interface pressure is the greatest regardless whether a mattress is present. The heel interface pressure is reduced by approximately 36%–37% when the heel is placed at a 60° rather than a 90° angle. The hospital mattress relieves some of the heel interface pressure (about 68%) while the pressure relieving mattress reduces more of the heel interface pressure (about 87%) when compared to no mattress used. It is obvious that the pressure relieving mattress is more effective than the hospital mattress as 60% more of the heel interface pressure can be reduced.

In addition, according to the individual results of the participants, all 11 who used a pressure relieving mattress have a heel interface pressure less than 32 mmHg when their foot was positioned at a 60° angle while 7 have an interface pressure less than 32 mmHg at a 90° angle. On the other hand, only 3 of the 40 participants who used a mattress have an interface pressure below the threshold at a 60° angle but none at a 90° angle to the supporting surface. Therefore, the pressure relieving mattress is more effective for reducing the heel interface pressure regardless whether the foot is placed at a 60° or 90° angle to the supporting surface.

There is no doubt that the use of a pressure relieving mattress can greatly relieve heel pressure in different positions when compared with the use of a hospital mattress. Although pressure ulcer development involves many different factors, interface pressure is one of the predictors. The results proved that the subjects who use a hospital mattress experience greater heel pressure than those who use a pressure relieving mattress. Regardless of the position of the heel, a hospital mattress cannot consistently reduce the mean interface pressure of the heel to less than the average arteriolar blood flow, which is 32 mmHg. This indicates that hospital mattresses are not effective enough to reduce heel pressure. Therefore, the use of a hospital mattress alone may not be adequate for the bedridden elderly. However, even though the pressure relieving mattress in this study shows less pressure induced onto the heel, some of the elderly who had their feet in an upright position still suffered a heel pressure greater than 32 mmHg, and the average is only slightly under 32 mmHg. Based on the above results, the relaxed position of the heel of some of the elderly participants is in the upright position. Therefore, a pressure relieving mattress may not be effective enough to relieve their heel pressure and prevent heel ulcers.

However, the results showed that for both groups, their heel pressures are greater when their heel is placed at an angle of 90° to the supporting surface as opposed to 60°. This may not be in agreement with the results in previous work in the literature, which have used MRI or finite element modelling to simulate the heel pressure (Sopher et al., 2011; Tenenbaum et al., 2013). Tenenbaum et al. (2013) used MRI scans to calculate the effective soft tissue and skin strains to study the effects of foot position on the soft tissue deformation of the heel in a supine position as shown in Figures 5.7 and 5.8. Sopher et al. (2011) created a finite element model in order to simulate the distribution of strain energy density and von Mises stresses in the fat pad of the heel in the neutral external rotation and upright positions with the foot resting on a support as shown in Figure 5.9 Their results indicated that the skin strain is greater when the foot is in an external rotation position as opposed to an upright position; however, they also showed that there is no significant difference in the subcutaneous tissue strains between the external rotation and upright positions of the foot. That is because they used the mean compression strain but not the localized strain in soft tissue, which is different from this study which measures the localized pressure. Although Sopher et al. (2011) also showed that the upright foot position is better than an abducted foot position, their result was theoretically based and only one case study was adopted. As skin strain and internal tissue deformation are different from skin contact pressure, the results of this study may not be in agreement with their results.

Table 5.1 Heel interface pressure measurements of different heel positions of elderly participants on different mattresses (Tong, Yip, Yick, et al., 2016)

Heel interface pressure (mmHg)		60° to mattress	90° to mattress
Subjects on standard hospital mattress (N=40)	Mean(±SD)	50.15 (±13.15)	78.71 (±12.77)
	Max	78.43	108.79
	Min	24.30	45.13
Subjects on pressure relieving mattress (N=11)	Mean(±SD)	19.83 (±3.90)	30.78 (±7.54)
	Max	25.32	43.04
	Min	13.95	21.45
Subjects without mattress (N=51)	Mean(±SD)	157.02 (±37.30)	247.45 (±44.30)
	Max	244.44	359.29
	Min	103.21	154.56

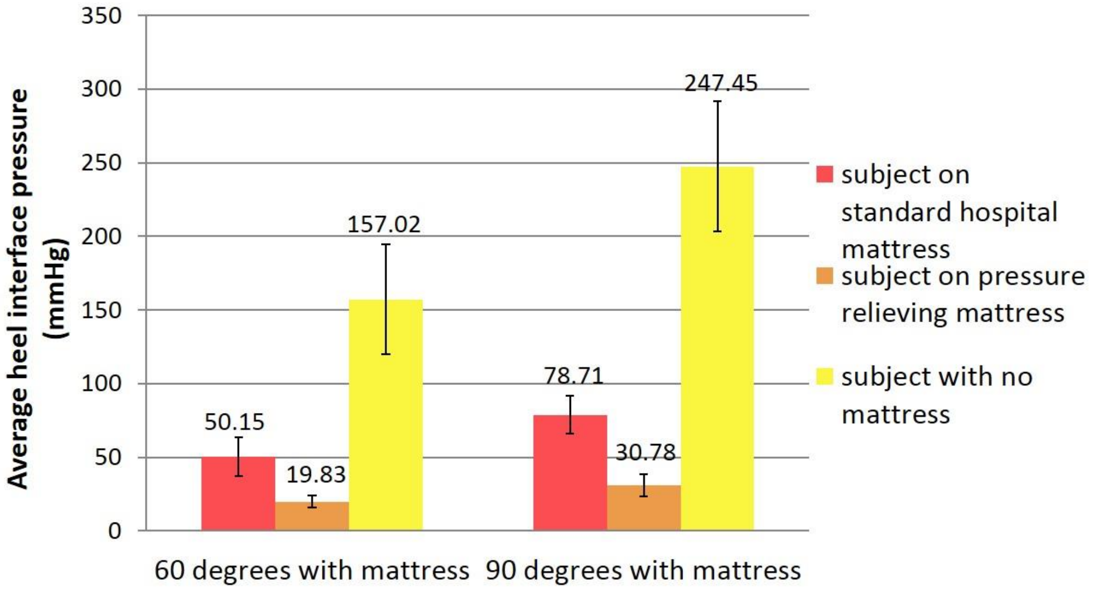


Figure 5.6 Average heel interface pressure of subjects on different mattresses in different positions (Tong, Yip, Yick, et al., 2016)

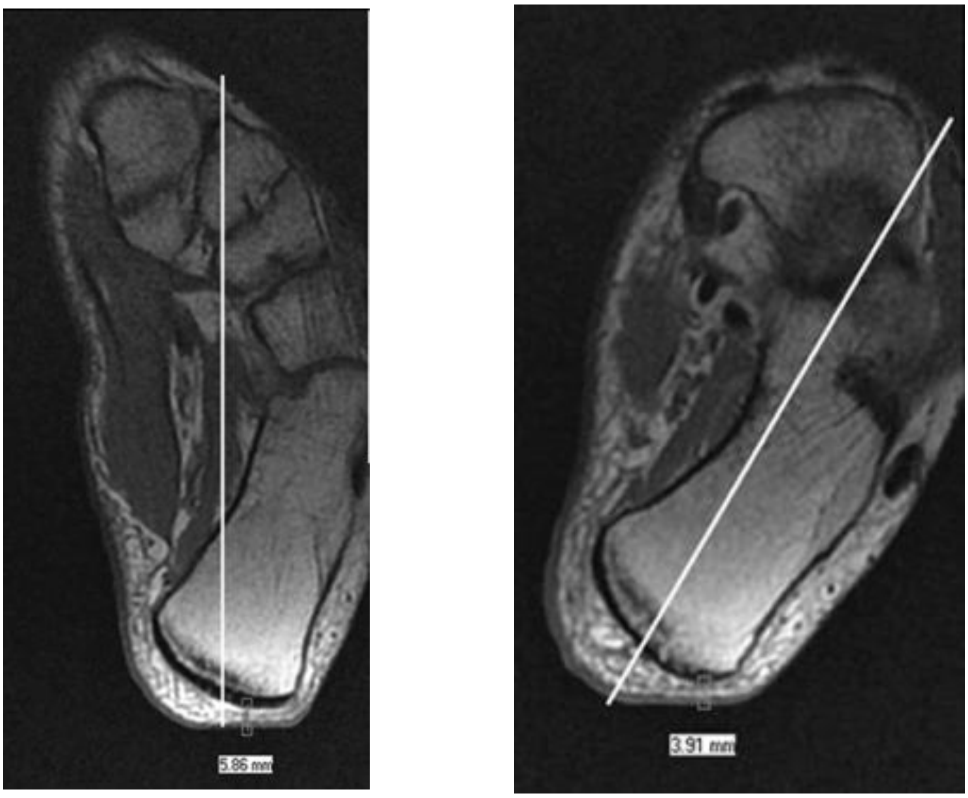


Figure 5.7 MRI results from Tenenbaum et al. (2013) (Left: foot in upright position; Right: foot in neutral external rotation position)

Tissue Measure	FWB (% tissue strain)
Skin–ER	36.75 ± 10.50 (30.24–43.26)
Subcutaneous–ER	64.25 ± 11.67 (57.02–71.48)
Total Soft Tissue–ER	59.40 ± 9.35 (53.60–65.20)
Skin–90°	32.21 ± 8.04 (27.23–37.19)
Subcutaneous–90°	62.76 ± 8.08 (57.75–67.77)
Total Soft Tissue–90°	50.11 ± 6.70 (53.96–62.26)

ER = external rotation, FWB = full weight bearing.

Figure 5.8 Tissue strains results measured by using MRI (Tenenbaum et al., 2013)

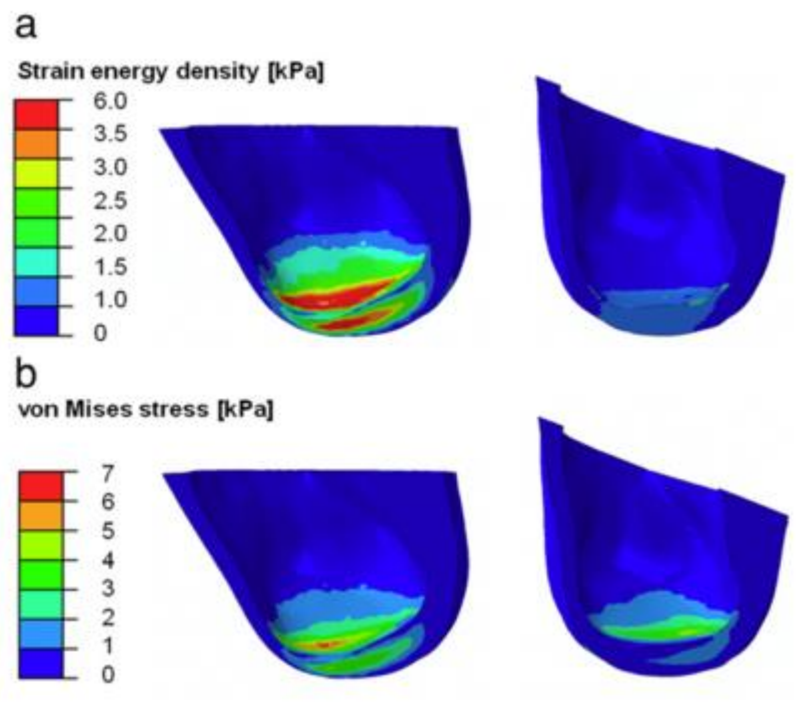


Figure 5.9 Finite element modeling results from Sopher et al. (2011) (Left: foot in neutral external rotation position; Right: foot in upright position) (Sopher et al., 2011)

In this study, four hypotheses are made: H1 – there is a significant difference between standard hospital and pressure relieving mattresses on heel interface pressure; H2 – there is a significant difference between foot posture and heel interface pressure under a standard hospital mattress; H3 – there is a significant difference between foot posture and heel interface pressure under a pressure relieving hospital mattress; and H4 – there is a significant difference among age, weight, BMI and heel interface pressure. Subsequently, a one-way analysis of variance (ANOVA) was carried out to examine the effects of mattress type and heel posture on the heel interface pressure among a sample of fifty-one participants and the results are shown in Table 5.2. The results show an overall significant difference in the heel interface pressure based on the mattress type used ($p = 0.000$). In addition, the results show a significant difference in the heel interface pressure based on the heel position of those who are using a hospital or a pressure relieving mattress ($p < 0.05$). There is also a significant difference in the heel interface pressure when no mattress is present ($p = 0.000$). However, age, weight, and body mass index (BMI) do not contribute to a significant difference in the heel interface pressure (p-values > 0.05).

The results of the one-way ANOVA also showed that a significant difference is found between heel pressure and mattress type. As well, there is a significant difference between heel pressure and heel position. The results prove that mattress type and heel position are important factors that affect the heel pressure of the elderly. However, a significant difference is not found between heel interface pressure and age, weight, and BMI. In considering that one of the criteria of the potential subjects is that they are to be 70 years old and older, this may have limited the results. Furthermore, the differences in weight and BMI of the elderly are minimal. Therefore, any significant difference of these factors with heel interface pressure is not obvious.

Table 5.2 One-way analysis of variance results of heel interface pressure (Tong, Yip, Yick, et al., 2016)

	Sig.(p-value)	Hypotheses
H1: There is a significant difference between standard hospital mattresses and pressure relief mattresses on heel interface pressure.	0.000*	Accepted
H2: There is a significant difference between foot posture and heel interface pressure under standard hospital mattress.	0.000*	Accepted
H3: There is a significant difference between foot posture and heel interface pressure under pressure relief mattress.	0.000*	Accepted
H4: There is a significant difference on heel interface pressure when the heel is placed at a 60 degree angle and at a 90 degree to the support surface.	0.000*	Accepted
H4: There is a significant difference among age, weight and BMI, and heel interface pressure.	>0.05	Rejected

*$p < 0.05$

5.3 Heel Skin Condition Assessments

Apart from the extrinsic factors, there are different intrinsic factors which contribute to the development of pressure ulcers. According to the literature, chronic illnesses, nutrition and skin conditions are the critical contributors. In Chapter 4, the importance of nutrition on the healing of pressure ulcer wounds was investigated. In addition, how age and chronic illnesses may inhibit the healing progress of pressure ulcer wound were examined in two case studies in Chapter 4. Therefore, this section reports on the risk of pressure ulcer development due to the skin conditions of the heels of the elderly, including examining skin properties such as moisture content, skin sebum and elasticity.

5.3.1 Assessment Results of Heel Skin Conditions

The assessment results of the heel skin of all the elderly participants in this study are provided in Tables 5.3 and 5.4, which are interpretations of the skin conditions of those who are 60 years old or older. The moisture and sebum contents as well as skin elasticity of those who use a hospital mattress versus a pressure relieving mattress are similar. Furthermore, the difference in the skin conditions between the female and male elderly participants is minor. The average moisture content is 10.17 and 11.31, respectively, while the average sebum content is 0.26 and 0.34, respectively. In terms of elasticity, the average value for those who use a hospital mattress is 76.32 while those who use a pressure relieving mattress is 73.92.

Table 5.3 Average values of skin properties of participating elderly in study

Average (±SD)		Moisture content	Elasticity	Skin sebum
Subjects who use standard hospital mattress	Female (20)	11.78±4.50	73.90±12.09	0.20±0.34
	Male (20)	8.57±3.34	78.73±9.95	0.33±0.47
	All (40)	10.17±4.24	76.32±11.20	0.26±0.41
Subjects who use pressure relief mattress	Female (5)	10.80±1.81	73.40±16.30	0.40±0.42
	Male (6)	11.73±5.67	74.35±12.81	0.28±0.45
	All (11)	11.31±4.20	73.92±13.73	0.34±0.42

Table 5.4 Interpretation of skin properties of those 60 years old or older (Tong, Yip, Yick, et al., 2016)

	Interpretation	Lower limit	Upper limit (excluded)
Moisture	Very dehydrated	0	30
	Slightly dehydrated	30	63
	Prevent dehydration	63	100
Elasticity	Low	0	25
	Medium	25	50
	Prevent loss of elasticity	50	100
Skin oil/ sebum	Low in oiliness	0	8
	Normal skin	8	21
	Oily	21	100

Source: Courage + Khazaka electronic GmbH Multi Skin Test Center MC900 built-in database.

It was hypothesized that there is a significant difference between the skin conditions of the heels of female and male elderly individuals, and a one-way ANOVA was carried out to examine the effects of gender among a sample of fifty-one participants. The results are shown in Table 5.5, which indicate that gender does not contribute to a significant difference in the heel skin conditions (p-values > 0.05).

Table 5.5 One-way analysis of variance results of heel skin conditions (Tong, Yip, Yick, et al., 2016)

	Sig.(p-value)	Hypotheses
H1: There is a significant difference between the skin conditions of the heels of female and male elderly individuals.	>0.05	Rejected

*$p < 0.05$

Many researchers have demonstrated that skin condition is one of the critical factors of pressure sore development. In general, the properties of moisture and sebum contents as well as the skin elasticity of the subjects who use a hospital or pressure relieving mattress are more or less the same. According to the results and with respect to the interpretation of the skin testing system, the skin of all the elderly participants can be regarded as very dehydrated with low sebum content. However, their skin elasticity is satisfactory. It is well known that dry skin is a very common skin condition of the elderly. The outer layer of the skin will become thinner with aging. Also, the connective tissues will change and cause the reduction of strength and elasticity of the skin. According to researchers (Maklebust & Sieggreen, 2001; Murray et al., 2001), the lack of skin moisture will increase skin abrasion and damage and thus increase the risk of pressure ulcers.

Although there is no local sebum production in the heel skin, sebum is one of the key contributors to the mechanical strength of skin (Tong & Yip, 2016). In Chapter 4, the normal skin care practices at an elderly home was studied. It was found that the routine practices include application of moisturizer after bathing, especially on dry body parts and parts that are at high risk of pressure ulcer development. However, no topical products, such as cleansers and moisturizers, were allowed for at least 8 hours before testing of the biophysical parameters. Yet the moisturizer used beforehand could still have been present on the skin surface, absorbed into the skin or metabolized. According to the literature (Lodén, 2012), 50% of applied moisturizers might still remain on the skin surface after 8 hours. Therefore, in order to obtain a thorough understanding of the heel skin condition of the elderly, skin sebum is also tested in this study. In addition, skin sebum acts as a lubricant between the skin and a supporting surface. However, the results showed that the sebum contents of the heels of the elderly are low. The lack of skin sebum may increase shearing forces and friction during movement and the risk for pressure sore development.

5.4 Chapter Summary

Pressure is one of the most critical extrinsic factors of pressure ulcer development. According to the previous literature, interface pressure is one of the simplest and common factors that can be used to predict the risk of pressure ulcer development. However, there is a lack of information on heel interface pressure especially in terms of the elderly. Furthermore, the effects of foot position on heel interface pressure are still unclear. Therefore, in this chapter, the neutral foot positions of the elderly who are using standard hospital and pressure relieving mattresses are studied. Moreover, the heel interface pressure in different foot positions is investigated. The relationships among heel interface pressure and mattresses, foot position, age, weight and BMI are studied. The results agree with those in the literature that the neutral foot position of the elderly in a relaxed state is the neutral external rotation position. However, there are also many subjects who place their feet in the upright position in the relaxed state. Therefore, the results show that upright and abducted foot positions are the neutral foot positions of the elderly. The results of the heel interface pressure measurements also show that an upright foot position puts a bedridden elderly at a higher risk for heel pressure ulcer development than the abducted foot position. Therefore, from the results, many of the relaxed positions of the heels are in an upright position, which may increase the risk for heel ulcer development. The pressure relieving property of pressure relieving mattresses is better than that of standard hospital mattresses. However, in some cases, they are still not effective enough to redistribute the heel pressure.

In order to have a better understanding of the intrinsic factors of pressure ulcers, different contributing factors like age, skin conditions and nutrition should be studied. In Chapter 4, the effects of age and nutrition on the development and healing of pressure ulcers have been studied. In this chapter, the skin conditions of the heels are examined. Previous research has proven that skin properties, including moisture content, skin sebum and elasticity, are critical factors that determine pressure ulcer development and healing. Lack of skin moisture may increase skin abrasion and damage while lack of skin sebum may increase the shearing forces and friction during movement. Finally, lack of skin elasticity may reduce the skin tolerance to abrasion and friction. From the results, the skin of the heels of the elderly participants is very dehydrated and lack sebum content. This may also increase their chances of developing heel sores.

All of the results in this chapter have been published in the Clinical Biomechanics journal in 2016 (Tong, Yip, Yick, et al., 2016).

Chapter 6 Evaluation of Spacer Fabrics as Cushioning and Absorbent Layer of Pressure Ulcer Wound Dressing

6.1 Introduction

According to the literature, ideal wound dressings should be able to absorb blood and exudates, and allow oxygen to pass through but prevent the dehydration and formation of scabs. Furthermore, they should protect the wound against secondary infections and mechanical damage. Ideal wound dressings should also be sterile, non-adhering, non-toxic and non-allergenic (Lou et al., 2008; Rajendran, 2009). Today, there are many different types of wound dressings in the market for pressure ulcer wounds such as foam, hydrocolloid and transparent film dressings. However, there is no single wound dressing that can be applied for all stages of a wound. In addition, the cost of using these kinds of wound dressings and treatment may become a costly burden on the patients and their family.

Based on the existing research, the consensus is that three-dimensional (3D) knitted spacer fabrics are typically used in technical and medical textiles (Bagherzadeh et al., 2012; Lazar, 2004; Yip & Ng, 2008). They show good linear elastic compressibility and perform well at reducing the peak pressure (Y. Liu et al., 2012). In addition, they also have good breathability and thermal conductivity. According to some of the research work, 3D knitted spacer fabrics have versatile properties, and have been recently used more and more as cushioning material for protective work clothing and in equipment to guard against impacts due to their excellent compression behavior and moisture-wicking and temperature controlling properties. Furthermore, they are widely used in shoes or insoles, for the face of fabrics for sports, in molded cups for intimate apparel (Yip & Ng, 2009) and other types of bandages. Researchers of the extant literature consider that 3D knitted spacer fabrics are becoming more popular as cushioning material, which has been previously dominated by polyurethane foam, and could be widely used in furniture in the future (Onal & Yildirim, 2012; Xu-hong & Ming-Qiao, 2008).

After analyzing the questionnaire responses of the registered nurses in Chapter 4, the results indicated that when choosing wound dressings for pressure ulcer patients, absorbency and breathability are their main concerns followed by cushioning, comfort and softness. However, the results also showed that they are not satisfied with the existing wound dressings that they are using for pressure ulcer patients especially in terms of the breathability and absorbency. They do not think that the wound dressings can help to relieve pressure.

In this chapter, some of the physical properties of the current wound dressings available in the market and both warp and weft knitted spacer fabrics are examined, in order to contribute to current knowledge on the properties of existing wound dressings in the market and investigate the possibility of using 3D knitted spacer fabrics as wound dressings for pressure ulcers. Induced pressure is one of the key factors for pressure ulcer development and may cause further ulceration of the wound. Therefore, the compressional properties of current wound dressings and 3D knitted spacer fabrics are evaluated. As mentioned before, absorbency and breathability are the most important criteria for choosing wound dressings, so the absorbency and air permeability of existing wound dressings and warp and weft knitted spacer fabrics are tested. Furthermore, wound dehydration may slow down the healing progress. Therefore, wettability, water vapor permeability and thermal conductivity tests are also carried out. Conformability is also critical for wound management and it is evaluated by its extensibility.

6.2 Compression Test

The compressional properties are a vital aspect of wound dressings as better compressional resistance can protect wounds from mechanical damage. In addition, pressure relief is important for preventing further ulceration of a wound, and therefore, the compressional properties of both current wound dressings in the market and 3D knitted spacer fabrics were analyzed.

6.2.1 Results and Discussion

A typical compression stress-strain curve of a knitted spacer fabric is shown in Figure 6.1. From the curve, the compressional behavior of the spacer fabric samples can be divided into three stages in accordance with their properties and configuration of the spacer yarns on the two surface layers (Y. Liu et al., 2012; Xu-hong & Ming-Qiao, 2008; Ye et al., 2007). Stage I is the initial and elastic stage, Stage II is the plateau stage and Stage III is the densification stage. In Stage I, the loose outer layers of spacer are first compressed. With increased compression force, the spacer yarns buckle under the compression load and are bound by the multifilament stitches. Therefore, the curve in Stage I shows a quick trend of increase. After that, as the bending of the spacer yarns nearly reaches their elastic limit, the spacer fabric is easily compressed even when only a small amount of pressure is applied, and a nearly constant pressure is induced. Finally, by gradually increasing the pressure, the compression also rapidly increases because of the rapid densification of the fabric and the collapse of the spacer yarns in the fabric (Y. Liu et al., 2012; Xu-hong & Ming-Qiao, 2008).

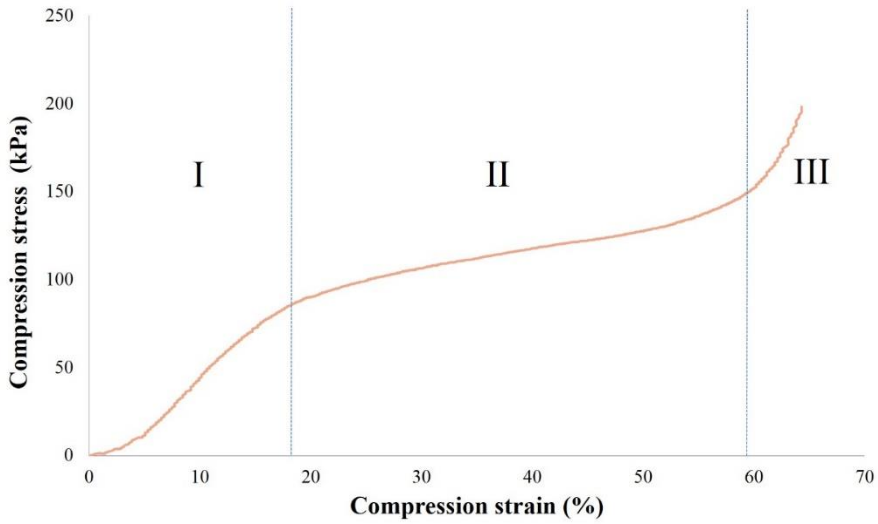


Figure 6.1 Plotted typical compression stress-strain curve of a spacer fabric (Tong, Yip, Yick, & Yuen, 2015)

In this study, a force is gradually is exerted onto all of the spacer fabrics and wound dressings until their thickness is reduced by 80% at a fixed speed of 12±3 mm/min. Figure 6.2 shows the compressive stress strain curves of the warp knitted spacer fabrics. In general, Warp_a_2 has the best performance while Warp_a_1 has the worst among the four samples, Warp_a_1 to Warp_a_4, all of which have the same knitted structure. This is because the areal mass and the angle of the spacer yarns are different. The results show that increasing the areal mass and the angle of the spacer yarns increases compression resistance which has also been proven in previous research work (Armakan & Roye, 2009; Y. Liu & Hu, 2011a; Y. Liu et al., 2011b). Warp_a_1 has the lowest compression resistance when applied force is increased as its strain is reduced by 80% which means that this sample can be easily compressed. In addition, this is also true for Warp_b_5 to Warp_b_7 which have the same knitted structure. Warp_b_6 and Warp_b_7 have a similar compression resistance as they have similar spacer yarn angles.

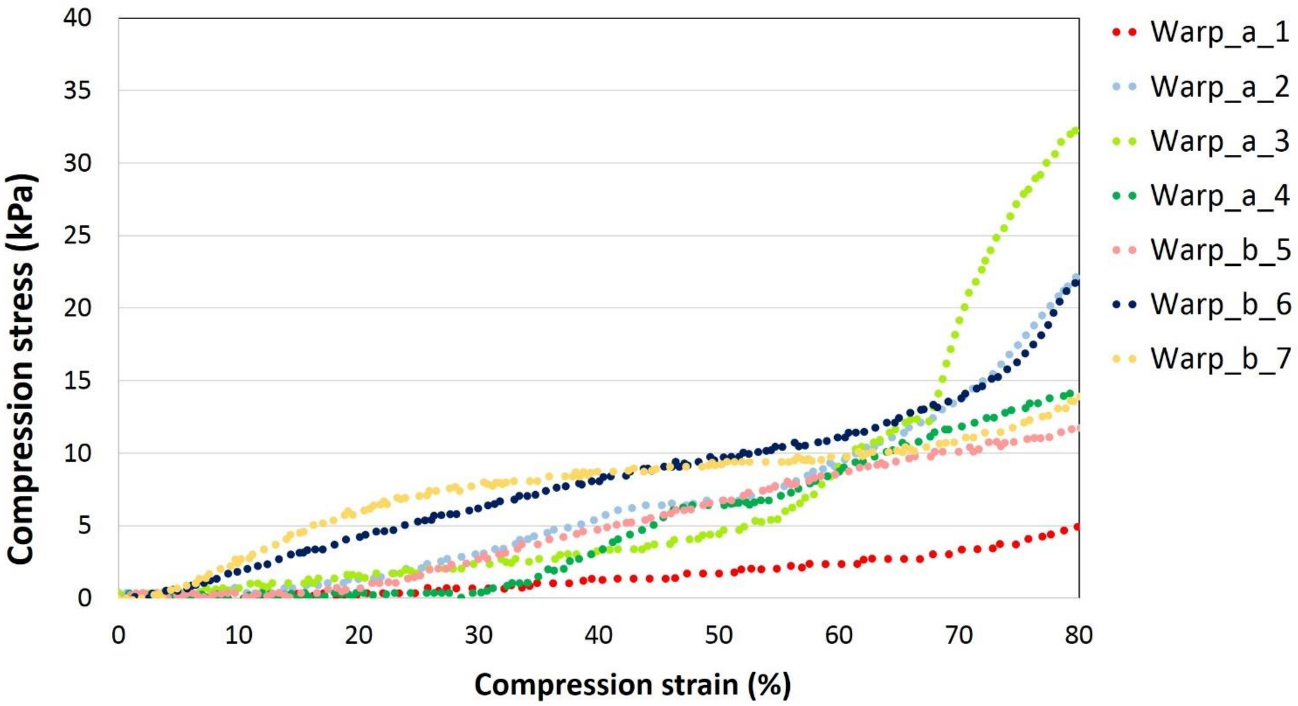


Figure 6.2 Plotted compressive stress strain curves of warp knitted spacer fabrics

The areal mass also affects the compression resistance of weft knitted spacer fabrics. As shown in Table 6.1, Weft_a_3 is compared with Weft_a_4 which have the same structure (Weft_a) and composition (93% polyester and 7% elastane); Weft_a_8 is compared with Weft_a_9, and Weft_b_12 is compared with Weft_b_13. Figure 6.3 shows the compressive stress strain curves of the weft knitted spacer fabrics. It can be observed that Weft_a_8 has a greater areal mass and is more thick than Weft_a_9. This is also true for Weft_b_12 and Weft_b_13. Weft_b_13, which is more thick and has a greater areal mass, and better compression resistance in comparison to Weft_b_12. Weft_a_3 and Weft_b_13 have the same composition and thickness. The results show that increasing areal mass and spacer yarn angles can enhance compression resistance, which holds true for Weft_a_4 and Weft_b_12.

Table 6.1 Physical properties of weft knitted spacer fabric samples

	Fabric type	Structure	Composition	Thickness (mm)	Spacer yarn type	Areal mass (kg/m²)	Bulk density (kg/m³)	Angle of spacer yarn (θ)	
								Course	Wale
Weft_a_3	Weft-knitted	Weft_a	93% Polyester 7% Elastane	2.99±0.06	Monofilament	0.4188±5.61	140.06±1.87	75.17°	75.41°
Weft_a_4	Weft-knitted	Weft_a	93% Polyester 7% Elastane	2.62±0.13	Monofilament	0.4204±12.96	159.09±4.91	79.65°	76.96°
Weft_a_8	Weft-knitted	Weft_a	89% Polyester 11% Elastane	3.30±0.12	Monofilament	0.4237±12.38	128.26±3.75	78.19°	68.32°
Weft_a_9	Weft-knitted	Weft_a	89% Polyester 11% Elastane	2.98±0.04	Monofilament	0.4102±4.28	137.65±1.44	69.46°	70.69°
Weft_b_12	Weft-knitted	Weft_b	93% Polyester 7% Elastane	2.60±0.06	Monofilament	0.3364±6.00	129.24±2.31	55.52°	39.63°
Weft_b_13	Weft-knitted	Weft_b	93% Polyester 7% Elastane	2.90±0.09	Monofilament	0.4370±9.16	150.70±3.16	71.84°	80.19°

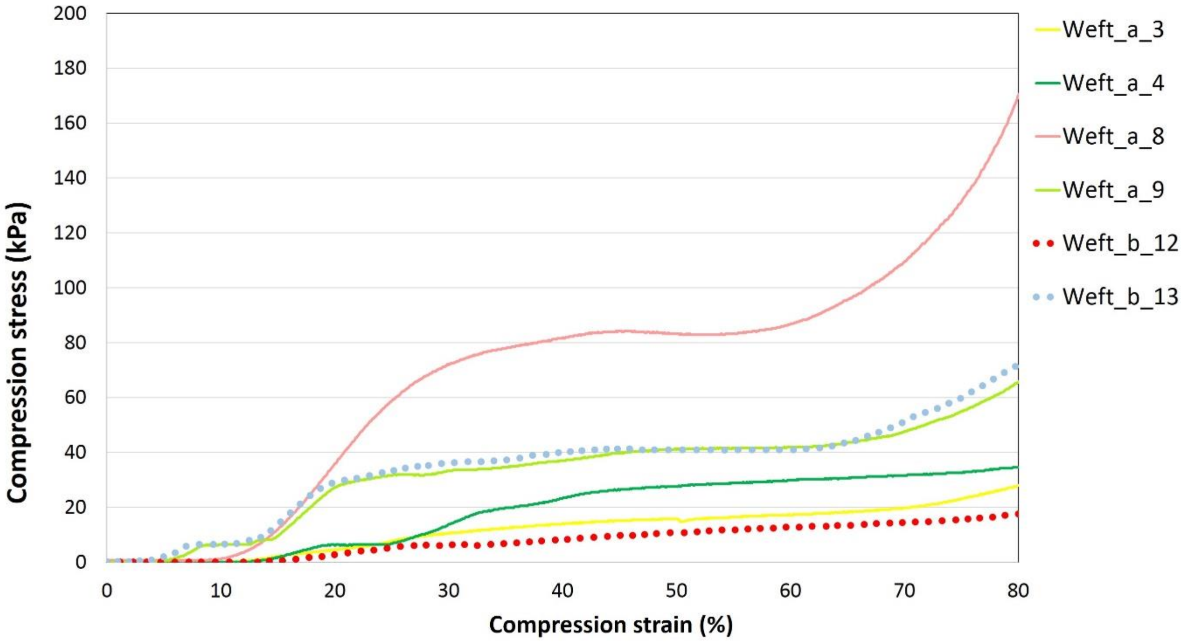


Figure 6.3 Plotted compressive stress-strain curves of weft knitted spacer fabrics

Six of the weft knitted spacer fabric samples with the best compression resistance performance were selected for further comparison with the existing wound dressings. Figure 6.4 shows the compression stress-strain curves for all of the 3D knitted spacer fabrics. It can be observed that the overall compression resistance of all the warp knitted spacer fabrics is always lower than that of the weft knitted spacer fabrics. The former has a larger mesh size on the outer layers and lower areal mass than the latter. This shows that the structure of spacer fabrics has a real effect on the compression property and agrees with previous research work that fabrics with a closed outer layer or smaller mesh size have better compression resistance (Y. Liu et al., 2011b). After comparing the compression results of the knitted spacer fabrics, Weft_a_8, Weft_a_9, Weft_a_10, Weft_b_13, Weft_b_14 and Weft_b_15 were selected for further comparisons with the wound dressings as they have better compression resistance.

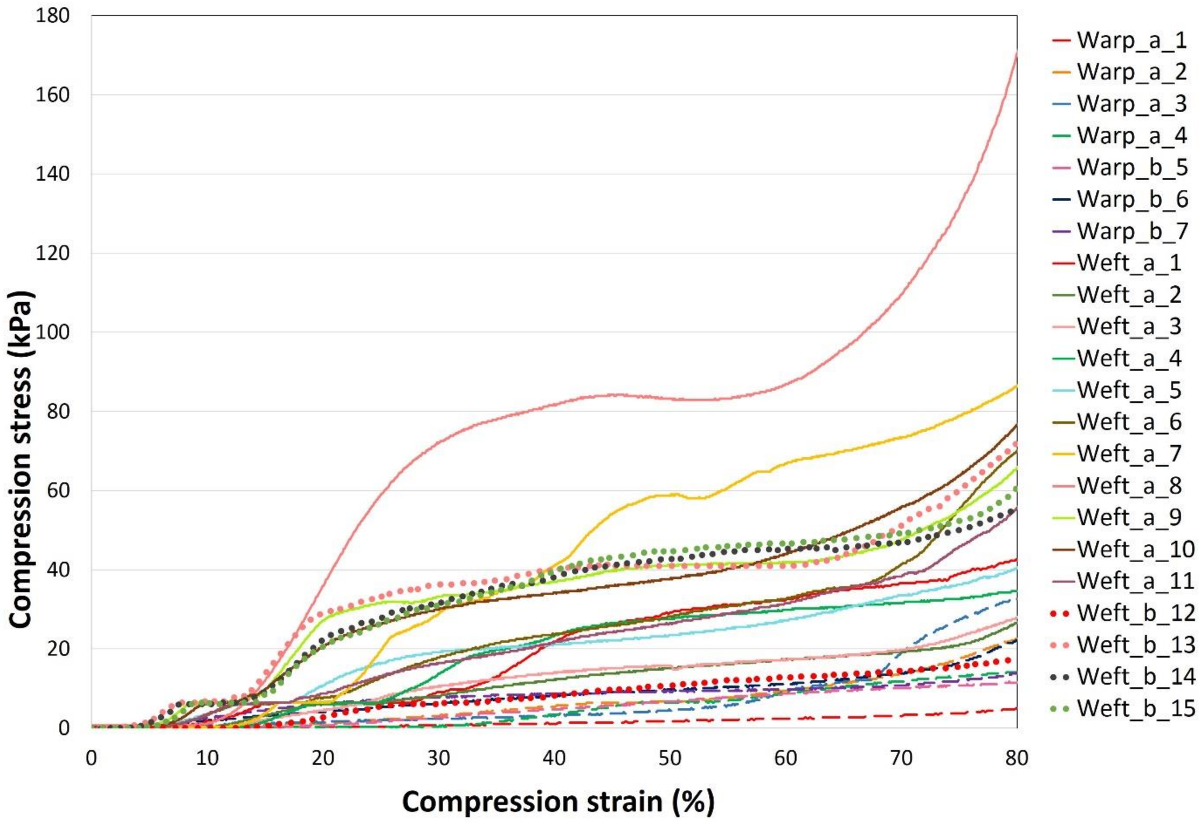


Figure 6.4 Plotted compressive stress-strain curves of all three-dimensional knitted spacer fabrics in study

In considering that spacer fabrics are expected to provide a cushioning effect in wound dressings for burns, ulcers and surgical wounds, the force loaded onto them is not very high. Previous research has pointed out that if a pressure greater than 32 mmHg (around 4.27 kPa) is exerted onto the body, this will shut off the capillary blood flow in healthy individuals (Davies & Williams, 2009b; Myers, 2004; Tymec et al., 1997), thus leading to pressure ulcers. Furthermore, based on the heel interface pressure measured of the individuals at the elderly center, the mean of the heel interface pressure of the elderly is 50.15 mmHg when their foot is positioned at a 60 on a standard mattress. On the other hand, when their foot is placed at a 90 degree angle on a standard mattress, the mean of the heel interface pressure of them is 78.71 mmHg. In addition, their maximum heel interface pressure is reached (108.75 mmHg) when their foot is placed on a standard mattress at a 90 degree angle. Therefore, in this study, the compression behavior of the spacer fabrics and wound dressings under a load of 4.27 kPa (32 mmHg), 6.69 kPa (50.15 mmHg), 10.47 kPa (78.71 mmHg) and 14.50 kPa (108.75 mmHg) will be given more attention.

It is obvious that the selected weft knitted spacer fabrics have greater compression resistance than the existing wound dressings at different pressures, see Figure 6.5. The compression resistance of Weft_a_9, Weft_a_10, Weft_b_13. Weft_b_14 and Weft_b_15 is similar and they have the best compression resistance among all of the spacer fabric and wound dressing samples. However, after they reach Stage II of the compression, the plateau stage at around 6.69 kPa shows that the spacer yarns have nearly reached their elastic limit due to bending, and a slight almost constant pressure can compress them continuously. However, at 15% of the compression strain, they become compressed rapidly with gradual increased pressure due to the rapid densification of the fabric samples, and the collapse of the spacer yarns. On the other hand, Weft_a_8 has a much lower compression resistance when compared to the other spacer fabrics under a load of 6.69 kPa. However, this is true for Stage I even after 14.50 kPa which indicates that the spacer yarns in the fabrics have not reached their elastic limit yet. Unlike the other samples, Weft_a_8 does not reach the plateau stage until 80 kPa, see Figure 6.5

Dressings 5 and 6 have the best compression resistance among all of the dressing samples when the applied pressure is less than 4 kPa. However, their compression strain rapidly increases with gradual increases in pressure. There is a turning point at approximately 4 kPa for Dressing 5, as its two layers have different compression properties. Dressings 3, 6 and 7 have similar trends of compression resistance as all of them are thinner than the other wound dressing samples, but have a large bulk density. Unlike the 3D knitted spacer fabrics, the wound dressings have no spacer yarns to support their structure. Although Dressings 6 and 7 are also made of hydrocolloids like Dressing 5, they are the least thick among all of the dressings and have a large bulk density like Dressing 3 which means that they are stiffer and able to resist pressure. Dressings 1, 2 and 4 have similar compressional resistance trends as all of them are made of polyurethane foam or polyurethane matrix with a similar areal mass. The compression resistance of Dressing 8 is the lowest at a pressure less than 6 kPa due to the loose structure of its non-woven materials. However, the material structure becomes less loose after continuous compression. Therefore, more pressure is needed for compression and its compression resistance excels that of Dressings 1, 2 and 4 after loading.

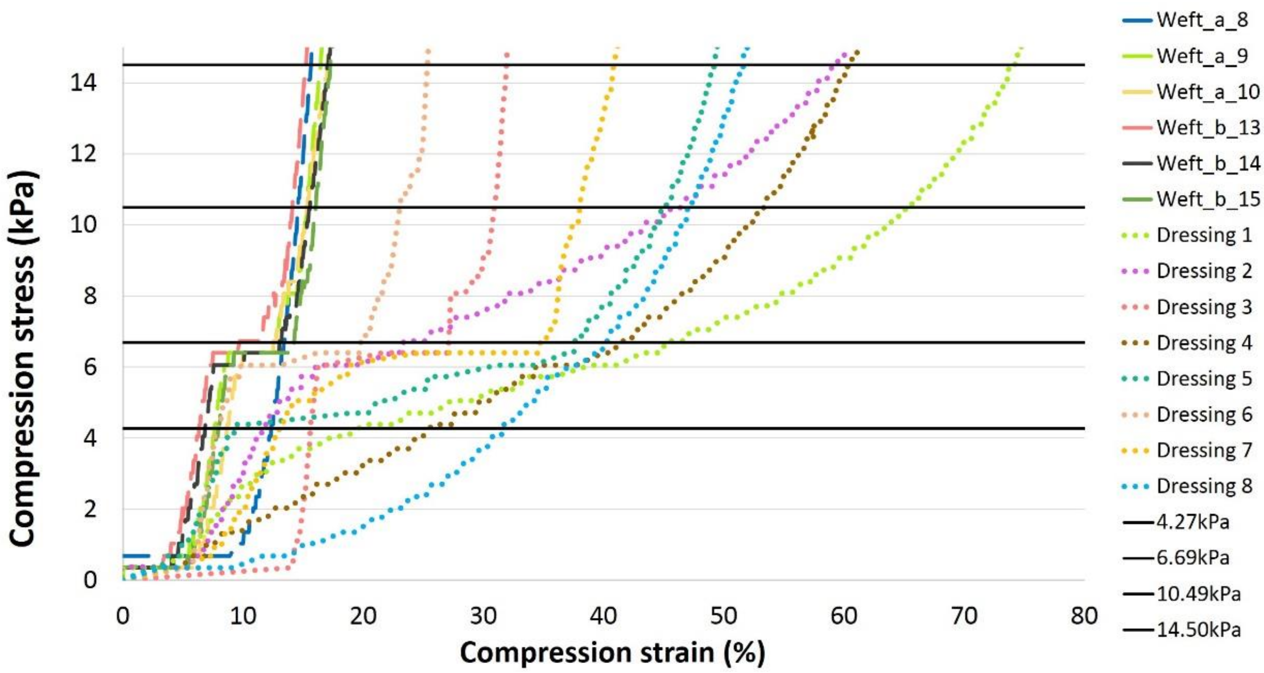


Figure 6.5 Plotted compression stress-strain curves of selected weft knitted spacer fabrics and wound dressings under different levels of exerted pressure

As 4.27 kPa is regarded as the point that the capillary blood flow will be shut off, the compression resistance results show that the weft knitted spacer fabrics can better resist pressure and maintain their thickness. From the results of the heel interface pressure tests, 6.69 kPa and 10.47 kPa are the average heel interface pressure for those who are using a standard hospital mattress when their heel is placed at a 60 and a 90 degree angle to the mattress respectively. In addition, 14.50 kPa is the average maximum pressure of those whose heel is placed at a 90 degree angle on a standard mattress. Since the most common and natural heel positions of the elderly are at angles of 60 and 90 degrees, the means to relief the heel interface pressure at those two angles is important. The compression results show that weft knitted spacer fabrics have better compression resistance than the pressure ulcer wound dressings. Therefore, weft knitted spacer fabrics can provide a good cushioning effect to protect wounds against mechanical collision.

Correlation testing was then utilized to examine the correlation between the compression resistance at different compression strains and different knitting parameters. The results are shown in Table 6.2. It can be seen that there are significant differences between the compression resistance of the spacer fabrics at different compression strains of 20%, 40%, 60% and 80%, and with different types of fabric (warp or weft knitted spacer), fabric structures, thicknesses, areal and bulk densities and spacer yarn angles in the course-wise and wale-wise directions ($p<0.05$). The results show that all of the knitting parameters have a positive correlation with compression resistance which means that increasing these parameters except for the fabric composition enhances the compression resistance of spacer fabrics.

Table 6.2 Correlation results of compression resistance of spacer fabrics

Correlations

			Warp_weft	Structure	Thickness	Areal_mass	Bulk_density	Spacer_yarn_angle_coursewise	Spacer_yarn_angle_walewise
Kendall's tau_b	Compression_at20percent	Correlation Coefficient	.631**	.609**	.480**	.592**	.417**	.627**	.601**
		Sig. (2-tailed)	.001	.000	.002	.000	.007	.000	.000
		N	22	22	22	22	22	22	22
	Compression_at40percent	Correlation Coefficient	.656**	.634**	.479**	.677**	.408**	.590**	.633**
		Sig. (2-tailed)	.000	.000	.002	.000	.008	.000	.000
		N	22	22	22	22	22	22	22
	Compression_at60percent	Correlation Coefficient	.677**	.615**	.459**	.683**	.378*	.578**	.552**
		Sig. (2-tailed)	.000	.000	.003	.000	.014	.000	.000
		N	22	22	22	22	22	22	22
	Compression_at80percent	Correlation Coefficient	.611**	.447**	.418**	.607**	.321*	.477**	.416**
		Sig. (2-tailed)	.001	.009	.007	.000	.037	.002	.007
		N	22	22	22	22	22	22	22

6.3 Absorbency Test

Absorbency is important in wound dressings as some wounds will produce different amounts of exudate. Therefore, the ability of wound dressings to absorb different amounts of fluids is particularly important. Furthermore, absorbency will affect the number of times that a wound dressing will need to be changed, as all exudates produced should be entirely absorbed by the dressing. So, better absorbency can reduce the number of times that a dressing needs to be changed.

6.3.1 Results and Discussion

Absorbency is the ability of a material to absorb liquid. A higher absorbency value means that more moisture can be absorbed and therefore, the material has better absorbency ability. Figure 6.6 shows the absorbency of all the tested samples with water and 0.9% saline water as the testing liquids. The results show that all of the spacer fabric and dressing samples can absorb more water than the 0.9% saline solution. This finding is in agreement with the results of previous studies (Deo & Gotmare, 1999; Kono, 2014; A. Li, Zhang, & Wang, 2007; Lokhande & Gotmare, 1999). The presence of sodium chloride (NaCl) particles in the 0.9% saline water increases the concentration of the electrolytes in the fluid and therefore the ionic strength which leads to a reduction in the difference of the osmotic pressure between the tested samples and the saline solution. Therefore, the absorbency of the tested samples is reduced when 0.9% saline water is used as the testing solution (Deo & Gotmare, 1999; Kono, 2014; A. Li et al., 2007).

Dressing 8 has the highest absorption ability as it is the thickest among all of the samples and has 4 plys of material and 5 layers of non-woven gauze swabs in which fluid can be absorbed between the fibres. Dressing 1 also has good absorption ability as it is made of a highly absorbent material (hydrocellular polyurethane) in which fluid can be directly absorbed into the fibres themselves rather than into the spaces between the fibres. Dressing 2 is also made of polyurethane foam, but is less thick than Dressing 1, so less space between the fibres means that it has less absorbency than Dressing 1. Dressing 4 has good absorbency ability as it is made of a thick layer of absorbent materials with hydrophilic polyurethane as the matrix. Although Dressings 3, 5, 6 and 7 are also made of absorbent materials, which are hydrocolloid and hydro-active polyurethanes as the matrix, they have poor absorbency because their surface has an adhesive layer which greatly reduces absorbency as the sticky film prevents the dressing from absorbing wound exudate.

In terms of the spacer fabrics, their absorbency is similar as they are all fabricated with polyester fibres which have poor water absorbency. When distilled water is used as the testing liquid, the absorbency ability of Warp_a_1 to Warp_b_7 increases with increasing thickness. In addition, the pores on their surface mean that fluid can easily pass through the fabric. Warp_a_1 and Warp_a_2 have the least absorbency as they are the bulkiest among all of the spacer fabric samples, so there is less space to retain fluid in the fabric. However, when 0.9% saline water is used, the absorbency of Warp_b_5 to Warp_b_7 has an even worse performance than that of Warp_a_1 to Warp_a_4 because the back surface structure of the former set of samples is different from that of the latter set of samples. The mesh of Warp_b_5 to Warp_b_7 is denser and the pores are smaller. Therefore, they will be further affected by the presence of the salt particles in the saline solution, and it will be more difficult for water to pass through them. As mentioned before, absorbency is greatly affected by the composition of the material. The results of the weft knitted spacer fabrics indicate that they have less absorbency with increasing elastane content as elastane is a waterproof human-made fiber. In addition, the ability of the weft knitted spacer fabrics to absorb water and the 0.9% saline water is more or less the same as the fabric structure of their face and back is denser than that of the warp knitted spacer fabrics. Therefore, there is less space to retain fluids and fluids cannot easily pass through them even though these are only small salt particles.

Based on the results, the absorption ability of spacer fabrics excels that of the wound dressings with a waterproof layer, that is, Dressings 3, 5, 6 and 7. Although the spacer fabrics, which are fabricated with polyester, have less absorbency than the dressings which are made of highly absorbent materials, that is, Dressings 1 and 8, the wicking ability of the spacer fabrics contributes to their strength as wound dressings because exudate may be drawn through the fabric and externally transferred, instead of being trapped within the fabric which may increase the chances of bacteria growth.

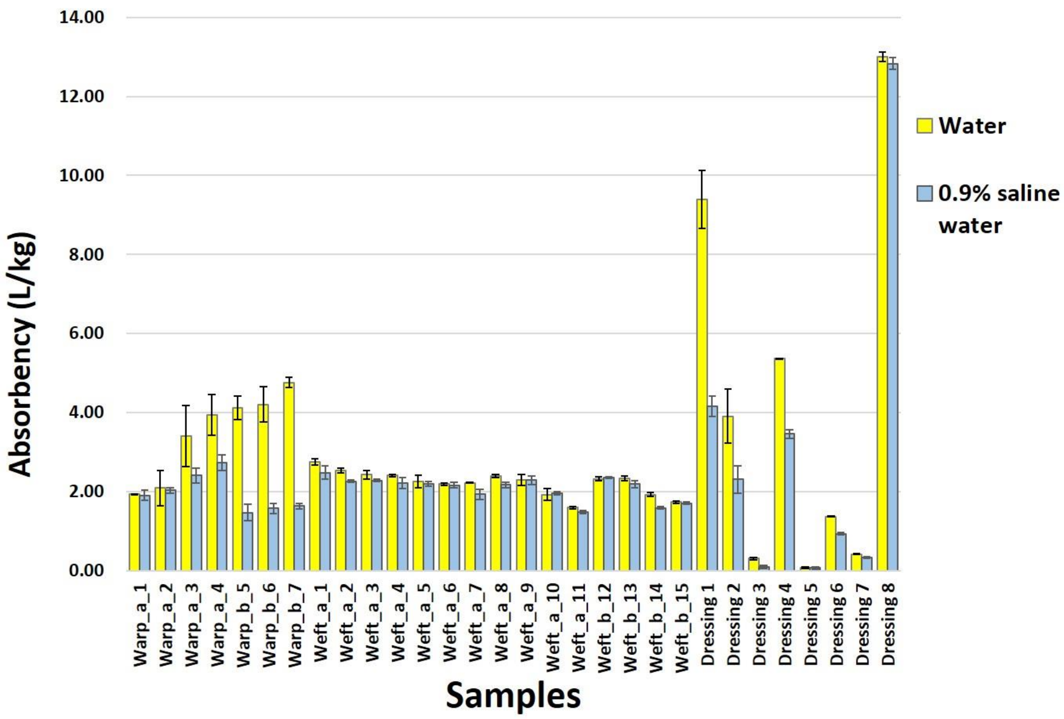


Figure 6.6 Absorbency results of different tested samples (Tong, Yip, & Yick, 2016; Tong et al., 2015)

Correlation testing was utilized to examine the effects of the type and structure of spacer fabrics, composition, and areal and bulk densities on the absorbency of spacer fabrics as shown in Table 6.3 The results showed that there are significant differences between absorbency and the type and structure of the fabric, composition, and areal and bulk densities ($p<0.05$). The results also showed that the areal and bulk densities are negatively correlated with absorbency while a high polyester content may increase the absorbency of fabrics.

Table 6.3 Correlation results of absorbency of spacer fabrics

Correlations

			Absorbency	Warp_weft	Composition	Areal_mass	Bulk_density
Kendall's tau_b	Absorbency	Correlation Coefficient	1.000	-.392*	.586**	-.481**	-.385*
		Sig. (2-tailed)	.	.032	.000	.002	.012
		N	22	22	22	22	22

6.4 Wettability

The wettability of wound dressings is an important criterion as it influences the ability of wound dressings to absorb wound fluids. The absorption rate indicates the rate that the wound dressings can take up wound fluids. Therefore, the wettability of existing wound dressings and warp and weft knitted spacer fabrics were evaluated.

6.4.1 Results and discussion

Wettability includes examining the contact angle of the testing liquid on a substrate and the rate that the liquid is absorbed. As the contact angle is influenced by adhesive and cohesive forces, a smaller contact angle means greater solid liquid interaction between the test sample and the liquid droplet as the liquid droplet spreads out over the tested surface. On the other hand, a large contact angle indicates that the solid liquid interaction is weak and the tested sample has low wettability. Table 6.4 shows the results of the measured contact angles and rate of absorption of the spacer fabrics and wound dressings. The wettability results show that most of the 3D weft knitted spacer fabrics have better wettability than most of the existing wound dressings with an adhesive layer except for Weft_a_9, Weft_a_11, Weft_b_12 and Weft_b_14. This is because the contact angles of spacer fabrics are smaller than those of the wound dressings which proves that the solid liquid interaction of the former is greater and the water droplet can spread out onto the fabric surface. The results also indicate that the overall wettability of the weft knitted spacer fabrics is higher than that of the warp knitted spacer fabrics as most of the former can absorb the water droplet immediately or within 5 seconds after the droplet is transferred onto their surface. Dressings 4 and 8 have the best wettability performance among all of the wound dressing samples followed by Dressings 1 and 2. Wound dressings with an adhesive layer, that is, Dressings 3, 5, 6 and 7, have larger contact angles which means that the water droplet did not spread much after it was transferred onto the material surface due to the weak solid liquid interaction.

Based on the above results, most of the weft knitted spacer fabrics have a good or even better wettability performance than the existing wound dressings that do not have an adhesive layer. Although Weft_a_9, Weft_a_11, Weft_b_12 and Weft_b_14 have the poorest wettability among all of the weft knitted spacer fabrics, their wettability is comparable to the dressings with a waterproof layer, that is, Dressings 3, 5, 6 and 7.

Table 6.4 Wettability results of different tested samples

	Contact angle (degree)	Absorption rate
Warp_a_1	N/A	Instant
Warp_a_2	102.57	> 30 seconds
Warp_a_3	102.00	> 30 seconds
Warp_a_4	107.11	> 30 seconds
Warp_b_5	104.40	> 30 seconds
Warp_b_6	110.36	> 30 seconds
Warp_b_7	N/A	Instant
Weft_a_1	N/A	< 5 seconds
Weft_a_2	N/A	< 5 seconds
Weft_a_3	N/A	< 5 seconds
Weft_a_4	N/A	< 5 seconds
Weft_a_5	N/A	Instant
Weft_a_6	N/A	< 5 seconds
Weft_a_7	N/A	Instant
Weft_a_8	N/A	Instant
Weft_a_9	107.67	> 30 seconds
Weft_a_10	N/A	Instant
Weft_a_11	108.29	< 30 seconds
Weft_b_12	106.22	< 30 seconds
Weft_b_13	N/A	Instant
Weft_b_14	109.25	> 30 seconds
Weft_b_15	N/A	Instant
Dressing 1	N/A	< 5 seconds
Dressing 2	N/A	< 5 seconds
Dressing 3	100.29	> 30 seconds
Dressing 4	N/A	Instant
Dressing 5	92.22	> 30 seconds
Dressing 6	87.11	> 30 seconds
Dressing 7	83.71	> 30 seconds
Dressing 8	N/A	Instant

6.5 Water Vapor Permeability Test

Water vapor permeability (WVP) or moisture transmission is important for wound dressings. WVP is regarded as one of the basic criteria of wound dressings as it allows ventilation of the wound by transferring wound exudates and sweat away from surrounding areas of the wound. Therefore, the WVP of existing wound dressings and warp and weft knitted spacer fabrics was evaluated.

6.5.1 Results and Discussion

WVP was examined by determining the amount of water vapor that passes from the skin to the outside environment through a fabric. A larger WVP value means that more water vapor has passed through the fabric. The results of the WVP testing of all the tested samples are shown in Figure 6.7. The bulk density and structure of the fabric are highly correlated with their WVP (Onal & Yildirim, 2012). In general, more water vapor passes through the spacer fabrics than those wound dressings except for Dressing 8. The pores on the spacer fabrics allow water vapor to pass through more easily. As more pores are found on the warp knitted spacer fabrics than the weft knitted spacer fabrics, the former have a larger WVP value. Furthermore, Warp_a_3 and Warp_a_4 have the lowest bulk density, so that water vapor will not be easily trapped in the fabric. Therefore, they have the highest WVP. When two different structures of the warp knitted spacer fabrics are compared, it can be observed that Warp_a_1 and Warp_a_2 have more pores on the fabric back, so that water vapor readily passes through them, even though their bulk density is greater than that of Warp_b_5 to Warp_b_7. Dressing 8 has a similar or even better WVP in comparison to the spacer fabrics. It has the best WVP among all of the wound dressings. It is made up of several layers of non-woven fabrics. Although Dressing 8 is thick, it has a low bulk density. Therefore, its loose structure means that water vapor can easily pass through the material. Dressings 1 and 2, which have the lowest bulk density among the wound dressings, have a relatively high WVP as water vapor easily passes through the dressing. On the other hand, the rest of the dressings have an extremely low WVP because they have a larger bulk density and most have an adhesive layer which makes it impossible for water vapor to pass through. The results show that the average WVP of the spacer fabrics is higher than most of the wound dressings due to their fabric structure.

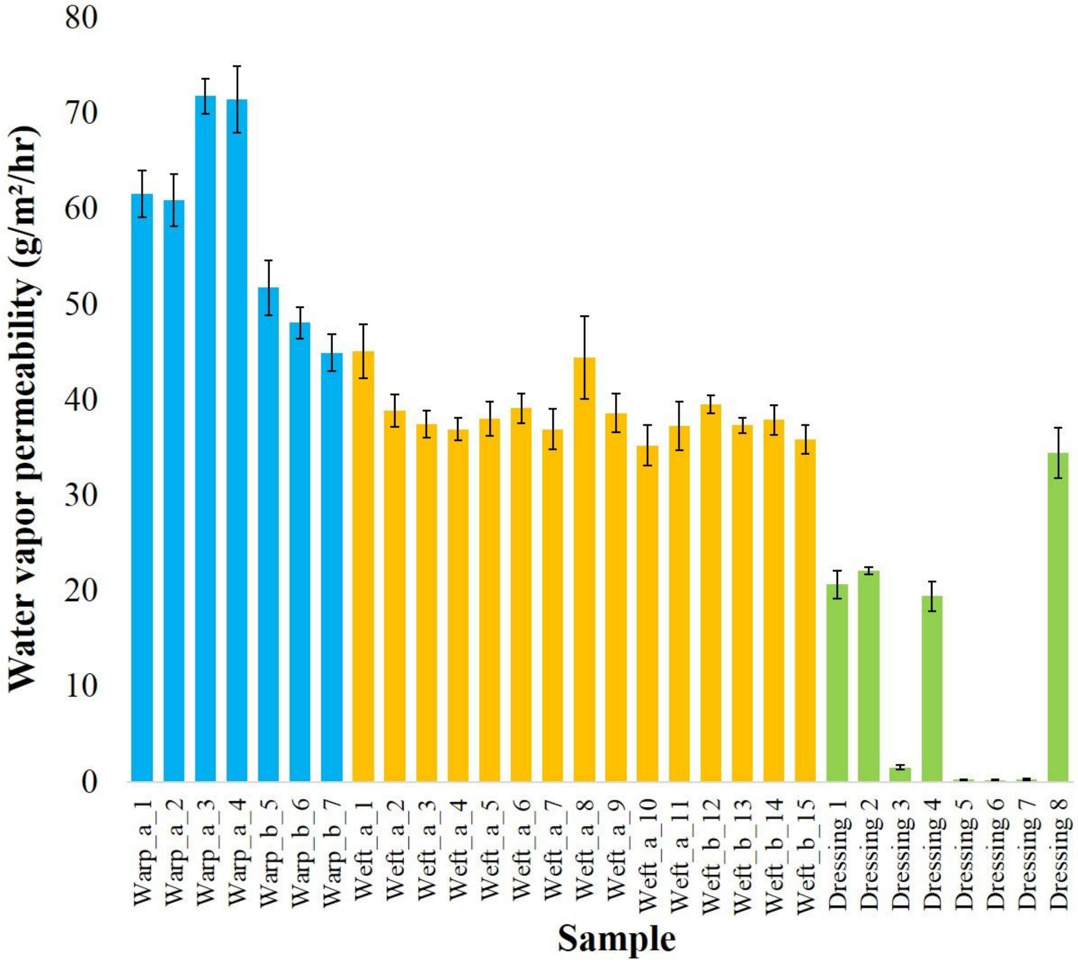


Figure 6.7 Water vapor permeability of different tested samples (Tong, Yip, & Yick, 2016; Tong et al., 2015)

Correlation testing was carried out to examine the effects of the type and structure of spacer fabrics, composition, and areal and bulk densities on the WVP among the spacer fabrics. The results showed that there are significant differences between the WVP and all of the variables ($p<0.05$) as shown in Table 6.5. Composition has a positive correlation with WVP while reduced areal and bulk densities may increase the WVP which is a negative correlation.

Table 6.5 Correlation results of water vapor permeability of spacer fabrics

Correlations

			Water_vapor_permeability	Warp_weft	Structure	Composition	Areal_mass	Bulk_density
Kendall's tau_b	Water_vapor_permeability	Correlation Coefficient	1.000	-.661**	-.638**	.614**	-.784**	-.498**
		Sig. (2-tailed)	.	.000	.000	.000	.000	.001
		N	22	22	22	22	22	22

6.6 Air Permeability Test

As mentioned above, air permeability is one of the most important basic criteria for a good absorbent layer in a wound dressing so as to provide a ventilated environment for wounds. Therefore, air resistance was examined to determine the amount of air that can pass through both the existing wound dressings and 3D knitted spacer fabric samples, and their results were also compared.

6.6.1 Results and Discussion

The air resistance (R) of all of the spacer fabrics and wound dressings was recorded and is shown in Figure 6.8. A higher R value indicates greater resistance of the fabric and that it is more difficult for air to pass through. Therefore, poor air permeability is the result. The air permeability of a fabric is highly correlated with its fabric density and thickness which are related to the fabric tightness (Yip & Ng, 2009). According to the R results, no data were recorded for Dressings 1 to 7 even when the largest holes were examined and the maximum range was used, which means that their R exceeds 500 kPa·s/m, thus indicating that they have very poor air permeability. Dressings 3, 5, 6 and 7 have a larger bulk density and an adhesive layer, so it is not easy for air to pass through and the result is that they have poor air permeability. In addition, Dressings 1, 2 and 4 have a greater thickness and higher bulk density values. Dressing 8 is the only dressing sample that allows air to pass through. When compared to the other dressings, although it is thicker, its bulk density is relatively low which shows that it has a more loose structure than the others and air can pass through.

In a comparison of the warp and weft knitted spacer fabrics, it is obvious that the former have higher air permeability due to their structure. Air can easily pass through their pores which means that the air permeability of all of the warp knitted spacer fabrics is similar. The R of Warp_b_5 to Warp_b_7 is greater as their fabric back is denser than that of Warp_a_1 to Warp_a_4. More air is trapped between the fabric, which results in poor air permeability. Apart from the fabric structure, the results showed that thickness will also greatly affect the air permeability as R increases with increased fabric bulk density which is evident in Warp_a_1 to Warp_a_4. The bulk density increases with increased R and poorer air permeability is the result. Weft_a_1 has better air permeability than the other weft knitted spacers as it is relatively less thick. As the bulk density of Weft_b_15 is the highest among all of the weft knitted spacer fabrics, its air permeability is the poorest. Although the weft knitted spacer fabrics have two different structures, only their interlayers are different while both their face and back are plain knitted fabric. Therefore, they have similar size pores on their fabric surface. The variation in their air permeability is attributed to their thickness, bulk density and the angle of their spacer yarn. In this study, the air permeability of the spacer fabrics used is comparable to that of existing wound dressings and even excels some of them.

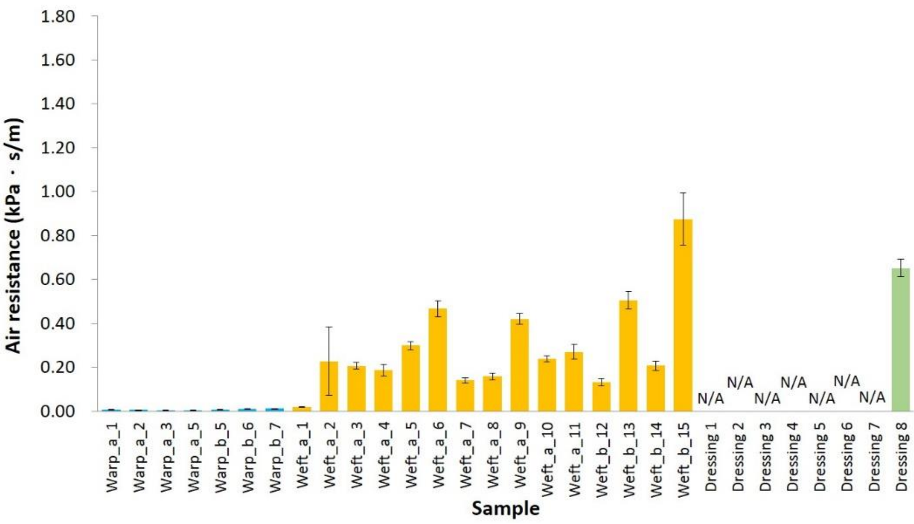


Figure 6.8 Air resistance of different tested samples (Tong, Yip, & Yick, 2016; Tong et al., 2015)

Correlation testing was carried out to examine the effects of fabric type, fabric structure, composition, thickness, areal and bulk densities and spacer yarn angle in the course-wise and wale-wise directions of the spacer fabrics on the air resistance performance. The results are shown in Table 6.6 It can be seen that there are significant differences between the air resistance and the listed knitting parameters ($p<0.05$). The results show that all of the knitting parameters have a positive correlation with the air permeability of the spacer fabrics except for composition. Increasing areal and bulk densities and spacer yarn angles increase the air resistance which means that it is more difficult for air to pass through the fabric. On the other hand, the polyester content in the spacer fabrics reduces their air resistance. The correlation between air permeability and thickness is not as high as that of the other parameters ($r=0.335$, $p=0.030$).

Table 6.6 Correlation results of air permeability of spacer fabrics

Correlations

			Air_permeability	Warp_weft	Structure	Composition	Thickness	Areal_mass	Bulk_density	Spacer_yarn_angle_coursewise	Spacer_yarn_angle_walewise
Kendall's tau_b	Air_permeability	Correlation Coefficient	1.000	.674**	.669**	-.614**	.335*	.628**	.619**	.524**	.636**
		Sig. (2-tailed)	.	.000	.000	.000	.030	.000	.000	.001	.000
		N	22	22	22	22	22	22	22	22	22

6.7 Thermal Conductivity Test

Thermal conductivity is critical for an ideal wound dressing as it helps to enhance good thermal regulation of the wound environment and reduces the accumulation of heat build-up. Therefore, the thermal conductivity of the existing wound dressings was studied and the results of the warp and weft knitted spacer fabrics were compared with those of the wound dressings.

6.7.1 Results and Discussion

Thermal conductivity is indicative of the amount of heat transferred from the skin to the fabric surface. Therefore, a higher thermal conductivity value means that the fabric sample has a better performance in dissipating heat away from the skin which imparts a cooling effect (Onal & Yildirim, 2012; Robinson, 2000; Yip & Ng, 2009). Figure 6.9 shows the results of the thermal conductivity testing for all the tested samples. According to some of the researchers in the literature, thermal conductivity is directly proportional to the thermal conductivity of the individual fibers, fabric density and thickness (Delkumburewatte & Dias, 2009; Mao & Russell, 2007; Yip & Ng, 2009). In consideration that all of the spacer fabrics in this study are fabricated with polyester, the differences in their thermal conductivity are due to their thickness. The results showed that the thermal conductivity of the spacer fabrics increases with increasing fabric thickness. Weft_a_10 has a higher thermal conductivity followed by Weft_a_7, Weft_a_8 and Weft_a_11 as they are the thickest among both the warp and weft knitted spacer fabrics. Although Warp_b_7 is thick, its bulk density is low. Therefore, its thermal conductivity is the highest among the warp knitted spacer fabrics but lower than most of the weft knitted fabrics. The results show that apart from thickness, fabric thermal conductivity is related to bulk density. A higher bulk density will mean that there is less space to trap air, therefore, it will be easier to transfer heat away from the fabric. Based on the results obtained, the thermal conductivities of the spacer fabrics are similar, but lower than those of the wound dressings, especially Dressings 3, 6 and 7 because they have an extremely high bulk density compared to the others. In addition, there is an adhesive layer on Dressings 3, 6 and 7 which makes it more difficult for heat conduction. The results show that the thermal conductivity of 3D knitted spacer fabrics is comparable to that of the existing wound dressings.

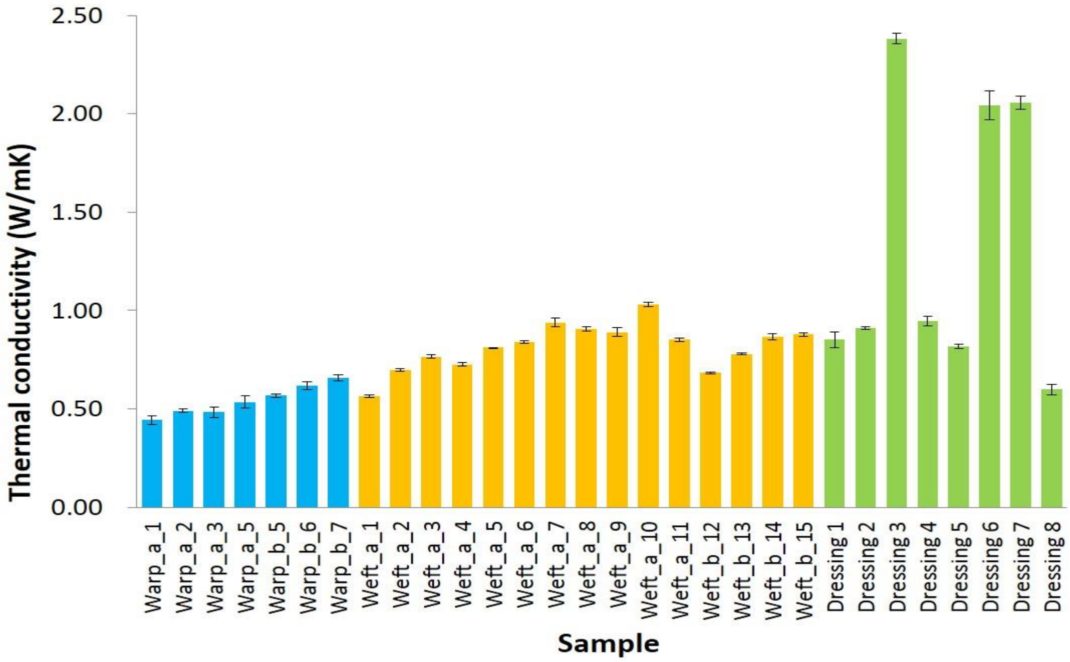


Figure 6.9 Thermal conductivity of tested samples (Tong, Yip, & Yick, 2016; Tong et al., 2015)

Correlation testing was carried out to examine the effects of the fabric type, fabric structure, composition, thickness, areal and bulk densities, and spacer yarn angle in the course-wise and wale-wise directions on the thermal conductivity of the spacer fabrics. The results are shown in Table 6.7. It can be seen that there are significant differences between the thermal conductivity and the knitting parameters provided above ($p<0.05$). The results indicate that all of the knitting parameters are positively correlated to the thermal conductivity of the spacer fabrics except for composition. The thickness, areal and bulk densities and spacer yarn angles increase the thermal conductivity of the fabrics. On the other hand, the composition is significantly negatively correlated to the thermal conductivity of the spacer fabrics as the polyester content reduces the thermal conductivity.

Table 6.7 Correlation results of thermal conductivity of spacer fabrics

Correlations

			Thermal_conductivity	Warp_weft	Structure	Composition	Thickness	Areal_mass	Bulk_density	Spacer_yarn_angle_coursewise	Spacer_yarn_angle_walewise
Kendall's tau_b	Thermal_conductivity	Correlation Coefficient	1.000	.636**	.544**	-.784**	.683**	.801**	.307*	.506**	.481**
		Sig. (2-tailed)	.	.000	.001	.000	.000	.000	.045	.001	.002
		N	22	22	22	22	22	22	22	22	22

6.8 Extensibility Test

As the conformity of a wound dressing to a wound is critical for wound healing and protecting the wound bed, extensibility is one of the most common ways to evaluate the conformity of wound dressings. Furthermore, when removing a wound dressing from the backing paper or applying the wound dressing onto a wound and making attempts to cover the wound, the dressing may be stretched in different ways. It is important that the wound dressing can maintain its original shape and structure without deformation. Therefore, in this section, the extensibility of existing wound dressings and 3D knitted spacer fabrics is evaluated.

6.8.1 Results and Discussion

Force was gradually exerted onto all of the spacer fabrics and wound dressings until their length extended by 80% at a fixed speed of 300 mm/min. Figure 6.10 shows the stress-strain curves of the warp knitted spacer fabrics. It can be observed that minimal force is required to greatly extend the warp knitted spacer fabrics which indicates that the extensibility of the warp knitted spacer fabrics is poor. This is because all of the warp knitted spacer fabric samples are 100% polyester. Initially, more force was needed to stretch the fabric samples in the wale-wise direction than those in the course-wise direction which is in agreement with the previous literature (Yip & Ng, 2008). However, most of them started to reach their breaking point after they were stretched 20% of their original length. Figure 6.11 shows the rupturing of the warp knitted spacer fabrics during elongation while Figure 6.12 shows the fabrics after 80% elongation. From Figure 6.12, it can be seen that the warp knitted spacer fabrics rupture after an 80%

stretch in the wale-wise direction while the fabrics show obvious deformation and poor recovery in the course-wise direction. On the other hand, less pressure is needed to stretch the samples in the course-wise direction, and they do not rupture even after being extended 80% over their original length. Warp_a_1 to Warp_a_4 have the same fabric structure and composition while Warp_b_5 to Warp_b_7 have different fabric structures but the same composition. From the results, it was found that if the fabric structure and composition are the same, increasing the areal mass increases the elasticity of the fabrics.

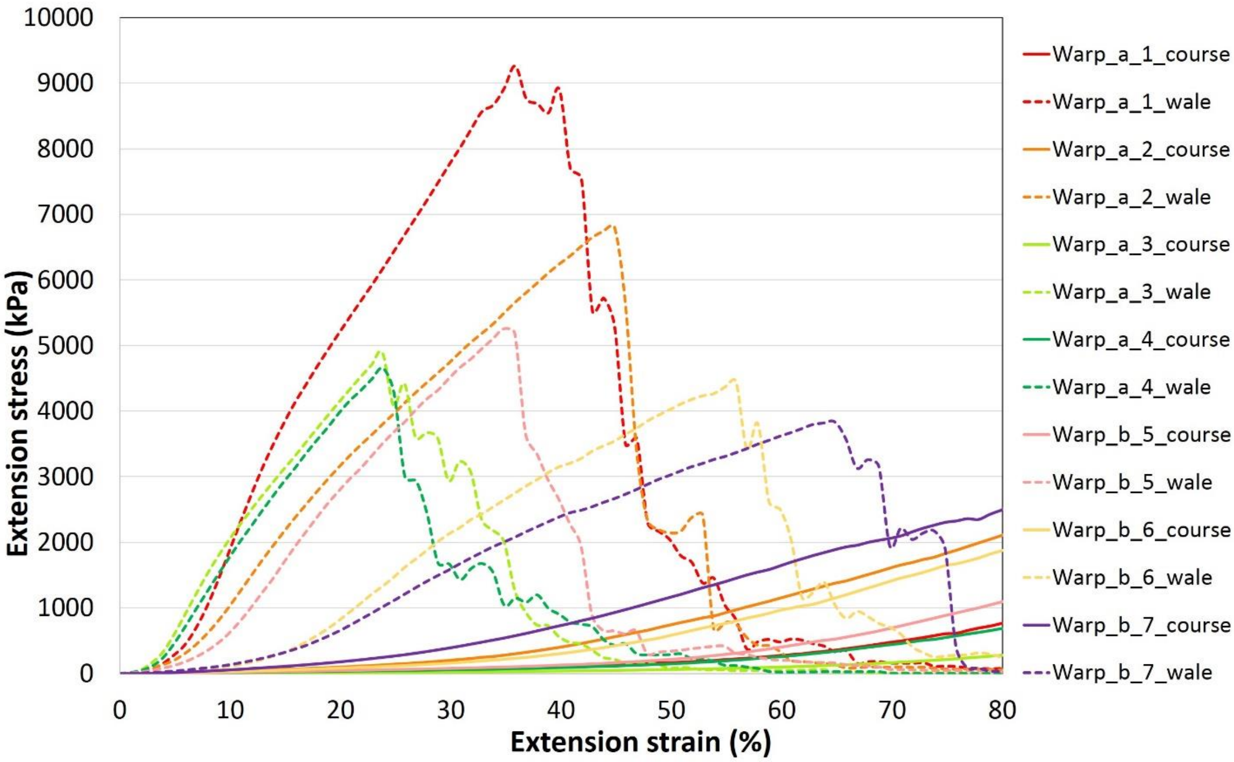


Figure 6.10 Stress-strain curves of three-dimensional warp knitted spacer fabrics

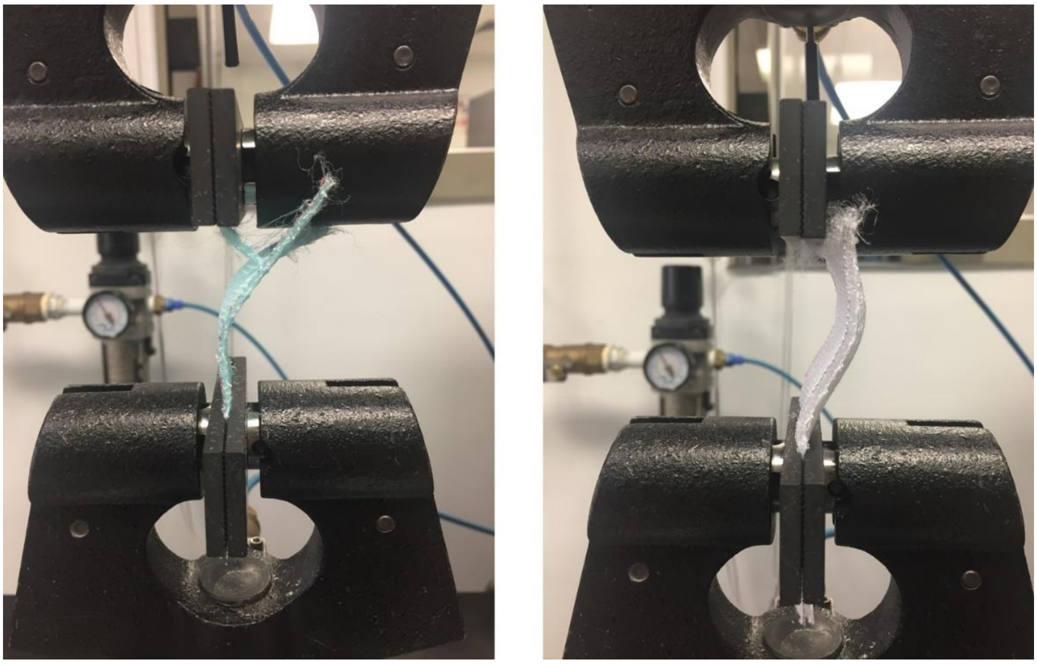


Figure 6.11 Rupturing of warp knitted spacer fabrics during stretching (Left: Warp_a_2; Right: Warp_b_5)

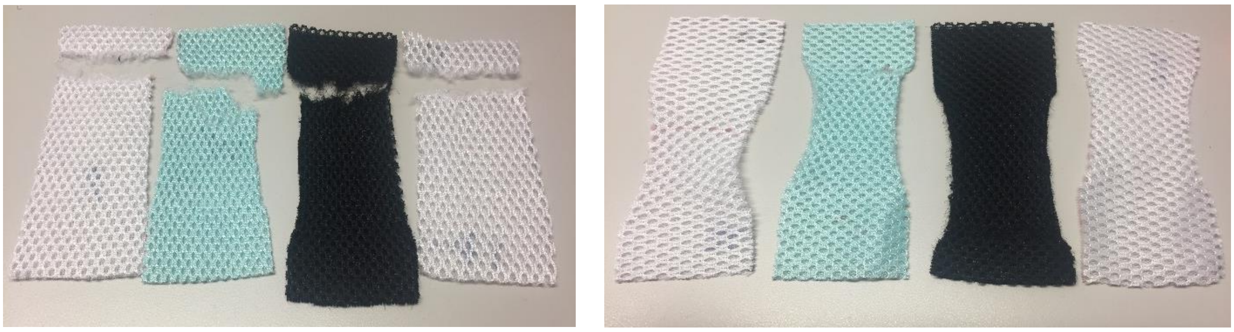


Figure 6.12 Warp knitted spacer fabric samples after stretching (Left: wale-wise direction; Right: course-wise direction)

On the other hand, the results of the weft knitted spacer fabrics show that more force is needed to stretch the fabric samples in the course-wise direction than in the wale-wise direction as shown in Figure 6.13. The results of Weft_a_1 also prove that fabrics with 100% polyester easily rupture during stretching like those warp knitted spacer fabrics as shown in Figure 6.14. Taking Weft_a_3, Weft_a_5 and Weft_a_9 as examples, they have the same fabric structure and composition. Increasing the areal mass increases the elasticity. This also agrees with the results of the warp knitted spacer fabrics. In addition, the results of Warp_a_3 and Warp_a_4 show that a thicker fabric increases the elasticity if the weft knitted spacer fabrics have the same structure and composition, and similar areal mass. This is also true for Weft_a_8 and Weft_a_9.

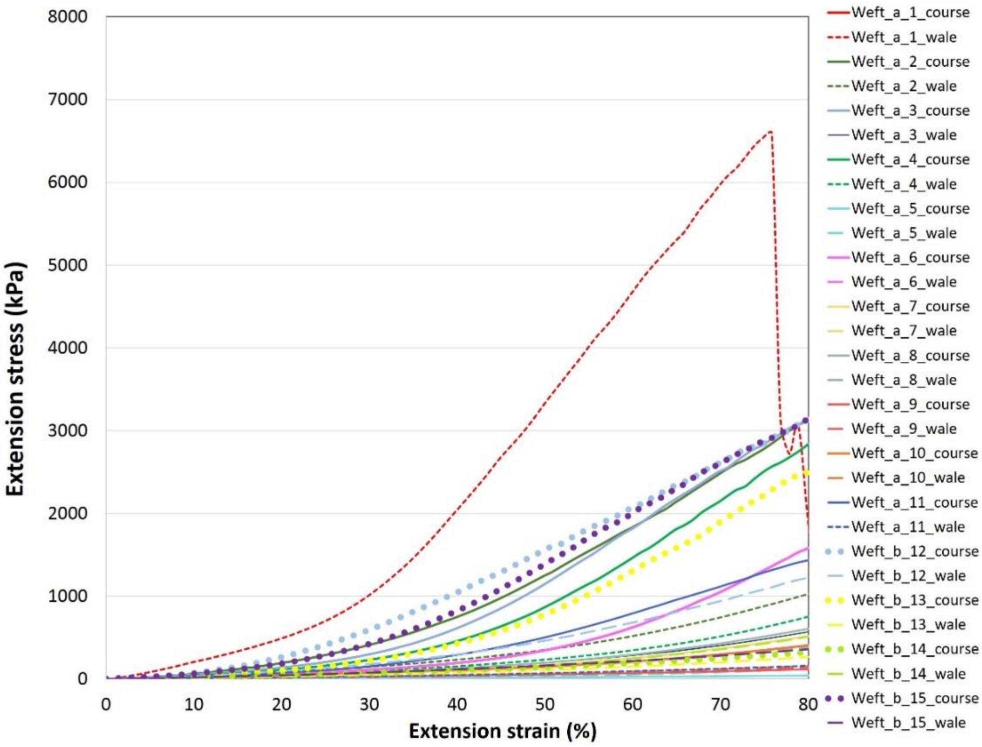


Figure 6.13 Stress-strain curves of three-dimensional weft knitted spacer fabrics

Figure 6.14 Weft_a_1 after stretched 80% (Left: wale-wise: Right: course-wise)

In order to compare the extensibility of the spacer fabrics and existing wound dressings, several spacer fabric samples with the best extensibility in both the course-wise and wale-wise directions were selected for further comparisons. According to the above results, the warp knitted spacer fabrics easily deform or even rupture during stretching. Therefore, they were not selected for further comparisons even if more pressure was needed to stretch them. According to the results of the weft knitted spacer fabrics, four samples with better extensibility performance in both directions were selected for comparison, including Weft_a_2, Weft_a_3, Weft_a_4 and Weft_b_12. Figure 6.15 shows the extensibility of these fours spacer fabrics and the existing wound dressings. From the results, Dressing 8 ruptures after 20% stretching and Figure 6.16 shows the ruptured Dressing 8 after 80% stretching. Due to its loose non-woven structure, it is not as strong as the other wound dressings. Dressings 3, 5, 6 and 7, which are the wound dressings with an adhesive layer, have better extensibility than those without the adhesive layer. Almost all of the spacer fabrics show better extensibility than the wound dressings in both the course-wise and wale-wise directions after being stretched 80%. In addition, the plotted trend of the extensibility of the weft knitted spacer fabrics tends to show increases when continuously stretched, while the plotted curves of the wound dressings reach their equilibriums after 20% stretching. The results show that the extensibility properties of the 3D knitted spacer fabrics are comparable to those of the existing wound dressings.

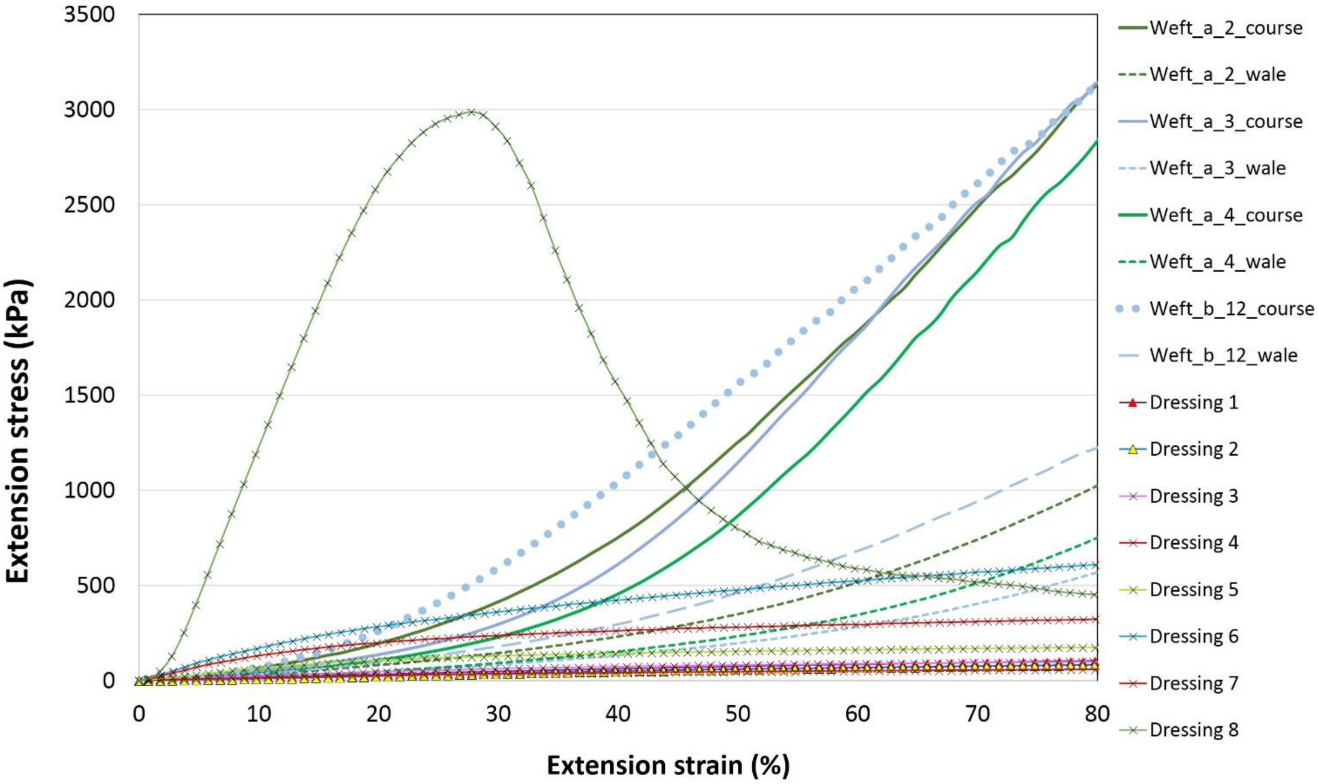


Figure 6.15 Extensibility curves of selected spacer fabrics and wound dressings

Figure 6.16 Dressing 8 after 80% stretching

6.9 Chapter Summary

The critical and necessary requirements of wound dressings for pressure ulcers have been taken into consideration in the work described in this chapter. A good wound dressing for pressure ulcers not only requires good absorbency, but also breathability and ability to regulate heat. Since pressure ulcer wounds are the focus in this study, wound dressings that not only absorb wound fluids but also provide a cushioning effect should be considered. In other to investigate the possibility of using 3D knitted spacer fabrics as a substitute material for the absorbent and cushioning layer of wound dressings, different warp and weft knitted spacer fabrics with different knitting parameters are selected and compared to existing wound dressings which are designed to absorb wound fluids and provide a cushioning effect for pressure ulcer wounds. In this study, compression resistance and absorbency are the two key properties of focus. Furthermore, the wettability, WVP, air permeability and thermal conductivity are examined. Moreover, the extensibility which is related to the conformity of the wound dressings to wounds is investigated.

Based on the results, the compression resistance of the weft knitted spacer fabrics is higher than that of the pressure ulcer wound dressings. This shows that spacer fabrics can provide a good cushioning effect to protect a fragile wound against mechanical collision. The absorbency of the spacer fabrics is comparable to Dressings 3, 5, 6 and 7 which have an adhesive layer. Although they have less absorbency than the wound dressings which are made of highly absorbent materials, such as Dressings 1 and 8, polyester has a wicking property which can draw wound exudates through the fabric rather than trapping the fluid inside the fabric. In addition, the wettability of most of the weft knitted spacer fabrics is better than or comparable to that of the existing wound dressings. The warp and weft knitted spacer fabrics show a better WVP performance than the existing wound dressings. In terms of breathability, the air permeability of the spacer fabrics excels that of the wound dressings due to their structure. Although the thermal conductivity of the spacer fabrics is lower than all of the dressings, they are still comparable to Dressings 1, 2, 4 and 5. The extensibility of the spacer fabrics used is therefore comparable to that of the existing wound dressings or even excels some of them.

In order to identify the spacer fabric for further study, the overall physical performance of the spacer fabrics are compared and listed in Tables 6.8 to 6.10. A spacer fabric with good overall physical performance especially in compression and absorbency would be chosen. In accordance with the results in Table 6.8 Weft_a_8 needs more stress to reduce its thickness in different compressive strains which indicates that it has the best compression resistance among all spacer fabrics. Therefore, it can retain its thickness under larger pressure. Table 6.9 shows the performance of spacer fabric in absorbency, wettability, water vapor permeability, air permeability and thermal conductivity tests. The absorbency of Weft_a_8 is comparable or even excel than most of the spacer fabrics. In wettability test, Weft_a_8 can absorb the water droplet instantaneously indicating that its absorption rate is higher than those spacer fabrics with lower wettability. Although Weft_a_8 does not allow as much water vapor as warp knitted spacer fabrics, its water vapor permeability results excel all of the weft knitted spacer fabrics except Weft_a_1. The air permeability and thermal conductivity performance of Weft_a_8 are comparable or even excel other spacer fabrics. According to Section 6.8, warp knitted spacer fabrics are ruptured after stretching to 80% of its original length. In Table 6.10, greater stress is needed to stretch the warp knitted spacer fabrics at the beginning. However, less stress is required when continuously stretched. The extensibility of Weft_a_8 in both coursewise and walewise directions is comparable or even excels some of the weft knitted spacer fabric. In accordance with the above results, Weft_a_8 has the best compression resistance and its absorbency and wettability are also excellent. The water vapor permeability, air permeability, thermal conductivity and extensibility of Weft_a_8 are also good.

To conclude, the physical properties of 3D knitted spacer fabrics, especially weft knitted spacer fabrics, are comparable or even excel those of the existing wound dressings. This shows that spacer fabrics can fulfill the criteria for wound dressings and it is possible that they can be used as a substrate for the absorbent and cushioning layer of wound dressings. The results discussed in this chapter also provide direction for the development of wound dressing composites. Weft_a_8 has good performance in overall physical experiments. Therefore, it is selected for further study.

Table 6.8 Compression stress of spacer fabrics at different compressive strains

	Compression stress (kPa)			
	Compression strain 20%	Compression strain 40%	Compression strain 60%	Compression strain 80%
Warp_a_1	0.35	1.03	2.35	5.05
Warp_a_2	1.35	5.37	9.40	22.50
Warp_a_3	1.70	3.02	9.07	32.58
Warp_a_4	0.35	3.37	8.73	14.10
Warp_b_5	0.68	4.7	8.73	11.42
Warp_b_6	4.05	8.07	11.08	22.15
Warp_b_7	6.05	8.73	9.75	13.78
Weft_a_1	6.40	21.83	32.23	42.30
Weft_a_2	6.05	12.42	17.12	26.53
Weft_a_3	4.38	14.10	17.12	27.88
Weft_a_4	6.05	23.18	29.88	34.58
Weft_a_5	10.75	21.15	27.20	40.28
Weft_a_6	7.40	23.50	32.58	70.15
Weft_a_7	6.40	40.95	66.80	86.60
Weft_a_8	35.93	81.90	86.92	170.48
Weft_a_9	27.20	36.92	41.95	65.77
Weft_a_10	20.48	34.25	43.97	76.53
Weft_a_11	8.73	21.5	31.55	55.73
Weft_b_12	2.70	8.07	12.78	17.45
Weft_b_13	28.87	39.95	40.95	71.82
Weft_b_14	22.15	38.27	45.32	55.73
Weft_b_15	20.48	39.60	46.65	60.42

Table 6.9 Summary of the results of absorbency, wettability, water vapor permeability, air permeability and thermal conductivity tests

	Absorbency (L/kg)		Wettability (degree)	Water vapor permeability ($g/m^2/hr$)	Air permeability (kPa·s/m)	Thermal conductivity (W/mk)
	Distilled water	Normal saline water				
Warp_a_1	1.9282	1.8993	N/A (instant absorbed)	61.6232	0.0068	0.4432
Warp_a_2	2.0846	2.0261	102.57	60.9606	0.0063	0.4906
Warp_a_3	3.4001	2.4059	102	71.834	0.0047	0.4835
Warp_a_4	3.9383	2.7295	107.11	71.5008	0.0037	0.5349
Warp_b_5	4.1168	1.4675	104.4	51.7919	0.0085	0.568
Warp_b_6	4.2052	1.5705	110.36	48.1244	0.0117	0.6173
Warp_b_7	4.7606	1.6356	N/A (instant absorbed)	44.9808	0.0125	0.6578
Weft_a_1	2.7503	2.4798	N/A (absorbed < 5 seconds)	45.1273	0.0198	0.5641
Weft_a_2	2.5260	2.2540	N/A (absorbed < 5 seconds)	38.9409	0.2282	0.698
Weft_a_3	2.4261	2.2773	N/A (absorbed < 5 seconds)	37.4777	0.2067	0.7651
Weft_a_4	2.4039	2.2061	N/A (absorbed < 5 seconds)	36.99	0.1872	0.7252
Weft_a_5	2.2507	2.1992	N/A (instant absorbed)	38.0425	0.299	0.8104
Weft_a_6	2.1865	2.1625	N/A (absorbed < 5 seconds)	39.1719	0.4672	0.8407
Weft_a_7	2.2201	1.9317	N/A (instant absorbed)	36.9643	0.1402	0.9386
Weft_a_8	2.3894	2.1685	N/A (instant absorbed)	44.4599	0.159	0.9061
Weft_a_9	2.2907	2.2828	107.67	38.6842	0.4201	0.89
Weft_a_10	1.9242	1.9619	N/A (instant absorbed)	35.270138	0.2395	1.0301
Weft_a_11	1.5878	1.4799	108.29	37.3237	0.2708	0.8519
Weft_b_12	2.3203	2.3486	106.22	39.556974	0.1328	0.6827
Weft_b_13	2.3256	2.1882	N/A (instant absorbed)	37.400721	0.5062	0.7797
Weft_b_14	1.9194	1.5864	109.25	37.9398	0.2078	0.8657
Weft_b_15	1.7299	1.7057	N/A (instant absorbed)	35.937549	0.8756	0.8787

Table 6.10 Extensibility results of spacer fabrics at different extension strain

	Extensibility in coursewise direction (kPa)				Extensibility in walewise direction (kPa)			
	at 20%	at 40%	at 60%	at 80%	at 20%	at 40%	at 60%	at 80%
Warp_a_1	41.55	109.32	276.12	760.97	5183.88	8898.06	482.14	78.06
Warp_a_2	99.09	399.55	1146.93	2094.2	3145.11	6244.66	337.05	57.95
Warp_a_3	15.89	40.37	100.46	278.17	4127.31	562.65	47.76	7.31
Warp_a_4	36.33	91.35	256.68	679.91	3969.34	897.9	17.55	4.72
Warp_b_5	45.4	127.66	398.31	1082.42	2774.35	2656.37	204.52	31.37
Warp_b_6	83.31	303.59	964.55	1864.34	806.28	3154.76	2506.76	257.31
Warp_b_7	178.14	727.93	1638.92	2482.16	644.08	2386.25	3616.46	35.44
Weft_a_1	59.49	188.36	611.05	1563.85	486.67	2027.48	4657.56	2051.54
Weft_a_2	191.27	744.25	1825.07	3122.24	81.12	230.37	513.81	1019.7
Weft_a_3	134.65	605.08	1808.23	3137.93	44.88	131.97	280.07	562.94
Weft_a_4	106.49	449.77	1451.91	2821.83	48.09	151.6	343.21	745.88
Weft_a_5	7.18	15.3	26.11	40.54	9.87	24.3	53.09	130.6
Weft_a_6	59.49	188.36	611.05	1563.85	13.6	35.13	73.16	130.76
Weft_a_7	39.94	107.86	250.06	516.9	31.13	91.85	197.32	364.29
Weft_a_8	47.15	127.7	292	601.15	38.18	103.27	210.67	386.36
Weft_a_9	20.67	40.54	71.14	116.17	16.17	36.91	74.77	142.28
Weft_a_10	48.76	106.34	209.6	407.37	15.62	43.17	89.46	153.94
Weft_a_11	71.16	288.9	787.32	1431.46	17.13	47.44	94.94	157.93
Weft_b_12	256	1033.54	2059.85	3120.23	96	294.23	677.31	1218.31
Weft_b_13	99.93	420.21	1291.31	2490.14	26.83	74	149.03	266.55
Weft_b_14	42.85	101.6	190.14	320.63	38.19	109.03	245.14	507.08
Weft_b_15	182.61	816.43	1998.14	3136.56	43.3	115.26	215.81	356.98

Chapter 7 Pressure Simulation Model for Pressure Ulcer Wound Dressing

7.1 Introduction

With the advancement of computer technology, finite element analysis (FEA) is one of the most common methods used for simulation, which can be extended to that of pressure distribution. According to the results of the heel interface pressure measurements in Chapter 5, an upright foot position puts a bedridden elderly at a higher risk for heel pressure ulcer development than the abducted foot position. Also, based on the results, the pressure redistribution ability of both standard hospital mattress and pressure relieving mattress are not effective enough to redistribute the heel pressure. Therefore, the 3D knitted spacer fabric is proposed to be the absorbent and cushioning layer of wound dressing in order to enhance the redistribution of the heel interface pressure during wound healing process. Furthermore, based on the results in Chapter 6, Weft_a_8 has better performance in overall physical experiments than existing wound dressings especially compression resistance and absorbency. However, the pressure distribution of 3D knitted spacer fabric under heel loading is still not yet investigated.

In this study, an FEA is used to investigate the parameters of 3D knitted spacer fabrics from a biomechanical perspective in accordance with their materials and structures. A 3D biomechanical model is thus developed to numerically simulate the interface pressure between the heel and spacer fabric with a finite element model (FEM). In this model, the geometrical shape of the heel, and mechanical properties of the 3D knitted spacer fabrics and human body tissues are incorporated into a numerical stress analysis. The corresponding magnitude of the heel interface pressure and pressure distribution over the 3D knitted spacer fabrics are simulated. By changing the material properties and structure of the 3D knitted spacer fabrics based on the simulation model of the heel and 3D knitted spacer fabrics, the pressure relief and pressure distribution of the 3D knitted spacer fabrics induced by the heel can be accurately predicted. There are no time consuming wear trials with real subjects and the difficulties of subject recruitment are eliminated, all of which are also the benefits of using FEA.

7.2 Finite Element Model Building

7.2.1 Geometric Model of Heel and Spacer Fabric

7.2.1.1 Construction of Heel Model

The foot contours were obtained in the form of frames with the use of the Artec Eva 3D scanner (Artec-Group, Luxembourg). After pre-processing with Artec Studio 10 Professional software, the frames obtained were combined through 3D reconstruction and then modifications to the scanned image were carried out as shown in Figure 7.1. Then, SolidWorks was applied to crop parts of the heel to form the model and remove the blurry parts to reduce computational resources as shown in Figure 7.2.

Figure 7.1 Foot scan image

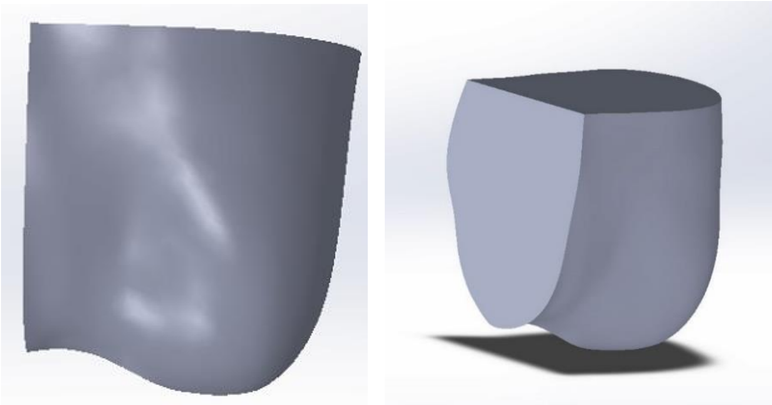


Figure 7.2 Different views of cropped heel scan

The heel of a skeleton model was scanned to obtain the contours of the heel bone as shown in Figure 7.3. The obtained contours of the heel bone were imported into SolidWorks. The imported model of the heel bone was rotated, deformed and resized by referring to an X-ray and CT scan from the literature to fit the heel model as shown in Figure 7.4 (Antunes, Dias, Coelho, Rebelo, & Pereira, 2008; The Editors of Encyclopædia Britannica, 2014). The heel and bone contours were then imported into Abaqus to create the FEM of the heel as shown in Figure 7.5.

Figure 7.3 Skeleton model used in heel scanning

Figure 7.4 CT scan (left) and X-ray (right) of foot used as reference (Antunes et al., 2008; The Editors of Encyclopædia Britannica, 2014)

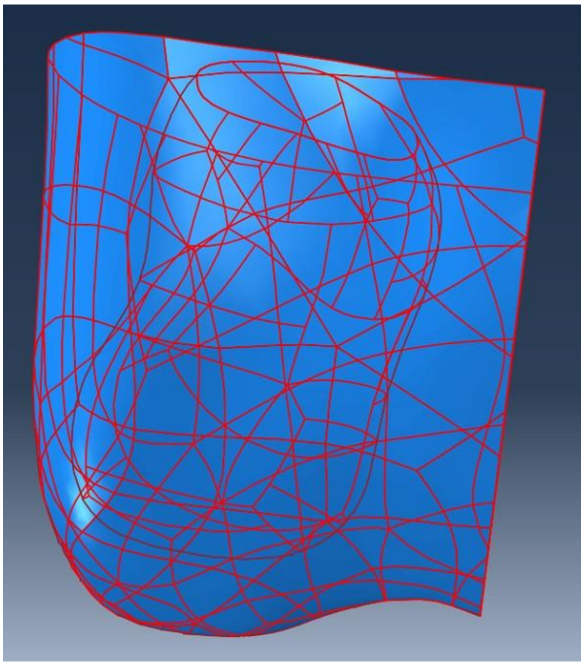


Figure 7.5 FEM of heel with heel bone

7.2.1.2 Geometric Model of Spacer Fabric

In accordance with the results of the testing carried out on the 3D knitted spacer fabric samples in Chapter 6, the overall physical performance of Weft_a_8 excels that of the others especially compression resistance. Therefore, Weft_a_8 was selected to develop the spacer fabric model. The images of the spacer fabric in Figure 7.6 are the microscopic views of Weft_a_8. Based on the parameters of the spacer fabric, a 3D spacer fabric model was created as shown in Figure 7.7. The 3D spacer fabric model was then imported into SolidWorks for further pre-processing and prepared to be further imported into Abaqus. The spacer fabric model was then imported into Abaqus as shown in Figure 7.8. However, the spacer fabric model was too complicated as there were too many curvatures and free forms of the model. The number of elements and the computational resource requirements increase with increasing complexity of a model. Previous studies have indicated that the deformation of the outer surface of spacer fabrics under loading is minimal (Hou et al., 2012; Y. Liu & Hu, 2015). Therefore, a simplified spacer fabric model was used rather than a detailed FEM. This simplified spacer fabric model was created in SolidWorks in which the top and bottom outer surfaces of the fabric were simplified into rectangular blocks. Figure 7.9 shows the micro views of the spacer fabric model created with SolidWorks. The spacer yarns are created in accordance with the information obtained from the microscopic images. This model is used to show the micro view of the behaviour of spacer yarns and analyse the structural changes or deformation of spacer yarns under loading. Figure 7.10 shows a micro view of the spacer fabric model in Abaqus (Spacer Model I). There is a compromise between the desired quality and computation cost (Sfarni, Bellenger, Fortin, & Guessasma, 2007). Here, a relatively simple model is developed which allows simulation to be quickly carried out instead of using a detailed model with relatively higher accuracy but longer processing time. Therefore, the resultant spacer fabric model was further simplified into 3 layers of rectangular block in order to provide a macro view of the entire spacer fabric (birdseye view). Based on the simulation of the macro view model (Spacer Model II), the overall behaviour of the spacer fabric under loading and the pressure distribution over the fabric can be investigated as shown in Figure 7.11.

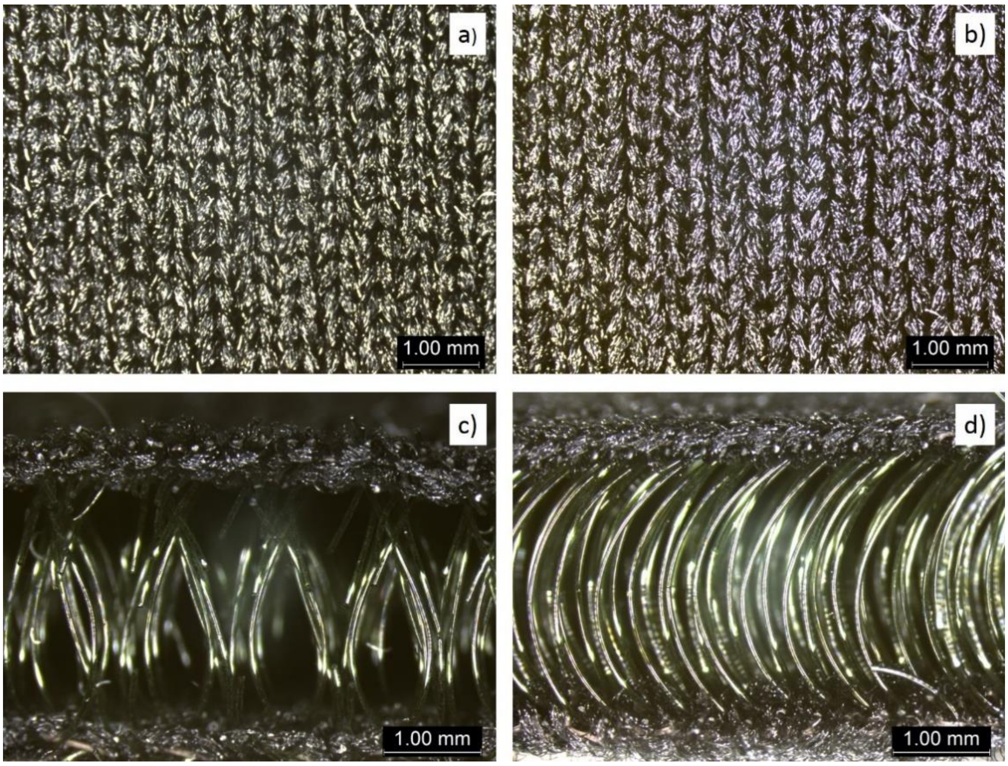


Figure 7.6 Microscopic view of Weft_a_8 (a: front view; b: back view; c: side view (coursewise); and d: side view (walewise))

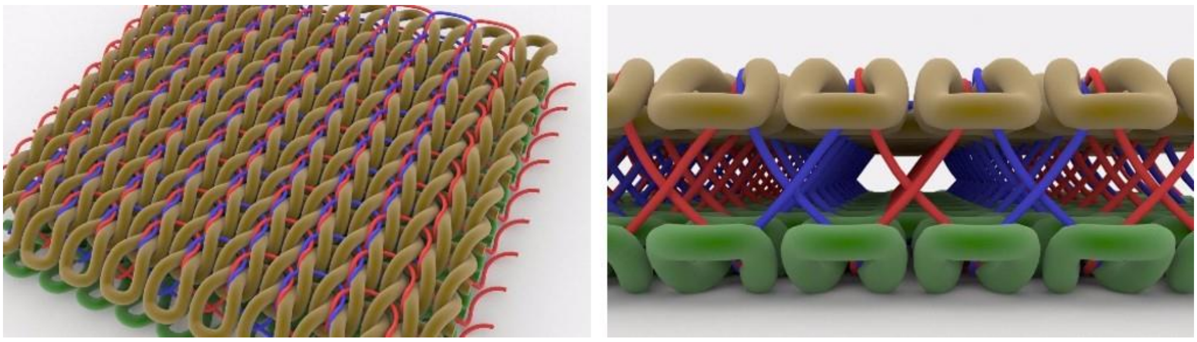


Figure 7.7 Three-dimensional knitted spacer fabric model

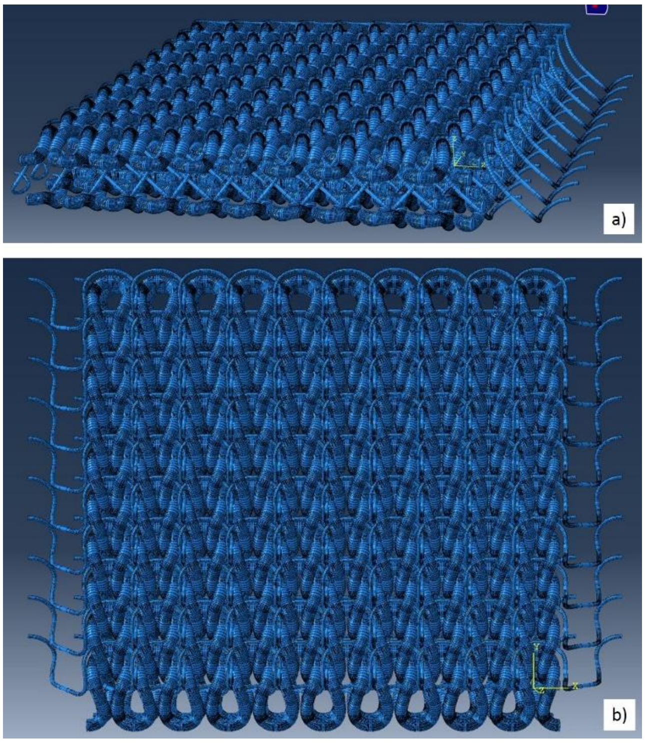


Figure 7.8 Different views of 3D spacer fabric model (a: side view and b: front view)

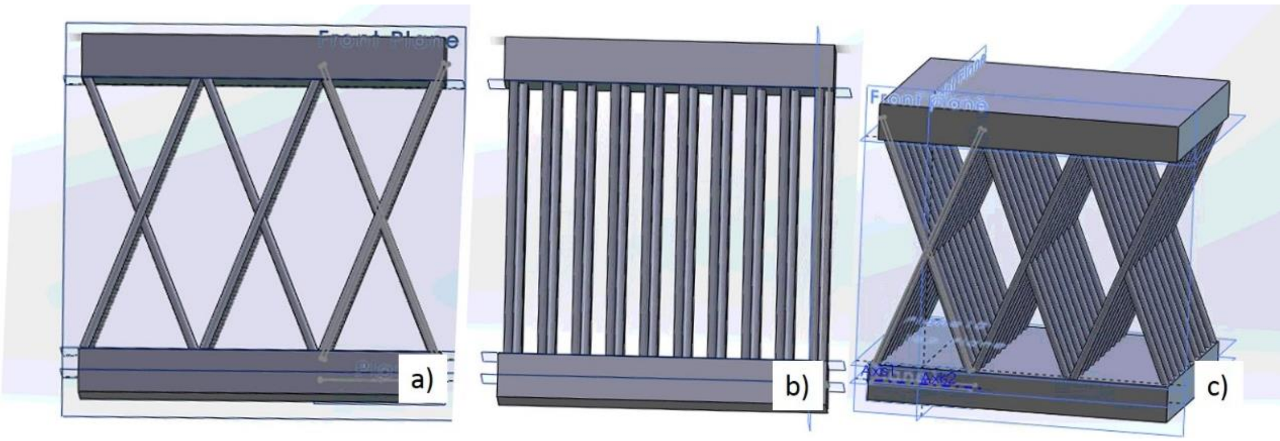


Figure 7.9 Micro view of spacer fabric model created with SolidWorks (a: side view (coursewise); b: side view (walewise); and c: birdseye view)

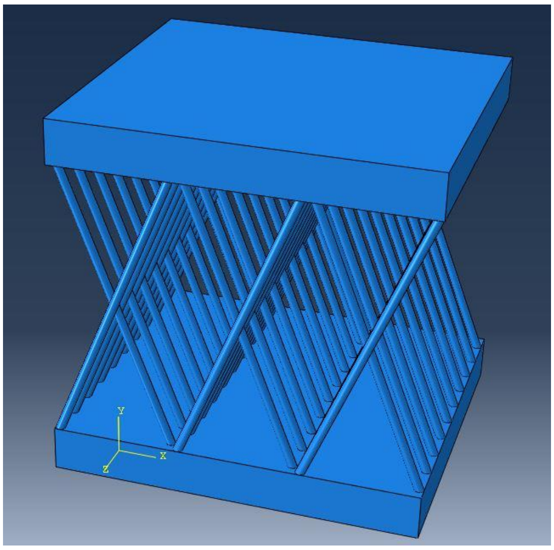


Figure 7.10 Micro view of spacer fabric model in Abaqus (Spacer Model I)

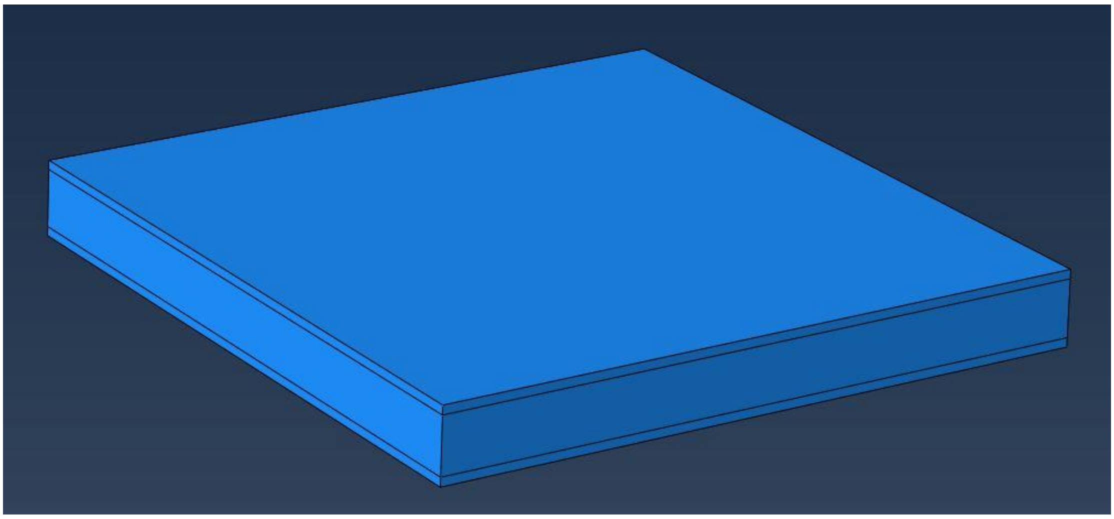


Figure 7.11 Macro view of rectangular block shaped spacer fabric model in Abaqus (Spacer Model II)

7.2.2 Defining Material Properties

The heel bone and tissue models and the spacer fabric model were imported into and assembled in Abaqus. The simulation model contained two material models including the heel and the spacer fabric. Previous works on the mechanical properties of the heel tissue and bone have defined the Young's Modulus ($\boldsymbol{E}$) and Poisson's ratio ($\boldsymbol{\nu}$) of the bone as 17 GPa and 0.3 respectively, and the Young's modulus (***E***) and Poisson's ratio (***ν***) of tissue as 216 kPa and 0.45 respectively (Klaesner, Commean, Hastings, Zou, & Mueller, 2001; Sopher et al., 2011; Yamada & Evans, 1970). The material properties adopted were used as references as the skin and dermis elasticity differ from person to person.

The compression resistance of the spacer fabric was examined with reference to Section 6.2 of Chapter 6. The Young's modulus (***E***) of the fabric was determined from the stress strain curve of the compression while the Poisson's ratio was defined based on previous research (Y. Liu & Hu, 2015). Figure 7.12 shows the compression stress-strain curve of the spacer fabric. The Young's modulus (***E***) and Poisson's ratio (***ν***) of the spacer fabric are 0.6493 MPa and 0.3 respectively (Y. Liu & Hu, 2015). The material properties used for the heel and spacer fabric models are shown in Table 7.1

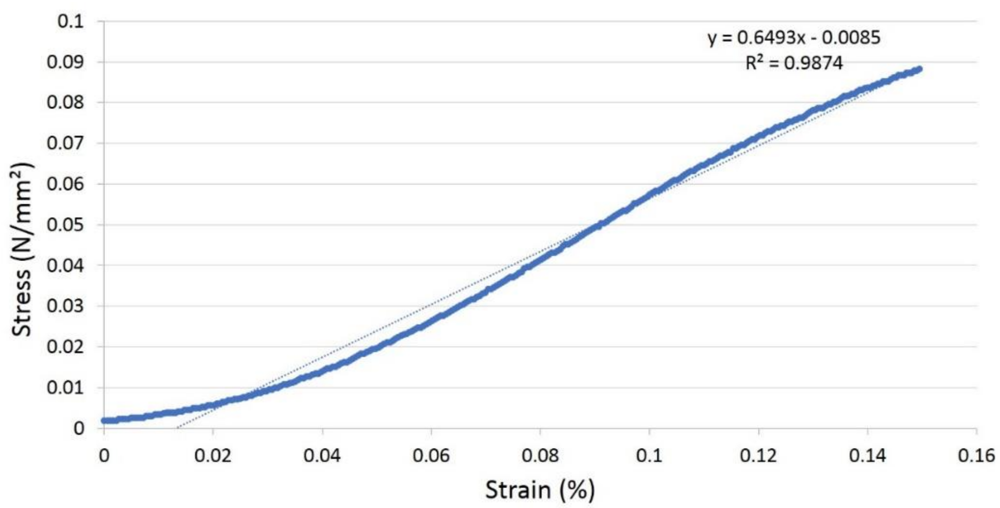


Figure 7.12 Compression stress-strain curve of spacer fabric

Table 7.1 Material properties of heel and spacer fabric models

	Young's Modulus (MPa)	Poisson's ratio
Heel bone	17000	0.3
Heel pad	0.216	0.45
Spacer fabric (Weft_a_8)	0.6493	0.3

7.2.3 Defining Mesh Element Type

The mesh elements used for the heel model were four-node linear tetrahedral elements with three degrees of freedom at each node (C3D4) as shown in Figure 7.13. The heel model consisted of 78,837 elements Figure 7.14 shows the meshed heel model. Spacer Model I consisted of 61,810 elements as shown in Figure 7.15. On the other hand, for Spacer Model II, 8-noded linear hexahedral elements with three degrees of freedom at each node (C3D8) were adopted. Spacer Model II consisted of 25,200 elements. Figure 7.16 shows the hexahedral elements used and Figure 7.17 shows Spacer Model II. Table 7.2 shows the topology and formulations of the heel model and Spacer Model II.

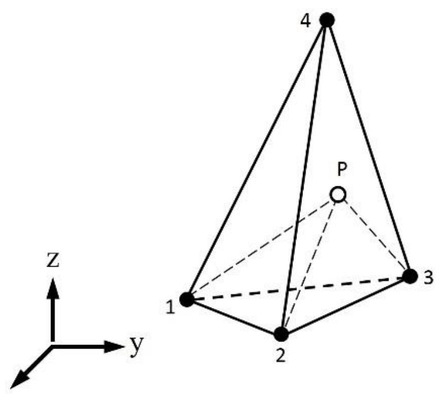


Figure 7.13 4-noded linear tetrahedral element

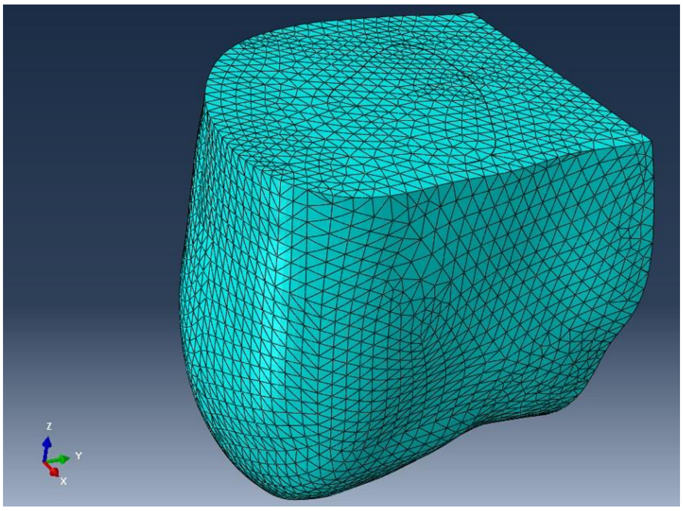


Figure 7.14 Meshed heel model

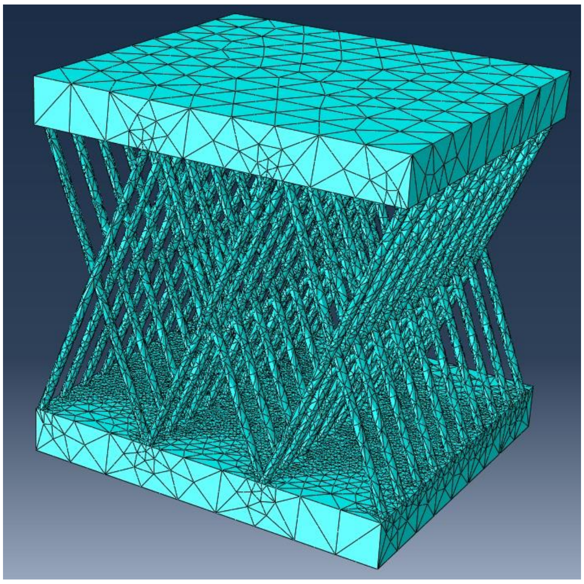


Figure 7.15 Meshed Spacer Model I

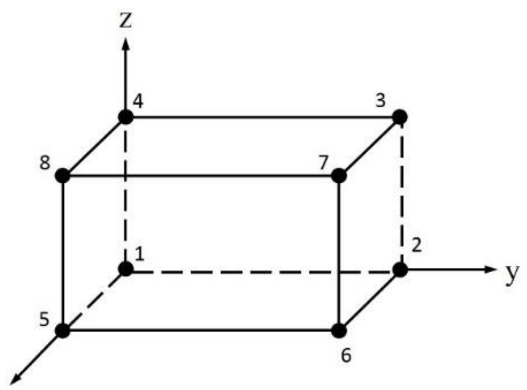


Figure 7.16 8-noded linear hexahedral element

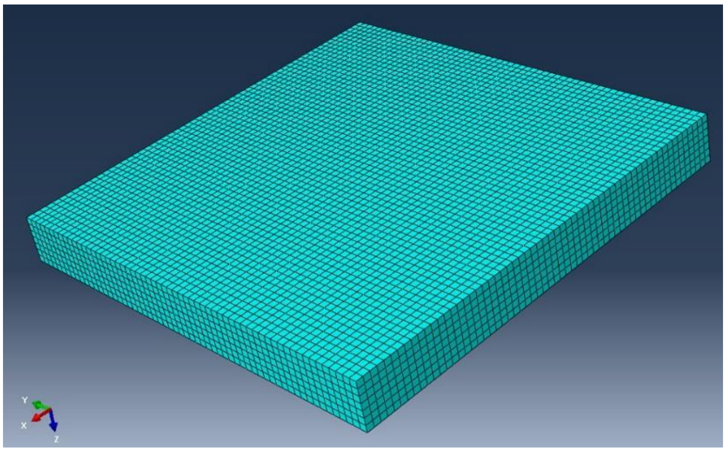


Figure 7.17 Meshed Spacer Model II

Table 7.2 Finite element topology and formulation

	Topology	Formulation
Heel model	3D- Tetrahedra (C3D4)	Linear
Spacer fabric model I	3D- Tetrahedra (C3D4)	Linear
Spacer fabric model II	3D- Hexahedra (C3D8)	Linear

7.2.4 Loading and Boundary Conditions of FEM

The boundary conditions for the FEM were defined based on real-life situations. As mentioned before, Spacer Model I was adopted to simulate the spacer yarn behaviour under loading for a micro view of the spacer yarns. On the other hand, Spacer Model II was used to predict the pressure distribution over the spacer fabric for a macro view of the entire fabric (birdseye view). Therefore, only pressure was applied on the top layer of the spacer fabric without any interaction with the heel in Spacer Model I. By contrast, Spacer Model II was interacted with the heel model in order to simulate a real-life situation in which heel loading is applied onto the spacer fabric.

The bottom surface of Spacer Model I was fixed by constraining all degrees of freedom to simulate placing the spacer fabric onto a surface as shown in Figure 7.18a. Only the bottom surface was fixed because this allows the top layer and the spacer yarn angle to move freely without any constraints so as to simulate the behaviour of the spacer yarn under loading Figure 7.18b shows the loading applied onto the surface of the top layer of Spacer Model I.

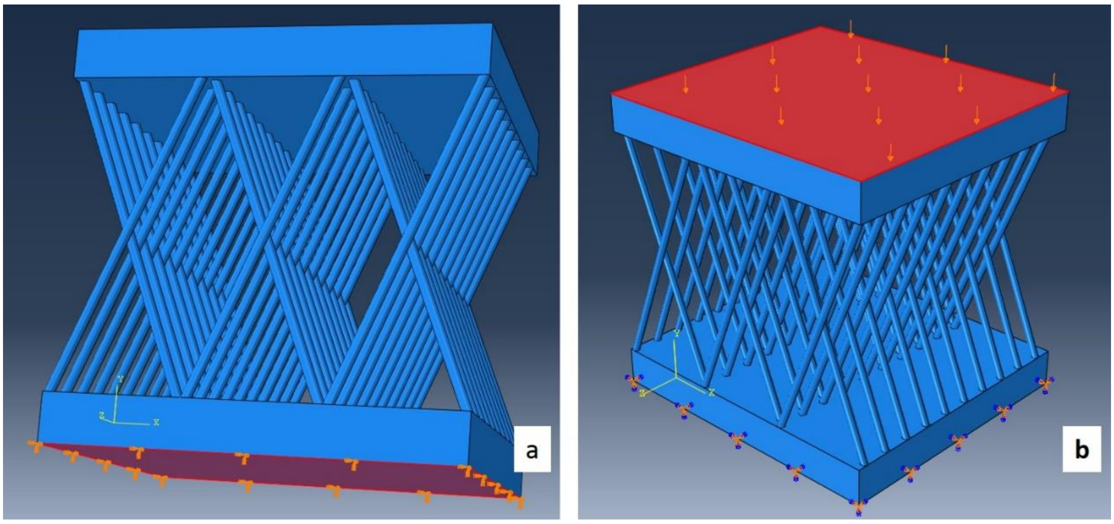


Figure 7.18 Boundary conditions (a) and loading (b) of Spacer Model I

On the other hand, Figure 7.19 shows the constraints of Spacer Model II and heel model respectively. The bottom surface of Spacer Model II was fixed by constraining all the degrees of freedom as shown in Figure 7.19a because in a real-life situation, the spacer fabric would be placed onto a supportive surface such as a mattress. For the four sides of Spacer Model B, all degrees of freedom were constrained except for the vertical axis in the Z direction as shown in Figure 7.19b. A set of nodes in the middle of the heel model was created and fixed by constraining its degrees of freedom except in the Z direction as shown in Figure 7.19c. Therefore, the heel model could move downwards when loading is applied.

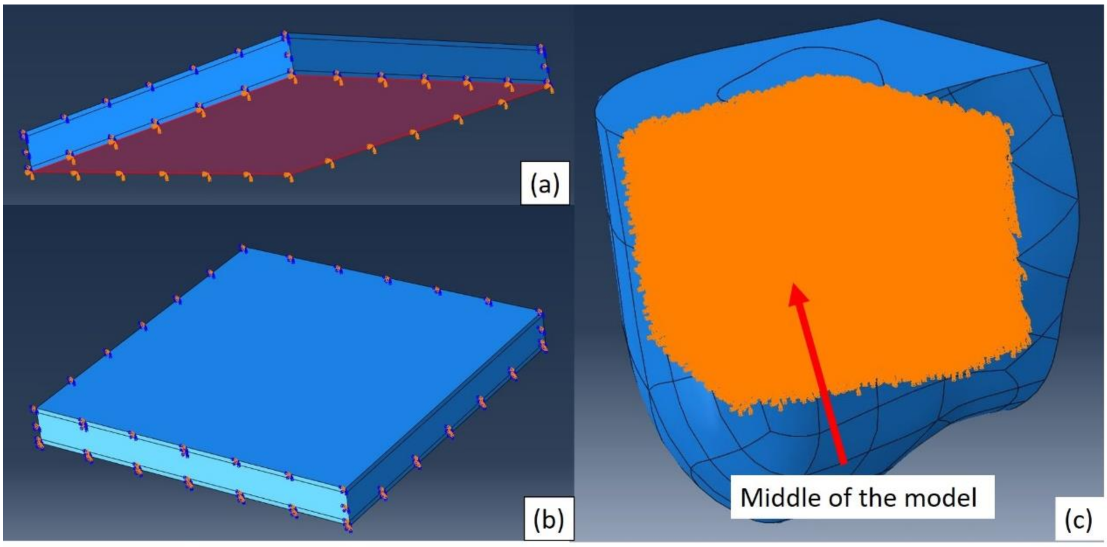


Figure 7.19 Boundary conditions of Spacer Model II (a: bottom surface and b: 4 sides) and heel model (c: middle of the model)

To simulate the inter-surface interactions between the heel and Spacer Model II, surface to surface interaction was adopted. Figure 7.20 shows the master surface and salve surface of the heel model and Spacer Model II. The heel is selected as the master surface while Spacer Model II is selected as the slave surface. The impact condition was set as a hard contact. According to previous researchers, hard contact assumes that two impact surfaces instantaneously acquire the same velocity in the direction of the impact (Yu et al., 2016). Penetration of the slave surface into the master surface at the constraint locations was restricted. The friction between the heel and Spacer Model II was neglected. Pressure was applied onto the surface of the heel model as shown in Figure 7.21. The amount of pressure applied was based on real situations which is 0.00981 MPa.

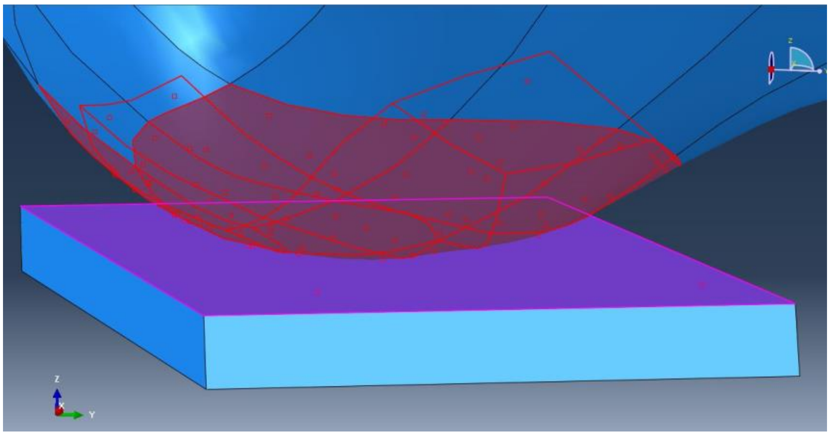


Figure 7.20 Master and slave surfaces for surface to surface interaction

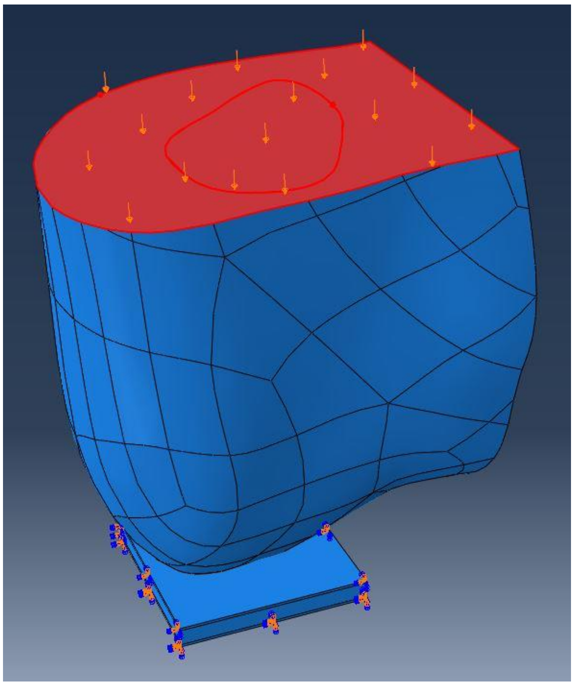


Figure 7.21 Pressure applied onto surface of heel model

7.2.5 Validation

Validation is important in simulation work as it verifies whether the simulation model can accurately predict the pressure distribution or the change in magnitude of pressure in real life situations. In this section, the simulated Spacer Model II and the heel model are validated. To validate the amount of pressure predicted by simulation, the heel interface pressure exerted onto the spacer fabric was measured and compared with the results of the FEM. A 3 cm x 3 cm pressure sensor (Novel Pliance X system, Germany) was used to measure the heel interface pressure on the spacer fabric. As the sensor has 9 sensing points, the spacer fabric was divided into 9 squares in a 1 cm x 1 cm grid accordingly as shown in Figure 7.22. The spacer fabric was placed under the heel of a subject when the subject was lying down on a hard surface. In the simulation, Spacer Model II was also divided into 9 squares into a 1 cm x 1 cm grid. In Figure 7.22 and 7.23, the notation of every column of grids is named A, B and C while every row is named 1, 2 and 3 respectively. The grid columns from top to bottom are A1, A2 and A3 while the grid rows from left to right are A1, B1 and C1 accordingly. Each square is further divided into 16 points and the pressure of these 16 points is averaged (Figure 7.23). The predicted pressure results on the spacer fabric model were then compared with the pressure sensor measurement results at the corresponding locations.

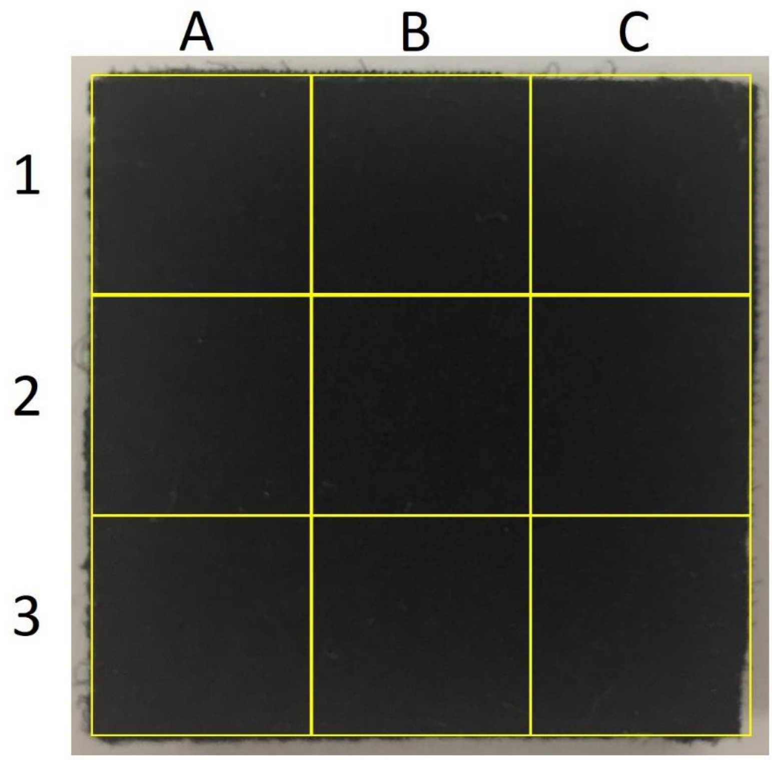


Figure 7.22 Grid squares on spacer fabric in accordance with 9 points of sensor

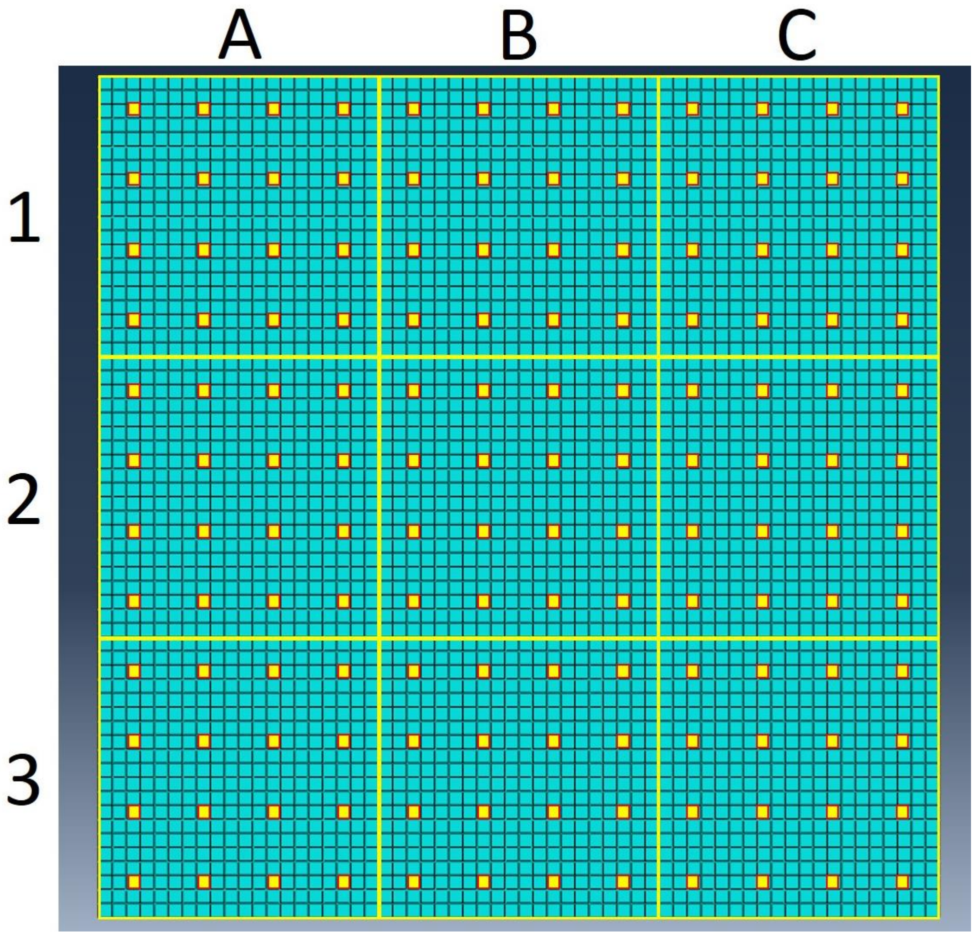


Figure 7.23 Grid squares and results of points of pressure

7.3 Results and Discussion

7.3.1 Spacer Model I

Spacer Model I was created to simulate the behaviour of the spacer yarns between two layers of fabric. Its displacement results in Figure 7.24 showed that when loading is applied onto the top layer of the spacer fabric, the top layer and the spacer yarns between the spacer fabric shift. In the simulation model, the top layer of the spacer fabric shifted to the right side under loading. Furthermore, the spacer yarns, i.e. those knitted from the top right to bottom left, shifted to the right side (see yellow arrows in Figure 7.24) while those knitted from the top left to bottom right shifted to the left side (see blue arrows in Figure 7.24. The results also indicated that the changes in displacement of the spacer yarns increase when they are in the peripheral areas. This could be due to the spacer yarn arrangement. In Figure 7.25, it can be seen that the spacer yarns are knitted in 2 directions; one from the top right to the bottom left (yellow arrows) and one from the top left to the bottom right layer (green arrows). In the centre of the spacer fabric, 2 spacer yarns are knitted in two different directions which provide more support for the fabric (orange circle). However, at the peripheral of the spacer fabric, only one spacer yarn, either from the right to left or left to right, provides support. Therefore, it is obvious that the spacer yarns in the peripheral areas are more likely to shift than those in the centre when loading is evenly applied onto the spacer fabric.

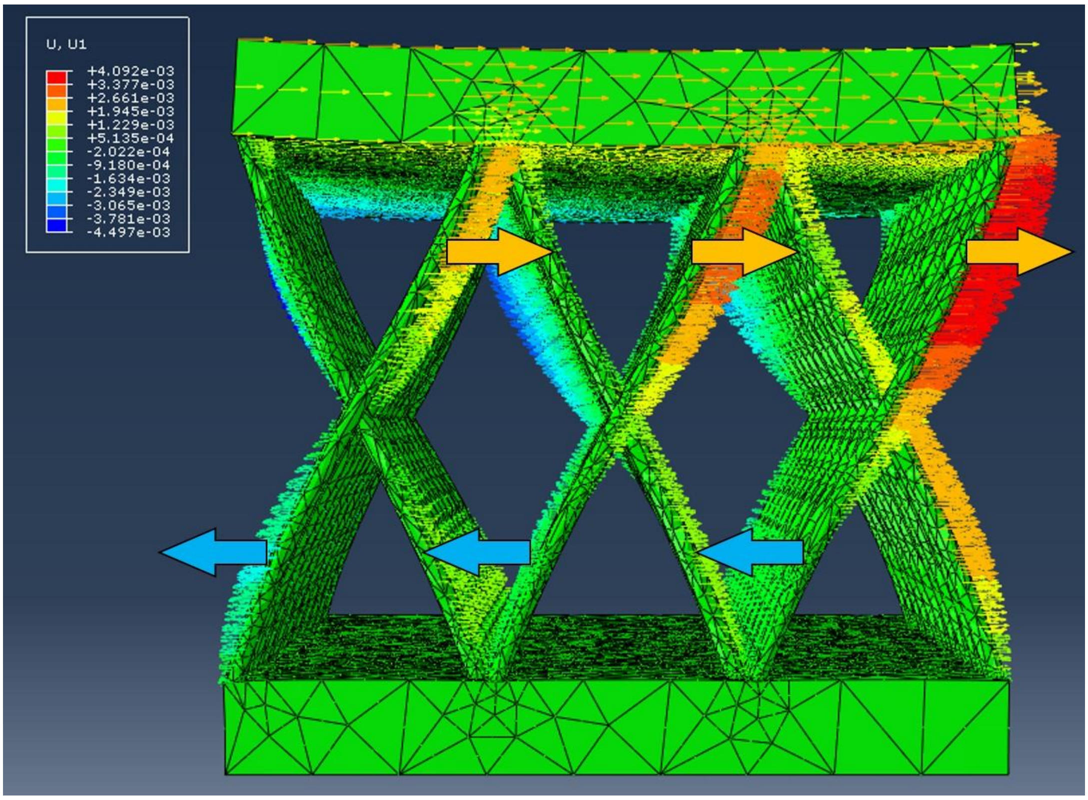


Figure 7.24 Displacement result of Spacer Model I

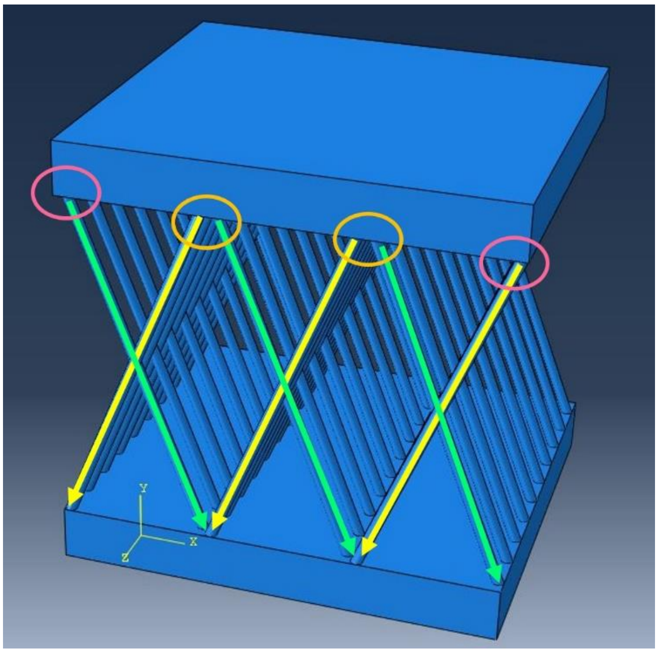


Figure 7.25 Arrangement of spacer yarns of Spacer Model I

7.3.2 Spacer fabric model II

In order to validate the created FEM, validation was carried out by comparing the predicted pressure on the spacer fabric with actual measurements. The pressure results obtained by the FEM and the measured results obtained by the sensor at different locations over the spacer fabric are shown in Figure 7.26. The values of the simulated pressure obtained by the FEM show a similar trend with the values of the measured pressure. In accordance with the results, the peaks of the simulated pressure are in the same locations as the measured points, i.e. B1, B2 and B3. The lowest points of the simulated pressure are close to those of the measured pressure. With reference Figure 7.27, when loading is applied by the heel (yellow arrows), Column B on the spacer fabric comes into contact with the heel first. Therefore, this part receives greater pressure when heel loading is continuously applied onto it. On the other hand, Columns A and C are the peripheral areas of the spacer fabric which come into contact with the 3D geometric shape of the heel model after B1, B2 and B3. The simulated pressure distribution on the spacer fabric model is shown in Figure 7.28. The results in Figure 7.28 also demonstrates that B1, B2 and B3 experience more pressure.

A human heel consists of different components, such as the heel bone, fat pad and thickened skin (The Editors of Encyclopædia Britannica, 2014). Each component of the heel has different material properties and the material properties are different among people due to their age, body weight, lifestyle, etc. In this simulation, the material properties assigned to the heel bone and heel pad are not the same as the heel of the subject used for validation because it is expensive and nearly impossible to measure the material properties of each heel component of a real subject. In addition, different specific structures of the heel components should be tailored for each subject in order to obtain a precise result. However, the purpose of this simulation model is to propose in general, a method to predict the pressure distribution and behaviour of spacer fabric under loading. Therefore, a prediction with a similar trend to a real life situation is acceptable and there is no need for a very precise result. The heel interface pressure predicted is greater than the measured heel interface pressure applied on spacer. Although that is the case, it is reasonable to see a difference between sensor measured pressure and the predicted pressure. However, on the basis on the proposed simulation model, researchers can obtain a better understanding on the pressure distribution and the behaviour of spacer fabric under loading; for example, the location of spacer fabric that undergoes greater amounts of pressure can be identified.

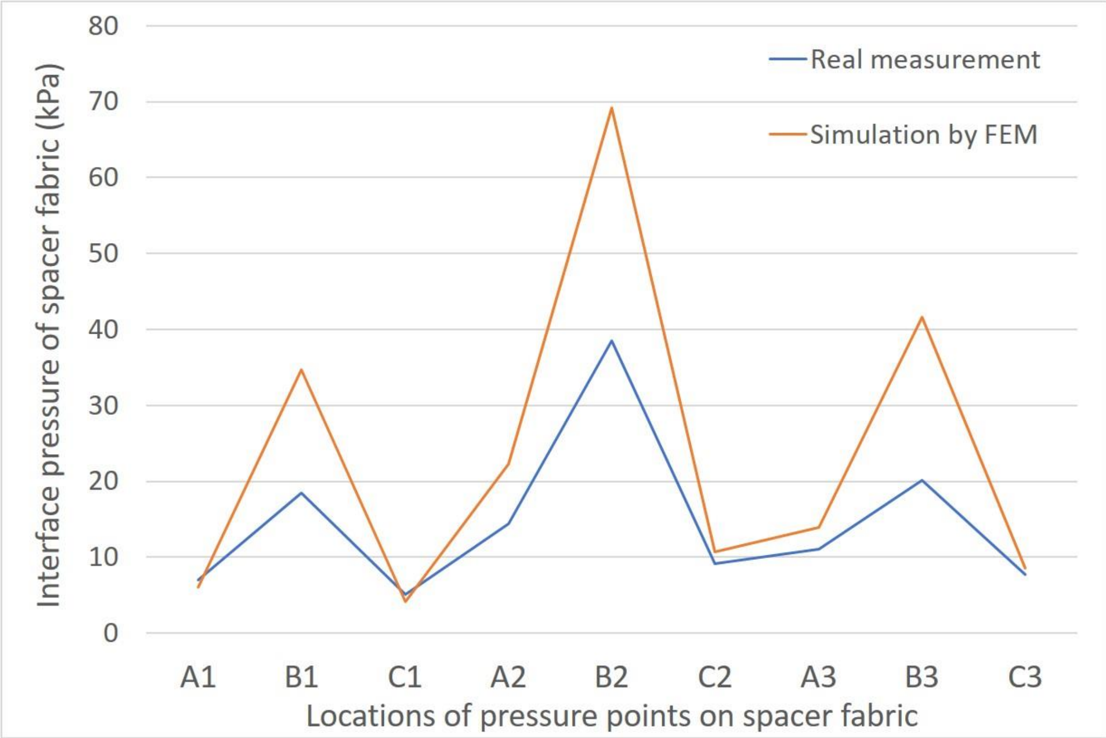


Figure 7.26 Comparison of predicted heel-spacer fabric interface pressure by FEM and measured interface pressure with sensor on spacer fabric exerted by heel

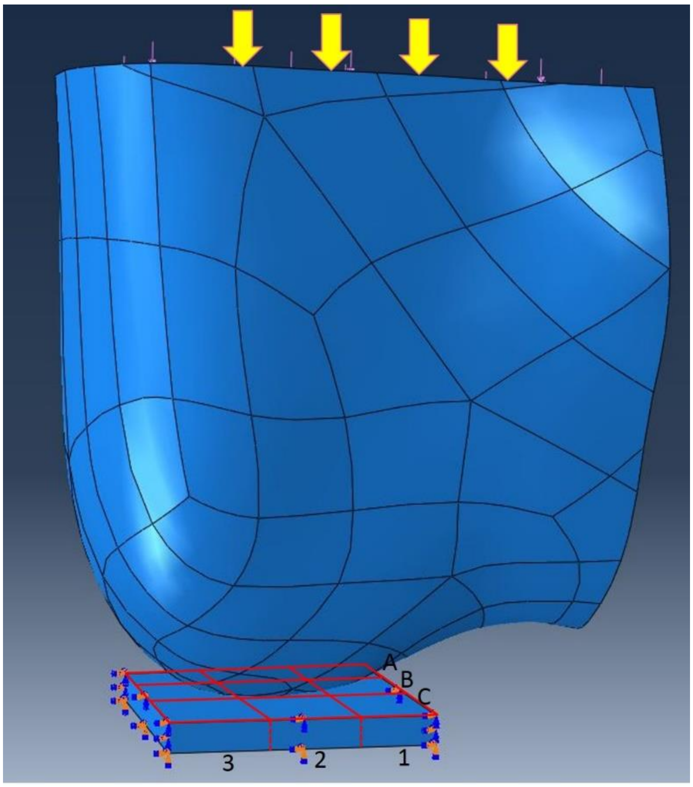


Figure 7.27 Heel-spacer fabric contact in FEM

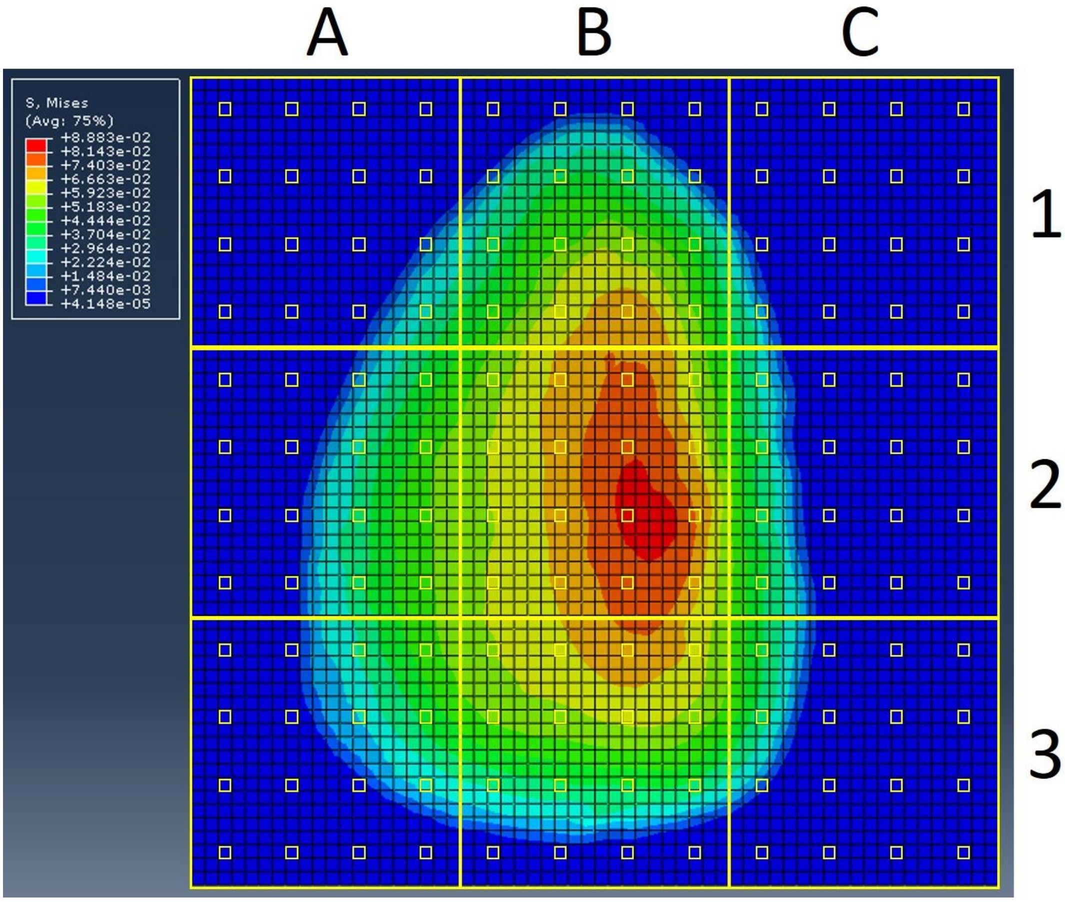


Figure 7.28 Simulation results of pressure distribution on spacer fabric by heel

7.4 Chapter Summary

In this chapter, two simulation models have been created: a spacer fabric model (Spacer Model I) which was used to show the micro view of the spacer yarns under loading, and a simulation model (Spacer Model II and heel model to provide a macro view which shows the interface pressure on the spacer fabric induced by the heel and the compression resistance performance of the spacer fabric). The FEM consists of a heel model and spacer fabric model. Spacer Model I shows that the spacer yarns shift to the sides under loading as well as the top layer of fabric. Furthermore, the results show that the centre of the spacer fabric supported by spacer yarns in two different directions has better compression resistance and there is less tendency of the yarns to shift. On the other hand, in the peripheral areas, the spacer yarns shift more as there is only one yarn that supports the fabric under loading.

In accordance with the heel model and Spacer Model II, the simulation could be used to predict the trend of pressure distribution and the displacement changes in the spacer fabrics under heel loading. By adjusting the corresponding material properties of the bone and tissue in the heel model, the predicted pressure by the spacer fabric model approximates the measured heel interface pressure on spacer fabric in real life situations. The model shows a reasonable accuracy in the prediction. With the use of this simulation model, the displacement changes in spacer fabric and the heel interface pressure distribution on spacer fabric can be determined. By adjusting the corresponding material properties to a new spacer fabric, the pressure distribution and changes in pressure can be easily predicted. Without the need to carry out experiments on real human subjects, the time required to find suitable subjects and pressure measurement can be eliminated. Not only applicable as the absorbent and cushioning layer of wound dressings, spacer fabric can also be used as a replacement for the material of heel protectors or used for other pressure relieving purposes. Therefore, by simply changing the material properties of the spacer fabric model, the pressure distribution on different types of spacer fabrics can be obtained which may contribute to selecting a suitable spacer fabric for heel pressure relief.

Chapter 8 Evaluation of Newly Developed Wound Dressings Composites

8.1 Introduction

According to the literature, typical wound dressings consist of three layers, including a wound contacting, an absorbent and a barrier layers (Yang & Hu, 2016a). The wound contacting layer is non-adherent, therefore, it comes directly into contact with the wound and prevents wound damage during wound dressing changes. The absorbent layer absorbs exudate and provides cushioning. The barrier layer is the adhesive coversheet for the outermost layer of the dressing for fixation purposes.

With reference to Chapter 6, the results of the testing on weft knitted spacer fabrics show that they are comparable or even have better physical properties than the existing wound dressings. Therefore, it is possible to replace the absorbent and cushioning layer of wound dressings with spacer fabric. The results discussed in Chapter 6 indicate that the overall performance of Weft_a_8 is better than the other samples. Therefore, Weft_a_8 is selected as the material for the absorbent and cushioning layer of the wound dressing composite in this study. Furthermore, three different types of wound contacting layers and adhesive outer surface layers are selected and combined with Weft_a_8 respectively to form three layers of a wound dressing composite. Table 8.1 shows the combination of the 3 layer wound dressing composites. The physical properties of these composites are evaluated by laboratory tests and the results compared with those of existing wound dressings. In addition, a bacterial inhibition test is carried out to evaluate the ability of the newly developed wound dressing composites to protect wounds against bacteria.

Table 8.1 Combinations of wound dressing composites

	Combination				
1A	• Barrier surface layer: Type **1** • Absorbent layer: Weft_a_8 • Wound contact layer: Type **A**	2A	• Barrier surface layer: Type **2** • Absorbent layer: Weft_a_8 • Wound contact layer: Type **A**	3A	• Barrier surface layer: Type **3** • Absorbent layer: Weft_a_8 • Wound contact layer: Type **A**
1B	• Barrier surface layer: Type **1** • Absorbent layer: Weft_a_8 • Wound contact layer: Type **B**	2B	• Barrier surface layer: Type **2** • Absorbent layer: Weft_a_8 • Wound contact layer: Type **B**	3B	• Barrier surface layer: Type **3** • Absorbent layer: Weft_a_8 • Wound contact layer: Type **B**
1C	• Barrier surface layer: Type **1** • Absorbent layer: Weft_a_8 • Wound contact layer: Type **C**	2C	• Barrier surface layer: Type **2** • Absorbent layer: Weft_a_8 • Wound contact layer: Type **C**	3C	• Barrier surface layer: Type **3** • Absorbent layer: Weft_a_8 • Wound contact layer: Type **C**

8.2 Compression Test

Pressure is one of the key contributing factors of pressure ulcer development (Bass & Phillips, 2007; Murray et al., 2001; Ostadabbas et al., 2011). Therefore, providing a cushioning effect is one of the main purposes for using spacer fabric as the middle layer of a wound dressing composite. The compression resistance of the newly developed wound dressing composites has been subsequently investigated and compared to the wound dressings in providing cushioning effects.

8.2.1 Results and Discussion

Weft_a_8 is selected as the absorbent and cushioning layer of the wound dressing composites. The spacer fabric layer is therefore assumed to have an important role in compression resistance. Figure 8.1 shows the compression stress-strain curves of the 3 layer wound dressing composites and the curve of Weft_a_8 is shown as reference. From the plot, it can be seen that the trends of the wound dressing composites follow that of Weft_a_8. With reference to the typical compression stress-strain curve (Figure 6.1 in Chapter 6) (Tong et al., 2015), all wound dressing composites are in the initial and elastic stage when the loose outer layer is first compressed. The spacer yarns buckle as they are fastened with multifilament stitches. When compressed to 60% of their initial thickness, almost all of them reach the peak which indicates that the bending of the spacer yarns is nearly reached at their maximum. Therefore, even a small amount of applied pressure can easily compress them. After that, they reached the densification stage, in which the spacer yarns collapse with increasing pressure applied.

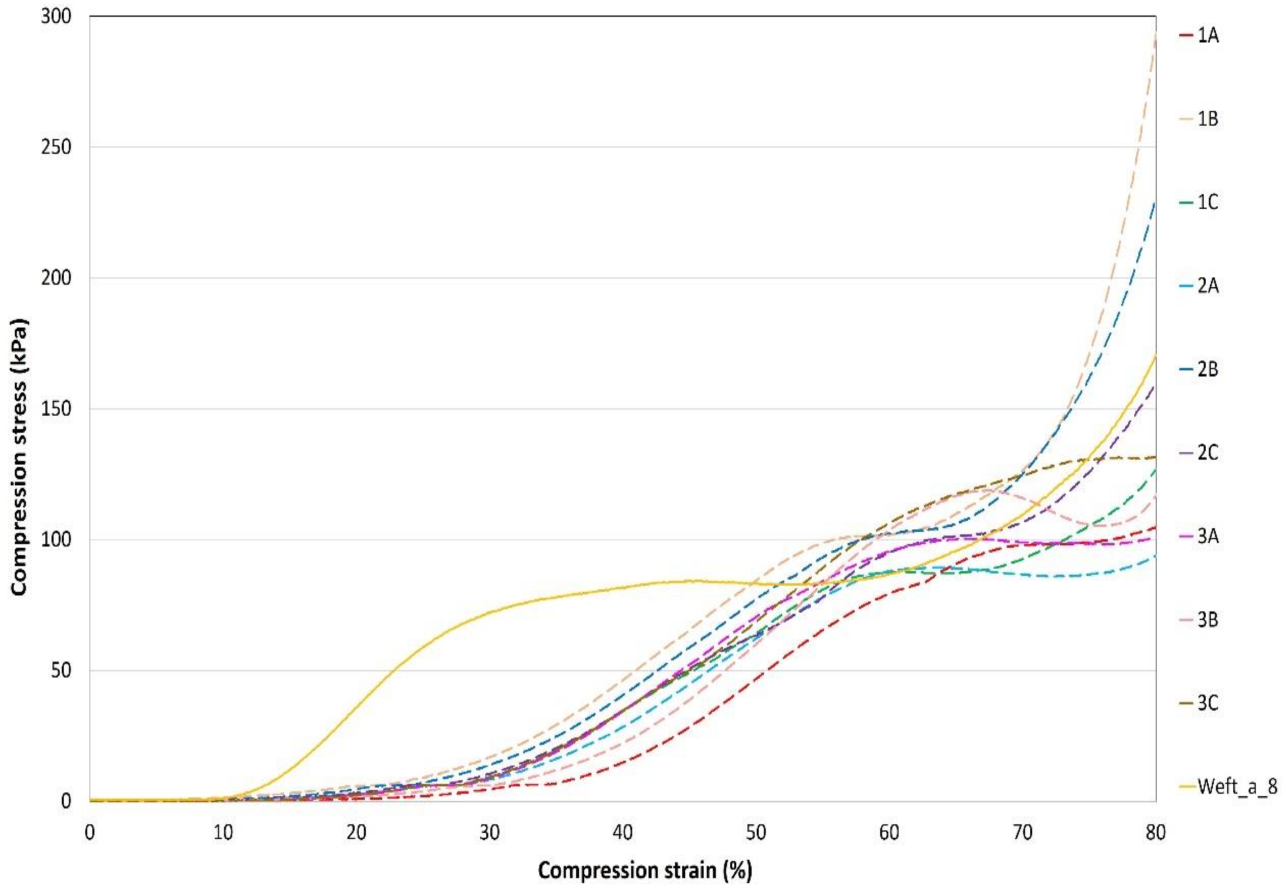


Figure 8.1 Compression stress-strain curves of wound dressing composites and Weft_a_8

As in Section 6.2 of Chapter 6 (the compression test results of the spacer fabrics), four different types of pressure were applied. Apart from the capillary breakdown pressure (4.27 kPa) (Phillips, 2007), the heel interface pressure from Chapter 5 was also taken into consideration: 6.69 kPa, 10.47 kPa and 14.50 kPa (Tong, Yip, Yick, et al., 2016). In accordance with the results of heel interface pressure (Section 5.2.2), 6.69 kPa (50.15 mmHg) is the average heel interface pressure experienced by the elderly subjects when their foot is positioned at 60 degrees to a standard hospital mattress. Furthermore, their maximum heel interface pressure when their foot is positioned at 60 and 90 degrees to a standard hospital mattress are 10.47 kPa (78.71 mmHg) and 14.50 kPa (108.75 mmHg) respectively.

Figure 8.2 shows the compression results of the three layer wound dressing composites and spacer fabric, Weft_a_8. As only Weft_a_8 is the only spacer fabric used as the absorbent and cushioning layer, the differences among the wound dressing composites are due to the different combinations of the wound contacting and barrier layers as shown in Table 8.2. From the results, it is found that all of them have similar trends. Their compression strain gradually increases with increases in the compressive stress. However, when the induced pressure is around 6 kPa, a small plateau stage in their curves which means that a small amount of applied pressure could easily compress them. After that, increasing the pressure applied reduces little of the compression strain. During the experiment, the wound contacting layer faced upward to allow simulation of the loading of the heel. Therefore, the wound contacting layer was compressed first. The wound contacting layer reached its maximum of compression at around 6 kPa and the result is a small peak. After that, a rapid increase in the compression resistance may mean that the spacer fabric layers started to be compressed. This is because after the shift of the curves, the trend of the curves is similar to that of the spacer fabric, Weft_a_8. At different amounts of applied pressure, the compression strains of 1B, 2B and 3B are the lowest among all of the wound dressing composites. This means that it is more difficult to compress these samples when the same amount of pressure is applied. Therefore, they have better compression resistance. 1B, 2B and 3B have the same wound contacting layer (Type B). The cotton/acrylic fiber pad in the middle of Type B increases the final thickness and areal mass of the wound dressing composites in comparison to Types A and C as shown in Table 3.11. In Chapter 6, the compression results proved that increasing the thickness and areal mass increase the compressive resistance. On the other hand, 1A, 2A and 3A with Type A wound contacting layers are always compressed more when compared to the others. Type A is a thin non-woven fabric, and the loose structure may have reduced its compressive resistance in comparison to other types of wound contacting layers.

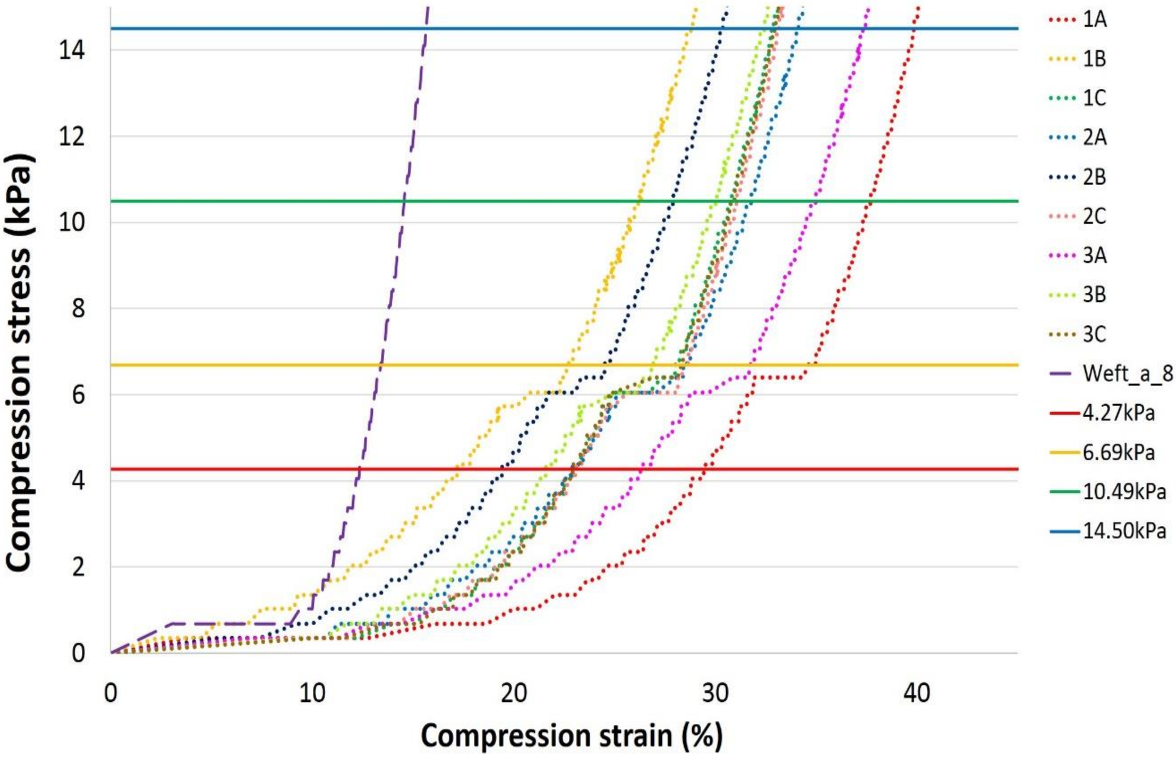


Figure 8.2 Compression stress-strain curves of three-layer wound dressing composites

Table 8.2 Compositions of different types of barrier and wound contacting layers

Barrier surface layer	Type 1	Type 2	Type 3
Composition	Non-woven	Hydrophilic polyurethane film	Non-woven
Wound contact layer	Type A	Type B	Type C
Composition	70% viscose and 30% polyester	① Low adherent perforated polyester film ② Cotton/acrylic fiber pad ③ Hydrophobic outer layer	8-ply 100% cotton

Based on the compression results of the wound dressing composites, Sample 1B with the best compressive resistance among all of the sample was selected for further comparisons with the existing wound dressings as shown in Figure 8.3. A detailed explanation of the compression behavior of the wound dressings has been provided in Section 6.2.

At 4.27 kPa, Sample 1B became compressed to around 16% of its original thickness. When compared to the existing wound dressings, the reduction of its compression strain is less than Dressings 1, 4 and 8 with the same amount of pressure. This demonstrates that 1B has better compressive resistance than Dressings 1, 4 and 8 when the pressure applied is 4.27 kPa.

At 6.69 kPa, the compression strain of 1B is about 23% of that with its original thickness. Its compression strain gradually decreased with increasing amounts of applied pressure. At 10.49 kPa, its compression strain is about 27% but did not exceed 30% even at 14.50 kPa. With reference to Figure 8.3, the compression strain of 1B is lower than most of the dressings except for Dressing 6 after applying a pressure of 6.69 kPa. The results show that the compression resistance of 1B is greater than most of the wound dressings after applying a pressure of 6.69 kPa and can retain its thickness without a significant reduction.

Based on the above results, it can be concluded that the newly developed wound dressing composites have a better compressive resistance than the existing wound dressings when the applied load is greater than 6.69 kPa. This shows that when the heel places pressure onto the wound dressing composites, they will not have a great reduction of thickness regardless whether the heel is placed at a 60 or 90 degree angle to the mattress.

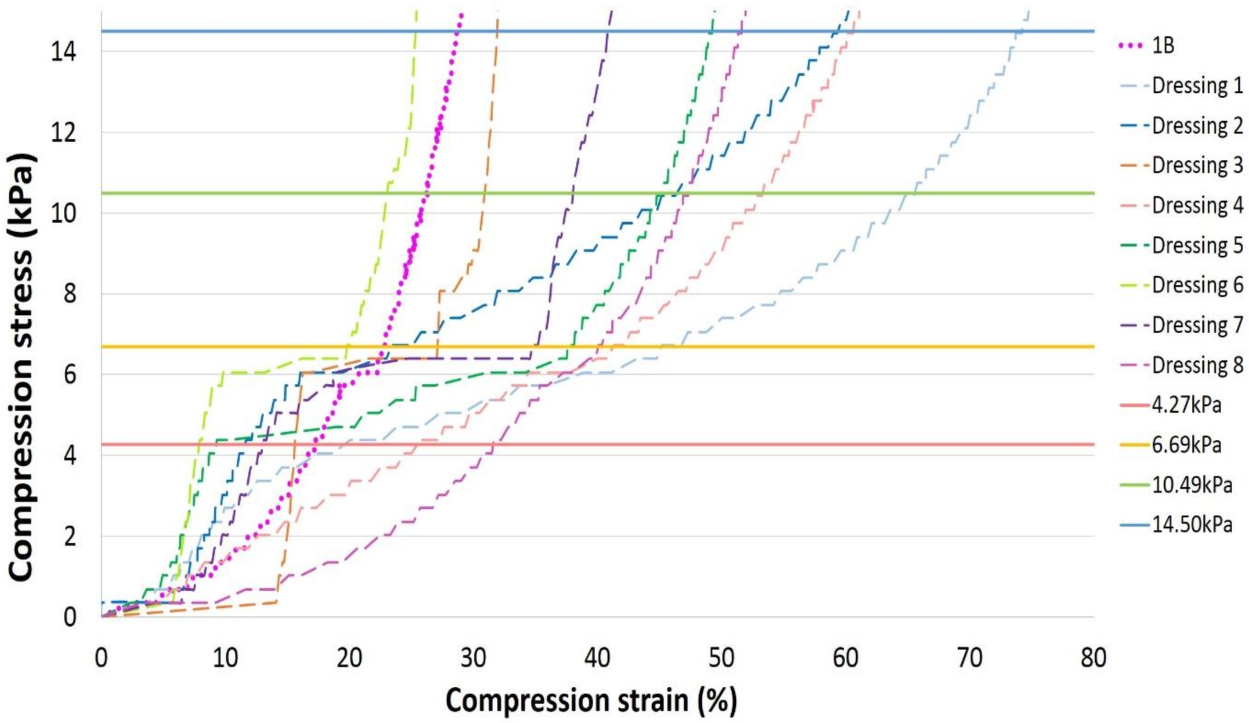


Figure 8.3 Compression stress-strain curves of 1B and existing wound dressings

8.3 Absorbency Test

With reference to the questionnaire results from the registered nurses in Chapter 4, absorbency is found to be another key requirement for developing the three layer wound dressing composites. The ability to absorb wound exudates and wound fluid retaining capacity are important for wounds and determines the frequency that the wound dressing needs to be changed (Augustine et al., 2014; Watson & Hodgkin, 2005; Weller & Sussman, 2006). Different types or stages of wounds may produce different amounts of exudate. Therefore, the absorbency of the newly developed wound dressing composites and existing wound dressings with different amounts of wound fluids was evaluated.

8.3.1 Results and Discussion

In order to simulate the wound fluid that exudes from the wound base, red colored fluid was dripped onto the wound contacting layer. Three different volumes, 4 ml, 8 ml and 12 ml, were used to simulate the different amounts of exudate. Tables 8.3 to 8.5 show the results of the newly developed wound dressing composites while Tables 8.6 to 8.8 show the results of the existing wound dressings accordingly.

From the top views of Tables 8.3 to 8.5, the area of the spread fluid is greater when Type A or B is used as the wound contacting layer. For wound dressing composites with Type C as the wound contacting layer, the fluid is gradually distributed across the layer but red colored fluid is also found at the edges when 12 ml is added. With reference to the bottom view in Tables 8.3 to 8.5, no wound fluid is found in the wound dressing composites even when 12 ml fluid is added. This means that the red colored wound fluid did not penetrate any of the wound dressing composites and reached the adhesive layer at different levels of exuding. This demonstrates that the fluid retaining capacity of the wound contacting and spacer fabric layers is good. The results also agree with those of a previous study by Davies and Williams (2009b) in that liquid is retained within the internal confinements of spacer fabric without leakage.

On the other hand, the existing wound dressings have different absorption and fluid handling capacities; see Tables 8.6 to 8.8. The top views of Dressings 3, 5, 6 and 7 show that they do not absorb the fluid and the fluid is retained as droplets that accumulate. Red colored fluid can be observed in the bottom views due to the transparency of the dressings but they did not penetrate through the dressings. The top and bottom views of the samples with 12 ml of fluid added are not available because the fluid leaked out of the dressing area during when 8 ml was being added. Figure 8.4 shows examples of the fluid leakage of wound dressings. By referring to the absorbency and wettability tests discussed in Sections 6.3 and 6.4, the results also show that the absorbency and wettability of Dressings 3, 5, 6 and 7 are poor due to the presence of the adhesive layer of the wound contacting layer. The hydrophobic property of the wound contact layers means that it is more difficult to absorb the fluid. This is also in agreement with previous research work, in that hydrocolloids may not be suitable for wounds that produce heavy exudate (Bluestein & Javaheri, 2008; Fonder et al., 2008). On the contrary, Dressings 1, 2, 4 and 8 have different absorbency performances. From the bottom views, red color fluid can be observed which shows that the fluid has penetrated from the top to the bottom of the wound dressings. In practical use, the changes of wound dressings depend on the spread of the discoloration on the dressings (Beldon, 2010). According to the results of Dressings 1, 2, 4 and 8, the spread of the discoloration shows that there is a need to change the dressings in real life practices. The wettability results in Section 6.4 also prove that Dressings 1, 2, 4 and 8 absorb the water droplets immediately. Among them, Dressing 2 has the poorest fluid retaining capacity. Previous researchers have also pointed out the importance of the absorption of excess exudate without leakage (Abdelrahman & Newton, 2011; Beldon, 2010). However, from the bottom views of Dressing 2 when 12 ml of red colored wound fluid is added, there is leakage under the dressing. This indicates that the dressing cannot retain fluid. Figure 8.5 shows photos of fluid leakage from Dressing 2. From the results of Dressing 8 when 12 ml of fluid is added, the discoloration area as seen from the top view is minimal, but that from the bottom view is larger. This means that Dressing 8 has the ability to absorb and transfer the fluid to the bottom layers.

When the results of the newly developed wound dressing composites and the existing wound dressings are compared, the absorbency and fluid handling capacity of the former excels that of Dressings 2, 3, 5, 6 and 7 and comparable to Dressings 1, 4 and 8.

Table 8.3 Top and bottom views of wound dressing composites (1A, 1B and 1C)

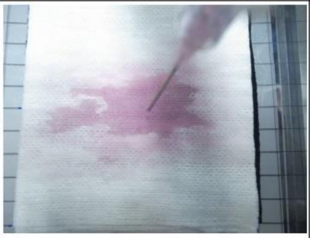
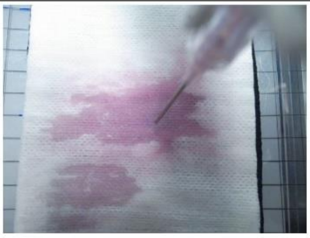
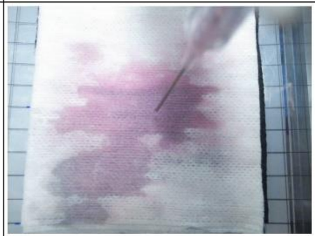
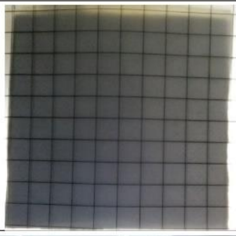
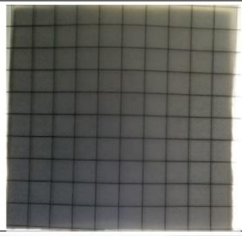
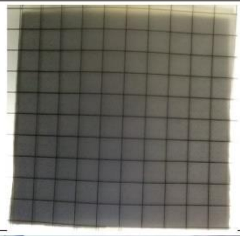
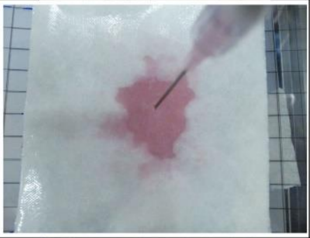
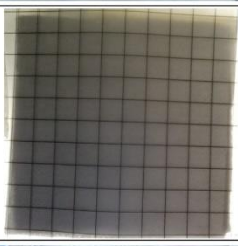
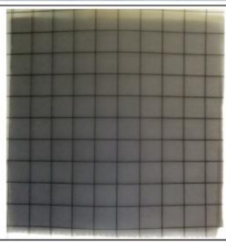
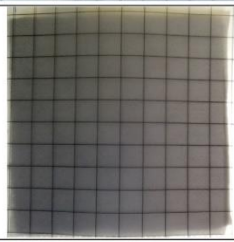
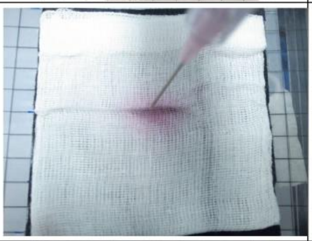
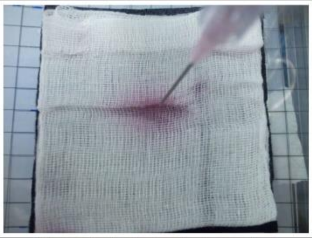
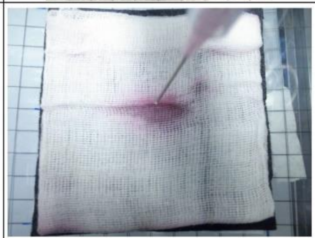
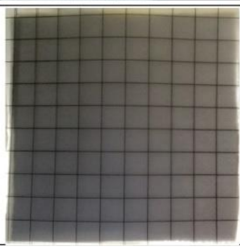
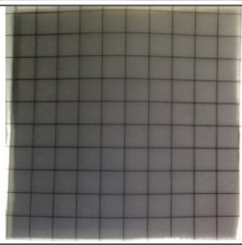
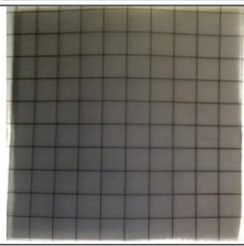
		4ml	8ml	12ml
1A	Top view			
	Bottom view			
1B	Top view			
	Bottom view			
1C	Top view			
	Bottom view			

Table 8.4 Top and bottom views of wound dressing composites (2A, 2B and 2C)

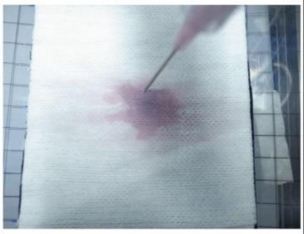
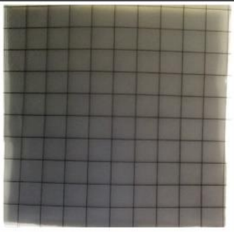
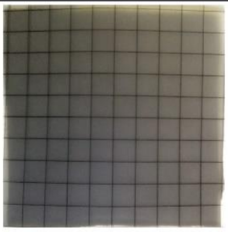
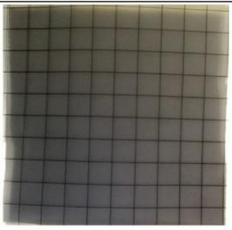
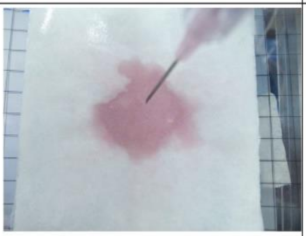
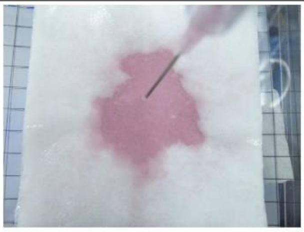
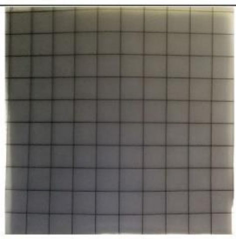
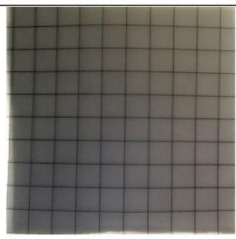
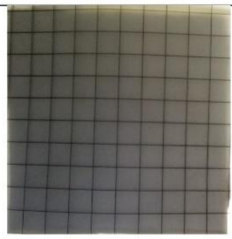
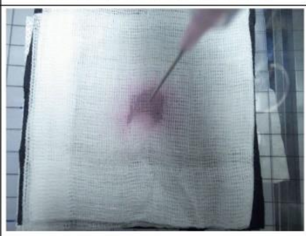
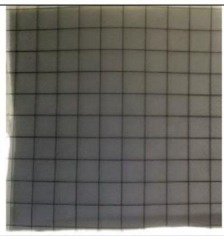
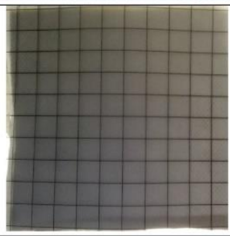
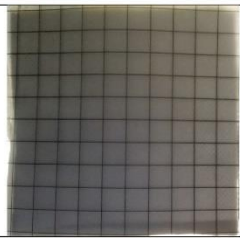
		4ml	8ml	12ml
2A	Top view			
	Bottom view			
2B	Top view			
	Bottom view			
2C	Top view			
	Bottom view			

Table 8.5 Top and bottom views of wound dressing composites (3A, 3B and 3C)

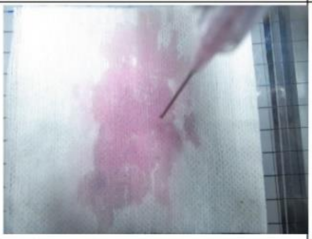
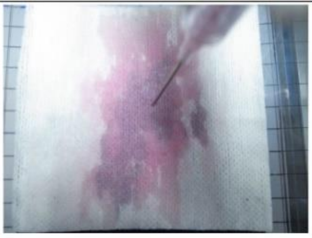
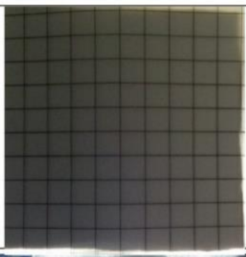
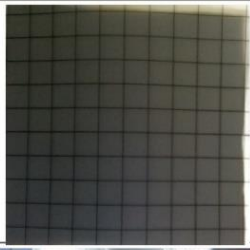
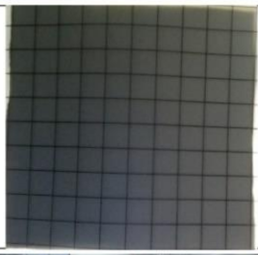
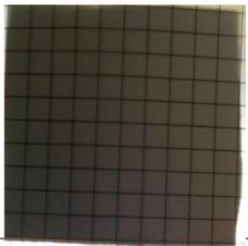
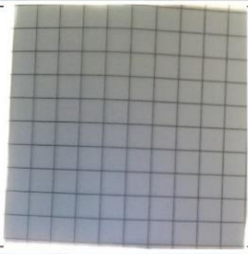
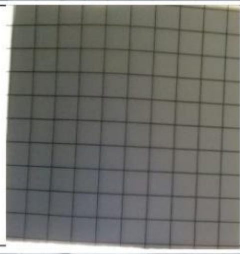
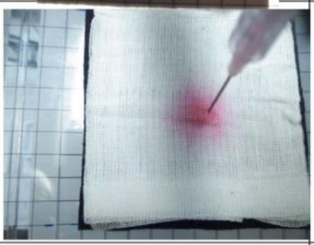
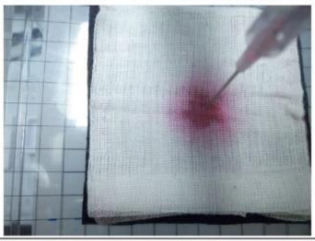
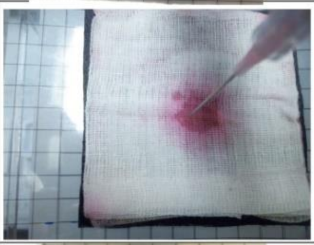
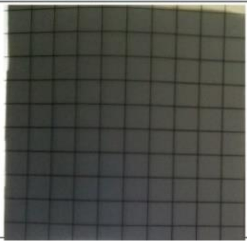
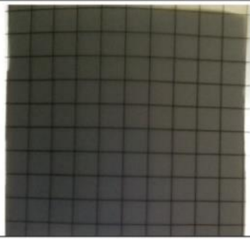
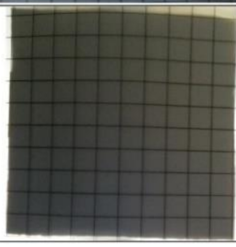
		4ml	8ml	12ml
3A	Top view			
	Bottom view			
3B	Top view			
	Bottom view			
3C	Top view			
	Bottom view			

Table 8.6 Top and bottom views of Dressings 1, 2 and 3

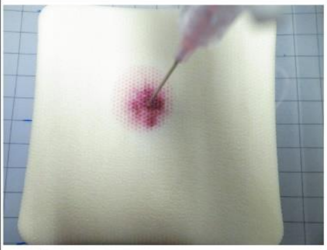
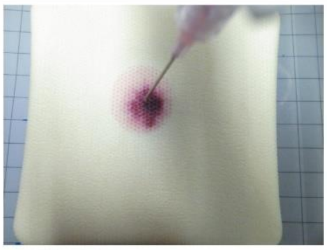
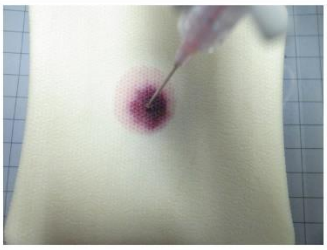
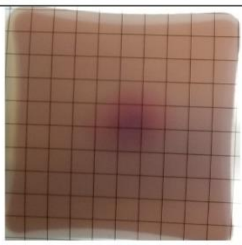
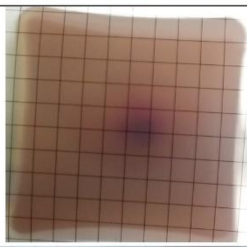
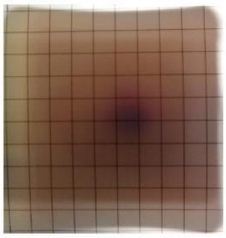
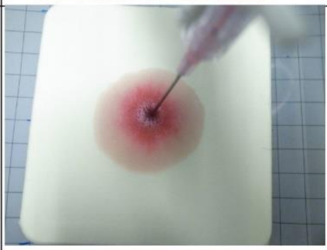
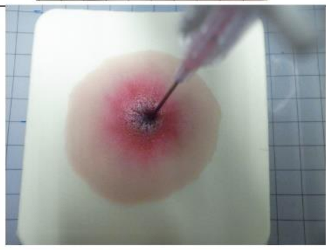
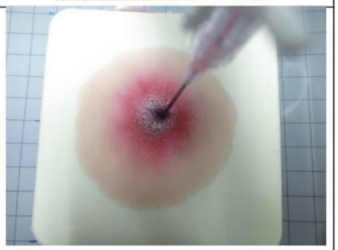
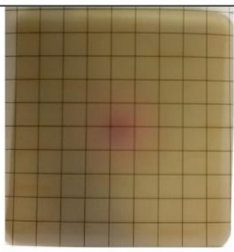
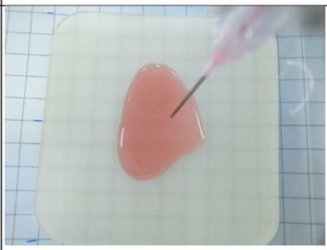
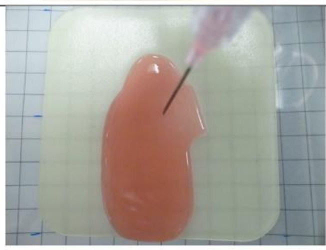
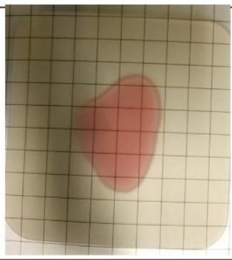
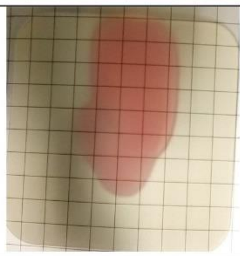
		4ml	8ml	12ml
Dressing 1	Top view			
	Bottom view			
Dressing 2	Top view			
	Bottom view			
Dressing 3	Top view			
	Bottom view			

Table 8.7 Top and bottom views of Dressings 4, 5 and 6

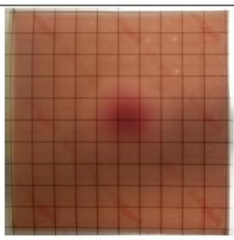
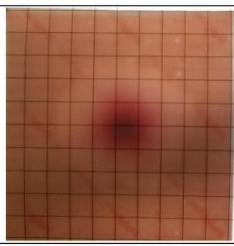
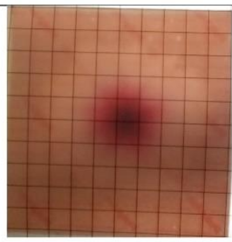
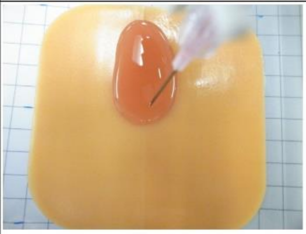
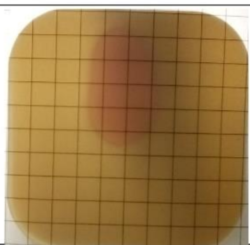
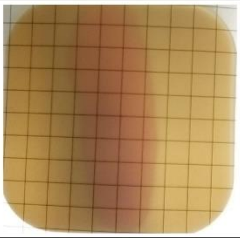
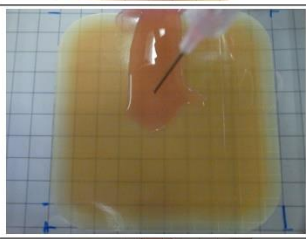
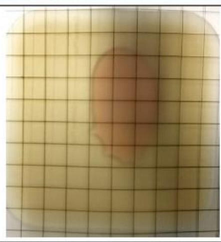
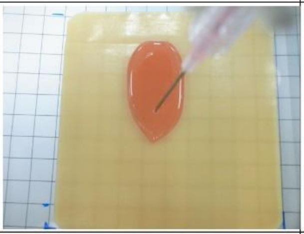
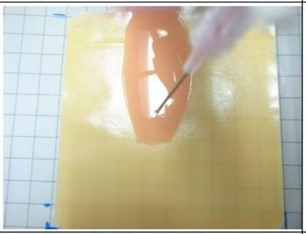
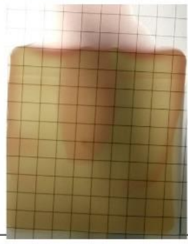
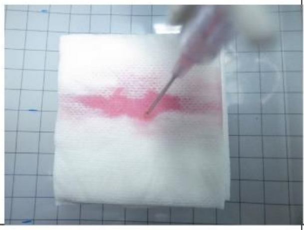
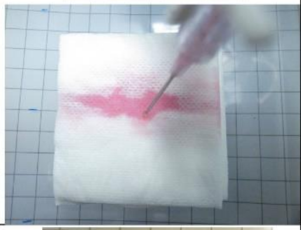
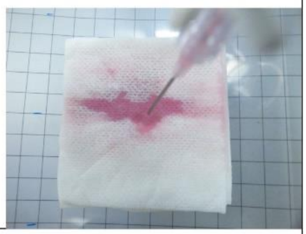
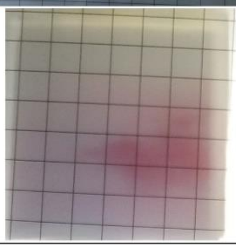
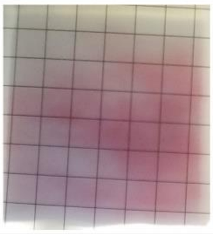
		4ml	8ml	12ml
Dressing 4	Top view			
	Bottom view			
Dressing 5	Top view			
	Bottom view			
Dressing 6	Top view			
	Bottom view			

Table 8.8 Top and bottom views of Dressings 7 and 8

		4ml	8ml	12ml
Dressing 7	Top view			
	Bottom view			
Dressing 8	Top view			
	Bottom view			

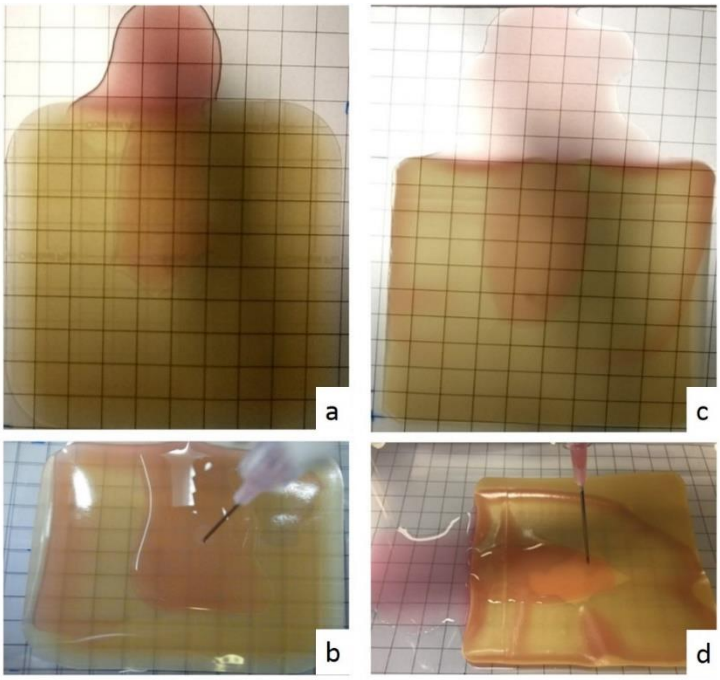


Figure 8.4 Fluid leakage from different wound dressing samples (a & b: Dressing 6; c & d: Dressing 7)

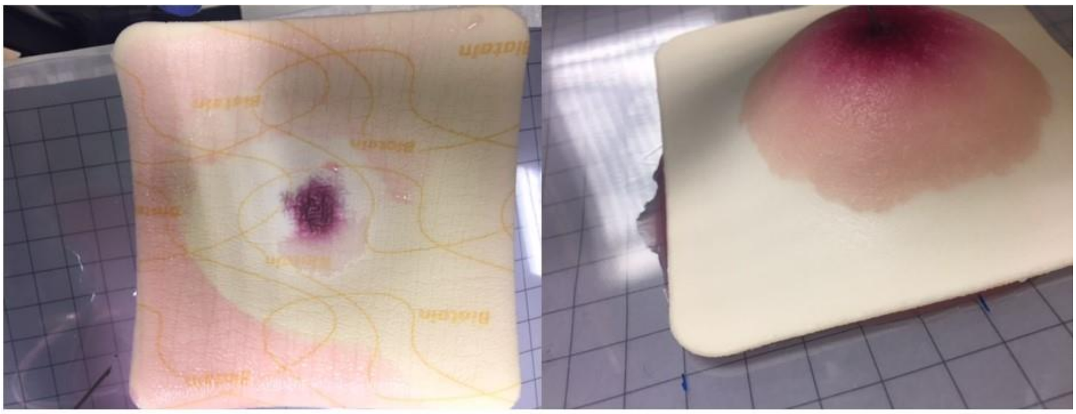


Figure 8.5 Fluid leakage from Dressing 2

8.4 Water Vapor Permeability Test

The water vapor permeability is the ability of materials to allow moisture transmission from the skin to the external atmosphere. It is important for wound dressings to maintain a ventilated environment for wound healing. Water vapor permeability is related to the sensation of comfort (Bagherzadeh et al., 2012). Therefore, the water vapor permeability of the newly developed wound dressing composites was investigated and compared to that of existing wound dressings.

8.4.1 Results and Discussion

The water vapor permeability results of the newly developed wound dressing composites and existing wound dressings are shown in Figure 8.6. The wound dressing composites which use Type 3 as the adhesive layer have a significantly poor water permeability. Type 3 is a thin plastic film so it may be difficult for water vapor to transmit to the outside environment. On the other hand, Types 1 and 2 have pores on the surface so that water vapor can easily pass through to the outside environment. Type C has a better water vapor permeability than Type A or B. Although Type C offers greater bulk density, its loose structure means larger pores through which water vapor can easily pass through. Therefore, 1C and 2C have the best water vapor permeability among all of the wound dressing composites. The water vapor permeability of the existing wound dressings has been discussed in Section 6.5 in detail.

When comparing the newly developed wound dressing composites to the existing wound dressings, it was found that the former has better performance in water vapor permeability than Dressings 3, 5, 6 and 7 which have an adhesive wound contacting layer. Dressings 3, 5, 6 and 7 are hydrocolloid types of wound dressings which according to previous research have low moisture transmission rates (Abdelrahman & Newton, 2011). Although their water vapor permeability may not as good as Dressing 8 which has a non-woven loose structure, their water vapor permeability, except for 3A, 3B and 3C, is better than or comparable to Dressings 1, 2 and 4.

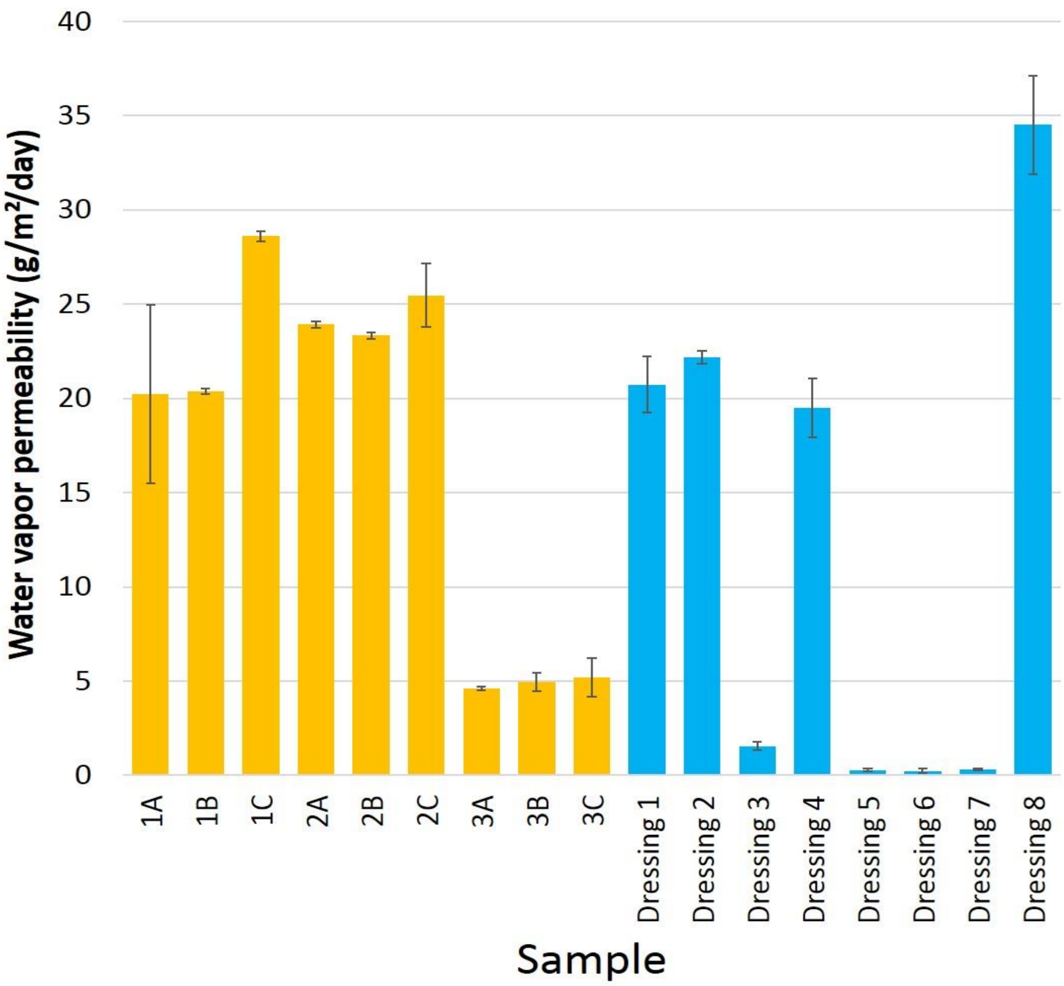


Figure 8.6 Water vapor permeability of newly developed wound dressing composites and existing wound dressings

8.5 Air Permeability Test

Apart from water vapor transmission, the transmission of air is also important for comfort (Abdelrahman & Newton, 2011; Bagherzadeh et al., 2012). According to the feedback and comments obtained from the nurses (Chapter 4), the breathability of wound dressings is one of the factors of most concern for wound dressing selection which is very much related to air permeability. To evaluate the ability of the materials to allow the passage of air from skin to the external environment, air permeability testing was adopted and the results of the newly developed wound dressing composites and existing wound dressings were then compared.

8.5.1 Results and Discussion

Figure 8.7 shows the results of the air resistance of the newly developed wound dressing composites and the existing wound dressings. Greater air resistance means that it is more difficult for the air to pass through the fabric to the external environment and poor air permeability is the result. According to the results, no data were recorded for 3A, 3B, 3C and Dressings 1 to 7. This indicates that their air resistance exceeds 500 kPa·s/m which is the maximum range of the testing machine. The details of the air permeability behavior of existing wound dressings have been discussed in Section 6.6. Similar to the results of water vapor permeability, the air permeability of 3A, 3B and 3C is poor due to the presence of a Type 3 with a thin film that has bacterial barrier ability. In a comparison among 1A, 1B, 1C, 2A, 2B and 2C with Types 1 and 2 as the barrier layers, the difference in their air resistance is due to the type of material used for the wound contacting layer. As Types 1 and 2 are similar, as both have pores on their surfaces, their air permeability performance is similar. 1C and 2C have the least air resistance because Type C is used as the wound contacting layer which has a loose structure and larger pores. 1B and 2B have greater air resistance as they are thicker when compared to Types A and C.

The results prove that the newly developed wound dressing composites that use Type 1 or 2 as the barrier layer have better air permeability than most of the wound dressings as the air resistance of most of the existing wound dressings exceeds the maximum values of the testing machine. When Type B is used as the wound contacting layer, the composite may have more poor air permeability than Dressing 8, but the air permeability of the wound dressing composites is better when Type A or C is used.

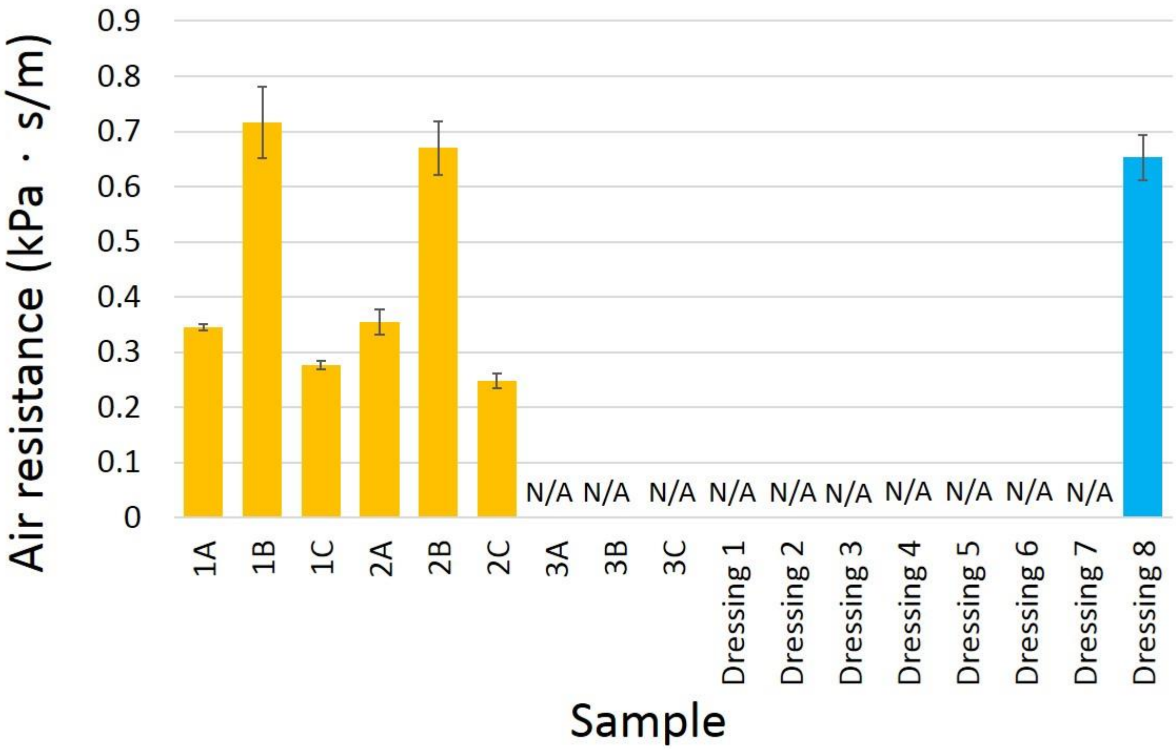


Figure 8.7 Air resistance of newly developed wound dressing composites and existing wound dressings

8.6 Thermal Conductivity Test

Thermal conductivity is also related to the comfort of the wound dressings. Wound dressings with good thermal conductivity can help to maintain good thermal regulation of the wound healing environment and prevent heat from accumulating underneath. Therefore, thermal conductivity testing was carried out for the newly developed wound dressing composites and the results were compared with those of the existing wound dressings.

8.6.1 Results and Discussion

Higher thermal conductivity values mean that the sample has better performance in transferring heat away from the skin to the sample surface. Figure 8.8 shows the thermal conductivity results of the newly developed wound dressing composites and the existing wound dressings. Dressings 3, 6 and 7 have the best thermal conductivity among all of the samples which indicates that heat can be transmitted away from the skin to the external environment. A detailed explanation on the results of existing wound dressings were discussed in Section 6.7. All of the newly developed wound dressing composites have similar thermal conductivity results since they have the same type of absorbent layer. In a comparison to the wound dressing samples, the thermal conductivity of the wound dressing composites is comparable to Dressings 1, 2, 4 ,5 and 8.

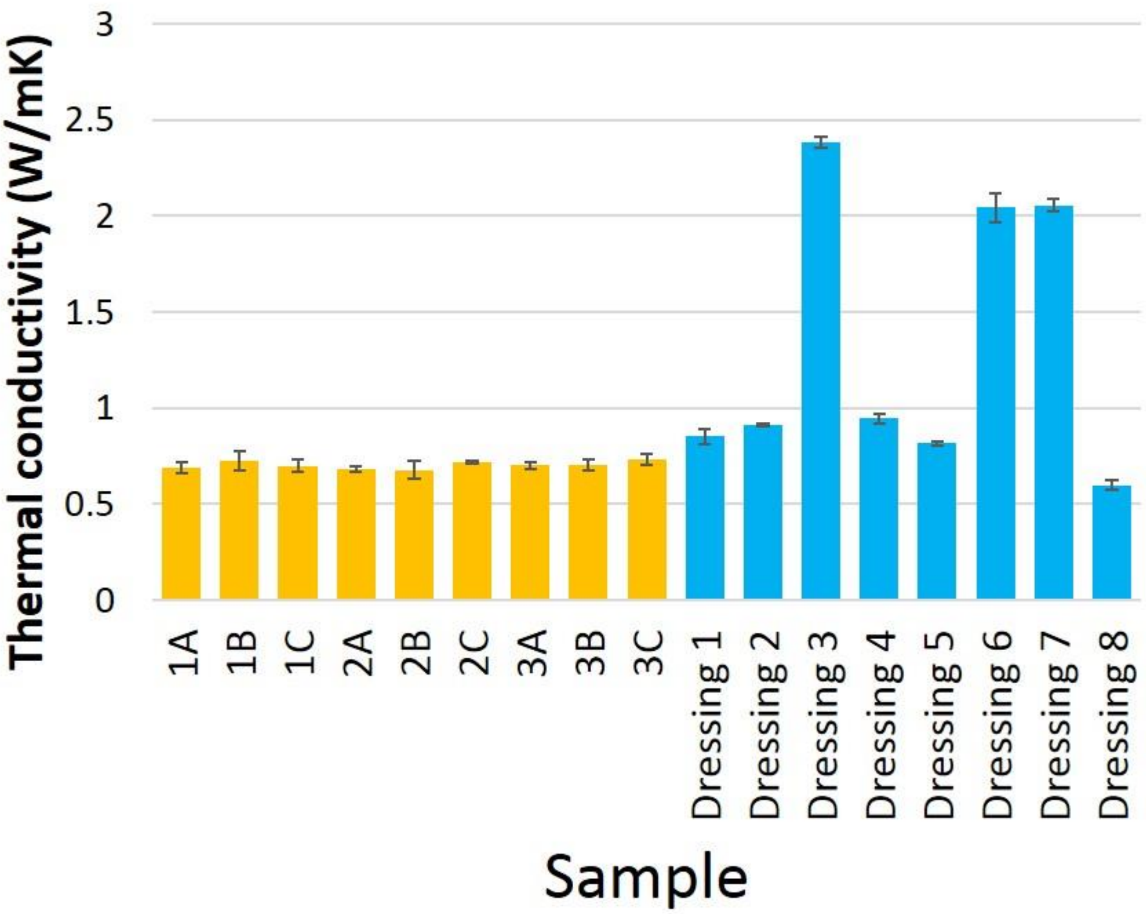


Figure 8.8 Thermal conductivity of newly developed wound dressing composites and existing wound dressings

8.7 Extensibility Test

Conformability is one of the requirements for wound dressings. When applying a dressing onto a wound, the dressing may stretch. Therefore, its extensibility and ability to maintain its original shape and structure without deformation or even damage are important. In the extensibility testing, the samples were stretched 20% of their initial length and the deformation in length after stretching was measured. The three layer wound dressing composites and existing wound dressings were tested.

8.7.1 Results and Discussion

Figure 8.9 shows the overall extensibility of the newly developed wound dressing composites and the existing wound dressings. When the results are compared, it can be seen that more pressure is needed to stretch 1C, 2C and 3C while less pressure is needed to stretch 1B, 2B, and 3B. However, the turning points of the curves of wound dressing composites with Type B or C as the wound contacting layer indicate that there is breakage, see Figure 8.10. For those with a Type B wound contacting layer, breakage occurs at around 14- 20% stretching of the original length. For those with Type C, breakage occurs at around 13-16% stretching of the original length and less than 200 kPa is needed to do so. Wound dressing composites with Type A do not show any turning point in their curves even after stretching 20% of its original length. The results prove that their extensibility is better. Although a greater amount of pressure is required to stretch 3C to 20% of its original length, the curve reaches its peak and the sample starts to break. However, around 400 kPa is needed to stretch 1A to 20% of its original length. Yet the curve still continuously slopes upwards which means that the material does not break apart. Detailed results of the wound dressings have been discussed in Section 6.8.

When comparing the results of the wound dressing composites with those of the existing wound dressings, it is obvious that the extensibility of the latter is poor and less pressure is required to stretch them to 20% of their original length. Furthermore, the results prove that about 40 kPa is needed to stretch the wound dressing samples to 20% of their original length. Therefore, most of the wound dressing composites have better extensibility than the wound dressings because more pressure is required to stretch them.

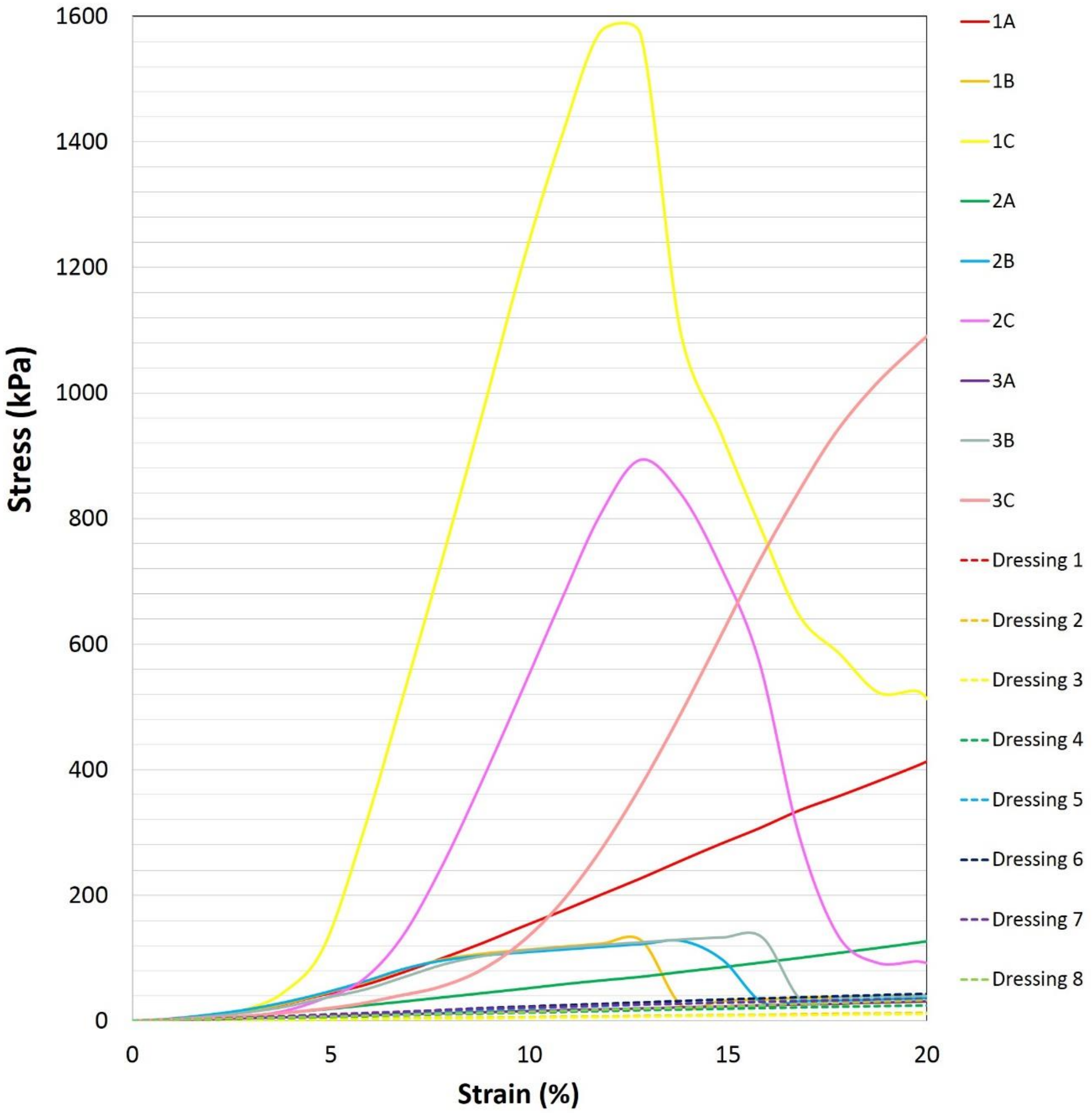


Figure 8.9 Overall extensibility of newly developed wound dressing composites and existing wound dressings

Figure 8.10 Breakage of wound dressing composites: Type B (Left) and Type C (Right)

The change in length after stretching was measured and shown in Figure 8.11. From the results, it can be found that the length of Dressing 8 changes the most, which may be due to its loose non-woven structure. The changes in the length of the wound dressing samples are fewer than most of the wound dressing composites. However, 3B and 3C and Dressing 1 have no changes in length after stretching. This indicates that their recovery is the best among all of the samples. In addition, the values in the changes in length of the wound dressing composites are comparable to those of the wound dressings as the difference is approximately 1 mm only.

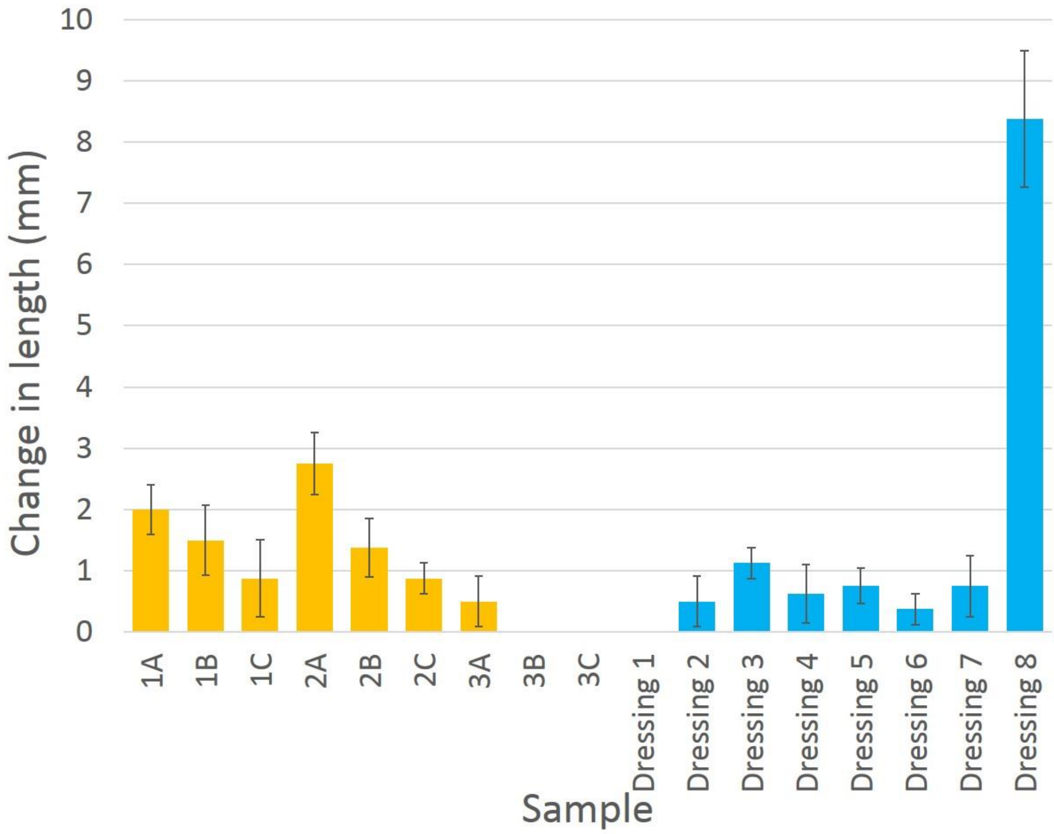


Figure 8.11 Changes in length of newly developed wound dressing composites and existing wound dressings after stretching

8.8 Surface Friction Test

According to the literature, shearing force and friction are also extrinsic contributors to pressure ulcer development (Murray et al., 2001). Therefore, in order to prevent further damage to pressure ulcer wounds, the surface properties of wound dressings should be considered. As some of the existing wound dressings contain an adhesive layer that comes into contact with the skin, it is not feasible to carry out a surface property test as the dressings will stick onto the sensor of the testing machine. In this part, the friction and roughness of the wound dressings which do not have an adhesive layer and three wound contacting layers of the wound dressings composites are the focus and evaluated.

8.8.1 Results and Discussion

In this study, the fabric friction and roughness are represented by the surface coefficient of friction (MIU), mean deviation of the coefficient of friction (MMD) and mean deviation of the surface contour (SMD). Higher MIU values indicate less tendency to slip while higher MMD values mean less smoothness and more roughness. SMD is the surface roughness in which a higher value indicates more surface unevenness.

The results of the MIU, MMD and SMD testing are shown in Table 8.9. As wound dressings may create friction onto the fragile wound bed of a pressure ulcer, a smoother surface is preferred. According to the table, the MIU values of three different wound contact layers are similar which indicate that they have a similar tendency to slip. When compared with the existing wound dressings, their MIU values are similar to Dressing 8. On the other hand, Dressings 1, 2 and 4 have the lowest MIU values, thus indicating that they have more tendency to slip. For the MMD values, Type A has the lowest value which is even less than Dressing 8. Types B and C have similar values which prove that their surface is rougher. Similar to the results of the MIU, Dressings 1 and 2 have the lowest MMD values which indicate that they have smoother surfaces followed by Dressing 4. The SMD value of Type B is similar to that of Dressings 2 and 4 and better than that of Dressings 1 and 8. This indicates that Type B has less surface unevenness. The larger SMD values of Types A and C prove that they have even more surface unevenness.

When comparing the overall results of the wound composites and the existing wound dressings, the wound composites are not as smooth as Dressings 2 and 4. However, their results, especially Type B, are somehow comparable to those of Dressings 1 and 8.

Table 8.9 Surface property results of composites vs existing wound dressings without adhesive layer

	MIU		MMD		SMD	
	Mean	SD (±)	Mean	SD(±)	Mean	SD(±)
Type A	0.2057	0.0049	0.0075	0.0012	4.0467	0.1706
Type B	0.2073	0.0290	0.0139	0.0008	1.6333	0.1591
Type C	0.2023	0.0032	0.0200	0.0089	10.0083	1.1873
Dressing 1	0.0050	0.0014	0.0007	0.0004	3.1777	0.0162
Dressing 2	0.0037	0.0021	0.0008	0.0003	1.3667	0.1102
Dressing 4	0.0077	0.0015	0.0030	0.0043	1.2883	0.0625
Dressing 8	0.2663	0.0343	0.0082	0.0017	2.2883	0.0153

8.9 Wettability Test

The wettability test is used to evaluate the hydrophobicity of the outer surface of the newly developed wound dressing composites and existing wound dressings. Surfaces that are hydrophobic will block water vapor from entering the outside environment (Yang & Hu, 2016b). This is also related to their ability to inhibit bacterial infiltration. There were only 3 different types of barrier layers, Types 1, 2 and 3. Furthermore, the hydrophobicity of the surface was evaluated. Therefore, in this study, three different outermost adhesive layers combined with spacer fabrics and the outer surface of existing wound dressings were tested.

8.9.1 Results and Discussion

The wettability results of the newly developed wound dressing composites and existing wound dressings are shown in Table 8.10. In this study, water droplets are transferred to the outermost surface of the wound dressing composites and wound dressings. The wettability test was adopted to investigate the absorbency of water vapor by the outer surface of the wound dressing composites and existing wound dressings in order to study whether they will absorb and transfer water vapor from the external environment to the wound. As wettability testing was used to evaluate the hydrophobicity of the sample surface, only three different types of outermost layers of the spacer fabrics that adhered were tested.

According to the results, a barrier layer with the use of Type 2 and Dressing 8 have stronger solid liquid interaction and regarded as having high wettability as they absorbed the water droplets quickly. This proves that they are hydrophilic. Type 1 has the largest contact angle among all of the samples which indicates that its solid liquid interaction is weak and it is regarded as having low wettability. According to previous studies, materials with a contact angle greater than 90 degrees are regarded as hydrophobic while those with a contact angle less than 90 degrees are regarded as hydrophilic (Ma, Cao, Feng, Ma, & Zou, 2007; Patankar, 2003). Hydrophobic surfaces can repel liquid droplets on the material surface while the droplets will be strongly attached to the material surface due to hydrophilicity. Therefore, from the results, layers with Types 1 and 3 are regarded as hydrophobic. Except for Dressings 3, 7 and 8, the other existing wound dressings are regarded as hydrophobic. Previous research also indicated that the outermost surface of foam dressings is hydrophobic (Jones, Grey, & Harding, 2006).

The results showed that Types 1 and 3 have a larger contact angle than the existing wound dressings thus indicating that they are more hydrophobic. They are therefore able to both successfully repel water droplets and protect wounds from contaminated fluids.

Table 8.10 Wettability of barrier layers of newly developed wound dressing composites and the existing wound dressings

	Contact angle (degree)
Type 1	111.60
Type 2	Absorbed < 5 seconds
Type 3	94.90
Dressing 1	88.20
Dressing 2	90.50
Dressing 3	36.60
Dressing 4	91.60
Dressing 5	92.40
Dressing 6	97.60
Dressing 7	64.20
Dressing 8	Absorbed immediately

8.10 Bacterial Static Test

It is important that wound dressings are impermeable to bacteria in order to protect fragile wounds against bacteria (Jones et al., 2006). Bacterial inhibition is one of the most common strategies to protect wounds from bacterial colonization. In this study, all of the existing wound dressings selected do not contain antiseptic which blocks bacterial transmission by killing bacteria. Instead, they have a physical barrier to block liquids and bacteria. In addition, the newly developed wound dressing composites do not contain any antiseptic. Therefore, in the experiments, the ability to block the transmission of bacteria by the existing wound dressings and newly developed wound dressing composites was investigated.

8.10.1 Results and Discussion

Tables 8.11 and 8.12 show the bacteriostatic results of the newly developed wound dressing composites and the existing wound dressings respectively. Control samples of each sample were used to ensure that there was no contamination on the fabric which may affect the results and to prove that any growth of microbials on the agar plate was due to the diffusion of bacteria from the sample surface. From the results of the control samples, it was found that there is no contamination.

No microbial growth took place in both the newly developed wound dressing composites and existing wound dressings that were inoculated with Escherichia coli or Staphylococcus aureus. Therefore, the bacterial inoculum could not pass through the samples onto the agar plate. This means that both the newly developed wound dressing composites and existing wound dressings have excellent bacterial inhibition which can protect wounds against developing an infection.

Based on the wettability results discussed in Section 8.9, most of the newly developed wound dressing composites and existing wound dressings have the ability to repel water droplets. Figures 8.12 and 8.13 show examples of the surface of the newly developed wound dressing composites after adding the inoculum for 24 hours respectively. Due to their hydrophobic surface properties, the bacterial inoculum is not transferred from the surface to the wound. Although wound dressing composites with a Type 2 adhesive layer and Dressing 8 are hydrophilic, they can still prevent the bacteria from passing through to the agar plates. Fonder et al. (2008) indicated that the ability of wound dressings to provide an effective barrier against bacterial invasion may be limited. However, from the study results here, it was found that Dressing 8 still has the ability to protect against wound infections. There was no microbial growth on the agar plates which means that its bacterial inhibition is good and can protect against wound infections.

Table 8.11 Bacteriostatic results of newly developed wound dressing composites

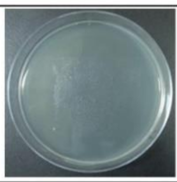
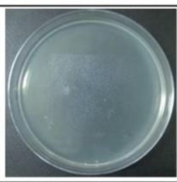
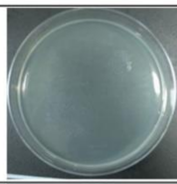
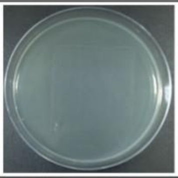
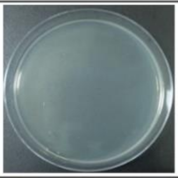
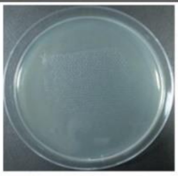
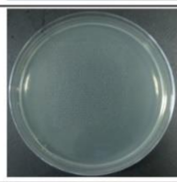
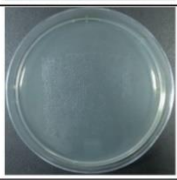
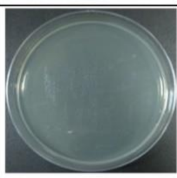
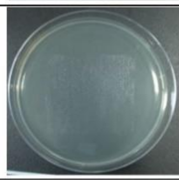
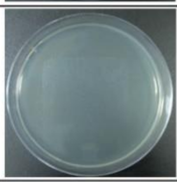
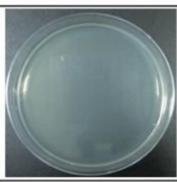
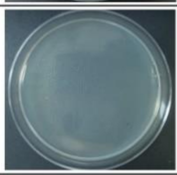
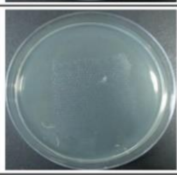
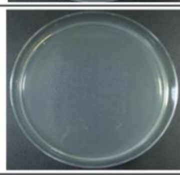
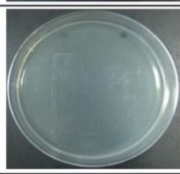
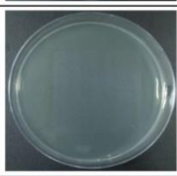
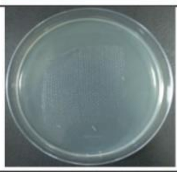
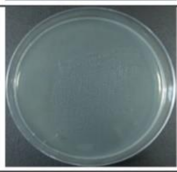
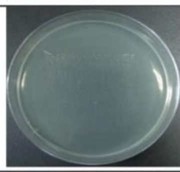
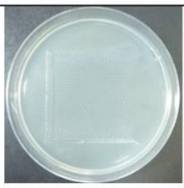
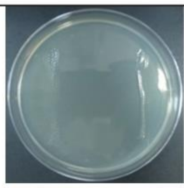
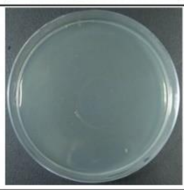
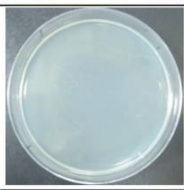
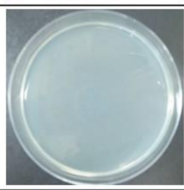
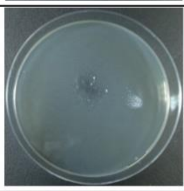
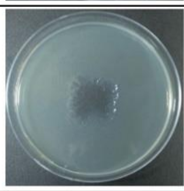
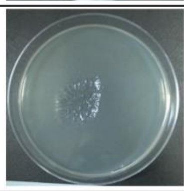
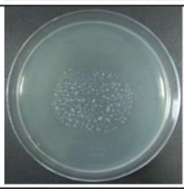
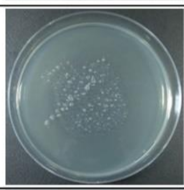
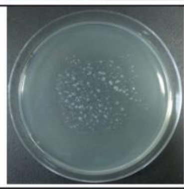
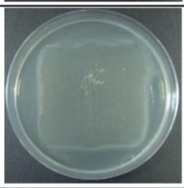
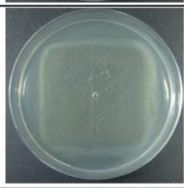
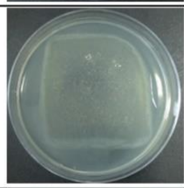
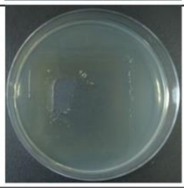
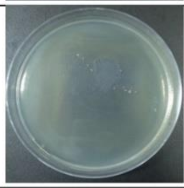
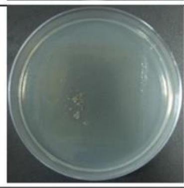
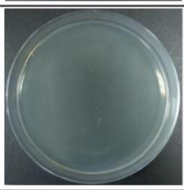
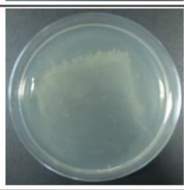
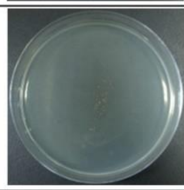
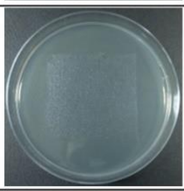
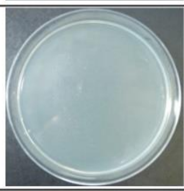
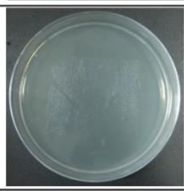
	Control	Escherichia coli	Staphylococcus aureus
1A			
1B			
1C			
2A			
2B			
2C			
3A			
3B			
3C			

Table 8.12 Bacteriostatic results of existing wound dressings

	Control	Escherichia coli	Staphylococcus aureus
Dressing 1			
Dressing 2			
Dressing 3			
Dressing 4			
Dressing 5			
Dressing 6			
Dressing 7			
Dressing 8			

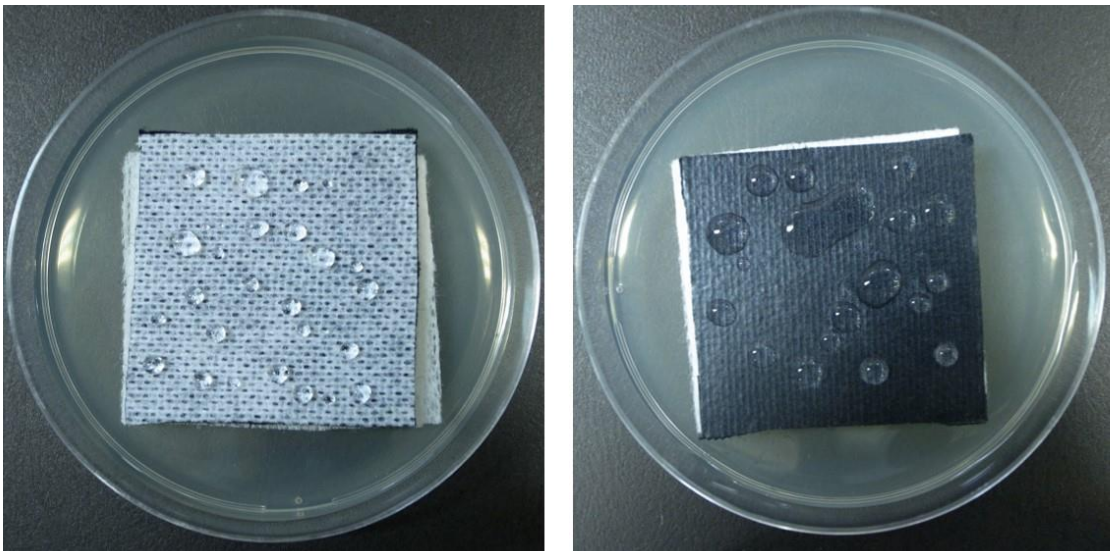


Figure 8.12 Adhesive surface of newly developed wound dressing composites with Types 1 and 3 after adding bacterial inoculum for 24 hours

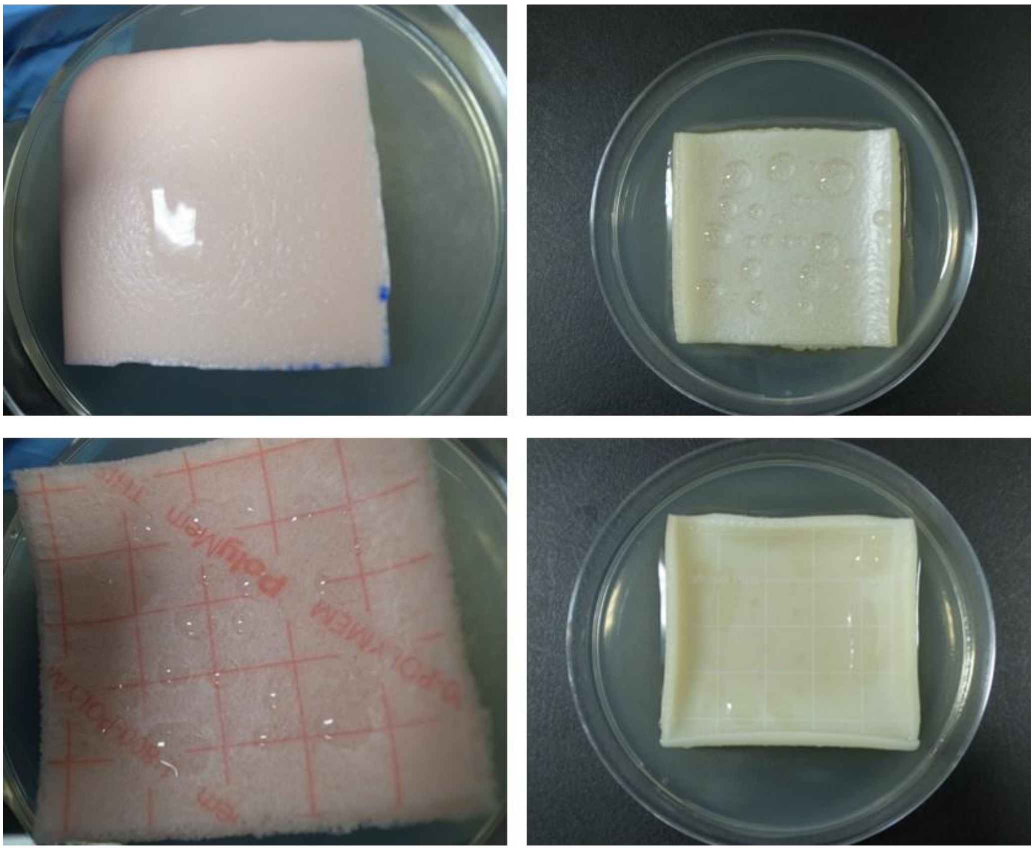


Figure 8.13 Adhesive surface of existing wound dressings after adding bacterial inoculum for 24 hours

8.11 Chapter Summary

In accordance with the results obtained in Chapter 6, the design and development of new wound dressing composites are discussed in this chapter. In order to evaluate their performance and determine whether they can fulfil the criteria of existing wound dressings, several physical tests have been carried out. The two key requirements are to provide a cushioning effect and absorbency. Furthermore, the water vapor and air permeabilities, and thermal conductivity of the samples are investigated for comfort. Extensibility which is related to conformity of the samples is evaluated. Moreover, testing on the bacterial inhibition is also carried out to ensure that the newly developed composites can protect wounds against bacteria in the external environment from infiltrating the wound site.

The results on the compression resistance show that the wound dressing composites have a better performance than the existing wound dressings when the applied pressure is greater than 6.69 kPa. With reference to Chapter 5, 6.69 kPa is the average heel interface pressure of the elderly subjects when their foot is placed at 60 degrees to a mattress and heel interface pressure is always greater than 6.69 kPa at 90 degrees to a mattress. Therefore, the results show that wound dressing composites will not have a great reduction in thickness regardless whether the heel is placed at 60 or 90 degrees to a mattress. The absorbency and fluid retaining capacity of the newly developed wound dressing composites are comparable to or even better than the existing wound dressings. They have better water vapor permeability performance than the dressings with an adhesive wound contacting layer (Dressings 3, 5, 6 and 7). They have comparable water vapor permeability to Dressings 1, 2 and 4, but not 3A, 3B and 3C. The air permeability of the wound dressing composites, except for 3A, 3B and 3C, excel that of the existing wound dressings. The thermal conductivity of the wound dressing composites is comparable to most of the existing wound dressings. As for the extensibility, most have a better performance than the wound dressings as more pressure is needed to stretch them. In addition, the changes in their length are comparable to those of the existing wound dressings. In the friction test, although the overall results of the wound contacting layers are not as good as those of the existing wound dressings with no adhesive wound contacting layer, the results, especially Type B, are somewhat comparable to Dressings 1 and 8. For the bacteria inhibition test, the results prove that all of the newly developed wound dressing composites have excellent ability to block bacteria just like the existing wound dressings. This means that they can protect a wound against infection due to the infiltration of bacteria from the external environment.

Chapter 9 Conclusion and Recommendations for Future Work

9.1 Conclusion

Pressure ulcers are a prevalent type of chronic wound among the elderly and bedridden patients and difficult to heal once they have developed. Ideal wound dressings for pressure ulcers should not only have a layer that allows for the transmission of liquid and gas, but also absorbs exudate, and provides cushioning to help relieve pressure at the same time. There are few wound dressings designed for pressure ulcer wounds on the market. Their pressure relief and cushioning performance are also ambiguous. The conformability of wound dressings to the 3D geometrical shape of the body parts, such as the heel region, is also poor. Moreover, studies on the heel interface pressure, especially in the elderly, and the effects of foot positions and mattresses on the heel interface pressure are lacking. Fortunately, 3D knitted spacer fabric has a versatile performance and widely used in different technical and medical textile applications. Therefore, the aims of this thesis are to understand the pathophysiology of pressure ulcers, address the knowledge gap in evaluating the heel interface pressure of elderly, investigate the effects of heel positioning on the heel interface pressure, evaluate the physical properties of currently available pressure ulcer wound dressings, analyse the physical performance of 3D knitted spacer fabrics, develop a simulation model by using FEA to predict contact pressure as well as develop and evaluate wound dressing composites with 3D knitted spacer fabrics as the absorbent and cushioning layer. The objectives, which are discussed in detail in Section 1.3 of Chapter 1, have been realised and the achievements of the research work are summarized as follows.

1) The research work started with a 6-month clinical study at an elderly home to observe the current preventive and healing methods for pressure ulcer wounds. The wound management of pressure ulcers on the heel and the wound healing

process of two elderly patients are investigated. It is difficult for pressure ulcers to heal which is especially true for the elderly who have chronic illnesses and low metabolism, i.e. more than 6 months is required. Furthermore, proper wound care, sufficient nutrition and careful daily care contribute to the healing of pressure ulcer wounds. Seven registered nurses have taken part in interviews and completed questionnaires which provide a better understanding of the problems that they face in real life practices and their opinions toward existing wound dressing products. The ability to absorb exudate, cushioning effect, breathability as well as conformability are the main concerns of the interviewees when choosing a wound dressing for pressure ulcer patients. An analysis of the interview and questionnaire responses shows that these physical properties are lacking in existing wound dressings. The findings therefore provide important information for the design and development of new wound dressing composites.

2) The neutral heel positions of the elderly in a relaxed state are examined when they are lying on a mattress. The neutral position that faces outwards or upright position is their neutral position when they are relaxed. The influence of heel positioning on the heel interface pressure and the effectiveness of standard hospital mattresses and pressure relief mattresses for pressure relief are investigated. The results show that the upright foot position may put the bedridden elderly at a higher risk for heel pressure ulcer development than the neutral position that faces outwards. Even if pressure relief mattresses are used, some of the elderly may be still at a high risk for heel pressure ulcer development which indicates that pressure relief mattresses may not always be effective enough to redistribute the heel pressure for all cases. The heel skin conditions of the elderly, including skin elasticity, and moisture and sebum contents are recorded and analysed. The results show that the skin on the

heel of the elderly is considered to be very dehydrated and lacks sebum. These issues may increase the risk of skin abrasion and friction as well as the chances of developing a pressure ulcer on their heel.

3) In this research, the physical performance of current wound dressings found in the market is evaluated and the possibility of using 3D spacer fabric as the absorbent layer for advanced wound dressings is explored. Seven types of warp knitted spacer fabrics, 15 types of weft knitted spacer fabrics and 8 types of existing wound dressings are examined in terms of their physical properties, including compression, absorbency, wettability, water vapor and air permeabilities, thermal conductivity and extensibility. The physical properties of the 3D knitted spacer fabrics, especially the weft knitted spacer fabrics, are comparable or even excel those of the existing wound dressings. The 3D knitted spacer fabrics can therefore fulfil the criteria for wound dressings. The analysis results provide direction for the future development of wound dressing composites.

4) The research in this thesis has predicted the interface pressure between the spacer fabric and heel by using a biomechanical simulation model obtained through FEA. The finite element model consists of a heel model with bones and tissues and a spacer fabric model. The geometrical and mechanical properties of the spacer fabric and human body tissues are taken into consideration in the simulation model. By modifying the corresponding material properties of the spacer fabrics and human tissues, the contact pressure that is distributed over the spacer fabric and the change in the magnitude of pressure given by heel onto the spacer fabric can be precisely predicted. Spacer fabric is not only limited to use as a substitute for the absorbent layer of wound dressings, but any pressure relief purposes for the heels, such as heel protectors. The simulation model can help with the selection of

suitable spacer fabrics with optimum compression performance for heel pressure relief without time consuming subject recruitment for testing through trial wears, or measurements done on real human subjects.

5) Three-layer wound dressing composites with spacer fabric as the absorbent layer are proposed based on the results collected from a clinical study along with evaluated material properties and biomechanical pressure. The 3-layer wound dressing composites consist of a non-adhesive wound contacting layer, 3D knitted spacer fabric as the absorbent and cushioning layer, and an adhesive barrier surface layer. The physical performance of these composites is investigated especially the absorbency and compression properties. The surface friction and bacterial barrier properties of the composites are also explored. The overall performance of the composites is comparable to or even excels that of the existing wound dressings. The proposed wound dressing composites not only can fulfil the requirements of wound dressings, but also improve the cushioning effect for heel pressure relief at a lower production cost.

9.2 Limitations of the study

Some of the limitations of this study that limit the generalization of the results are listed as follows.

1) In the clinical study that was carried out at an elderly home to gain a better understanding of the treatment and healing process of pressure ulcer wounds on the heel, the number of examined cases is relatively small. Only three elderly individuals had pressure ulcers of which two had a pressure ulcer on their heel and the other had a pressure ulcer on the sacrum. Hence, due to the difficulties of finding an adequate number of individuals with a heel ulcer and limitations of time, only two cases are examined in this study. There might also be some inter-subject

variations, such as different chronic illnesses. A larger sample size could reduce the inter-subject variation and increase the clinical significance of the study. The findings of this study have only highlighted the importance of proper wound care, nutrition and pressure relief methods, but could also contribute to knowledge on the healing process of heel ulcers. The number of registered nurses and care takers who took part in the interviews and completed questionnaires is also a small sample. Although it is found that their comments about existing wound dressings and the requirements of wound dressings for pressure ulcers show similarities, more interviewees would increase the robustness of the results.

2) The 3D knitted spacer fabrics used in this study are purchased from the market. The findings show that the different knitting parameters of the spacer fabrics have an effect on their physical performance and that their physical properties can meet the needs of wound dressings. However, the optimum knitting parameters have not been determined. Material selection and fabric construction are also the critical parameters influencing the physical properties of spacer fabrics. With the findings, future in-depth investigations can be carried out to determine the optimum knitting parameters so as to improve the physical properties of spacer fabrics.

3) The material properties of the bones and tissues assigned to the heel model in this study are used with reference to the previous literature. However, there may be differences in the material properties of the heel of subjects in real life as the skin and dermis elasticity are different from person to person. However, due to the limitations of the equipment in this study, the material properties of the heel of real subjects have not been evaluated. This is also one of the reasons why the trend of the predicted contact pressure is similar to that of the measured pressure but with a range of differences in magnitude. However, the simulation model developed in

this study can act as the preliminary model for further development and improvement.

4) Wear trials of the proposed wound dressing composites on subjects with a heel ulcer wound have not been done due to the ethical concerns. The findings of the material testing prove that the proposed wound dressing composites can fulfil the criteria of wound dressings. In addition, based on an analysis of the results, the proposed wound dressing composites have better performance in terms of absorbency, cushioning and breathability, but cannot satisfy the requirements for bacterial prevention. However, wear trials on real heel ulcer wounds are a more comprehensive means to prove whether the proposed wound dressing composites can enhance healing in real life situations.

9.3 Recommendations for future work

A few recommendations for future work based on the established research findings are provided as follows.

1) A more detailed and precise heel model which includes the bones, skin and tissues, will allow further improvements and developments to the research work. A comprehensive database of the material properties of the heel components, including the bones, skin and fat pad, would considerably improve the accuracy of the prediction of pressure by the model as well as the pressure distribution and compression behaviour of the spacer fabric.

2) A simulation model of the different heel positions, such as the neutral position that faces outwards, can be further developed to provide a thorough understanding the effects of heel position on the interface pressure between the spacer fabric and heel.

3) Different material properties and constructions of spacer fabric can be investigated by using FEM to improve the development of wound dressing composites with

spacer fabric as the absorbent layer or any pressure relieving product which uses spacer fabric as the cushioning material. The results of the biomechanical model show that spacer fabric with optimum performance can be produced and wear trials can be carried out to evaluate the performance of the wound dressing composites or the pressure relieving products in real life situations.

Appendix I Questionnaire (English version)

Questionnaire

Part 1

Personal information

Name: ______________________ Date: ______________________

Gender: ☐Male ☐Female

Working in: ☐ Hospital ☐ Home of the Elderly ☐ Others: (please specify) ____________

Experience: ☐ <1 year ☐ 1-5 years ☐ 5-10 years ☐ 11-15 years ☐ 16-20 years ☐ >20 years

Part 2

About pressure ulcer and preventive methods

Directions: Please place an "X" mark in the box of your answer.

1. Times of turning per day recommended	☐ 0	☐ 1-2	☐ 3-4	☐ 5-6
	☐ 6-7	☐ 8-9	☐ 9-10	☐ >10
2. Type of mattress preferred	☐ Foam mattress	☐ Air mattress	☐ Water mattress	☐ Others (please specify) ____________
3. Overlays or cushion suggested	☐ Overlay only	☐ Cushion only	☐ Both	☐ None
4. Mattress overlays or cushions suggested (select one or many, as appropriate)	☐ Foam	☐ Fibre-filled	☐ Air-filled	☐ Water-filled
	☐ Sheepskin	☐ Synthetic fleece	☐ Gel	☐ Other (please specify) ____________

5. Wound dressing used (select one or many, as appropriate) recommended	☐ Foam	☐ Hydrogel impregnated	☐ Hydrocolloid	☐ Transparent film
	☐ Alginate	☐ Hydrofibre	☐ Antimicrobial	☐ Others (please specify) ______________
6. Time for changing wound dressings preferred	☐ < 1 hour	☐ 1-2 hours	☐ 3-4 hours	☐ 5-6 hours
	☐ 7-8 hours	☐ 9-10 hours	☐ 11-12 hours	☐ 13-18 hours
	☐ 19-23 hours	☐ 1-2 days	☐ 2-3 days	☐ Other (please specify) ______________

Part 3

Priority of choosing wound dressings

Directions: Please indicate the priority in the box of your answer.

From 1 to 10 which 1st is the most important property while 10th is the least important one.

☐ Comfort	☐ Breathability	☐ Absorption ability	☐ Pressure relief	☐ Less pain during removal
☐ Softness	☐ Dampness	☐ Fit the wound size and shape	☐ Convenience to use	☐ No. of times that dressing needs to be changed

Part 4

Overall feeling of pressure ulcer wound dressings

Directions: Please place an "X" mark in the box of your answer.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1. I think that the wound dressing(s) has/have good thermal feel.	☐	☐	☐	☐	☐
2. I think that the wound dressing(s) is/are breathable.	☐	☐	☐	☐	☐
3. I think that the wound dressing(s) has/have good absorption of wound extrude.	☐	☐	☐	☐	☐
4. I think that the wound dressing(s) become too damp.	☐	☐	☐	☐	☐
5. I think that the wound dressing(s) can relieve pressure.	☐	☐	☐	☐	☐
6. I think that the surface of wound dressing(s) is/are soft.	☐	☐	☐	☐	☐
7. I think that the wound dressing(s) can reduce the pain during changing of dressings.	☐	☐	☐	☐	☐
8. I think that the wound dressing(s) reduce the number of times that the dressing(s) need to be changed.	☐	☐	☐	☐	☐
9. I think that the wound dressing(s) fit(s) the size and shape of the wound.	☐	☐	☐	☐	☐
10. I think that the wound dressing(s) can prevent the development of pressure ulcers.	☐	☐	☐	☐	☐
11. I think that the wound dressing(s) can heal pressure ulcer wounds.	☐	☐	☐	☐	☐
12. I think that the wound dressing(s) can improve the quality of life.	☐	☐	☐	☐	☐
13. I think that the wound dressing(s) are convenient to use.	☐	☐	☐	☐	☐
14. I think that the wound dressing(s) are good.	☐	☐	☐	☐	☐
15. I am satisfied with the wound dressing(s)	☐	☐	☐	☐	☐
16. I want to try other wound dressings.	☐	☐	☐	☐	☐

This is the end of the questionnaire.
Thank you so much for your precious opinion.

Appendix II Questionnaire (Chinese version)

問卷

第一部分

個人資料

姓名: ____________________ 日期: ____________________

性別: ☐男 ☐女

工作地點: ☐ 醫院 ☐ 老人中心 ☐其他: (請註明) ____________

工作經驗: ☐<1 年 ☐1-5 年 ☐5-10 年 ☐11-15 年 ☐16-20 年 ☐>20 年

第二部分

關於壓力瘡和預防方法

指示: 請在你的答案框中用 "x" 標記。

1. 建議每日翻身次數	☐0	☐1-2	☐3-4	☐5-6
	☐6-7	☐8-9	☐9-10	☐>10
2. 推薦的床墊	☐海綿床墊	☐空氣床墊	☐水床墊	☐其他: (請註明) ____________
3. 推薦的床蓋或墊	☐只使用床 (請到 7)	☐只使用墊 (請到 8)	☐兩者都有使用 (請至 7 和 8)	☐沒有使用 (請到 9)
4. 床蓋 (選擇一個或多個（如適用）)	☐海綿	☐纖維填充	☐充氣	☐充水
	☐羊皮毛	☐合成羊毛	☐凝膠	☐其他: (請註明) ____________
5. 墊 (選擇一個或多個（如適用）)	☐海綿	☐纖維填充	☐充氣	☐充水
	☐羊皮毛	☐合成羊毛	☐凝膠	☐其他: (請註明) ____________

6. 使用的傷口敷料 (選擇一個或多個（如適用）)	☐海綿 (Foam)	☐水凝膠 (Hydrogel impregnated)	☐親水膠質 (Hydrocolloid)	☐透明薄膜 (Transparent film)
	☐海藻酸鈉 (Alginate)	☐吸濕纖維 (Hydrofibre)	☐抗菌 (Antimicrobial)	☐其他: (請註明) __________
7. 更換傷口敷料的時間	☐ 少於 1 小時	☐1-2 小時	☐3-4 小時	☐5-6 小時
	☐7-8 小時	☐9-10 小時	☐11-12 小時	☐13-18 小時
	☐19-23 小時	☐1-2 天	☐2-3 天	☐其他: (請註明) __________

如果使用多於一種傷口敷料在壓力瘡病人上，請到第三部分。

第三部分

選擇傷口敷料的優先考慮因素

指示: 請註明您在選擇傷口敷料時的優先考慮因素。

從 **1** 至 **10** 其中第 **1** 是最重要的因素，而第 **10** 是最不重要的一種

☐舒適度	☐透氣度	☐吸收能力	☐壓力的緩解	☐移除時的痛楚
☐柔軟度	☐濕度	☐是否附合傷口大小和形狀	☐使用是否方便	☐ 更換的次數

第四部分

對壓力瘡傷口敷料的總體感覺

指示: 請說明您對以下有關壓力瘡的陳述的同意程度。請在你的答案框中用 “X” 標記。

	非常不同意	不同意	中立	同意	非常同意
1. 我認為正在使用的敷料具有良好的溫度控制。	☐	☐	☐	☐	☐
2. 我認為正在使用的敷料是透氣的。	☐	☐	☐	☐	☐
3. 我認為正在使用的敷料有良好的吸收能力。	☐	☐	☐	☐	☐
4. 我認為正在使用的敷料太潮濕。	☐	☐	☐	☐	☐
5. 我認為正在使用的敷料可以緩解傷口的壓力。	☐	☐	☐	☐	☐
6. 我認為正在使用的敷料是柔軟的。	☐	☐	☐	☐	☐
7. 我認為正在使用的敷料能在更換敷料時減輕疼痛。	☐	☐	☐	☐	☐
8. 我認為正在使用的敷料減少更換的次數時間。	☐	☐	☐	☐	☐
9. 我認為正在使用的敷料大小和形狀都適合傷壓力瘡口。	☐	☐	☐	☐	☐
10. 我認為正在使用的敷料可以預防壓力瘡的形成。	☐	☐	☐	☐	☐
11. 我認為正在使用的敷料可以治愈壓瘡傷口。	☐	☐	☐	☐	☐
12. 我認為正在使用的敷料能改善病人的生活質素。	☐	☐	☐	☐	☐
13. 我認為正在使用的敷料方便使用的。	☐	☐	☐	☐	☐
14. 我認為正在使用的敷料是很好的。	☐	☐	☐	☐	☐
15. 我很滿意正在使用的敷料	☐	☐	☐	☐	☐
16. 我想試試其他的傷口敷料。	☐	☐	☐	☐	☐

這是調查問卷的末端。

非常感謝你為你的寶貴意見。

Appendix III Information sheet for pressure ulcer patients (English version)

INFORMATION SHEET

Development of 3-Dimensional Spacer Fabrics as Absorbent and Cushioning Layer for Advanced Composite Wound Dressing

This research study is supervised by Dr. YIP Yiu Wan, Joanne, a staff member of Institute of Textiles and Clothing, The Hong Kong Polytechnic University and her team members. Please take time to read the following information carefully and discuss it with friends, relatives and your family doctor if you wish. Ask us if there is anything that is not clear or if you would like to have more information. Take time to decide whether or not you wish to take part.

Purpose of the study

The purpose of this study is to gain the clinical information necessary for the design of an advanced composite wound dressing by using 3-dimensional spacer fabrics. The advanced composite wound dressing can provide both absorbent and cushioning qualities for wound. Participants' age, body mass index, conditions of the wound and surrounding skin, dressing conformability, ease of application and removal of the dressing, signs of infection, perception in relation to thermal environment and pressure distribution will be recorded in order to optimize the design for comfort and functional performance of the advanced composite wound dressing.

Who will be invited to participate in this study?

People with heel pressure ulcers will be invited to participate in a thorough evaluation.

What will happen if you decide to take part?

First, your personal information including medical records will be recorded. Also, the non-invasive tests as follow will be carried out:

1. A quantitative survey will be implemented with your clinicians in order to assess the conditions for the surrounding skin, comfort, dressing conformability, ease of application and removal, and factors related to infection. Various factors, such as age and body mass index, and the clinical procedure for wound management, will also be recorded. All the measurements obtained will be used to determine the status of the pressure ulcers of the participants. The interview takes around 10 minutes.

2. Patients will be invited to participate in a 6-month monitoring studying. Every week, photos will be taken for pressure ulcer examination and documentation of the improvement of pressure ulcer wounds and the wound healing progress and the wound management procedure will be recorded. The measurements take around 15 minutes.

Do you have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time without giving a reason. The choice of participation in the study would not affect the standard of care you receive in the clinic. During the study, if you failed to turn up at appointments, your participation in this study will be immediately terminated without further notice.

What are the disadvantages and risks of taking part?

All the evaluations methods are no risk to health and do not cause skin allergy and/or discomfort. In such, there are no special compensation arrangements in this study.

What are the benefits of taking part?

The potential benefit is to provide an option of patients with pressure ulcers with better design, fitting and comfort to provide an optimum healing environment for the wounds of pressure ulcers, and thus improve the wound healing process and pressure relief of ulcerations on legs.

What if something goes wrong?

There are no special compensation arrangements in this study. If you wish to complain about any aspect of the way you have been approached or treated during the course of this study, you can also contact The Secretary of the Human Subjects Ethics Sub-Committee of The Hong Kong Polytechnic University in person or in writing (c/o M1303, Human Resources Office of the University).

Will my taking part in this study be kept confidential?

If you agree to take part in this study, the measurement results will only be reviewed by the research team to obtain essential information. All information collected will be kept confidential.

What will happen to the results of the research study?

The results will be published in referred journal.

Who is organizing and funding the research?

The research is organized by Institute of Textiles and Clothing, The Hong Kong Polytechnic University.

Who has reviewed the study?

The study has been reviewed by Departmental Research Committee of Institute of Textiles and Clothing, The Hong Kong Polytechnic University.

Please keep this information sheet for your reference, together with a signed consent form.

If you have any query, please do not hesitate to contact Dr. YIP Yiu Wan at 2766 4848. Thank you very much in helping us to improve our patients' care.
Updates of this study will only be informed, if necessary.

Dr. YIP Yiu Wan, Joanne
Principle Investigator/Chief Supervisor

Appendix III Information sheet for pressure ulcer patients (Chinese

version)

<u>資料篇</u>

<u>發展利用三維間隔織物提供吸濕和緩衝作用的高級的綜合傷口敷料</u>

我們誠意邀請閣下參與一項研究，這項研究由香港理工大學紡織及製衣學系教職員葉曉雲博士及其成員籌劃。請詳細閱讀以下資料，亦可與親友或醫護人員商量。 若有任何不清晰的地方或需要更多資料，請隨便向我們提出。

<u>研究主旨</u>

這項研究的目的是根據臨床資料，發展利用三維間隔織物提供吸濕和緩衝作用的高級的綜合傷口敷料。先進的綜合傷敷料可為傷口提供吸濕和緩衝的特性。我們會量度參加者的年齡，身體質量指數等資料，並記錄參加者的治療程序,傷口和周圍皮膚的情況，敷料的貼合性和舒適度，敷料是否容易使用和去除，傷口感染的跡象，,熱量變化，壓力分佈，身體感覺以及臨床反應，從而優化適用於不同下支部位的壓瘡並具舒適性和功能性的綜合傷口敷料。

<u>誰會被邀請參與這項研究？</u>

此研究會邀請被診斷在腳後跟患有壓瘡的病人進行徹底的評估。

<u>決定參加後,你需要做什麼?</u>

我們首先會記錄參加者的個人資料,身高體重，醫療記錄等。另外，我們亦會為患者進行以下非入侵性測試：

一. 你的臨床醫生或護理員會填寫一份<u>有關壓力瘡問卷</u>， 以評估傷口周圍皮膚的情況，敷料的舒適度,貼合性，應用和移除的方便程度和受感染因素等。所得的資料均會用於確定參加者的壓瘡狀態。時間須約十分鐘。

二. 參加者被邀請參與為時 6 個月的觀察計劃。每星期，患者的壓瘡傷口情況及傷口處理方法和康復進度都會被<u>拍照及記錄</u>。時間須約十五分鐘。

<u>參與此研究有風險嗎?</u>

所有檢查均無危險性及並不會引起皮膚敏感或不適。故與此研究有關的創傷均沒有任何意外賠償。

參加此研究有什麼實際益處?

與現有的傷口敷料相比，我們希望可以為壓瘡病人提供一項不論在設計上，貼合程度上和舒適感上都更好的選擇，從而為壓瘡傷口提供最佳的癒合環境，改善足部壓瘡的傷口癒合過程和舒緩傷口的壓力。

參加此項研究，你有什麼補償?

本研究對受試者沒有提供補償安排。如果閣下對這項研究有任何人權問題,你亦可親身或以書面形式聯絡香港理工大學人事倫理委員會秘書(地址：香港理工大學人力資源辦公室 M1303 室轉交)。

我參與這研究資料是否保密?

如閣下同意參與此項研究,凡有關閣下的資料均會保密，一切量度結果只有研究人員知道,並用作研究用途。 其他的資料一概保密。

我們會怎樣處置研究結果?

我們會把結果發報在紡織設計刊物等。

是誰統籌和資助此研究?

是項研究是由香港理工大學紡織及製衣學系統籌。

誰審核過此研究?

是項研究經香港理工大學紡織及製衣學系研究委員會審核。

請保存這份資料和同意書作日後參考。

如有疑問，請至電 27664848 向葉曉雲博士查詢。

特此再次多謝你的參與，閣下的支持定能對將來改善醫院病人的服務有很大的幫助。

有關此研究的更新資料或資訊,有須要時,將會個別另行通知。

葉曉雲博士

研究組組長

Tel: 27664848

Email: tcjyip@

Appendix IV Information sheet for normal eldelry (English version)

INFORMATION SHEET

Development of 3-Dimensional Spacer Fabrics as Absorbent and Cushioning Layer for Advanced Composite Wound Dressing

This research study is supervised by Dr. YIP Yiu Wan, Joanne, a staff member of Institute of Textiles and Clothing, The Hong Kong Polytechnic University and her team members. Please take time to read the following information carefully and discuss it with friends, relatives and your family doctor if you wish. Ask us if there is anything that is not clear or if you would like to have more information. Take time to decide whether or not you wish to take part.

Purpose of the study

The purpose of this study is to gain the clinical information necessary for the design of an advanced composite wound dressing by using 3-dimensional spacer fabrics. The advanced composite wound dressing can provide both absorbent and cushioning qualities for wound. Participants' age, body mass index, conditions of the wound and surrounding skin, dressing conformability, ease of application and removal of the dressing, signs of infection, perception in relation to thermal environment and pressure distribution will be recorded in order to optimize the design for comfort and functional performance of the advanced composite wound dressing.

Who will be invited to participate in this study?

People who are at higher risks for pressure ulcer development will be invited to participate in a thorough evaluation.

What will happen if you decide to take part?

First, your personal information including age and medical records will be recorded. Also, the non-invasive tests as follow will be carried out:

1. Heel interface pressure of participants will be measured by pressure sensors. The measurements take around 20 minutes.

2. The heel skin conditions, including elasticity, moisture and sebum contents of participants will be accessed by skin tester. The measurements take around 15 minutes.

Do you have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time without giving a reason. The choice of participation in the study would not affect the standard of care you receive in the clinic. During the study, if you failed to turn up at appointments, your participation in this study will be immediately terminated without further notice.

What are the disadvantages and risks of taking part?
All the evaluations methods are no risk to health and do not cause skin allergy and/or discomfort. In such, there are no special compensation arrangements in this study.

What are the benefits of taking part?
The potential benefit is to provide an option of patients with pressure ulcers with better design, fitting and comfort to provide an optimum healing environment for the wounds of pressure ulcers, and thus improve the wound healing process and pressure relief of ulcerations on legs.

What if something goes wrong?
There are no special compensation arrangements in this study. If you wish to complain about any aspect of the way you have been approached or treated during the course of this study, you can also contact The Secretary of the Human Subjects Ethics Sub-Committee of The Hong Kong Polytechnic University in person or in writing (c/o M1303, Human Resources Office of the University).

Will my taking part in this study be kept confidential?
If you agree to take part in this study, the measurement results will only be reviewed by the research team to obtain essential information. All information collected will be kept confidential.

What will happen to the results of the research study?
The results will be published in referred journal.

Who is organizing and funding the research?
The research is organized by Institute of Textiles and Clothing, The Hong Kong Polytechnic University.

Who has reviewed the study?
The study has been reviewed by Departmental Research Committee of Institute of Textiles and Clothing, The Hong Kong Polytechnic University.

Please keep this information sheet for your reference, together with a signed consent form.

If you have any query, please do not hesitate to contact Dr. YIP Yiu Wan at 2766 4848. Thank you very much in helping us to improve our patients' care.
Updates of this study will only be informed, if necessary.

Dr. YIP Yiu Wan, Joanne
Principle Investigator/Chief Supervisor

Appendix V Information sheet for normal eldelry (Chinese version)

資料篇

發展利用三維間隔織物提供吸濕和緩衝作用的高級的綜合傷口敷料

我們誠意邀請閣下參與一項研究，這項研究由香港理工大學紡織及製衣學系教職員葉曉雲博士及其成員籌劃。請詳細閱讀以下資料，亦可與親友或醫護人員商量。 若有任何不清晰的地方或需要更多資料，請隨便向我們提出。

研究主旨

這項研究的目的是根據臨床資料，發展利用三維間隔織物提供吸濕和緩衝作用的高級的綜合傷口敷料。先進的綜合傷敷料可為傷口提供吸濕和緩衝的特性。我們會量度參加者的年齡，身體質量指數等資料，並記錄參加者的治療程序,傷口和周圍皮膚的情況，敷料的貼合性和舒適度，敷料是否容易使用和去除，傷口感染的跡象，,熱量變化，壓力分佈，身體感覺以及臨床反應，從而優化適用於不同下支部位的壓瘡並具舒適性和功能性的綜合傷口敷料。

誰會被邀請參與這項研究？

此研究會邀請被診斷有較高機會患有壓瘡的人進行徹底的評估。

決定參加後,你需要做什麼?

我們首先會記錄參加者的個人資料,身高體重，醫療記錄等。另外，我們亦會為患者進行以下非入侵性測試：

一. 使用壓力感應器測試參加者的腳後跟的壓力和壓力分佈，時間須約二十分鐘。

二. 使用皮膚分析儀量度參加者腳後跟的皮膚狀態,包括彈性,水份和油份。時間須約十五分鐘。

參與此研究有風險嗎?

所有檢查均無危險性及並不會引起皮膚敏感或不適。故與此研究有關的創傷均沒有任何意外賠償。

參加此研究有什麼實際益處?

與現有的傷口敷料相比, 我們希望可以為壓瘡病人提供一項不論在設計上, 貼合程度上和舒適感上都更好的選擇, 從而為壓瘡傷口提供最佳的癒合環境, 改善足部壓瘡的傷口癒合過程和舒緩傷口的壓力。

參加此項研究，你有什麼補償?

本研究對受試者沒有提供補償安排。如果閣下對這項研究有任何人權問題,你亦可親身或以書面形式聯絡香港理工大學人事倫理委員會秘書(地址：香港理工大學人力資源辦公室 M1303 室轉交)。

我參與這研究資料是否保密?

如閣下同意參與此項研究,凡有關閣下的資料均會保密，一切量度結果只有研究人員知道,並用作研究用途。 其他的資料一概保密。

我們會怎樣處置研究結果?

我們會把結果發報在紡織設計刊物等。

是誰統籌和資助此研究?

是項研究是由香港理工大學紡織及製衣學系統籌。

誰審核過此研究?

是項研究經香港理工大學紡織及製衣學系研究委員會審核。

請保存這份資料和同意書作日後參考。

如有疑問, 請至電 27664848 向葉曉雲博士查詢。

特此再次多謝你的參與, 閣下的支持定能對將來改善醫院病人的服務有很大的幫助。

有關此研究的更新資料或資訊,有須要時,將會個別另行通知。
葉曉雲博士

研究組組長

Appendix VI Consent form (English version)

PARTICIPANT CONSENT FORM

Title of Project: Development of 3-Dimensional Spacer Fabrics as Absorbent and Cushioning Layer for Advanced Composite Wound Dressing

Name of Researchers: Dr. YIP Yiu Wan, Dr. YICK Kit-lun and Prof. YUEN Chun-Wah

1. I confirmed that I have read and understand the information sheet dated ____/____/____ for the above study and have had the opportunity to ask questions.
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reasons, without my legal rights being affected.
3. I understand that sections of any of my medical notes may be looked at by responsible individuals from the researcher's team or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to my records.
4. The results will be published in referred journal. All information collected will be kept confidential.
5. I agree to take part in the above study.

________________________	____________________	________________
Name of participant	Date	Signature
________________________	____________________	________________
Name of witness (if applicable)	Date	Signature
________________________	____________________	________________
Researcher	Date	Signature

Copies to:

- Participant
- Researcher's file

Appendix VII Consent form (Chinese version)

參與研究項目同意書

研究主題：發展利用三維間隔織物提供吸濕和緩衝作用的高級的綜合傷敷料

研究人員名稱：葉曉雲博士，易潔倫博士，袁駿華教授及唐淑芬小姐

1. 本人確定已詳細閱讀並了解於_____/____/____提供之資料單張,並已有足夠時間發問問題。

2. 本人明白是次參與全是自願性質, 本人有權隨時退出而不必提出任何理由, 而本人法律權利不會有改變。

3. 本人明白及同意本人之病歷記錄需要時給與研究員和有關人事作參考。

4. 研究結果將會發報在醫學矯形和紡織設計刊物內。其他收集的資料一概保密

5. 本人同意參與此項研究。

________________	______________	____________________
參加者姓名 日期	簽名	
________________	______________	____________________
見証人(如適用)	日期	簽名
________________	______________	____________________
研究員	日期	簽名

副本給與:
- 參加者
- 研究員

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