DEVELOPMENT OF PRESSURE THERAPY GLOVES FOR HYPERTROPHIC SCAR TREATMENT

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DEVELOPMENT OF PRESSURE THERAPY GLOVES FOR HYPERTROPHIC SCAR TREATMENT

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

Pressure garments are commonly used in the treatment of hypertrophic and deformed scars. These garments need to be continuously worn so that adequate pressure can be applied to the hypertrophic scar, so as to flatten the scar and prevent contracture. Thus, pressure monitoring, patient compliance and comfort sensation are crucial in pressure garment therapy. Based on the body dimensions of patients, pattern pieces are developed in a reduced size so as to exert pressure onto specific parts of the recipients of garment pressure therapy. The amount of reduction is called the reduction factor (RF). Due to the lack of actual garment/scar interfacial pressure measurement in hospitals, the amount of pressure exerted by current therapy garments and fabrics can only be subjectively assessed based on the experience of individual practitioners. The patient compliance rate of the continuous use of pressure gloves is another concern. Most of the complaints with regards to pressure garments are related to wear comfort, which include barriers to mobility, sweating, itching, pain and poor fit. These problems are especially substantial with respect to pressure therapy gloves as the hand is most often used in the performing of daily activities and sensitive to different sensations.

The aim of this research project is to improve the quality of treatment for hypertrophic scars on the hand by increasing the wear comfort of pressure therapy gloves and facilitating understanding of the pressure delivery of the glove. First, there will be a review of current custom-made pressure therapy gloves and clinical situations through an 18-week study on 5 patients with hypertrophic scars on their hands. This will help to identify the possible direction for improving treatment outcomes.

The measuring of hand anthropometric data for the development of optimal fitting

gloves is crucial. In pursuing greater accuracy in hand anthropometric measurements, the scanning of hand surfaces with the aid of an image analysis system to acquire measurements is an alternative to manual means. A new hand measuring approach that uses 2D and 3D scanning has been proposed and evaluated through comparisons with manual measurements. It is found that hand data taken from 3D image analysis have no significant differences compared with the manual measurements made on the hand and wrist circumferences, length and breadth.

To understand the pressure given by pressure gloves made of different materials and RFs, the tensile properties and tension decay after the extension of seven types of fabrics which determined their pressure delivery ability are examined. Based on the fabric tensile behaviour, the corresponding glove pressure is predicted by the local strain, fabric tension per unit length and curvature of the hand surface. No statistical difference is found between the predicted glove pressures and the measured values. It is also revealed that the pressure measurement positions and their corresponding curvature and geometry changes caused by hand movements and postures are closely associated with the interfacial pressure delivered by the glove.

The physiological and psychophysical effects of pressure therapy gloves on human responses have been investigated. The heart rate (HR), blood pressure (BP), glove-skin microclimate, hand performance, forearm muscle activity, grip strength and psychophysical responses when wearing pressure gloves made of various fabric types and with different RFs are studied through a series of wear trials with 10 subjects who do not have hypertrophic scars. The results indicate that the impacts of the different gloves on the HR and BP are not significant. However, the pressure gloves show a noticeable influence on the skin-glove microclimate. Fabric properties which include air permeability, moisture retention and drying rate are identified as the main factors that affect the skin-glove temperature. Both the fabric type and RF of the pressure gloves have no significant effects on the tactile sensitivity of the fingertips. Nevertheless, the active range of finger motion, dexterity of the fingers in carrying out daily tasks and maximum gripping force are negatively affected. The adoption of a high RF of 20% in the glove pattern can negatively impact hand functions. The forearm muscle activity, which is measured by using surface electromyography (SEMG), is affected by the tightness of the glove. Besides that, the glove with a tighter pressure (RF of 20%) contributes to less perceived comfort and ease of hand motion.

In this study, it is also found that the current glove making process fails to provide patterns that properly fit the hand geometry, thus leading to inadequate pressure exerted onto the scar region, particularly in the finger web area. A new approach that considers the web spaces between fingers in the pattern development process of glove production is introduced. The angle of the finger web slants of 79 individuals are measured and evaluated by using a 3D scanning and image analysis method. Glove prototypes with modifications on the web spaces between fingers are produced and assessed through a wear trial with 10 subjects. The results show that gloves made with 45° finger web slants can effectively improve glove fit, comfort and ease of hand motion.

Insert materials made of thermoplastic (e.g. Plastazote®) are often placed underneath pressure garments to increase the local pressure for effective scar treatment. However, the currently used insert material, Plastazote®, is barely breathable and quite uncomfortable. Therefore, spacer fabric is proposed as a potential insert material. The physical properties, compression behaviour and pressure delivery ability of five types of spacer fabrics are evaluated. The results show that the spacer fabrics are not only able to provide much lower air resistance (0.05-0.12 kPa s/m) and higher water vapour transmission rates (WVTRs; 34.35-102.39 g/h·m^2) than Plastazote®, but also produce an interfacial pressure that is comparable to Plastazote® at various locations on the hand dorsum. A 24 week clinical study in which spacer fabric inserts are used in pressure gloves and applied to four hands with hypertrophic scarred skin also support that the spacer fabric insert is effective in scar treatment by providing good comfort and breathability, and hence pressure treatment acceptance and compliance are increased.

With a full picture of the pressure amount given by a pressure glove, practitioners can more easily prescribe suitable pressure treatment. By using the finite element method (FEM), a biomechanical simulation model that simulates the skin pressure in relation to the contours of the human hand and fabric properties of the pressure therapy glove has been developed. The simulation model can show a trend of pressure distribution with good accuracy.

As shown above, the research results provide useful information for the selection of suitable materials and RFs for pressure glove therapy. Feasible solutions to improve the glove fit and comfort of pressure therapy are suggested. The simulation model used to predict the pressure distribution over the hand dorsum can also enhance the effectiveness and treatment quality of pressure glove therapy. The output of this project can extend to the development of other pressure garments and will advance our knowledge on a new dimension of medical clothing for hospital patients.

PUBLICATIONS FROM THE THESIS

Journal Articles

Yu A., Yick K.L., Ng S.P. and Yip J. Prediction of fabric tension and pressure decay for the development of pressure therapy gloves. Textiles Research Journal, 83(3):269-287. (February 2013)

Yu A., Yick K.L., Ng S.P. and Yip J. 2D and 3D anatomical analyses of hand dimensions for custom-made gloves. Applied Ergonomics, 44(3):381-392. (May 2013)

Yu A., Yick K.L., Ng S.P. and Yip J. The effect of pressure and fabrication of pressure therapy gloves on hand sensitivity and dexterity. Journal of Burn Care and Research 36(3):e162-175. (April 2015)

Yu A., Yick K.L., Ng S.P. and Yip J. Orthopaedic textile inserts for pressure treatment of hypertrophic scars. Textiles Research Journal (Accepted on Jan2015)

Yu A., Yick K.L., Ng S.P. and Yip J. The effect of pressure glove tightness on forearm muscle activity and psychophysical responses. Human Factors (First published online before print April 2015)

Yu A., Yick K.L., Ng S.P. and Yip J. Effect of pressure therapy gloves on heart rate and blood pressure. (In submission to Journal of Textiles Bioengineering and Informatics Society)

Yu A., Yick K.L., Ng S.P. and Yip J. Prediction of contact pressure between hand and pressure therapy glove by using Finite Element Method. (In submission to Burns)

Conference Paper

Yick K.L., **Yu A.**, Ng S.P., Yip J. and Ng S. Fabric comfort and elasticity properties for pressure therapy garments. The Fibre Society 2011 Spring Conference, Hong Kong, paper ID O6, 23-25 May 2011.

Yu A., Yick K.L., Ng S.P. and Yip J. Effect of pressure therapy gloves on microclimate and subjective sensation. International Conference on Medical Textiles and Healthcare Products MedTex13, NC, USA,13-15 May2013.

Yu A., Yick K.L., Ng S.P. and Yip J. Modification of finger web gusset for improving fit and comfort of pressure therapy gloves. The 7th Textile Bioengineering and Informatics Symposium 2014, HongKong, 6-8 Aug 2014.

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LIST OF ABBREVIATIONS

A

AATCC	American Association of Textile Chemists and Colorists
AROM	Active range of motion
APDF	Amplitude probability distribution function
ANOVA	Analysis of variance

B

BP	Blood pressure

C

CT	Computer tomography

D

DM	Direct anthropometric measurement method
DIP	Distal interphalangeal

E

ED	Extensor digitorum

F

FPL	Flexor pollicis longus
FDS	Flexor digitorum superficialis
FEM	Finite element method

H

HR	Heart rate

I

IP	Interphalangeal

K

KES	Kawabata Standard Evaluation System

M

MRI	Magnetic resonance imaging
MANOVA	Multivariate analysis of variance
MP	Metacarpophalangeal
MVC	Maximum voluntary contraction
MVE	Maximum voluntary electrical activation

P

POSAS	Patient and Observer Scar Assessment Scale
PIP	Proximal interphalangeal
PP	Purdue Pegboard

R

RF	Reduction factor
RMSE	Root mean square error
RMS	Root mean square

S

SEMG	Surface electromyography
SMD	Surface roughness
SWMT	Semmes-Weinstein monofilament test

T

TUPS	Tissue ultrasound palpation sensor

V

VSS	Vancouver Scar Scale

W

WVTR	Water vapour transmission rate

2D	Two-dimensional
3D	Three-dimensional

Chapter 1 Introduction

1.1 Background of research

Pressure therapy garments are most commonly used to treat hypertrophic scars resultant of burns. Hypertrophic scarring occurs after the process of wound healing due to the excessive deposition of wound collagen. Hypertrophic scars are thick, raised, highly vascular and dark red in appearance, which may result in pain, cosmetic disfigurement, skin hypersensitivity and itchiness, and their maturation has been reported to vary from person to person. The scars are commonly located over areas of high tension and movement, as well as flexor areas of the extremities. The outcome can be complications with joint contractures, limb deformities and negative effects on cosmetic appearance.

The rationale for pressure therapy is that pressure reduces collagen production within a developing or an active scar. The related garment must fit like a second skin for patients and are engineered to apply adequate pressure onto various body parts with the aims to increase the rate of scar maturation, prevent contracture formation, and enhance cosmetic appearance without impairing circulation [1]. The amount of pressure delivered therefore directly affects the treatment outcomes. Apart from this, patient compliance is an important aspect of pressure-garment therapy. For an optimal outcome, the use of pressure garments is to be continuous for 23 to 24 hours a day (removing them only for hygienic purposes or laundering), for 12-18 months or until the scar matures in 2 or 3 years. Due to garment discomfort, poor fabrication and activity limitations, a limited number of pressure garment wearers fully comply with treatment, which thus adversely affects the effectiveness of the treatment and formation of smooth scars.

Hands are involved in many daily activities and a very common body part that receives burns and scald injuries. Particular attention is often paid to hands in hypertrophic scar management since the finger and thumb joints are very sensitive and the range of motion can be gone quickly. Therefore, a systematic study on optimizing the performance of pressure therapy gloves and hence the outcome of scar treatment is essential in this aspect. The main purpose of the study would be to develop custom-fitted pressure therapy gloves, which not only enhance the comfort of patients, but also deliver suitable amounts of pressure which thus optimise the compliance rate and efficacy of the treatment. This study would also provide more in-depth rationalisation and practical use of new innovative textile materials.

1.2 Problem statement

Pressure therapy gloves are an important treatment option for hypertrophic scars found on the hands. However, there are two main problems associated with pressure gloves which influence the treatment outcomes. They are unsatisfactory treatment compliance and uncertainty of the amount and control of pressure for therapy.

1) Unsatisfactory treatment compliance

A long period of adherence to the use of pressure therapy gloves is necessary in hypertrophic scar treatment. In Hong Kong, custom-made pressure garments and gloves are extensively used by occupational therapists and physiotherapists for patients who are receiving treatment for hypertrophic scars. The gloves are locally developed in the occupational therapy departments found in hospitals. However, the rate of patient compliance in terms of the continuous use of pressure gloves has not been satisfactory. This can be explained by the hot and humid climate in Hong Kong, which results in a high level of garment discomfort from heat and perspiration. Therefore, there is the need to improve the design, fabrication and comfort of pressure gloves so as to improve compliance.

2) Uncertainty in amount and control of pressure

Due to the lack of actual garment/scar interfacial pressure measurement in hospitals, the amount of pressure exerted by current therapy garments and gloves cannot be exactly determined. The fit of the garments and gloves and the efficacy of this type of treatment can only be subjectively assessed based on the experience of individual practitioners. The measurement taking of the hand by using a measuring tape is not precise and results in much trial and error during the glove making process. Despite anecdotal and clinical evidence of the beneficial effects of pressure therapy for hypertrophic scars, there is little scientific evidence available to measure the pressure transmitted to the scar or skin by a pressure garment. The literature has indicated that the optimal pressure has varied over the years due to the non-linear stress-strain properties of textile materials, large variation in body curvature and pressure at different anatomic sites, deterioration of the elasticity of the gloves, the corresponding pressure and pattern engineering techniques, etc. A systematic study of this problem is required to ensure a correct amount of pressure is maintained over the course of the treatment.

1.3 Research objectives

The research objectives of this study are as follows:

1) to establish a thorough scientific basis for understanding the physiological mechanism, psychological needs, responses and behaviours of patients who wear pressure therapy gloves in relation to various clinical situations,
2) to develop an efficient measuring system for hand anthropometry and analyse the anthropometric measurements, and morphology and curvature of hands in order to develop optimal fitting pressure therapy gloves,
3) to evaluate the effective pressure in gloves used in hypertrophic scar treatment and establish a psychophysical relationship between pressure distribution and subjective sensory comfort perception, and formulate a biomechanical model to simulate skin pressure in relation to the fabric mechanical properties, curvature of the anatomic sites, deterioration of fabric elasticity, etc.,
4) to design and develop, on the basis of clinical and textile science analyses, optimal fitting pressure therapy gloves which can exert adequate pressure on hands for hypertrophic scar treatment, improve physiological comfort of patients and facilitate the flexible and continuous use of the gloves, and
5) to undertake wear trials to evaluate whether the intended objectives of pressure therapy gloves can be achieved, and determine the effectiveness and practical use of pressure therapy gloves.

1.4 Project originality and significance

Pressure garments are commonly used in the treatment of hypertrophic scars. Associated problems, such as garment discomfort, activity limitation, and poor fabrication and fit, induce a low rate of patient compliance during pressure-garment therapy and thus risk of cosmetic deformities of body parts and even functional limitation. The amount of pressure exerted by current therapy garments is somewhat uncertain. Pressure gloves are one of the most complicated pressure therapy items due to the complex anatomy and curvature of hands. Therefore, the originality of this project is to fill the knowledge gap which exists in the design and development process of pressure therapy gloves, which not only will provide precise and effective pressure therapy, but also improve the physiological comfort of patients, and provide practical and flexible use during the course of the treatment.

The project proposes the use of a non-contact scanner system as an effective way to obtain hand anthropometric measurements and formulate a biomechanical model to simulate skin pressure in relation to fabric mechanical properties, curvature of anatomic sites, and deterioration of fabric elasticity. It also evaluates the physiological and psychophysical impacts of pressure glove on human body response. This provides useful information for the selection of suitable fabric and the determination of suitable pressure in relation to various clinical situations. The output of this project can extend to the development of other pressure garments and will advance our knowledge on a new dimension of medical clothing for hospital patients. More importantly, it can enhance the effectiveness of pressure therapy treatment and therefore, patients can be reintegrated into their homes, schools, and society without further issues.

1.5 Outline of the thesis

The structure and framework of this study is presented in a flow diagram, see Figure 1.1.

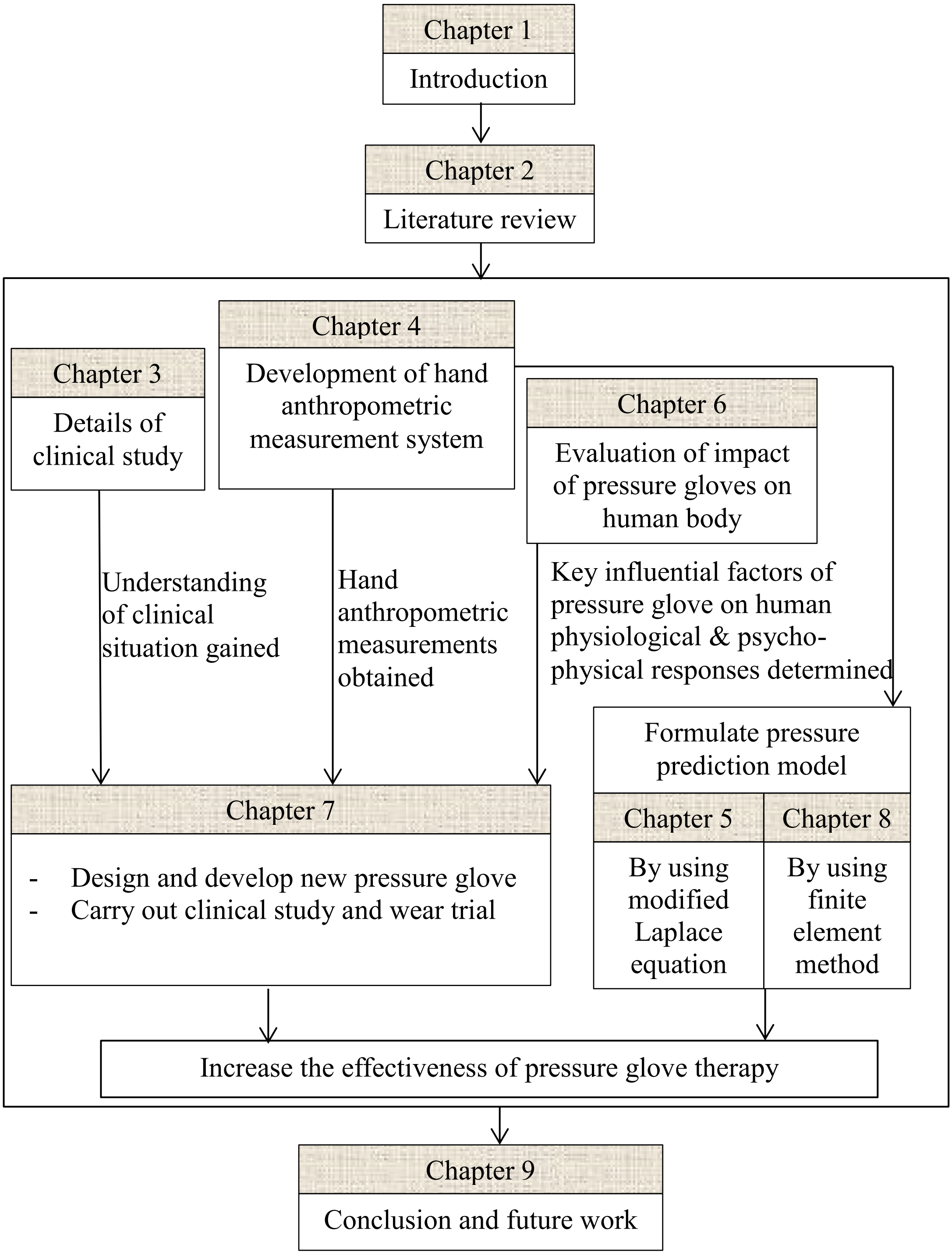


Figure 1.1 Flow diagram of research methodology

There are 9 chapters in this thesis. Chapter 1 provides the background information, concept, rationale and objectives of the present study.

Chapter 2 is the literature review which includes a review on hypertrophic scar formation and treatment, pressure therapy gloves and associated problems, current hand anthropometric measurements and garment-skin interfacial pressure methods.

In Chapter 3, the current clinical situation is explored, and a possible direction is identified for improving treatment outcomes through a clinical study. The setting of an occupational therapy department, traditional ways of hypertrophic scar treatment with current design and development processes, and difficulties in manufacturing custom-made therapy gloves are examined. The interfacial pressures delivered by the gloves, the microclimate conditions under the gloves and the scar conditions of patients are examined. The attitude of and comments from the patients toward pressure glove treatment are also investigated by using face-to-face interviews. A fundamental understanding of the fabrication, use, handle, and wear of current pressure therapy gloves are acquired which provide direction and form the basis of this study.

In Chapter 4, a new approach of taking hand anthropometric measurements by using two-dimensional (2D) and/or three-dimensional (3D) image analyses is provided, and the approach is compared against the traditional direct measurement method. The equipment for obtaining a 2D image is a domestic colour scanner and for capturing a 3D image, a portable laser scanner. The use of an image analysis approach can minimise contact with the hand during measurement taking so as to avoid any potential discomfort to the patients. This is carried out with the aim to provide a useful reference for the development of hand anthropometric studies. The hand anthropometric information obtained from the 3D image analysis can be useful for the formulation of a prediction model for glove-skin interfacial pressure and the development of new glove prototypes.

A pressure prediction model for pressure therapy gloves based on Laplace's law is formulated in Chapter 5. A novel approach of evaluating the pressure delivery performance of pressure therapy gloves is proposed. Curvatures of the hand obtained from cross-sections of 3D hand images are incorporated into the prediction of the glove-skin interfacial pressure. The effects of the fabric tension decay properties and reduction factors (RFs) in the pattern development which affect the dimensions of the glove patterns on the compression performance of the pressure therapy gloves are also examined. A key contribution of this chapter is the development of a methodology that predicts glove pressure by using an empirical model for the development of pressure therapy gloves. This would act as a reference in the selecting of suitable fabrics for developing pressure gloves and maintaining suitable glove-skin interfacial pressures, and thus formulating an optimal programme for hypertrophic scar treatment and improving the compliance rate and efficacy of pressure therapy treatment.

The effects of current pressure gloves on human physical responses and sensation are evaluated in Chapter 6. Physiological parameters, including heart rate, blood pressure, muscle activity, temperature and humidity in the glove-skin interfacial micro-environment, are investigated through wear trials on subjects without hypertrophic scars. The effects of glove fabrication and the glove-skin interfacial pressure induced onto the hand and finger dexterity are also investigated. The psychophysical responses at the beginning and end of the wear trials are recorded and compared. The physical properties of the fabrics are measured by using standard tests. These aim to determine the key factors of pressure therapy gloves that bring about significant influence on the body of wearers and their perceived sensations so as to find an approach that will manage comfort and preserve hand sensitivity and dexterity without sacrificing the effectiveness of pressure therapy. The findings will become a reference for fabric selection and design of pressure therapy apparel with the ultimate goal of developing a glove that provides adequate pressure to treat hypertrophic scars with minimal amount of discomfort so as to enhance the practical use of pressure gloves in normal daily life activities and increase patient compliance.

Based on the findings from the previous chapters, new glove fabrication methods are investigated in Chapter 7 to optimise the design for comfort and functional performance. Pattern modifications on the finger webs are suggested for improving the fit of the glove. The application of 3D warp knitted spacer fabrics is proposed as a textiles insert to enhance breathability, thermo-regulatory characteristics and pressure-controlling effect of the gloves. An advanced seaming method that uses thermoplastic adhesive tape is also proposed to prevent the displacement of the textile inserts. New prototypes of the pressure therapy gloves are designed and developed, and a clinical wear trial of the prototypes is conducted. The efficacy of the treatment and patient compliance are then analysed. Various dimensions of the prototype, namely comfort, flexible use and design features, are examined and recorded. The acceptability of the pressure therapy gloves and the efficacy of the pressure-therapy treatment are surveyed by using a questionnaire. The progress of the changes in the scars and the actual pressure distributions at the scar locations are assessed over the course of the treatment. Data collected from observations and the questionnaires are analysed and compiled. An improved pressure therapy glove with better control of glove-skin interfacial pressure, comfort and better patient treatment compliance has been developed.

The pressure prediction model formulated in Chapter 5 requires the measurement of the curvature of the hand to carry out prediction on related points. Therefore, a biomechanical model is established in Chapter 8 to simulate the glove-skin interfacial pressure distributed over the hand dorsum when the pressure gloves are worn. The development of the model is based on the elastic mechanical properties of the fabrics, contour of the human hand and the contact interaction between the hand and glove by means of FEM. The hand geometry is defined through the new 3D image scanning method presented in Chapter 4. This has the aim of optimising the design for comfort and functional performance of the pressure gloves by taking into consideration the predicted pressure in the manufacturing of the gloves. With the use of the simulation model and hand geometry, the pressure distribution induced by the pressure gloves can be precisely and objectively quantified. The most effective amount of pressure could be prescribed and maintained over the course of the treatment.

The last chapter is a general conclusion on the thesis work and provides suggestions for future works.

Chapter 2 Literature Review

2.1 Introduction

Pressure therapy gloves are an important means of treatment for hypertrophic scars that appear on hands. In this chapter, an overview on hypertrophic scars and pressure therapy gloves is provided. There will be a review on the fabrication of current pressure gloves and their associated problems. The possible physiological and psychological impacts caused by garment pressure on humans are discussed. Besides that, there will be a discussion on the existing hand anthropometric measurement methods which directly affect the fit of the gloves. The glove-skin interfacial pressure is a major factor that affects the outcome of the treatment. Finally, the available methods of pressure evaluation and simulation are also reviewed.

2.2 Hypertrophic scars

2.2.1 Formation of hypertrophic scars

Hypertrophic scars (Figure 2.1) are scars that rise above the skin level and stay within the confines of the original lesions [2]. They occur as the result of burns and appear soon after surgery, are an abnormality that affects general wound healing, and usually develop within one to three months after an injury [3]. Scar formation is part of the natural continuum of tissue repair when a wound heals. In the wound healing process, inflammatory and endothelial cells, fibroblasts and keratinocytes work together to form new blood vessels, produce an extracellular matrix and migrate from the wound edges to create a layer that covers the surface of the wound [3]. The extracellular matrix is composed of an interlocking mesh of fibrous proteins which are mostly collagen and glycosaminoglycans. It is important for closing and repairing wounds. However, if an overabundant extracellular matrix is produced, this results in the formation of a raised hypertrophic scar. As high synthesis of collagen occurs in hypertrophic scar formation [4], the reduction of matrix production and promoting of collagen degradation are important to the growth of the scars. Children and individuals who have darker pigmented skin more frequently develop hypertrophic scars [5].

Figure 2.1 Hypertrophic scars on different body parts [6]

2.2.2 Impact of hypertrophic scars on the human body

Hypertrophic scars pose a significant challenge for burn and scald survivors. The scars are thick, raised, highly vascular and dark red in appearance, which may result in pain, cosmetic disfigurement, skin hypersensitivity, itchiness, etc. Hypertrophic scars not only influence the appearance of a person but are also associated with continuous pain and itch during their active growth. The scars can also affect the normal physical functions of the body. Since they are commonly located over areas of high tension and movement, and during flexing of the extremities, the outcome can comprise complications with joint contractures and limb deformities, and finally loss of their normal functions [7]. If hypertrophic scars are not properly treated, they will grow and develop into keloids. Particular attention should always be paid to the hands in hypertrophic scar management since the finger and thumb joints are very sensitive and the range of motion can be gone quickly [8-10]. Oedema forms rapidly and is a serious threat to hand functions. Uncontrolled oedema collects on the dorsum of the hand where tissues are loose. This causes the metacarpophalangeal joints to hyperextend, stretching the long flexor tendons of the hand so that the interphalangeal joints are pulled into flexion and result in a clawed hand [1]. Besides that, hands carry out movements to handle daily activities. Once hypertrophic scars are allowed to grow on the joints and finger webs of the hands, hand dexterity will be greatly reduced, thus bringing about inconvenience to daily life.

2.2.3 Evaluation of hypertrophic scar conditions

The current practice in hospitals for the evaluation of hypertrophic scar conditions is mainly based on observations by clinicians which are recorded by using different scar grading systems, such as the Vancouver Scar Scale (VSS) and the Patient and Observer Scar Assessment Scale (POSAS) [11-13] .

The VSS is extensively used and applied to burn scar patients. It consists of four subscales to describe the vascularity, height, pliability, and pigmentation of a scar. The VSS (Figure 2.2), along with self-assessment subscales provided by the patients, is widely adopted to describe pain and itch. However, the VSS may not accurately describe the scar volume [14, 15].

Pigmentation

- 0 Normal
- 1 Hypopigmentation
- 2 Hyperpigmentation

Vascularity

- 0 Normal
- 1 Pink (Slight increase in local blood supply)
- 2 Red (significant increase in local blood supply)
- 3 Purple (excessive local blood supply)

Pliability

- 0 Normal
- 1 Supple
- 2 Yielding
- 3 Firm
- 4 Banding
- 5 Contracture

Height

- 0 Normal (flat)
- 1 < 2mm
- 2 > 2mm and < 5mm
- 3 > 5mm

Pain

- 0 None
- 1 Occasional
- 2 Requires medication

Itchiness

- 0 None
- 1 Occasional
- 2 Requires medication

Figure 2.2 Vancouver Scar Scale for assessment of scar conditions

There are several objective assessment methods of scar conditions that use mechanic and electronic instruments (Figure 2.3). The spectrocolorimeter has been recommended as an objective tool for assessing skin or scar colour [16-18], and quantifies scar pigmentation for a more precise recording and comparison. The cutometer is based on suction which means negative pressure is applied to measure the elasticity of the scars [19]. The pneumatonometer and durometer can also be used to measure the pliability of scars [20]. An objective way to assess the thickness of scars includes ultrasonic devices like the Dermascan and tissue ultrasound palpation sensor (TUPS) [16]. Some studies have suggested the use of 3D imaging analysis systems to study scar surface conditions [11, 21-23]. These can provide scar surface assessment without direct contact with the patient, and the 3D images can serve as a record for monitoring of treatment outcomes. The objective evaluation results obtained from different equipment provide a more reliable, repeatable and accuracy assessment on scar conditions. However, each piece of equipment can only assess the scar for one specific aspect and there is no comprehensive scar condition assessment tool that is currently available. Certain expertise and technical requirement are needed to operate some of these instruments and interpret the measured data. Therefore, these tools have limitations in use for research and few are put into real practice.

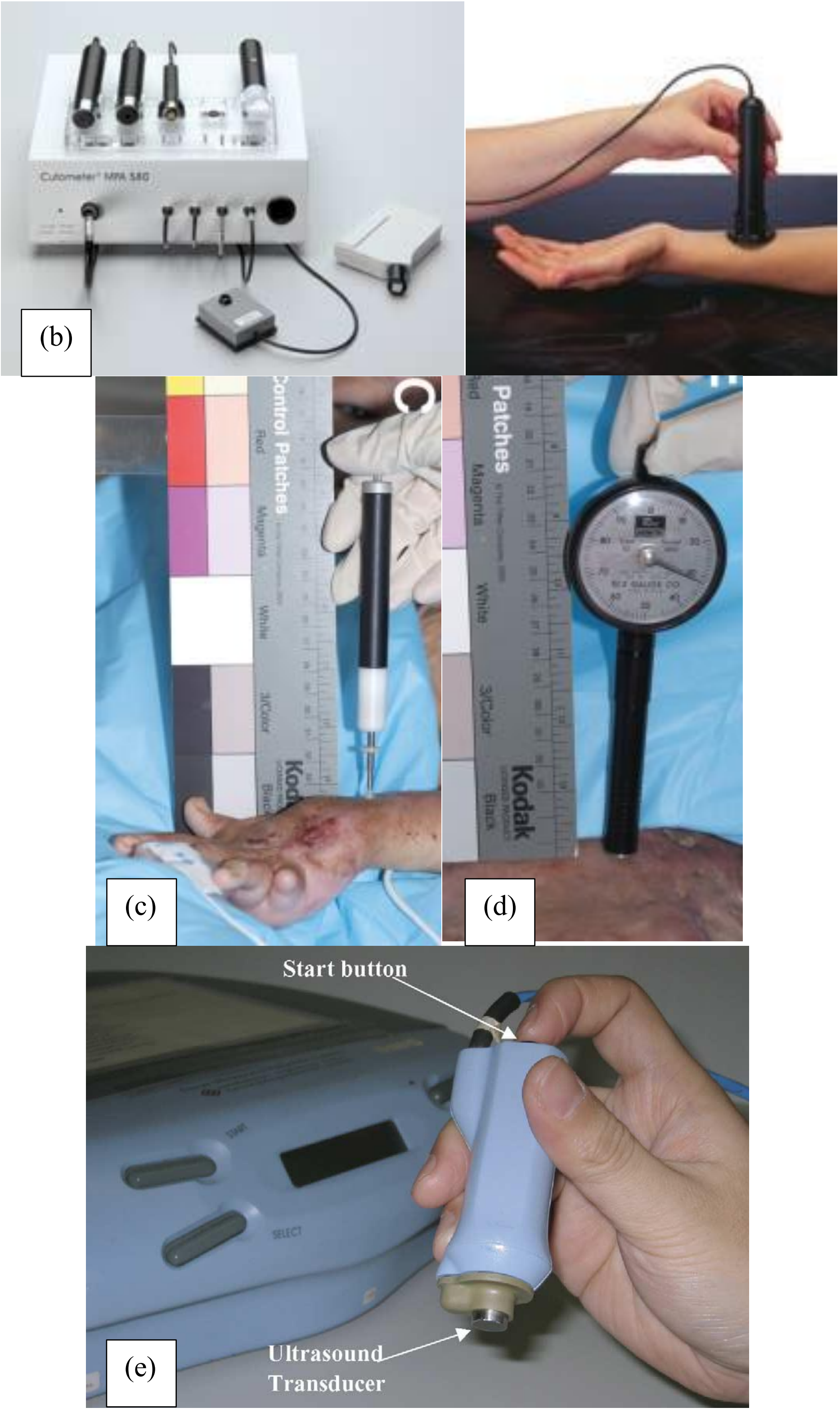


Figure 2.3 Objective scar condition assessment devices: (a) hand-held spectrocolorimeter [24], (b) cutometer [25], (c) pneumatonometer [20], (d) durometer [20] and (e) tissue ultrasound palpation sensor [16]

2.2.4 Treatments available for hypertrophic scars

There are different treatment methods available nowadays to treat hypertrophic scars. Surgical excision can directly reduce the size of hypertrophic scars, but is associated with pain and high recurrence rates [26]. The injection of cortical steroid or various agents (e.g. α or γ interferon, 5-fluorouracil) is commonly used to treat facial scarring [27, 28]. Hypertrophic scars are usually treated by suppressing collagen synthesis and enhancing collagen catabolism. However, injections can lead to some side-effects, such as skin atrophy, and the recurrence rate is also high [29]. Silicone gel sheeting was first suggested as a treatment for contracture and hypertrophic scars in 1983 [30] and in recent years, its usage continues to be well known and advocated. Although there is a lack of information on the mechanism of the exertion of silicone gel on scars, several studies have shown that treatment with silicone sheets is effective for treating hypertrophic scars by increasing the surface temperature of the scar [31-34]. Different kinds of lasers, such as carbon dioxide and erbium yttrium aluminium garnet lasers, have also been used to treat hypertrophic scars [35]. However, pressure therapy garments are generally regarded as the best non-invasive means to prevent and control the formation of hypertrophic scars through the use of pressure [36]. Since the 1970s, it has become the mainstay of scar treatment [1, 37-41].

2.3 Pressure therapy gloves

2.3.1 Principles of pressure therapy garments

Pressure therapy garments are garments that are tailor made into a smaller size than the actual anthropometric measurement of the body part in order to deliver pressure onto hypertrophic scars. Various types of pressure garments for different body parts are shown in Figure 2.4. The pressure applied onto the skin causes a decrease in the blood flow which can lead to fibroblast and collagen degradation, decrease in overabundant extracellular matrix production and hence control in the growth of hypertrophic scars [4]. Besides that, the pressure continuously applied by pressure garments is able to increase the rate of scar maturation, prevent contracture formation and enhance cosmetic appearance [42-45]. The pressure garments have to be worn for 23 to 24 hours a day to have the best effectiveness [46-49]. The amount of pressure delivered from the pressure garment also impacts the treatment efficacy. The literature has indicated that a continuous pressure at a capillary level of 25 mmHg could affect the realignment of collagen bundles and might effectively control over-exuberant collagen synthesis [1, 39, 50]. Positive clinical results have been reported with pressure levels as low as 15 mmHg [51-53]. Several randomized clinical trials have been conducted to evaluate the efficacy of pressure garment therapy. For instance, Van den Kerckhove et al. [52] carried out a wear trial with 60 burn scarred patients over a period of 3 months. The patients were randomly assigned to treatment with a normal (15-20 mmHg) or lower (10-12 mmHg) compression. The 'normal' treatment demonstrated better outcomes in terms of reducing scar thickness, but there was no significant difference in scar colour between the two groups. Lai et al. [54] carried out a wear trial on 17 Chinese patients who were suffering from hypertrophic scars. The patients were randomly assigned to two groups; one who received high (20-25 mmHg) and one who received low (10-15 mmHg) amounts of pressure for a 5-month intervention process. Both groups showed a reduction in scar thickness and redness, but the group who received a high amount of pressure showed more improvement. A within-wound trial was carried out by Engrav et al. [55] on 67 patients with hypertrophic scars on the forearm. The patients wore pressure garments with normal (17-24 mmHg) and low (<5 mmHg) compression randomized to either the proximal or distal zone of the forearm. The zone treated with normal compression was found to be softer, thinner and better in appearance. However, when pressure garments deliver a pressure that exceeds 40 mmHg, maceration and paraesthesia may occur [13]. Therefore, the monitoring of the amount of pressure is crucial for optimizing therapy outcomes. The duration of the pressure garment therapy varies from patient to patient. Pressure therapy should be started as early as possible once the wounds are completely healed and stable. It is recommended that the pressure garments are worn until the scars become fully mature which takes several months to even years depending on the physical condition of the patients and the compliance towards the treatment.

Figure 2.4 Pressure therapy garments for different body parts [56]

2.3.2 Current pressure glove design and fabrication

Amongst the various body parts, hands are a very common site for burns and scald injuries because they are usually exposed, and often used in reflex actions to protect the face from danger. An appropriate pressure therapy glove (Figure 2.5) not only prevents fingers from deformation, but also minimise wrist or finger flexion. The fabrication of pressure therapy gloves is vital since fabric compression is induced by fabric tension when the pressure glove is stretched and worn by the patient. Pressure therapy garment were traditionally composed of elastic fabrics. Warp-knitted fabrics in either nylon spandex or cotton spandex were commonly used. Warp-knitted fabrics, such as powernet fabric, are able to provide good air permeability and a stable structure without much shrinkage and deformation after wash. Different fibre contents, densities and fibre structures can bring about different degrees of comfort and tension in the pressure gloves. Pressure garments made of cotton spandex fabric which has better softness are commonly prescribed at the beginning of the pressure therapy treatment when the wound condition is not stable and may easily breakout again. The fabrics for pressure garments are also available in different colours to match the different skin tone of the patients. The fabric is always under extension during donning and wearing. The hand motions in daily activities further increase the frequency and amount of extension on the fabric which cause the pressure glove to deteriorate and thus, it can no longer provide sufficient pressure for the treatment. The use of certain ointments and cleaning processes can also contribute to a more rapid deterioration. Monitoring on the fit and replacement are therefore essential and needs to be carried out on a regular basis.

Figure 2.5 Pressure therapy gloves

A pressure therapy glove is usually custom-made by occupational therapists to fit the hand of a patient. The outline of the hand is first traced and marked onto a piece of paper (Figure 2.6). The hand is placed onto the paper with the fingers relaxed and in a neutral position with the tracing pen maintained in a vertical position. Then, certain key dimensions of hand including the circumference, wrist, fingers and circumference between the palm and thumb are manually measured by using a measuring tape (Figure 2.7). The web space length, length of the root of the thumb to the inner wrist and fingers lengths are also required to be measured by using this measuring tape. Based on the hand outline and the measured dimensions, a pressure glove production pattern can be developed. In making the production pattern, 10% to 20% reduction from the actual circumferential dimensions would be applied in accordance with the fabric extensibility [38, 57]. The amount of the reduction which comprises the RF determines the intensity of the pressure delivered onto the scars. A certain level of pressure can therefore be delivered onto the scars to control the formation of excess wound collagen and suppress their growth. The pressure glove produced from the production pattern needed to be fitted by the patient and occupational therapists or clinicians will need to assess and adjust its fit and tightness. After that, the patient has to visit the occupational therapists regularly to verify the fit and check for any deterioration of the glove. Apart from this type of glove fabrication by occupational therapists, medical care manufacturers, such as Jobst Institute, Barton-Carey Company, etc. provide custom-made and ready-to-wear pressure garments. These pressure garment manufacturers have their own measurement charts and follow their own measuring manuals. Therefore, pressure garments have to be returned to the company for modifications.

Figure 2.6 Tracing the hand outline onto a piece of paper

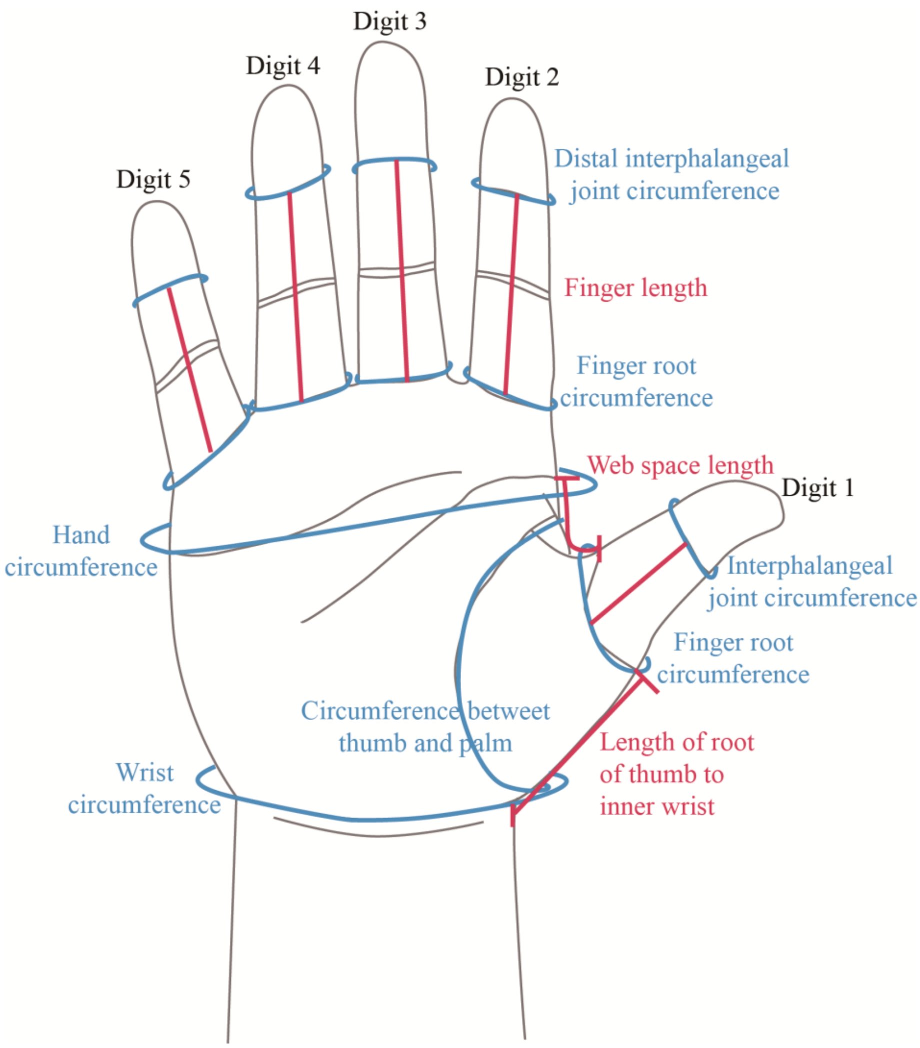


Figure 2.7 Hand dimensions measured by using measuring tape for pressure glove production

The pressure garment alone is often insufficient to deliver the desired pressure to actively growing scars, especially in some of the anatomical zones with concave curvature. In pressure therapy for actively growing hypertrophic scars on the hands, insert materials are supplemented and added to the pressure garment to provide additional local pressure to prohibit their growth [58, 59]. Thermoplastic (for example, Plastazote® as shown in Figure 2.8), foam, silicone gel sheets and hydrogels are the most commonly used insert materials that fit under the surface of pressure garments for increasing the local pressure [60, 61]. They are available in various thicknesses and can be made into different shapes according to the scar locations and conditions. For inserts made of relatively soft materials like foam, they have a better fit to accommodate the contours of the hand and body. Inserts made of Plastazote® which is more rigid are especially effective and suitable for severe hypertrophic scars [54]. The production of Plastazote® inserts involves the use of an oven to soften and heat-set them into shapes that match the body contours. Inserts can be also useful for preventing the growth of scars in areas such as the finger web [62]. However, inserts are usually thick and lack breathability which bring about discomfort and inconvenience, and thus are an extra burden to patients.

Figure 2.8 Plastazote® [63]

2.3.3 Problems associated with pressure therapy gloves

The amount of pressure delivered by pressure therapy gloves and adherence to therapy are the two main factors that directly affect the outcome of treatment. The non-circular shape and special contours of the hand mean that a pressure therapy glove will have a relatively complex structure. This increases the difficulty in controlling and obtaining the optimum pressure over hypertrophic scars on the hand. A prospective randomised study indicated that the use of cotton spandex pressure garments results in significantly better patient compliance than garments made of nylon spandex [64]. The hand is a part of the body that is used for touching and receiving of sensation. The type of fabric used for pressure gloves can easily trigger different subjective perceptions that probably affect treatment adherence. The choice of fabric and RF and even the hem edges and workmanship could affect both the glove-skin interfacial pressure and treatment adherence [65]. Consequently, these issues render the control of the glove pressure and fit and the promotion of treatment adherence as the main concerns in pressure glove therapy.

2.3.3.1 Control of glove-skin interfacial pressure and fit

Sufficient garment pressure is crucial to suppress the formation of extracellular matrix and thus the growth of hypertrophic scars. Due to the lack of measuring devices, time and space in clinical practice, there is an absence of actual measurements for garment-skin interfacial pressure in hospitals to objectively monitor the efficiency of the pressure garment from time to time. The actual amount of pressure remains unknown throughout the therapy and thus the pressure dose for treatment may often vary. After a certain period of use, the fabric of the pressure garments deteriorates and becomes loose which lead to a reduction in the pressure, thus affecting their effectiveness and practical use. The effects of the non-linear tensile properties of textile materials and deterioration in the elasticity on the compression performance of pressure garments are still unknown [66-68]. Instead, the fit of pressure garments is checked and adjusted regularly by practitioners throughout the whole treatment period. The fit of the pressure garment is assessed by observing the hypertrophic scar conditions and simply stretching the pressure garment for assessment of fit and tightness so as to make suitable modifications based on the experience of individual practitioners. A clear understanding of the actual amount of pressure given by the garment can promote a more efficient hypertrophic scar treatment and provides important information to evaluate the optimum amount of pressure for the treatment.

Some of the previous work has measured and/or simulated pressures exerted onto the limbs of the body by constructing pressure sleeves in a tubular form [65, 69, 70], but there is a lack of related work on hand and pressure therapy gloves. Body curvature and fabric tensile properties have both been proven to be closely related to skin-and-garment interfacial pressures [71]. Nevertheless, the anatomy of the hands is non-circular and gloves are one of the most complicated engineered apparel products with a complex construction that allows patients to freely and comfortably move their hands. The geometry and curvatures of hands also change with different hand movements during daily activities. Therefore, the amount of interfacial pressure on a hand is even more difficult to be maintained at a suitable level.

The production of pressure gloves involves the manual tracing of the hand shape onto a piece of paper and measuring the hand dimensions. Current hand dimension measuring tools used in hospitals which are mostly measuring tapes cannot give a very accurate measure with poor repeatability among different times and operators in the measurement taking. Much time consuming trial and errors will occur to obtain a fit for pressure gloves. If the glove fit is improper or the amount of glove-skin interfacial pressure is not carefully controlled, too much or too little pressure would be the result. The control of the glove pressure is closely associated with hand anthropometric dimensions and their corresponding pattern making process. Thus, an accurate and efficient measurement of hand anthropometric dimensions for pattern development is crucial. Besides that, the angle of the finger web slant is difficult to be measured [62] and the current approaches in glove pattern designs fail to take the finger web slant into consideration. This results in pressure therapy gloves that cannot properly accommodate the finger web slants of their wearers. Due to poor glove fitting, the amount of pressure exerted onto the finger web areas is often too low to achieve satisfactory treatment outcomes [72]. Additional insert materials are therefore placed between the finger webs so as to control the growth of scars on the finger webs which can probably lead to another problem with comfort.

2.3.3.2 Compliance to pressure therapy gloves

Pressure therapy should be started immediately after the re-epithelialization of the wound until the scar has matured which may takes 1 to 3 years or more. For an optimal treatment outcome, pressure garments must be continuously worn for 23 to 24 hours a day and removed only for hygienic purposes or laundering. The success rate of pressure therapy largely depends on patient compliance. However, adherence to pressure therapy by patients has not been satisfactory [38]. Johnson et al. [48] reported an adherence rate of 41% in a study of burn patients who were treated with pressure therapy garments. The overall garment discomfort as well as physical impairment and emotional stress caused by the garments have been proven to be closely correlated to the rate of patient compliance during pressure-garment therapy [38, 48, 48] . As reported by Ripper et al. [73], the most common complaint with regards to pressure garments is function and physical impairments caused which include issues with mobility, sweating, itching and pain. Other than those, problems such as poor fit, obsolete functional design and appearance, and feeling hot are also reasons for poor compliance to treatment with pressure garments [13].

Patients who wear pressure therapy gloves generally experience substantial issues. The hands are one of the body parts that are used most often and important in performing all sorts of daily activities. During hand movements, pressure gloves induce extra pressure onto the hand which not only affects dexterity, but also causes discomfort. Besides that, tightly fitted pressure gloves increase the skin temperature, giving feelings of being hot, causing sweating of the hand, and resulting in discomfort which finally lead to poor compliance. Apart from that, the wearing of gloves is often considered to hinder hand dexterity and performance [74] and lowers tactile sensitivity. It is an additional interface between the hand and the object to be touched or held, thus affecting touch when handling an object. The thickness of a glove may change the hand dimensions and result in a negative impact on gripping strength endurance [75, 76]. As reported by numerous authors in the literature, conventional gloves, such as those made of leather, latex, vinyl and nitrile, negatively influence the grip and pinch strength, dexterity, ease of tool manipulation and functional hand use [77-86]. O'Brien et al. [87] and Dewey et al. [88] modified pressure gloves by using a suede, rubber or silicon attachment on the palm surface which can enhance the hand function in gross and fine motor activities and functional grip as compared to traditional pressure gloves that are solely made of warp-knitted powernet fabrics. Ward et al. [8] conducted a study of burn patients and revealed that pressure garments do not lead to changes in joint range of motion (ROM). However, this study did not take garment tightness or pressure delivery into consideration. Despite anecdotal and clinical evidence of the beneficial effects of pressure therapy on hypertrophic scars, few studies have been carried out that examine the effects of fabric choice and RFs on hand dexterity, performance and anticipated comfort perception.

As previously mentioned, insert materials are important for increasing the local pressure to reach the sufficient treatment level. As the pressure garment and the insert have to conform to the body shape and be continuously worn, the insert materials are required to be resilient, elastic, durable and comfortable. There are many different materials available to produce under garment inserts for pressure therapy. However, the inserts are usually associated with the lack of wear comfort. Improperly shaped inserts may not provide good contact with the hypertrophic scars and thus reduce the effectiveness of treatment. Body movements during daily activities also result in frequent displacement and repositioning of the inserts, thus affecting the contact conditions of the pressure therapy gloves. Frequent modifications of the shape of the inserts are required so that they accommodate the changes of the scars. Yip et al. [89] provided an innovative suggestion of using Lego® as the insert material. Lego® is hard and rigid enough to provide a high degree of pressure and can easily be combined to form different shapes to suit the scars. However, the rigid material can be difficult to fit onto body parts that have high curvature and is uncomfortable. Therefore, relatively softer materials, such as foam, are crucial in providing a certain amount of flexibility to conform to body contours. Yelvington et al. [90] suggested the use of neoprene to make patches or splints for scar management and its effectiveness in treating hypertrophic scars was also proven. Neoprene is commonly used as an orthopaedic modality for joint positioning to relieve stress from bony prominences and absorb shock. It is also valued for its ability to maintain warmth and prevent evaporative heat loss. This insulation property may be suitable for some places that are often very cold. An ideal pressure therapy should provide an adequate amount of pressure to treat scars with minimal and acceptable discomfort so as to maintain the therapy compliance of patients. The poor air permeability, moisture absorbance and wicking properties of traditional insert materials, however, cause patients to perspire as heat builds up, and hence, affect adherence to treatment.

In Hong Kong and China, pressure therapy garments are mostly custom-made for hypertrophic scar patients by occupational therapists, whose main concern is usually with the tightness of a garment for suppressing scars. The high interfacial pressure of pressure therapy gloves may impair hand movement and finger dexterity. The discomfort and inconvenience caused by pressure therapy gloves are often placed in a lower priority of consideration. However, these can lead to poor treatment adherence and eventually poor treatment outcomes.

2.4 Human physiological and psychological responses to garment pressure

For pressure therapy gloves, the magnitude of the glove-skin interfacial pressure is one of the influential factors on the sensation of comfort. Various researchers have made significant efforts to understand the influence of compression wear on psycho-physiological responses during special sports and various fitness activities [91-94]. It is found that the dynamic interactions between garments, the human body and environment stimulate and trigger different sensation receptors, which lead to varying tactile and pressure sensations, thermal and moisture comfort perceptions, and even overall psycho-physiological responses [95-100]. It is believed that the pressure magnitudes and distributions induced by the pressure garments not only affect psychophysical sensation, but also some other aspects of the human body, thus adversely affecting the rate of patient compliance during the course of the treatment. Experiments have demonstrated that the pressure on skin exerted by compression wear can affect physiological parameters in humans, such as the heart rate (HR), blood pressure (BP), and the levels of urinary catecholamines and cortisol [101, 102]. However, the effects of pressure therapy gloves on human physiological responses are not very well known. Since certain hand functions may be lost due to the effects of pressure therapy gloves on psycho-physiological responses such as poor tactile sensation and perception of discomfort, the negative impacts and stress associated with the use of pressure gloves should also be investigated.

Thermal comfort is also well recognised as one of the most important components that affects the overall comfort of clothing. For garments that are in direct contact with the skin during wear, the moisture content and the speed of moisture movement across the fabric are closely related to thermal sensation and comfort [103-106]. Heat and perspiration have also been reported as sources of discomfort or even causes of blistering, ulcerations and scar breakdown when wearing pressure therapy garments, particularly in warm weather [36]. Thermal comfort is mainly affected by the human metabolic rate, environmental conditions and clothing properties [107-109]. The fabric properties that are related to the transmission of heat and moisture determine the thermoregulatory responses of the wearers and hence the comfort sensation [110]. These properties, including thermal conductivity, thermal resistance, air permeability, WVTR, etc., depend on the fibre content, fabric structure, and thickness and density of the fabric [111, 112]. With good heat and moisture transfer properties, the fabric can quickly reduce extra heat and sweat on the skin, and leave the skin with a cooling sensation. Investigation on the microclimate conditions under clothing is important for understanding their influence on human physiological responses and comfort sensation.

In addition, the tightness and fit of gloves directly control the amount of pressure delivery to the hand and at the same time, can influence the muscle activities of the hand and forearm in performing daily tasks. Several studies have used surface electromyography (SEMG) to evaluate the effect of work or protective gloves on muscle effort [86, 113-117]. SEMG measurement (Figure 2.9) is a non-invasive biomechanical assessment that provides information on muscle activation characteristics [118]. The SEMG amplitude is linearly related to the tension exerted by muscles and represent the force required of local muscles during a task [119]. Significant effects on the ratio of the peak force to flexor muscle in SEMG activity between different glove types in terms of material and fit have been reported [113, 116]. Increased glove thickness and stiffness were identified as the key attributes that contribute to the increase of muscle effort to perform manual tasks [115, 117]. Thinner and better-fitting gloves were found to provide better transmission of muscular force to the measured grip force. However, there is a lack of research on the effect of pressure glove tightness on muscle activity. It is therefore crucial to strike a balance between glove tightness and minimised influence on daily life.

Figure 2.9 SEMG system for assessment muscle activity of forearm muscles

2.5 Hand anthropometric measurements

2.5.1 Manual measurement techniques

To obtain body dimensions, anthropometers (Figure 2.10a), callipers (Figure 2.10b) and measuring tapes (Figure 2.10c) are usually used to directly obtain manual measurements from the human body. In the fabrication of custom-made gloves, apart from measuring tape and callipers, direct measurement tools such as measuring boards and rulers can also be used to obtain hand dimensions for glove design and pattern development [120, 121]. They are generally small in size, easy to use and inexpensive. However they are time consuming to use and result in low accuracy due to the complex anatomy and curvature of the wrists, thumbs, fingers and related joints. As the human body is supple and flexible, the tension of a measuring tape and the curvature of the corresponding landmarks and positions can influence the hand dimension results, which lead to poor repeatability and large variances, particularly when measurements are taken by different people. Currently, inaccurate hand dimensions due to the lack of suitable measuring equipment in hospitals result in re-measurements and repeated adjustments for glove fitting, thus adversely affecting the efficacy of pressure therapy treatment. The current glove making process is therefore very time-consuming and alternatives have involved much trial and error based on the experience of individual practitioners.

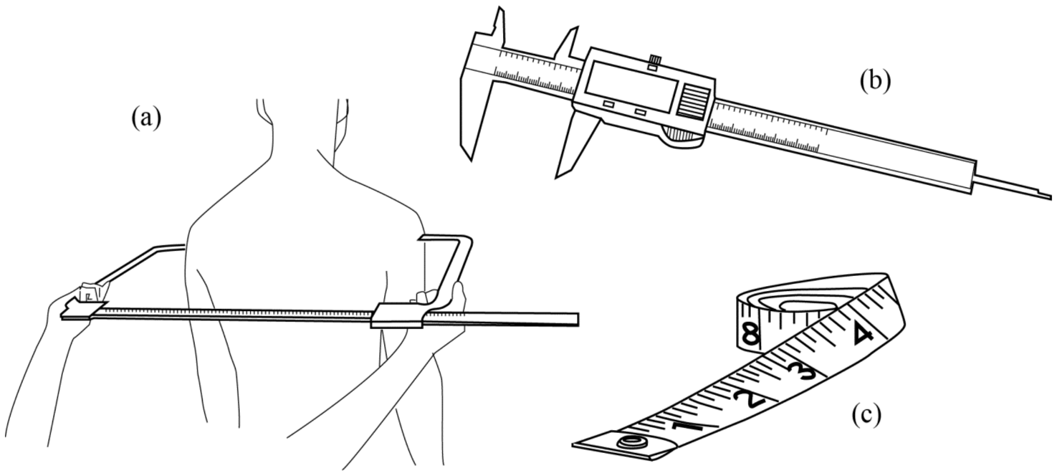


Figure 2.10 (a) Anthropometer, (b) calliper and (c) measuring tape

2.5.2 Image analysis methods

Apart from direct measurement methods, more recently, image analysis methods have been widely adopted to take body dimensions in the design of various fashion and medical products [122-126]. The size, shape and body dimensions are measured from images captured from the human body instead of directly measuring the human body. Human body images can be obtained by cameras or 3D scanners. The use of the former obtains images through 2D photogrammetry, stereogrammetry and multi-camera photogrammetry. 2D photogrammetry is the quantification of the surface features and comparison of anthropometry with standard 2D photographs [127]. As the human body is an irregular 3D object, linear measurements made by using measuring tapes, callipers as well as the distance measurements from 2D photographs may be inadequate because these neglect the body contour. Stereogrammetry is a method that captures a pair of images and their differences by using two cameras, otherwise known as parallax [128] (Figure 2.11). 3D images can be constructed with these two images to provide contour information that will overcome the problems associated with 2D photogrammetry. However, stereogrammetry can only provide information with a narrow field of view, mainly on the single surface that is facing the cameras. Multi-camera photogrammetry is the use of two or more cameras placed around the target to obtain 2D images from different viewing angles (Figure 2.12). Then, the 2D images can be combined to generate a 3D image that provides a relative broad range of information. The techniques of multi-camera photogrammetry has been well developed in various studies and used in different medical applications, such as monitoring the shape of the face, skin wounds, teeth abrasion, etc. [129-131]. Based on the measuring principle of multi-camera photogrammetry, the surface data of hands can be acquired by registering 2D hand images from different viewing angles within a second of capture. Digital cameras are also relatively less expensive. However, the images obtained can be easily affected by the number of images that are registered, the viewing angle and also the lighting [132].

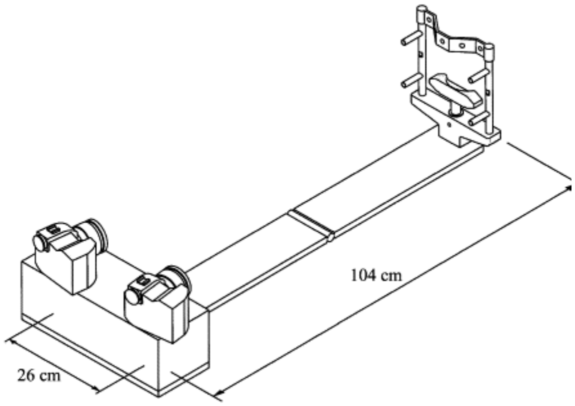


Figure 2.11 Stereophotogrammetric set-up for measuring facial anthropometry [128]

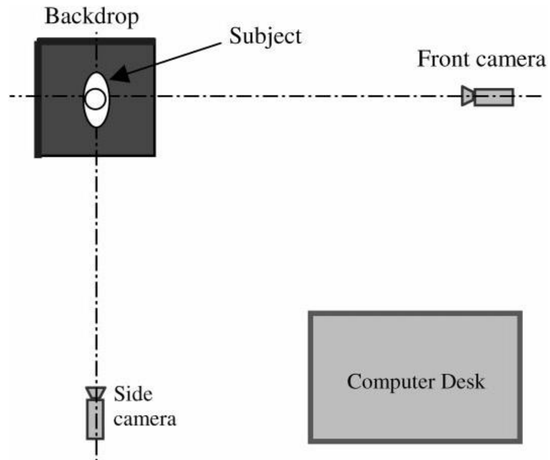


Figure 2.12 Plane view of 2D image capture set up for body anthropometric measurement [130]

Three dimensional body scanning technology has become popular in recent years. A laser based 3D scanner can capture several images of a human body from various angles which are then combined to form a 3D image. Body dimensions could be obtained from this 3D image with the aid of a computer program. Some hand held laser scanners have made the whole scanning process more portable and flexible for obtaining images of particular body parts (Figure 2.13). However, any small body movement can affect the quality of the images created and hence, the accuracy of the anthropometric measurements. Moreover, certain techniques are required for the image capturing process, which are landmarking, 3D image registration and hand dimension analysis [133]. These also directly affect the accuracy of the results. Nowadays, most of the 3D scanning technologies that use computer programs for image analysis are specifically designed to measure the dimensions of the entire body. There is no specific 3D body scanning system for the hands available in the market to directly obtain the required dimensions, such as finger length and circumference, to create custom-made gloves. Although there is a large reduction in the prices of 3D scanners recently, the cost of the equipment itself and its maintenance are still more shortcomings. However, compared with other hand measurement methods, 3D scanning can provide a geometrical representation of the human body that is useful for the development of a computer simulation model.

Figure 2.13 Measurement of resin hand model by using a 3D hand-held scanner [134]

2.6 Garment-skin interfacial pressure

2.6.1 Methods of interfacial pressure measurement

A number of pressure sensors are available to determine the amount of pressure given by a pressure garment, and these have also been adopted for measuring the interfacial pressure between garments and the skin. The pneumatic pressure sensing method was employed in an early study on garment pressure [135]. By placing an air cushion between the clothes and the skin, the pneumatic pressure inside the air cushion was recorded. Some other researchers also adopted pneumatic pressure sensing in measuring garment pressure [136-138]. The hydrostatic pressure-balanced method is another means to measure garment pressure. A water filled pressure detector or a liquid pack manometer is used to measure the hydrostatic pressure changes caused by garment pressure [139, 140]. Electrical pressure transducers are a popular means nowadays to measure garment interfacial pressure. Several commercial electrical pressure sensors, including Flexiforce® (Tekscan, Inc., USA), the Pliance system (Novel GMBH, Germany) and I-scan sensor (Tekscan, Inc., USA), give precise measurements on the pressure of tight-fitting garments [141-143]. The Pliance system which has a single sensor has been validated for measuring the interfacial pressure generated by pressure garments [141]. The single sensor consists of a circular sensing area with a diameter of 10 mm (area=78.54 mm^2) and thickness of 0.95 mm. An extended non-sensing conductive strip allows insertion to access the desired measurement points. This is a capacitive sensor with a sensing pressure range between 0.5 and 60 kPa, and the experimental error is less than 0.13 kPa. It has high linearity between the applied pressure and sensor outputs and good repeatability with coefficients of variation less than 0.1. However, the pressure sensor requires the sensing area to be located on a flat surface for accurate measurement.

Instead of measuring the interfacial pressure between the garment and skin, Giele et al. [71] directly measured the garment pressure exerted onto the cutaneous layer of patients by inserting needles which were connected to a pressure transducer under the subdermal tissue. Even though this is more accurate, its invasiveness means that the method is not popular. Although there is a variety of pressure sensing equipment available, they are seldom used in hospitals to measure the pressure delivered by pressure garments because pressure sensors can only measure pressure at a certain point(s), but not over certain area(s) and thus it is difficult and time consuming to understand the pressure distribution over the body parts. Body movements and postures can lead to variation in garment pressure. The pressure sensing data can be complicated to interpret. The tight fit of pressure gloves and the irregular shape of hands also make interfacial pressure measurement much more difficult.

2.6.2 Mathematical prediction of garment pressure

As the direct measurement of pressure given by pressure garments can be difficult and time consuming, various pressure prediction methods have been developed in response. The prediction of the pressure amount by using mathematical equations can help to estimate the interfacial pressure. Laplace's law was adopted for the study and prediction of the amount of pressure delivered to the skin by pressure garments in several studies [37, 69, 144, 145]. It was originally used to compute the surface tension on liquid droplets, but modified to determine garment pressure by dividing the fabric tension with the radius or curvature of the body. Equation (2.1) shows the Laplace's equation in calculating pressure:

$$P=T/R \qquad (2.1)$$

where P= garment pressure (Pa), T= tension per unit fabric length (N/m), and R= radius of the cylindrical object (m).

Equation (2.1) assumes that human body parts are circular in shape. It can easily estimate the pressure exerted by a pressure garment onto the human body with a short computation time. Based on Laplace's law and the tensile properties of elastic fabric, Hui and Ng [66] created a pressure model with elastic fabric for the development of pressure garments for the limbs and/or trunks of the body. Macintyre and Ferguson [57] also developed a pressure garment design tool to calculate the amount of pressure induced onto the limbs. However, the pressure model based on Laplace's law is limited to the cylindrical shape. Unlike limbs and trunks, the anatomy of the hand is somewhat non-cylindrical in shape. The equation might not be applicable to arbitrary body shapes. Hence, it is crucial to identify an appropriate empirical model to predict skin pressure when pressure gloves are worn. Hasegawa and Ishikawa [146] modified the Laplace's equation into Equation (2.2) to take into consideration the difference in the curvature of the body in the horizontal and vertical directions, and the tensile behaviour of a garment in the wale and course directions:

$$P = T_w K_w + T_c K_c \tag{2.2}$$

where P= garment pressure (Pa), T_w = fabric tension per unit length in the wale direction (N/m), T_c = fabric tension per unit length in the course direction (N/m), K_w = dome curvature along the wale direction of the fabric (m^{-1}), and K_c = dome curvature along the course direction of the fabric (m^{-1}). The body curvature of the points where the pressure is measured can be determined by using Equation (2.3) which has also been used in a study that predicted pressure on skin induced by a tight-fitting girdle [67]. The study also indicated that consideration of body curvature is crucial in predicting garment pressure which can enhance the accuracy of prediction models and prevent adverse physiological hazards, bruises and/or ischemic injury to the wearer.

$$K = 2h/[h^2 + (\phi/2)^2] \tag{2.3}$$

where h= depth of the dome, and ϕ= breadth of the dome.

2.6.3 Computational modelling and simulation of garment pressure

Three dimensional biomechanical models can be developed to numerically simulate garment-skin interfacial pressure by means of computation modelling. The finite element method (FEM) is one of the most common computer simulation methods adopted in garment pressure prediction studies. FEM has been introduced early to handle mechanical problems. With the advancement of computer technology, many researchers then adopted FEM to handle more complicated biomechanical problems. This method solves problems by using differential equations. The simulation model is created based on certain assumptions and boundary conditions which determine the degree of complexity and accuracy of the model. The geometric and mechanical properties of the garment and human tissue are the fundamental components to building the simulation model. Magnetic resonance imaging (MRI) and computer tomography (CT) are two common methods to visualize the anatomic structure of the human body [147]. With the use of MRI and CT, obtained scanned images not only provide the outer shape of the body but also identify the position of different tissues inside the body. However, tomographic images produced with the use of computer-processed X-rays means that the radiation used in CT can cause adverse effects to the human body. MRI obtains body images by using strong magnetic fields and radio waves but with less radiation and harm to the human body. However, regardless whether the images are obtained by using CT or MRI, the scanning equipment itself is very large and expensive which limits its flexibility of use. Three dimensional laser body scanners are a simpler, less costly method to obtain 3D geometric images from a body. However, they only provide external scanning to capture the surface contours. The preciseness of the human body geometrical model is closely related to the accuracy of the simulation and the difficulty in building the model. With the use of FEM, the garment and human body structures are approximated into a mesh of smaller finite number of 'elements' where the interacting points of each element are called 'nodes'. FEM connects many simple equations over the finite elements to approximate a more complex equation over a larger domain. In addition to consideration of the contact and interaction between the garment and the skin, the interfacial pressure can be estimated through FEM. A completed simulation also provides various calculated variables such as stress, displacement, contact pressure, etc. which help to understand the impact of the garment on the human body. Finally, the simulation model has to be validated by comparing the predicted values with the experimental values to ensure accuracy. With the use of FEM, the impact of the different mechanical properties of garments on the interfacial pressure can be observed simply by changing the input parameters of the simulation model instead of setting up complicated experiments.

As garment pressure can affect the overall wear comfort, several studies have developed numerical models for simulating the pressure between the garment and body parts by using FEM. Many of the studies focused on predicting garment pressure on the legs. Lin et al. [148] investigated the effect of the compression properties of sportswear fabrics on the contact pressure distribution on a leg with FEM. Dan et al. [149] simulated displacement and pressure distribution on the human leg caused by men's socks by using FEM to look for a functional relationship between pressure and displacement. Liu et al. [150] used a computation model based on FEM to simulate the dynamic pressure functional performance exerted by graduated compression stockings from ankle to thigh. There are also studies simulated the garment pressure on top part of body. Liu et al. [151] studied the garment pressure induced by sports vests on the female body bust. Zhang et al. [152] developed a model to predict the dynamic mechanical behaviour of perfectly fitting garments on a rigid trunk body during wear. Ishimaru et al. [153] predicted the garment pressure given by a half-length sleeve underwear made of knitted fabric on a female body. These previous studies mostly focused on predicting the garment pressure on limbs or the trunk, but not many provide a simulation model on the hands which have relatively complicated contours. By understanding the pressure distribution over a hand, the quality of treatment with pressure gloves can better be maintained. A simulation model can provide the interfacial pressure information with minimal time and effort from subjects/wearers with respect to measurement.

2.7 Summary

Hypertrophic scars caused by burn injuries or surgery affect appearance and physical body functions. The most popular, effective and non-invasive method in treating hypertrophic scars is through pressure garment therapy. Pressure therapy gloves are especially important in treating scars on hands to prevent permanent loss of their functions. The pressure delivered by pressure gloves can suppress collagen formation and flatten hypertrophic scars. The control of the amount of glove-skin interfacial pressure is a key factor in maximizing treatment effectiveness. It can be adjusted by using different types of fabrics, insert materials and RFs. However, there has been a lack of interfacial pressure measurements carried out in clinical practice and so the actual amount of pressure delivery by pressure gloves is not well understood. The tightness of pressure gloves are entirely determined by the experience of the individual practitioner. A prediction model for glove-skin interfacial pressure should be created to allow better pressure control during therapy.

Precise anthropometric hand measurement is necessary to produce pressure gloves with optimal fit. Nevertheless, measuring tapes which have relatively low repeatability and accuracy are the most popular tools used in current practices to obtain hand dimension measurements. Time consuming trial and errors are involved in the fitting of pressure gloves throughout the glove making process. Therefore, an accurate and practical hand dimension measuring method is necessary to minimise the problems of glove fit caused by measurement errors.

Patient compliance to pressure therapy is another important factor which impacts the treatment outcome. Effective pressure treatment requires patients to wear the pressure garment for 23-24 hours each day to continuously induce pressure onto the hypertrophic scars. However, adherence to the wearing of pressure gloves is often unsatisfactory due to discomfort, problems with mobility, itchiness, poor aesthetic appearance, heat, perspiration, etc. It is important to investigate new fabrications or modifications to pressure gloves in order to address these problems and improve patient compliance to treatment.

The pressure exerted by compression garments has been proven to somewhat physiologically and psychologically influence the human body. It is important to determine if pressure therapy gloves which continuously give a certain amount of pressure to the wearer would trigger any psycho-physiological responses that would affect the body of the wearer. The use of hands is needed in many daily activities. Previous studies have shown that the wearing of some form of protective gloves can bring about a negative impact to hand functions, but no related study on pressure therapy gloves can be found. An understanding on the factors or the properties of pressure gloves that affect hand dexterity can help to identify the direction required to develop a better glove.

Chapter 3 Clinical Study and Practical Use of Pressure Therapy Gloves

3.1 Introduction

There are specific manufacturers, such as the Jobst Institute and Barton-Carey Company, who produce ready-to-wear pressure therapy garments for hypertrophic scar treatment for the American or Australian market. In many other places, for example, China and Hong Kong, pressure therapy garments are prescribed by occupational therapists to treat hypertrophic scar patients. Hospitals refer patients to the occupational therapy department at the time that their wounds close and are ready to receive pressure therapy. The occupational therapy department handles the assessment of the scar condition and fabrication of pressure garments from body measurement taking to designing, sewing, adjusting and modifying of the pressure garments. The patients are required to visit the occupational therapists regularly to monitor the condition of the scars and assess the suitability of the pressure garment treatment. Adjustment or renewal of pressure garments and the application of inserts are also provided by occupational therapists when necessary. Consequently, it is important to perform an on-site study to understand the clinical situation, development processes, difficulties, and practical use of current custom-made pressure therapy gloves so as to identify a possible approach to improve the treatment outcomes. In this study, the interfacial pressure delivered by a pressure therapy glove, microclimate conditions under the glove surface and the scar conditions of the patients are examined. The attitude of and comments from the patients toward the pressure glove treatment are also investigated by using face-to-face interviews and questionnaires.

3.2 Experimental

Five male patients aged 26 to 55 (SD: 11.41) from the Occupational Therapy Department of the Prince of Wales Hospital, Hospital Authority, Hong Kong, were invited to take part in the study. They provided 7 hypertrophic scarred hand samples. A written consent form was signed by each participant and the procedure of the study was fully explained prior to the study (See Appendix I). During the period of study, suitable pressure therapy gloves and inserts were designed and custom prescribed by a well-experienced occupational therapist. Following the normal clinical practice, the treatment was designed on the basis of the scar condition, recovery progress and subjective assessment of glove tightness and glove-skin interfacial pressure. The pressure therapy could be either implemented (1) with the pressure therapy gloves alone or (2) the pressure therapy gloves together with Plastazote® insert(s) (Figure 3.1). All of the gloves were made with the same powernet fabric. Custom-made Plastazote® inserts were prescribed and inserted inside the pressure glove to increase the localised pressure. The details of the glove fabric and insert are shown in Table 3.1.

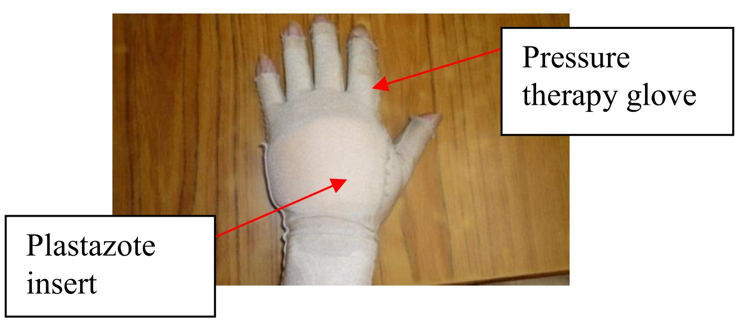


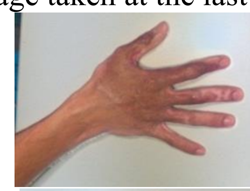
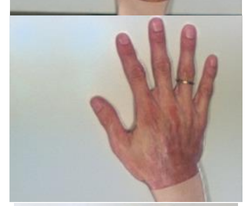
Figure 3.1 Pressure therapy glove and Plastazote® insert

Table 3.1 Details of materials used for pressure therapy on hands

	Material	Content	Thickness (mm)	Weight (kg/m^2)	Mass Density (kg/m^3)
Glove	Powernet Fabric	68% Nylon 32% Spandex	0.430	0.204	N/A
Insert	Plastazote®	Cross-linked polyethylene foam	3.122	0.361	115.536

A randomised clinical study was carried out to evaluate the interfacial pressure and micro-environment conditions of the pressure therapy gloves and examine the subjective feelings of the wearers toward the wearing of the pressure gloves. The study was carried out between May and December 2011. The duration of the study on each subject was 18 weeks within which there were 6 meetings in total. The scar conditions of each subject were documented with photos and VSS (Figure 2.2) weighted by the same occupational therapist on the first and last meetings. The photos and VSS records are presented in Tables 3.2 and 3.3 respectively.

Table 3.2 Photos of participant hands taken at the first and last meetings

Subject	2D image taken at the 1st meeting	2D image taken at the last meeting
1		
2 Left hand		
2 Right hand		
3 Left hand		
3 Right hand		

4  

5  

Table 3.3 Burn, treatment modality and scar condition records of the participants

Subject No.	1		2				3				4		5	
Age	39		55				26				46		51	
Job	Swimming pool maintenance technician		Retired				Unemployed				Interior decorator		Electricity technician	
Date of receiving burn	30-Dec-2010		21-Apr-2009				29-Apr-2011				28-Oct-2009		25-Apr-2011	
Start of pressure glove therapy	8-Feb-2011		6-Jul-2009				7-Jun-2011				09-Dec-2009		22-Jun-2011	
Period of clinical study	3-May to 6-Sep 2011		3-May to 6-Sep 2011				7-Jun to 1-Nov 2011*				7-Jun to 11-Oct 2011		2-Aug to 6-Dec 2011	
Treatment modality														
Pressure glove only	√		√										√	
Pressure glove + Plastazote®							√				√			
VSS record														
Scarred Hand	Right		Left		Right		Left		Right		Right		Right	
Meeting	1st	6th	1st	6th	1st	6th	1st	6th	1st	6th	1st	6th	1st	6th
Pigmentation (0,1,2)	2	2	2	2	2	2	2	2	2	2	0	0	2	2
Vascularity (0-3)	1	1	1	1	1	1	2	2	2	2	2	2	2	1
Pliability (0-5)	1	1	2	2	1	1	1	2	1	2	2	2	2	1
Thickness (0-3)	1	1	2	2	1	1	1	2	1	2	2	2	1	1
Pain (0-2)	0	0	1	1	1	0	0	0	0	0	1	1	0	0
Itchiness (0-2)	1	1	1	2	1	0	1	1	1	1	0	0	1	0

*The third meeting was postponed for 3 weeks.

A force sensor (Flexiforce, Tekscan, Inc., USA) was used in each meeting to measure the pressure delivered to the hands of the subjects by the pressure glove. A sensor was placed underneath the glove surface to record the interfacial pressure (Figure 3.2). The glove-skin interfacial pressure was measured at the centre of the hand dorsum for each subject. Interfacial pressures were measured when the hand was laid flat on a table and when clenched into a fist. A sensor (thick: 5.89mm, diameter: 17.35mm) which can record the temperature and humidity (Thermocrons HC, OnSolution) was placed inside the pressure glove or underneath the insert to investigate the micro-environmental conditions. Direct contact of the sensor with the hand is needed to measure the skin temperature. The gloves or inserts were modified by the occupational therapist who attached the sensor onto them so that the sensor could come into direct contact with the scars without affecting the therapy (Figure 3.3). As illustrated in Figure 3.4, the sensors were placed inside the pressure gloves or underneath the Plastazote® inserts at the first, third and fifth meetings. They were taken out at the second, fourth and sixth meetings. The sensors were given to the participants for 2 weeks in each cycle of data collection and in between each cycle was a time period of 6 weeks. A total of 3 cycles of data collection were carried for each participant. The temperature and humidity data were taken every minute. The participants were required to record the period of time that they were wearing the pressure glove together with the sensor on the record table inside the information sheet given to them (see appendix II). To investigate the influence of the pressure therapy gloves on the life and work of the patients and obtain comments on their pressure therapy glove, a face-to-face interview was carried with each participant at the second, fourth and sixth meetings. The participants were asked to openly express their feelings towards the wearing of the pressure therapy glove, including those on the thermal and moisture conditions, fatigue, pressure, overall performance, and even the visual and aesthetic aspects, during the interview. The interview questions can be found on Appendix III.


Figure 3.2 Force sensor


Figure 3.3Modification of Plastazote® insert and pressure gloves to accommodate a temperature and humidity sensor

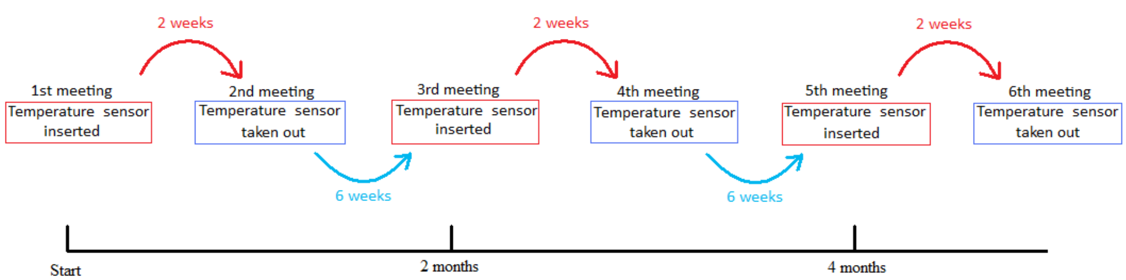


Figure 3.4 Schedule for the 6 meetings in the clinical study

3.3 Results and Discussions

3.3.1 Treatment outcomes

According to the VVS, there was no recorded change in the pigmentation of the scars for all seven scars after 18 weeks. The VSS of the scars of Subjects 1 and 4 remain unchanged throughout the 18 weeks of the study while that of Subjects 2 and 5 improved. However, the scars of Subject 3 increased in pliability and thickness in the 18 weeks of study. This is because the scar of Subject 3 was still in a very active state and grew quickly over the study period.

3.3.2 Glove-skin interfacial pressure

The amount of pressure delivered by the pressure therapy glove onto the hand of each participant was measured in each of the meetings. The overall interfacial pressure when the hand was relaxed is 0.85 kPa (SD: 1.28). The pressure significantly increased to 7.59 kPa (SD: 10.47) when their hand was clenched into a fist. As shown in Figure 3.5, the presence of the Plastazote® insert, this resulted in a substantial increase in the interfacial pressure for both the lying flat and clenched.

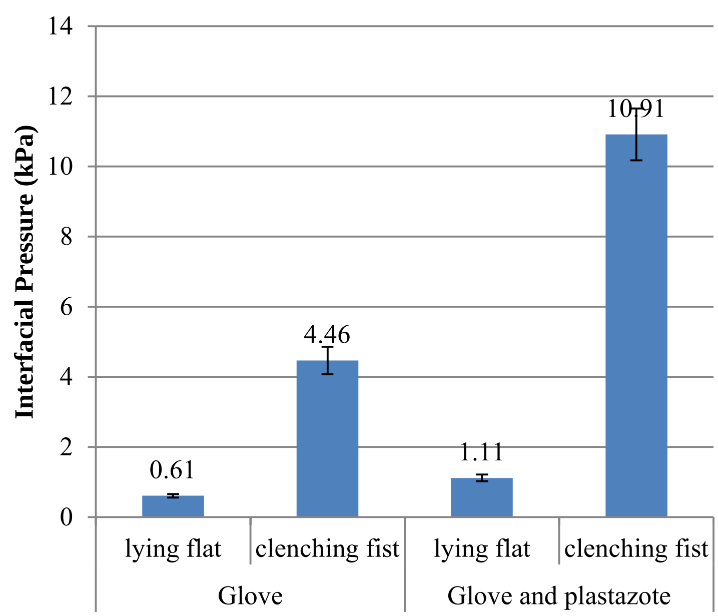


Figure 3.5 Glove-skin interfacial pressure when hand is laid flat and also when clenched. (Error bars indicate ± standard errors)

3.3.3 Temperature and humidity

The temperature and humidity inside the pressure therapy gloves measured from the participants during the three cycles of data collection are presented in Table 3.4. The temperature recorded ranges from 23.99℃ to 36.99℃ and the humidity recorded ranges from 29.79% to 130.56%. The data obtained from the same participant in the three data collection cycles are very similar. The average humidity during the day is usually slightly higher than that at night while the average temperature is similar for both day and night time.

In order to examine the effects of: (1) the type of pressure therapy design (pressure glove alone or with Plastazote® insert), and (2) the temperature and humidity inside the pressure therapy glove with respect to time of the day, a two-way multivariate analysis of variance (MANOVA) was carried out by using SPSS. The alpha level was set at 0.05 for statistical significance. The results revealed that during the day, the hands performed different motions to assist with daily activities and more heat energy is generated when compared with night time. However, the results showed no significant ($p>0.05$) difference between the time of the day for both temperature and humidity. Due to the presence of the pressure therapy glove and/or Plastazote® insert, hand dexterity is affected. Besides that, the participants had the tendency to protect their injured hand and avoided unnecessary movements with the hand. Therefore, the amount of hand motions made by the participants is minimal during the day which means that there is no significant changes inside the glove in terms of the temperature and humidity throughout the day. No significant difference in humidity can also be found with the use of the Plastazote® insert. Without the insert, the glove humidity obtained during the day

(95.1%) is relatively higher than that obtained at night (90.31%). Surprisingly, the insertion of an additional insert under the glove does not further increase the humidity (94.01% during the day and 93.63% at night). On the other hand, the use of the Plastazote® insert led to a significant increase in the skin temperature inside the pressure therapy glove ($p<0.05$). The insert thus became an additional medium for conserving heat energy generated during hand movement. The Plastazote® insert is relatively thicker and more rigid than the glove fabric. It not only enhances the localised pressure and skin temperature at the scar region, but also limits hand dexterity, all of which adversely affect the overall glove comfort.

Table 3.4 Temperature and humidity inside pressure therapy glove or under Plastazote® insert

Subject No.	Hand	Cycle of data collection	Temperature (℃)			Humidity (%)		
			Entire day	Night Time	Day Time	Entire day	Night Time	Day Time
1	Right hand	1st	34.15	34.15	N/A	89.81	89.81	N/A
		2nd	34.05	34.10	33.88	90.54	88.97	94.55
		3rd	34.06	33.99	34.21	96.12	93.63	101.09
2	Left hand	1st	32.83	32.82	32.41	81.25	80.16	82.26
		2nd	32.11	32.19	32.20	77.00	76.85	79.19
		3rd	32.94	33.37	31.45	51.19	48.52	57.26
2	Right hand	1st	32.65	32.61	32.34	80.76	80.01	81.32
		2nd	32.48	32.55	32.57	79.16	77.70	86.75
		3rd	32.97	33.27	31.74	57.00	54.54	60.07
3	Left hand	1st	34.37	34.49	33.98	73.20	73.57	70.89
		2nd	31.95	31.60	32.64	101.44	101.57	101.18
		3rd	31.39	31.14	31.88	97.49	96.79	98.88
3	Right hand	1st	34.14	34.30	33.59	76.41	77.04	72.38
		2nd	32.21	31.69	33.25	95.96	98.93	90.03
		3rd	33.37	33.14	33.84	98.52	98.13	99.31
4	Right hand	1st	34.31	34.08	34.76	103.79	105.07	101.22
		2nd	34.76	34.55	35.19	89.89	89.25	85.74
		3rd	34.55	34.52	34.61	105.03	103.80	107.50
5	Right hand	1st	34.63	34.40	35.09	99.61	99.05	100.73
		2nd	34.18	34.32	33.91	105.32	103.69	108.57
		3rd	34.23	34.39	33.92	N/A	N/A	N/A

*Subject 1 did not put in the sensor during the day in the first cycle of the data collection. The glove-skin humidity of Subject 5 in the third cycle of the data collection could not be properly measured due to a technical issue with the sensor.

3.3.4 Interviews

Each participant was interviewed three times so as to understand his/her subjective sensations towards the pressure therapy at different time periods.

(1) *Attitude and adherence towards pressure therapy treatment of scars*

The results indicated that the five subjects show good compliance towards the pressure glove therapy and a positive attitude in treating the scars. Comparatively, a higher compliance rate and positive attitude towards the wearing of pressure gloves were found in patients who have been prescribed the treatment for over one year.

(2) *Subjective feelings on efficiency of pressure therapy treatment*

Seven-point-scale ratings on four statements were used to understand how the subjects felt about the efficacy of the pressure gloves. As shown in Table 3.5, four of the subjects agree with the efficacy of the pressure glove and provide a rating of 5 or more for each statement. That means they felt the pressure glove is effective and can help to smoothen, control the growth and reduce the size of the scars. On the other hand, one of the individuals, Subject 3, initially rated the statements with 5 or less. His scars were very active and the tissue easily expanded. In observing the aggravation of the scars, he had doubts about the efficacy of the pressure therapy treatment. However, he began to notice the efficacy of his pressure glove after receiving the treatment for a longer period of time and consequently, provided a higher rating.

Table 3.5 Subjective ratings on the efficacy of pressure therapy treatment by 5 of the subjects from 3 interviews

	Strongly disagree 1	2	3	4	5	6	Strongly agree 7
The pressure glove is effective.	0	0	0	0	7	7	1
The scar is becoming smooth after wearing the pressure glove.	0	0	0	1	5	8	1
The glove can help to control the growth of the scar.	0	0	0	2	4	8	1
The scar is becoming smaller after wearing the pressure glove.	0	1	2	0	3	8	1

(3) Problems associated with wearing of pressure garment

The subjects were asked to express how the pressure glove affected their daily life and work, and point out the associated problems. Three of them mentioned that they need to wear an extra plastic glove or work glove over their hands as well as the pressure glove when working so that the pressure glove would not become dirty or wet. Three of the subjects indicated that they cannot perform work that required fine motor skills when wearing their pressure glove. They also pointed that the glove restrained hand and finger movements and caused limitations in their daily life and work, thus reducing their work efficiency. Displacement of the gloves was also a problem mentioned by four of the subjects. Problems with breathability, durability, comfort, improper pressure exerted onto the hand and fingers, and aesthetic appearance were all mentioned as issues.

3.4 Summary

In this study, the scar conditions of 4 out of the 5 subjects have shown an obvious improvement. The subjects agree with the effectiveness of the pressure therapy glove. The observable treatment outcomes minimise negative impressions and increase adherence to the glove. Once the patients became accustomed to wearing the pressure glove, the treatment compliance would increase. Discomfort that came from feeling hot, moisture as a result of sweating, and poor breathability triggered by the glove is also closely associated with the rate of treatment compliance. The additional Plastazote® insert can induce a significantly higher temperature inside the pressure glove. Therefore, improvement on the thermal comfort of the pressure glove and replacement of the non-breathable insert with other types of materials are crucial in pressure glove development. The fit, tightness and pressure delivery of the pressure gloves are mainly controlled by experienced pressure therapists and can only be subjectively assessed based on personal judgement. Thus, a better interfacial prediction model is essential for optimising the treatment quality. The influence on work and daily life caused by the wearing of the pressure gloves is another problem. Further studies are necessary to investigate the impact of pressure therapy gloves on hand dexterity so as to identity improvement methods. Patients face a difficult time when wearing the pressure gloves at the beginning of the treatment. The modifying of the glove design or investing in a tool to assist with the wearing of the glove is therefore needed.

Chapter 4 Development of an Efficient Measuring System for Hand Anthropometry

4.1 Introduction

Measurements of the hand dimensions not only affect the fit and design of pressure therapy gloves, but also the functional performance, such as finger sensitivity and mobility, when the gloves are worn. As observed from the clinical study outlined in Chapter 3, the occupational therapist only uses a measuring tape to measure the hand dimensions in the fabrication of a new pressure glove. Further assessments and adjustments on the size are often required once the glove is finished. To develop high quality custom-made pressure therapy gloves that perfectly fit the hands of the wearers, occupational therapists, designers and manufacturers have to gain a deeper understanding of the true values of the hand anthropometry by adopting a more efficient and accurate measuring method in order to achieve better fit and performance. With accurate hand measurements, a better fitting pressure glove can be produced and time spent on adjusting the fit can be minimised. The purpose of this part of the study is to develop efficient and reliable hand anthropometric measurement methods by using 2D or 3D image analyses. The developed hand measuring methods can also be extended to use in the production of other types of custom-made gloves, like golf and baseball gloves.

4.2 Experimental

4.2.1 Participants

A total of 10 healthy volunteers, 5 males and 5 females, were invited to participate in this study. Their ages are between 20 and 28 (mean: 22.5, SD: 2.77). The mean and standard deviation of the hand circumference, hand length and root circumference of the third digit finger of the left hands of the male and the female participants are provided below.

- Hand circumference: males (mean: 204 mm, SD: 1 mm); females (mean: 186 mm, SD: 8 mm)
- Hand length: males (mean: 176 mm, SD: 5 mm); females (mean: 170 mm, SD: 10 mm)
- Root circumference of third digit finger: males (mean: 64 mm, SD: 7 mm); females (mean: 60 mm, SD: 5 mm)

Their hand sizes are within a range in which variations between different methods of hand measurement can be readily compared.

4.2.2 Methodology of measurement

Instead of scanning the real hands of the participants, plaster hand models are used in this study to minimise potential discrepancies from the real hands during the measuring and/or image scanning process for a proper evaluation of the different hand anthropometric measuring methods. As the plaster hand models are rigid and fixed in shape, the influence of hand posture on the results of the hand measurement could be neglected. Therefore, a plaster hand model was made for the left hand of the 10 volunteers with abduction of the fingers.

The hand dimension requirements for the pressure therapy glove pattern were based on a study by Kwon et al. [154], which originated from a 1988 US Army hand anthropometric survey report [155]. These are used to determine the key dimensions for a glove sizing system that comprises 49 landmarks (Figure 4.1) and 33 dimensions (Table 4.1) for examination in this study. Each plaster hand was measured with a traditional direct anthropometric method (DM) and three indirect methods of measurement, namely, Methods IM-I, IM-II and IM-III respectively. DM was carried out by using a measuring tape (with a minimum scale of 1 mm and thickness of 0.4 mm) to take the circumference dimensions, and a digital calliper (with an accuracy of 0.01 mm) to measure the length and breadth respectively. Measurements were taken from the palmar surface of the hand by following the ISO 7250-1:2008 standard.

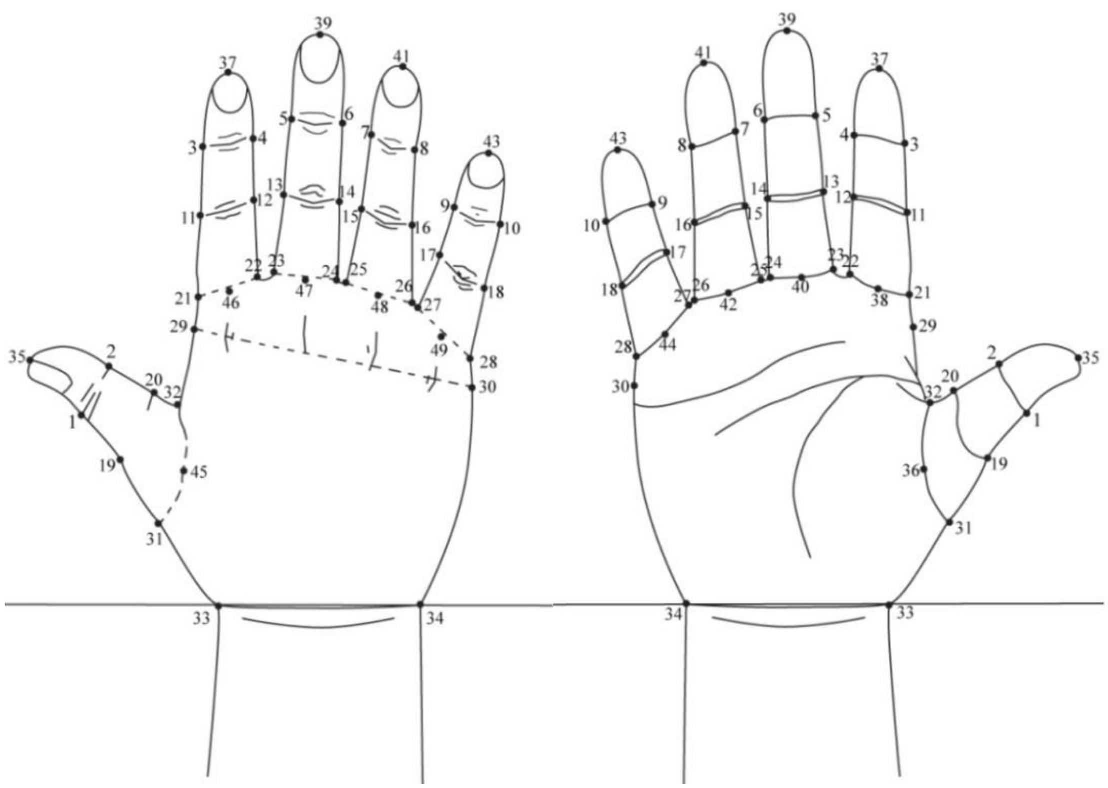


Figure 4.1 Landmarks for hand measurement

Table 4.1 Hand dimensions measured in the present study

Type	No.	Dimension	Landmarks
Circumference	C1	Digit 1 interphalangeal joint circumference	across 1 and 2
	C2	Digit 2 distal interphalangeal joint circumference	across 3 and 4
	C3	Digit 3 distal interphalangeal joint circumference	across 5 and 6
	C4	Digit 4 distal interphalangeal joint circumference	across 7 and 8
	C5	Digit 5 distal interphalangeal joint circumference	across 9 and 10
	C6	Digit 2 proximal interphalangeal joint circumference	across 11 and 12
	C7	Digit 3 proximal interphalangeal joint circumference	across 13 and 14
	C8	Digit 4 proximal interphalangeal joint circumference	across 15 and 16
	C9	Digit 5 proximal interphalangeal joint circumference	across 17 and 18
	C10	Digit 1 finger root circumference	across 19 and 20
	C11	Digit 2 finger root circumference	across 21 and 22
	C12	Digit 3 finger root circumference	across 23 and 24
	C13	Digit 4 finger root circumference	across 25 and 26
	C14	Digit 5 finger root circumference	across 27 and 28
	C15	Hand circumference (passing over metacarpal of Digits 2 and 5)	across 29 and 30
	C16	Circumference between thumb and palm	across 31 and 32
	C17	Wrist circumference	across 33 and 34
Length	L1	Digit 1 Finger length (from fingertip to root)	from 35 to 36/45
	L2	Digit 2 Finger length (from fingertip to root)	from 37 to 38/46
	L3	Digit 3 Finger length (from fingertip to root)	from 39 to 40/47
	L4	Digit 4 Finger length (from fingertip to root)	from 41 to 42/48
	L5	Digit 5 Finger length (from fingertip to root)	from 43 to 44/49
	L6	Digit 1 tip to wrist-crease length	from 35 pass through 36/45 to the line across 33 and 34
	L7	Digit 2 tip to wrist-crease length	from 37 pass through 38/46 to the line across 33 and 34
	L8	Digit 3 tip to wrist-crease length	from 39 pass through 40/47 to the line across 33 and 34
	L9	Digit 4 tip to wrist-crease length	from 41 pass through 42/48 to the line across 33 and 34
	L10	Digit 5 tip to wrist-crease length	from 43 pass through 44/49 to the line across 33 and 34
	L11	Length of root of index-finger to the root of thumb	from 21 to 20
	L12	Length of root of little finger to outer wrist	from 28 to 34
	L13	Length of root of thumb to the inner wrist	from 19 to 33
	L14	Palm length (perpendicular distance from the base of Digit 3 to the wrist crease base line)	from 40 to the line across 33 and 34
Breadth	B1	Hand breadth (distance from radial edge to ulnar edge of hand)	from 29 to 30
	B2	Wrist breadth (between the ulnar projection and the radial projection of the distal wrist crease)	from 33 to 34

4.2.2.1 Two dimensional image analysis

A colour scanner was used to minimise the time required for calibration and setting up of the camera for 2D image capturing. An Epson Perfection 1240U domestic colour scanner was used to scan the plaster hands to generate a 2D image for each hand. A plaster hand was directly placed on the scanning screen with the palm facing down and an image was then taken (Figure 4.2). This method is called Method IM-I in the present study. The scanner was calibrated beforehand to ensure that the measurements obtained from the 2D imaging were identical to the scanned object. The scanning process could be completed in 2 minutes. The scanned images were saved as bitmap files with a resolution of 300 dpi and then imported into a computer software (CorelDRAW X5, Corel Corporation) to measure the required hand dimensions. The scanner was calibrated beforehand to ensure the measurements obtained from the 2D image were identical to the scanned object. First, a standard piece of a grid paper with a grid size of 1 x 1 cm^2 was scanned. The image was then imported into the software and the size of the grid was measured with a minimum scale of 0.1 mm. The amount of variation obtained from the grid image was less than 1% which is within the tolerance of measurement. As the cover of the scanner could not be completely closed during the hand scanning, the scanning process was conducted in a dark environment to avoid the potential influence of light intensity. It is worth noting that the circumferences of the thumb, fingers, and related joints could not be taken as 2D images. A calliper was therefore used to measure the finger, hand and wrist thicknesses (Figure 4.3) along the landmarks. With the width and thickness, the circumference dimensions of the finger, hand and wrist could be predicted by using a mathematical model. The circumferences are shaped like an ellipse and thus Ramanujan's approximation of the ellipse perimeter is chosen to calculate the circumferences.

$$C \approx \pi(a+b)\left(1+\frac{3\left(\frac{a-b}{a+b}\right)^2}{10+\sqrt{4-3\left(\frac{a-b}{a+b}\right)^2}}\right) \tag{4.1}$$

where C is the circumference of the ellipse, *a* is the semi-major and *b* is the semi-minor axes of the ellipse.

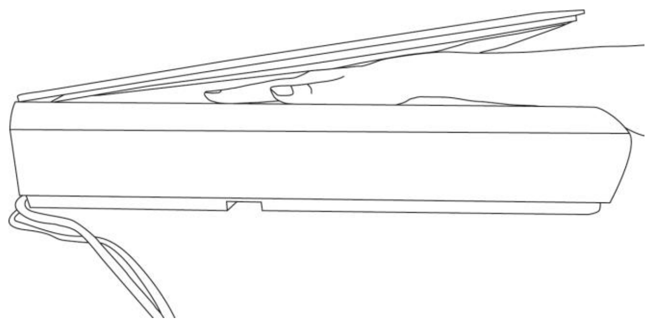


Figure 4.2 Colour scanner used to take 2D images

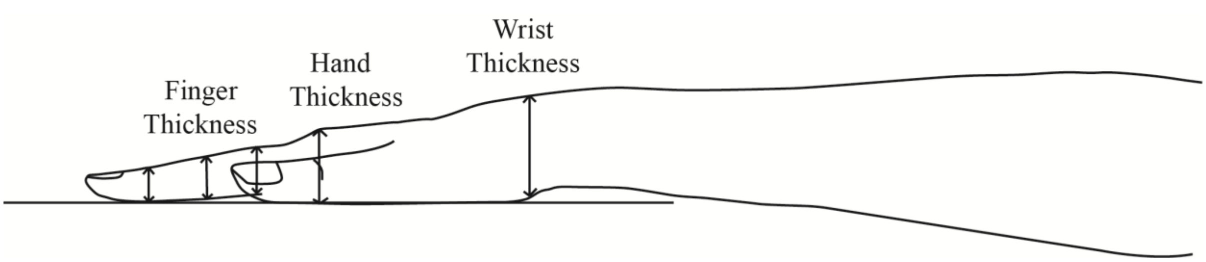


Figure 4.3 Finger, hand and wrist thickness measurement

4.2.2.2 Three-dimensional image analysis

A portable 3D laser scanner (NextEngine Inc.) was used to scan the 3D images of the plaster hands. The scanner was operated with a scanning software, ScanStudio HD (NextEngine Inc.). After a 3D image of the hand was obtained, the hand dimensions were extracted by a reverse engineering software, RapidForm 2006 (INUS Technology Inc.). Two ways of 3D image capturing are investigated in this study, and they are denoted as Methods IM-II and IM-III. To form a complete 3D image of a plaster hand from the 3D scanner, several scans that capture all of the parts of the plaster hand are essential. In Method IM-II, a plaster hand was placed onto a rotatable disc that was connected to the 3D scanner with the fingers pointing to the sky (Figure 4.4). The 3D scanner was simultaneously operated with the disc and automatically scanned images after each rotation. The disc rotated 36˚ after each image capture and stopped once to return to the original position. Therefore, ten captures from different angles of view were obtained and then combined into a 3D image with complete surface data by the scanning software. The images were taken in standard configuration mode, which took about 2 minutes to complete the capturing of each image.

Speed and user-friendliness are crucial elements for a scanning method to be considered as acceptable. Therefore, in this study, a simplified approach of 3D image analysis is proposed; three captures from three different viewing angles are combined. In Method IM-III, the 3D surface data of the plaster hand were captured on a flat surface with the palm facing down. The 3D scanner only scanned the back side of the plaster hand three times from three different angles to obtain the top, and left and right side views (Figure 4.5) with the support of a tripod. This method aims to minimise the number of hand images and scanning time to obtain a 3D hand image of the dorsal surface. It also allows the participants to comfortably rest their hands, thus minimising undesired hand movements. There were measurement landmarks on both the palm and back of the hand. When obtaining the length measurement of a hand, the focus of Method IM-III was on the landmarks on the back of the hand while the other three methods focused on the landmarks on the palm. This is because Method IM-III can only capture images that show the back of the hand. To measure the circumference of the fingers, it was assumed that fingers are cylindrical and their circumference is based on the arc length and shape. The palm and wrist circumferences were calculated by doubling the arc length of the palm measured from the back of the hand.

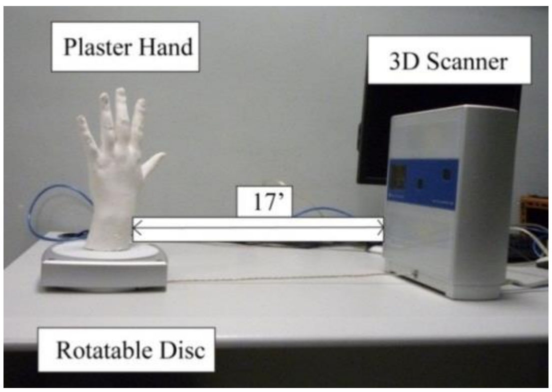


Figure 4.4 Setup for 3D scanning of a plaster hand with the use of Method IM-II

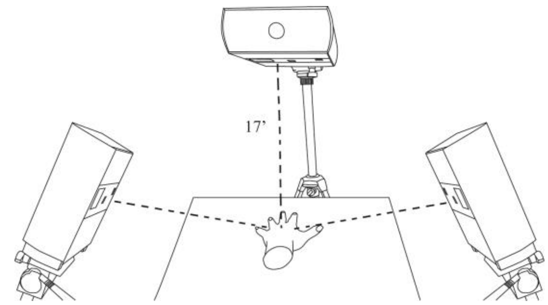


Figure 4.5 Setup for capturing 3 images by 3D scanner with the use of Method IM-III

4.3 Results and Discussions

4.3.1 Images captured

A 2D image of a plaster model hand is shown in Figure 4.6. The corresponding length and breadth can be easily extracted by using CorelDRAW X5. Figures 4.7(a) and 4.7(b) show 3D images obtained with the use of Methods IM-II and IM-III. The results reveal that the use of Method IM-II with 10 captures can successfully establish a complete and smooth 3D hand model, whilst the 3D hand model that combines 3 captures with the use of Method IM-III is comparatively incomplete. The image quality is relatively poor and blurry, particularly along the hand edges.

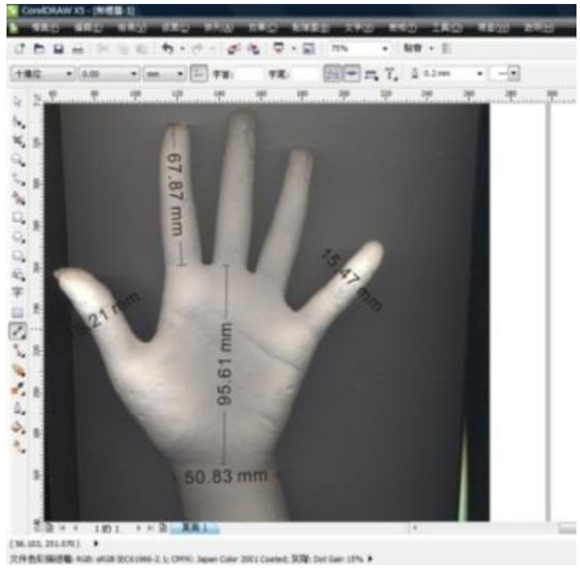


Figure 4.6 Hand dimension measured on a 2D image by using CorelDRAW X5

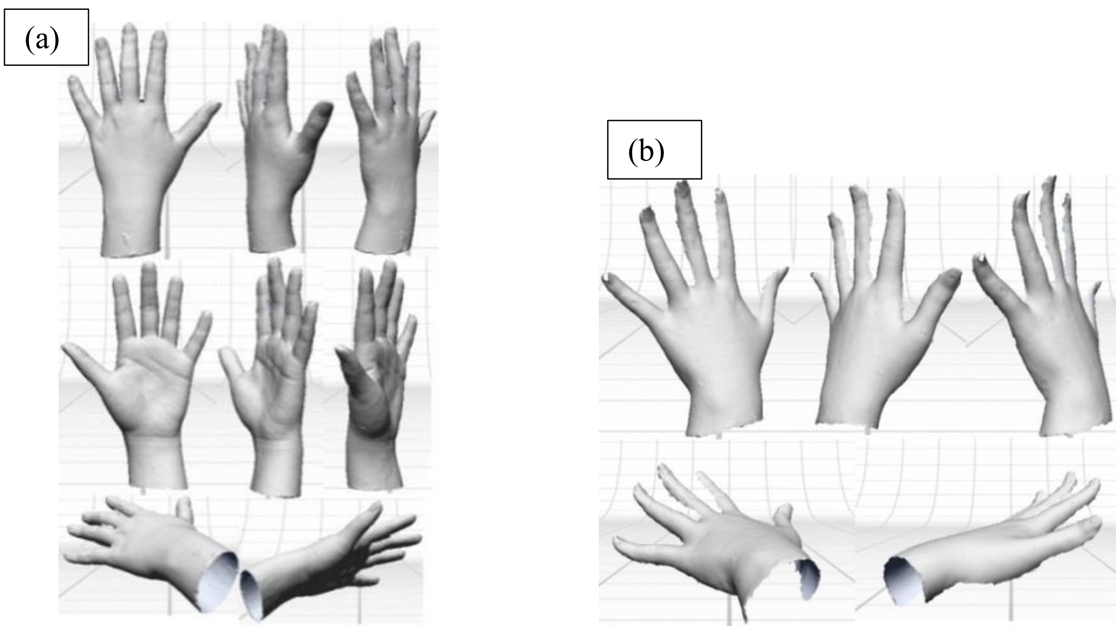


Figure 4.7 Various 3D images with different views taken with the use of (a) Method IM-II and (b) Method IM-III

4.3.2 Comparison of different methods of measurement

Statistical analysis was carried out to evaluate the methods of hand measurement by using SPSS. The alpha level was set at 0.05 for statistical significance. The Pearson correlation coefficients for the relationships between the four principal study variables ranged from 0.993 to 0.997 which indicate that they are highly positively correlated with one another. With the use of repeated-measures analysis of variance (repeated-measures ANOVA), the significance of the differences among the different means of hand measurement based on the four methods could be tested. Huynh-Feldt corrections are applied in this study for cases where the Mauchly's test of sphericity assumption was violated. The results indicated that 26 out of the 33 hand dimensions have significant mean differences amongst the four methods. Only (1) hand circumference, (2) circumference between thumb and palm, (3) wrist circumference, (4) finger length of Digit 1, (5) finger length of Digit 5, (6) tip to wrist-crease length of Digit 2 and (7) tip to wrist-crease length of Digit 3 have no significant differences.

Sidak pair wise comparison tests were chosen for post hoc testing to further examine the relationship between each pair of means from the measurements made with these four methods and the results are presented in Table 4.2. At least half of the hand dimensions in each comparison have no significant differences. Most of the length dimensions of the hands do not have significant differences between any pair in the comparisons. However, significant differences between the DM and Method IM-I, and between DM and Method IM-II, are observed in the measurement of the finger circumferences. There are 27 hand dimensions measured with the use of Method IM-III which showed no significant differences when compared with those with the use of DM. However, only 18 and 17 hand dimensions show no significant differences between the DM and Method IM-I or IM-II respectively. Yet, there are 24 hand measurements which show no significant differences between Methods IM-II and IM-III.

Table 4.2 Summary of pairwise comparisons of the significant differences in hand dimensions measured with different methods

Dimension	DM VS IM-I	DM VS IM-II	DM VS IM-III	IM-I VS IM-II	IM-I VS IM-III	IM-II VS IM-III
C1	0.01	0.002	0.129	0.826	0.012	0.258
C2	0.008	0.001	0.275	1	0.14	0.011
C3	0.005	0	1	0.418	0.171	0.01
C4	0.01	0.004	0.511	0.901	0.886	0.278
C5	0.809	0.001	1	0.091	0.692	0.005
C6	0.007	0.005	1	0.795	0.003	0
C7	0	0	0.179	0.012	0	0.047
C8	0.004	0.001	0.178	1	0.002	0.016
C9	0.061	0.061	0.202	1	0.093	0.509
C10	0.069	0.67	0.006	0.017	1	0.005
C11	0	0	0.054	0.005	0.001	0.702
C12	0	0.001	0.008	0.011	0.001	0.976
C13	0.001	0	0.001	0.104	0.098	0.543
C14	0.023	0.009	0.023	0.255	0.74	0.919
C15	1	0.458	0.712	0.997	0.985	0.992
C16	0.976	0.027	0.654	0.835	0.995	0.935
C17	0.483	0.487	0.91	0.983	0.939	1
L1	0.993	1	0.065	0.99	0.1	0.172
L2	0.997	0.97	0.216	0.982	0.088	0.315
L3	0.943	0.541	0.043	1	0.131	0.17
L4	1	1	0.054	1	0.03	0.186
L5	0.249	0.046	1	0.685	0.979	0.764
L6	0.032	0.033	0.718	0.999	0.545	0.239
L7	0.869	0.99	0.516	0.965	1	0.203
L8	0.335	0.633	0.101	0.57	0.823	0.773
L9	0.998	0.188	0.998	0.049	0.783	0.033
L10	0.027	0.703	0.946	0.039	0.078	1
L11	0.974	0.423	0.96	0.014	0.363	0.8
L12	0.999	0.074	0.305	0.045	0.355	0.978
L13	0.814	0.996	0.111	0.629	0.031	0.277
L14	0.397	1	0.027	0.451	0.364	0.014
B1	0.002	0.007	0.056	0.106	0.017	0.936
B2	0.002	0.991	1	0	0	0.985

*Adjustment for multiple comparisons: Sidak

In order to understand the discrepancies of the hand dimensions obtained from the image analysis methods, the root mean square error (RMSE) between the DM and each image analysis method was calculated respectively. As shown in Table 4.3, small differences are found in the hand dimensions between DM and each of the image analysis methods. In comparison with the dimensions obtained by the DM, Method IM-I provides the smallest differences in finger length measurements; the RMSE ranges from 0.85 to 3.05 mm. In the case of Method IM-III, the corresponding finger length differences are relatively high; the RMSE ranges from 2.23 to 4.38 mm. However, the dimensional differences obtained from the finger interphalangeal joint circumferences, and hand and wrist breadths, are relatively small; the RMSE ranges from 0.82 to 3.52 mm. The corresponding differences in the hand and wrist breadths obtained with the use of Method IM-I are relatively high, in which the RMSE ranges from 1.61 to 7.57 mm. Amongst the 3 image analysis methods, Method IM-II exhibits the least amount of discrepancies for the circumferences of the finger roots, hand and wrist, fingertip to wrist lengths and palm length as compared with the DM.

Table 4.3 Hand dimensions taken with various measurement methods and the RMSE between DM and different image analysis methods

No.	Measurements (mm)				RMSE (mm) between DM and		
	DM	IM-I	IM-II	IM-III	IM-I	IM-II	IM-III
C1	63.5	59.35	60.4	61.84	5.02	3.5	2.46
C2	50.5	47.05	47.05	49.33	4.12	3.79	1.96
C3	50	48.11	47.33	50.12	2.21	2.74	2.16
C4	46.9	44.93	44.28	45.76	2.38	3.03	2.25
C5	43.25	42.63	41.47	43.29	1.61	1.97	0.82
C6	60.75	55.19	56.51	60.76	6.6	4.95	2.76
C7	61.8	54.45	57.51	60.26	7.57	4.64	3.52
C8	58.25	53.44	53.69	56.72	5.6	5.02	2.37
C9	51.8	48.22	48.09	49.63	4.89	5.07	3.43
C10	70.9	65.79	69.14	65.39	6.95	4.18	6.37
C11	68.4	58.08	63.84	65.45	10.81	4.97	3.99
C12	67.9	55.51	63.01	61.64	13.08	5.37	7.48
C13	65.3	57.14	60.49	59.31	9.13	5.05	6.69
C14	59.4	53.7	55.31	54.68	7.22	4.91	5.98
C15	195.8	195.37	194.42	193.75	6.3	2.63	4.77
C16	100.3	97.3	93.66	95.74	12.11	8.51	10.08
C17	167.5	164.13	165.69	166.04	6.53	3.52	4.5
L1	53.04	52.43	53.17	50.77	3.05	3.3	3.13
L2	67.24	67.5	67.91	69.53	1.57	2.59	3.66
L3	73.23	73.72	73.92	76.53	1.66	1.39	4.38
L4	68.66	68.58	68.59	71.03	0.85	1.4	3.2
L5	54.64	53.11	53.33	54.5	1.8	1.61	2.23
L6	126	120.68	121.19	123.83	6.89	6.25	5.08
L7	165.6	163.59	164.8	163.14	5.7	3.83	4.88
L8	171.65	168.2	170.4	169.49	6.03	2.71	3.11
L9	160.7	158.14	160.53	158.61	5.67	3.53	3.87
L10	137.65	132.88	136.49	136.45	6.11	2.68	4.12
L11	34.42	33.67	36.25	35.24	2.98	3.4	3
L12	65.17	64.46	68.18	67.65	4.82	4.19	4.24
L13	56.22	54.25	57.37	60.3	5.14	6.34	5.94
L14	97.49	94.96	97.49	91.75	4.62	1.15	7.35
B1	80.4	75.75	78.45	78.94	5.29	2.32	1.98
B2	58.17	52.08	57.56	57.95	6.85	2.94	2.3

4.4 Summary

Two and three dimensional image analyses are proposed in this study as more repeatable and reliable measurement methods of hand dimensions. With the 2D image analysis method (Method IM-I), the palm and fingers of the plaster hand in a fixed position could not completely come into contact with the scanning screen, thus leading to measurement variations. This problem is reduced when real hands are measured, as they are more flexible and can be placed onto the scanning screen as opposed to a plaster hand. The time for image taking with Method IM-I is much less than that for whole hand dimensions as measured by the DM. This is even more evident when more measurements need to be taken, and important for increasing the efficiency of pressure glove making and reducing the inconvenience of patients during the measuring.

However, the use of 3D image analysis can obtain results that are closer to those of the DM with a smaller RMSE as opposed to Method IM-I. Once a 3D image is captured, any dimension on the hand at any point desired could be extracted anytime and anywhere, thus providing a complete record of the hand to keep track of any dimensional changes over a period of time. It is especially useful in understanding the healing progress of burn scars in pressure glove therapy. Moreover, it is a non-contact hand measurement method. The tissue compression placed onto real hands, which occurs with the use of tape measurement and leads to poor repeatability can be avoided. The repeated-measures ANOVA results and RMSE obtained from using the DM indicate that the accuracy of Method IM-III is not any less than that of Method IM-II. Hypertrophic scars are commonly found on the back of hands. A 3D image of the dorsal surface of the hands obtained with the use of Method IM-III is therefore desirable in medical applications that need to acquire irregular hand shape changes and prescribe an adequate amount of pressure onto scars. Additionally, a new approach that combines Methods IM-I and IM-III is also suggested. The hand surface data on the palm side is obtained with the use of Method IM-I and the corresponding data on the back of the hand is captured with the use of Method IM-III. This can compensate for the missing surface data in Method IM-III, but is more user-friendly and less time-consuming than Method IM-II.

Chapter 5 Formulation of Pressure Prediction Model for Pressure Therapy Gloves

5.1 Introduction

The amount of pressure used in pressure therapy is critical to the treatment outcomes. When the pressure is too low, the growth of hypertrophic scars cannot be inhibited and the scars cannot be flattened. On the other hand, overly high pressure can cause pain, numbness or even bruises or wound breakdown. However, it is time consuming to accurately measure the glove-skin interfacial pressure distributed over the hand surface by using currently available pressure sensors. It is also difficult to obtain an understanding of the actual treatment pressure. In previous studies, interfacial pressure prediction models have been developed for compression garments but mainly for the limbs and trunks only, which are assumed to be circular structures. Therefore, a pressure prediction model for hands that can provide information to assist with the fabrication of a suitable pressure glove is necessary. This study aims to formulate a pressure prediction model to predict the amount of pressure delivered by pressure gloves and their pressure decay after wearing based on fabric tensile behaviour and hand curvature. With the pressure prediction model, the amount of interfacial pressure given by pressure gloves can be better controlled and therefore, increase the effectiveness of pressure therapy.

5.2 Experimental

A flow chart diagram which shows the steps of developing the pressure prediction model is illustrated in Figure 5.1. Seven types of fabrics that are commonly used to produce pressure therapy garments are selected for testing. The fabric specifications and fabric structural diagrams are presented in Table 5.1 and Figure 5.2 respectively.

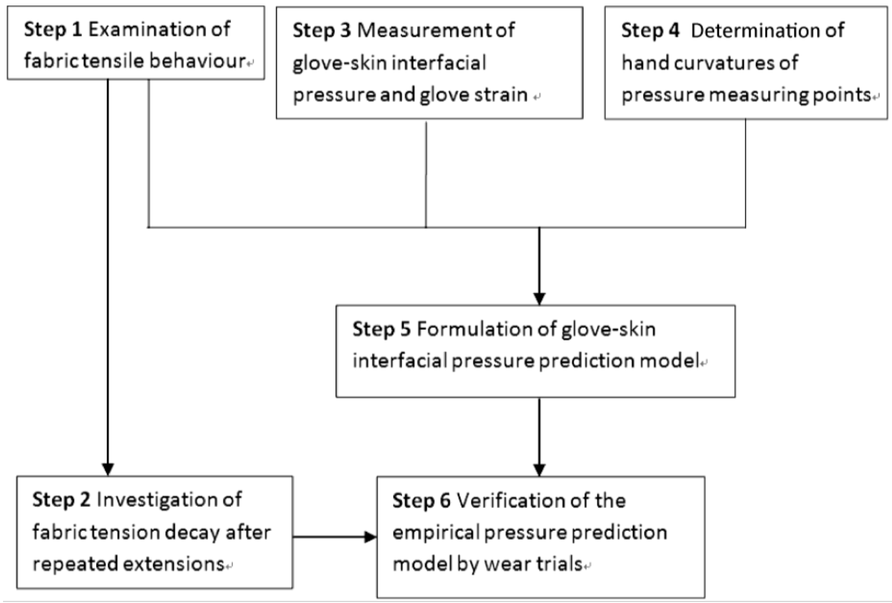


Figure 5.1 Flowchart of the experimental design

Table 5.1 Warp-knitted fabric specifications

No.	Fibre Content	Fabric Structure	Gauge	Thickness (mm)	Fabric Weight (g/m²)	Fabric Density(threads per cm)	
						Wale	Course
A	60/40 Nylon/ Spandex	Powernet	32	0.42	201.8	13	20
B	68/32 Nylon/ Spandex	Powernet	46	0.43	199.8	13	20
C	82/18 Nylon/ Spandex	Powernet	28	0.45	164.2	11	13
D	79/21 Nylon/ Spandex	Satinnet	56	0.47	166.3	11	17
E	60/40 Nylon/ Spandex	Powernet	32	0.39	188.2	20	14
F	60/40 Nylon/ Spandex	Powernet	32	0.42	221.0	19	15
G	62/19/19 Nylon/ Spandex/ Cotton	Weftlock	56	0.74	235.3	17	15

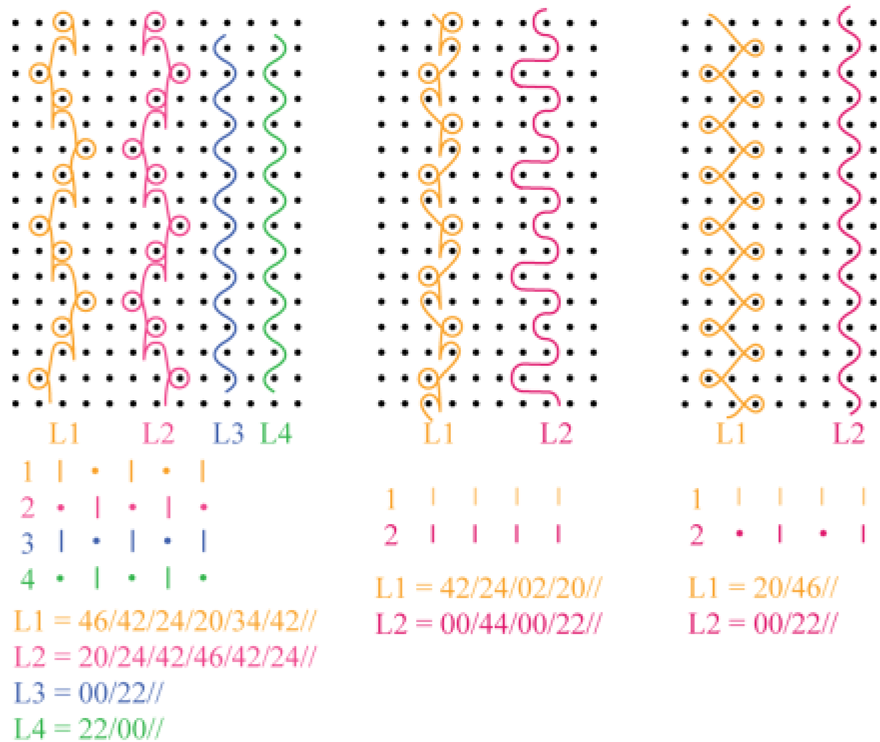


Figure 5.2 Structural diagrams of (a) powernet, (b) satinnet and (c) weftlock fabric

Steps 1 and 2- Investigation of Fabric Tensile Behaviour and Tension Decay

The initial tensile behaviours of the 7 types of fabrics in both the wale and course directions were investigated by using a tensile tester (Model 4411, Instron). The size of the fabric samples was 5 cm x 20 cm with a testing area of 5 cm x 10 cm. With reference to the strain calculation equation given in Equation (5.1), the corresponding fabric strains of the pressure gloves with RFs of 10%, 15% and 20% are 11.1%, 17.6% and 25% respectively.

$$\varepsilon = (l_1 - l_0) / l_0 \times 100\% \quad (5.1)$$

where ε = engineering strain, l_1 = elongated length of fabric during wearing (mm), and l_0 = initial length of fabric (mm).

In consideration of the possible high fabric strains when the pressure glove is worn, a 50% loading strain was also examined. Therefore, fabric tension per unit width at strains of 11.1%, 17.6%, 25.0% and 50.0% were recorded.

As fabric tension decreases after repeated wear and deformation erodes the effectiveness of a pressure garment over time, the impact of fabric tension properties on glove-skin pressures against repeated use was investigated. A fabric extender (Figure 5.3) was used to simulate the repeated use of the gloves for evaluating the deterioration of fabric elasticity. This extender was actuated by a pneumatic cylinder with a diameter of 8.3 cm and length of 30 cm which was controlled by a computer programme. The specimens were cut and sewn into a tubular form with circumferences of 23.5 cm, 22.2 cm and 20.9 cm in accordance with the standard RFs of 10%, 15% and 20%, respectively. The change in fabric tension after repeated extensions was measured again. The percentage of tension decay was calculated as Equation (5.2):

$$\text{Fabric tension decay} = (T_0 - T_1)/T_0 \times 100\% \quad (5.2)$$

where T_0 = the tension of the original fabric (N/m) and T_1 = the tension of fabric after 360 cycles of extension (N/m).

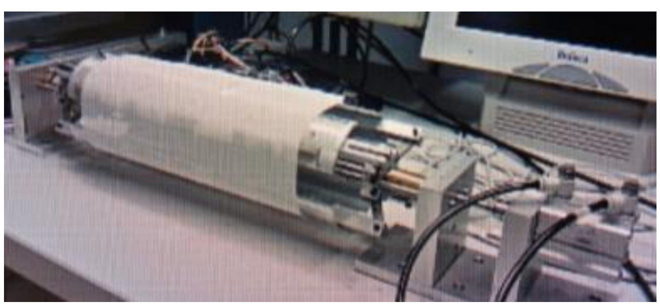


Figure 5.3 Fabric extender

Step 3- Measurement of Glove-skin Interfacial Pressure and Glove Strain

In Step 3, the amount of glove-skin interfacial pressure was measured. A total of 4 healthy female subjects aged 19 to 23 years old (mean: 20.25 SD: 1.89) were recruited for the testing. Based on the hand dimensions of each subject, a series of pressure gloves were custom-made for them by using Fabrics A, D and G, respectively which represent 3 different fabric structures. The left hand of each subject was first scanned with a 3D laser scanner (NextEngine Inc.) to obtain a 3D hand image and the required measurements. For each type of fabric, 3 pressure gloves were made with applied RFs of 10%, 15% and 20%. A total of 9 pressure therapy gloves were therefore developed for each subject. A pressure sensor (Pliance X system, Novel, Germany) was adopted for measuring the glove-skin interfacial pressure. As shown in Figure 5.4, interfacial pressure measurements are taken at six different points. Location P1 is on the metacarpal of the middle finger, locations P2, P3, P4 and P5 are on the dorsum of the hand, whilst location P6 is on the middle finger. Hence, the impact of hand variables such as curvature, soft tissue insert and rigidity on glove-skin interfacial pressure can be examined. To simulate the practical use of the pressure gloves, the amount of glove-skin interfacial pressure for three different hand postures, including resting their hand on a table, holding a cylindrical water bottle and clenching the hand into a fist tightly, were also recorded. To measure the fabric strains when the gloves are worn, 1 cm x 1 cm grid squares were carefully marked onto the glove sample (Figure 5.5). The actual sizes of the grid squares were further verified by using a digital calliper. The dimensional changes of the grid squares when the glove was worn were then measured. Fabric strains at the six locations (P1, P2, P3, P4, P5 and P6) were calculated by using Equation (5.1). Based on the fabric strains and the measured fabric tensile behaviour obtained, the resultant fabric tensions of the nine glove samples on each subject could be determined respectively.

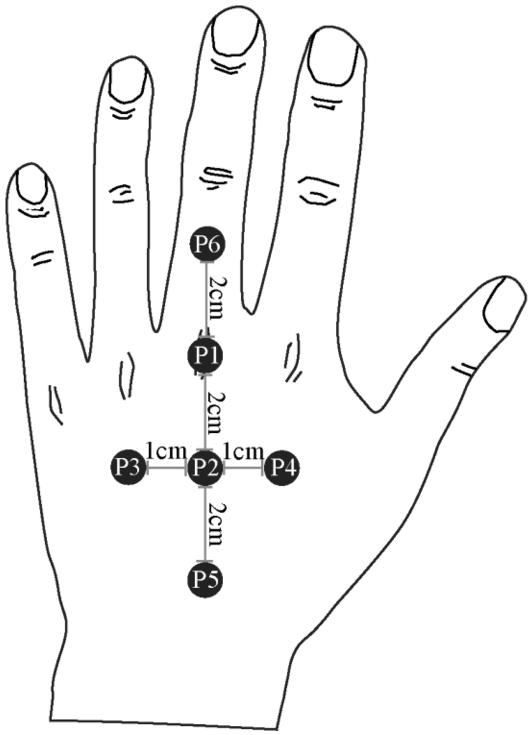


Figure 5.4 Pressure measurement points on the dorsum of hand

Figure 5.5 Pressure therapy glove with 1 cm x 1 cm grid squares

Step 4- Determination of Hand Curvatures

The 3D coordinates of any point of a 3D hand image can be determined with the use of the RapidForm 2006 software (INUS Technology Inc.). In this study, Directions I and II for the hand shown in Figure 5.6 are defined as the horizontal and vertical directions respectively. To quantify the vertical and horizontal curvatures of a measured pressure point, a total of five 3D coordinates at each pre-defined measured point as illustrated in Figure 5.7 were recorded. The distance between points H1 and H2 and that between points V1 and V2 were taken as the breadth of the curvature (ϕ) in the horizontal and vertical directions respectively. The breadths can be calculated by using Equation (5.3) with the notation of one point as (x_1, y_1, z_1) and the other point as (x_2, y_2, z_2). The depth of the curvature (h) was identified as the distance between C (x_0, y_0) and the mid-point of the line from H1 to H2 or V1 to V2, which can be calculated by using Equation (5.4).

As a result, hand curvatures in both the vertical and horizontal directions can be determined by using Equation (2.3).

$$\phi = [(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2]^{1/2} \quad (5.3)$$

$$h = [(y_2-y_1)(x_0-x_1)/(x_2-x_1) - y_0 + y_1] / \{[(y_2-y_1)/(x_2-x_1)]^2 + 1\}^{1/2} \quad (5.4)$$

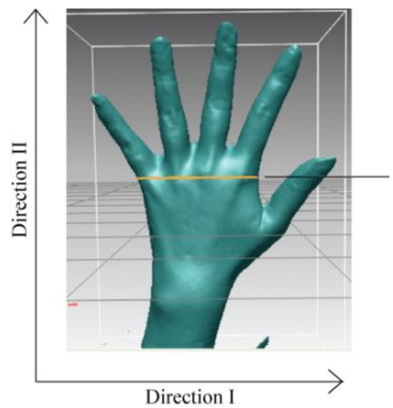


Figure 5.6 Cross-section of a hand extracted with 3D image analysis

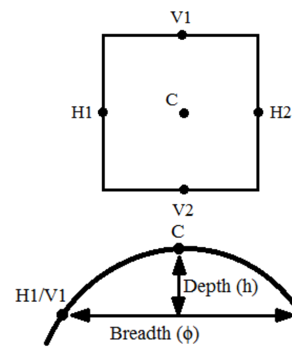


Figure 5.7 Five coordinates on a measured point to be obtained from a 3D image

Steps 5 and 6- Formulation and Verification of Pressure Prediction Model

On the basis of the hand curvatures and the actual fabric tensions obtained above, the magnitudes of the glove-skin interfacial pressures induced by the pressure therapy gloves at the six locations for each type of fabric and each subject could be predicted respectively by using the pressure model by Hasegawa and Ishikawa (Equation 2.2). The empirical prediction model for the glove-skin interfacial pressure and the amount of pressure decay over repeated use were then verified. The 4 subjects were further asked to wear each of the 9 gloves (made of Fabrics A, D and G with RFs of 10%, 15% and 20%) for 80 consecutive hours, except during daily hygienic cleaning. The amount of glove-skin interfacial pressure at the 6 locations when carrying out the 3 different hand postures (resting their hand on a table, holding a cylinder and clenching the hand into a fist tightly), were measured respectively. The extent of the pressure changes obtained over the simulated wear trial were recorded and analysed.

5.3 Results and Discussions

5.3.1 Fabric Tensile Behaviour and Tension Decay (Steps 1 and 2)

Fabric tensions at strains of 11.1%, 17.6%, 25% and 50% in the wale and course directions are shown in Figures 5.8 and 5.9 respectively. Amongst the 7 types of fabrics, Fabrics A, B, C, E, and F exhibit a very similar trend in tensile behaviour, since they are all powernet fabrics. Except for Fabric C, the fabric tensions range from 186 to 291.6 N/m in the wale direction, and from 200.33 to 279.13 N/m in the course direction at a strain of 50%. Fabric C has an extraordinarily high tension of 410.67 N/m in the course direction, which is considerably higher than that of the wale direction (197.67 N/m). This high tension result may be explained by its low spandex content and yarn density which means that it is difficult to stretch this fabric in the course direction. Fabrics D (satinnet) and G (weftlock) have different tensile behaviours which are attributed to the powernet fabric. The tension results of Fabric D obtained in the course direction are remarkably higher than those obtained in the weft direction. The difference in wale and course tension behaviour is even greater in Fabric G. Fabric G has very low tension results in the wale direction, but the tension significantly increases when the strain is increased to 25% and reaches 504.53 N/m at a strain of 50% in the course direction.

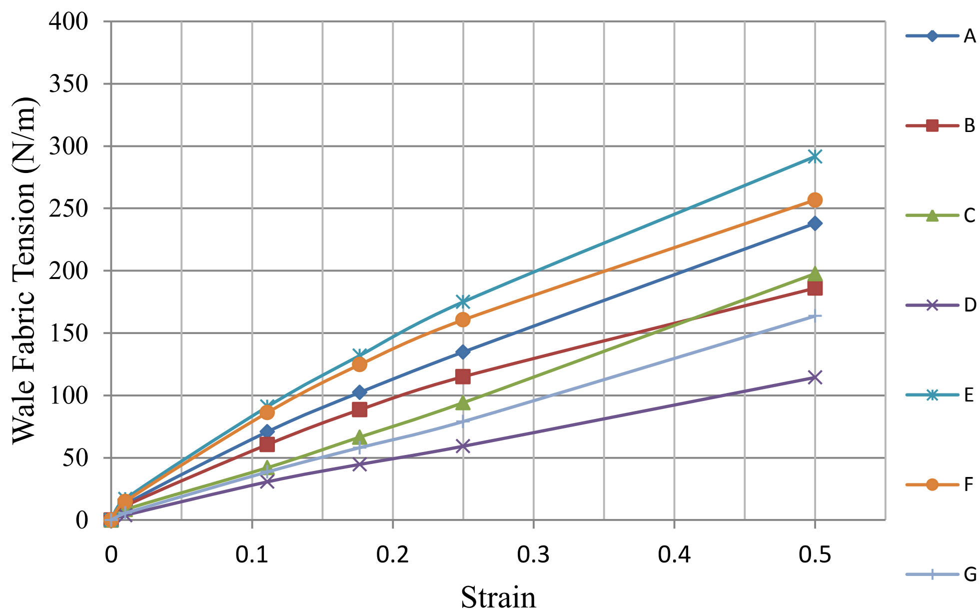


Figure 5.8 Initial fabric tensions in the wale direction of the seven types of fabrics

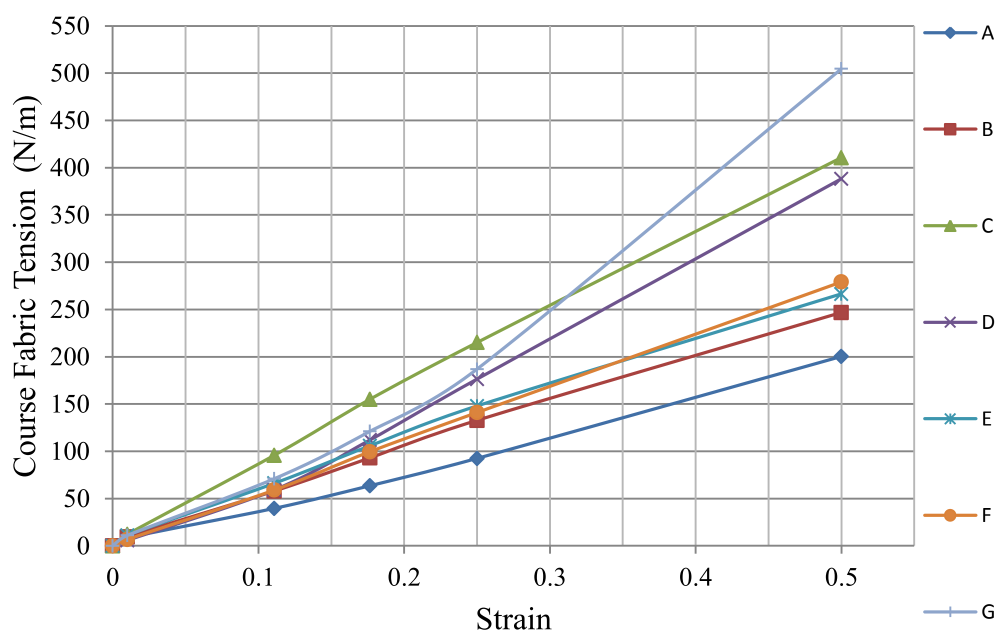


Figure 5.9 Initial fabric tensions in the course direction for the seven types of fabrics

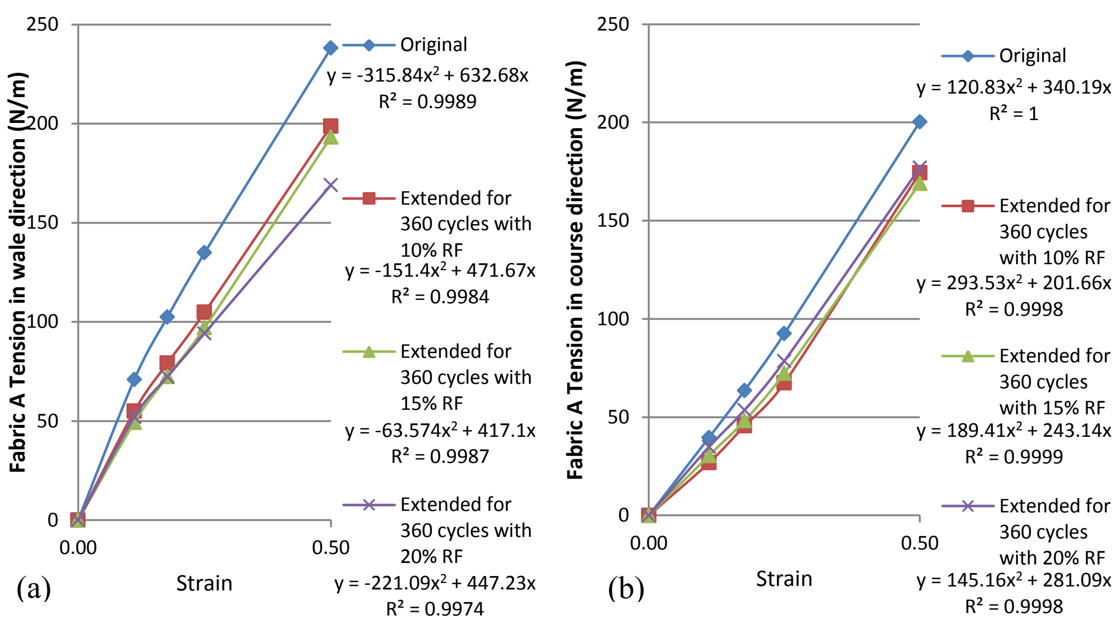
To determine the effectiveness of the pressure garment in the scar treatment, the extent of fabric tension deformation after repeated extensions was examined. As shown in Table 5.2, the powernet fabrics share a similar trend of tension decay after repeated extensions. Amongst the 5 types of powernet fabrics, Fabrics C and E have higher percentages of tension reduction in both the wale and course directions after repeated extensions. This may be explained by their relatively light fabric weight (164.2 g/m^2 and 188.2 g/m^2). Fabrics A, B and F are relatively heavier in weight (201.8 g/m^2, 199.8 g/m^2 and 221.0 g/m^2), which are less affected by tension deformation upon repeated extensions. There may be some association that exists between fabric weight and tension decay behaviour. Fabric D is satinnet and the structure is relatively stable, particularly in the weft direction. The tension decay performance of Fabric G is also relatively stable in the wale direction due to its weftlock structure; however, the fabric is considerably decayed in the course direction. The results reveal that fabrics with a high initial tension tend to have major deformations upon repeated extensions and use, which lead to significant fabric tension loss and potential changes in the amount of pressure induced. The fabric structure appears to be one of the main factors that affect the tensile behaviour of a fabric. The initial stress/strain curves of Fabrics A, D and G which represent 3 different structures, and their tension decay with RFs of 10%, 15% and 20% in the wale and course directions are further plotted in Figure 5.10. Each stress/strain curve is fitted with a second order polynomial as per Equation (5.5). The polynomial function of each stress/strain curve and the R^2 value are also given in Figure 5.10.

$$T = a_1\varepsilon^2 + a_2\,\varepsilon \tag{5.5}$$

where T = fabric tension (N/m), and a_1, a_2 = coefficients

Table 5.2 Fabric tension decay after 360 cycles of extension

Fabric	Fabric Tension Decay after 360 Cycles of Extension							
	Wale Direction				Course Direction			
	Tension at strains of				Tension at strains of			
	11.10%	17.65%	25%	50%	11.10%	17.65%	25%	50%
	10% Reduction Factor							
A	22.60%	22.60%	22.20%	16.60%	32.40%	28.30%	27.10%	12.90%
B	22.60%	22.60%	20.00%	7.60%	33.50%	26.60%	24.90%	9.70%
C	46.50%	43.80%	39.70%	26.70%	40.20%	35.10%	29.70%	5.90%
D	12.70%	16.30%	13.20%	8.60%	36.90%	31.80%	26.40%	23.30%
E	42.50%	39.10%	37.10%	25.40%	49.90%	41.80%	36.30%	10.40%
F	33.50%	33.30%	31.50%	20.50%	16.50%	15.20%	12.20%	4.80%
G	3.30%	5.60%	4.50%	4.90%	34.30%	31.40%	29.40%	18.60%
	15% Reduction Factor							
A	30.50%	29.30%	28.00%	18.80%	23.20%	24.20%	21.70%	15.60%
B	31.80%	33.30%	30.10%	22.20%	37.60%	30.80%	27.20%	16.30%
C	42.90%	41.60%	39.70%	24.00%	43.10%	36.90%	32.50%	12.40%
D	12.70%	13.50%	13.90%	8.60%	30.30%	22.20%	19.10%	19.10%
E	52.30%	44.20%	43.00%	31.90%	45.90%	40.60%	36.30%	11.40%
F	36.70%	35.50%	34.60%	21.60%	25.90%	23.40%	17.90%	2.90%
G	0.70%	5.20%	7.90%	14.80%	38.10%	34.70%	33.40%	26.60%
	20% Reduction Factor							
A	26.70%	29.30%	30.10%	29.00%	12.30%	15.70%	15.00%	11.60%
B	29.40%	28.90%	27.20%	17.70%	35.50%	29.50%	26.90%	18.50%
C	53.20%	47.70%	45.40%	33.50%	43.10%	38.70%	33.80%	13.70%
D	4.20%	10.00%	8.70%	8.60%	35.20%	30.90%	26.80%	26.80%
E	48.70%	46.20%	44.80%	35.60%	45.90%	40.50%	36.30%	16.40%
F	39.60%	38.70%	36.10%	25.80%	21.20%	20.70%	16.00%	0.00%
G	10.00%	9.80%	12.00%	16.40%	49.10%	44.70%	40.80%	32.50%



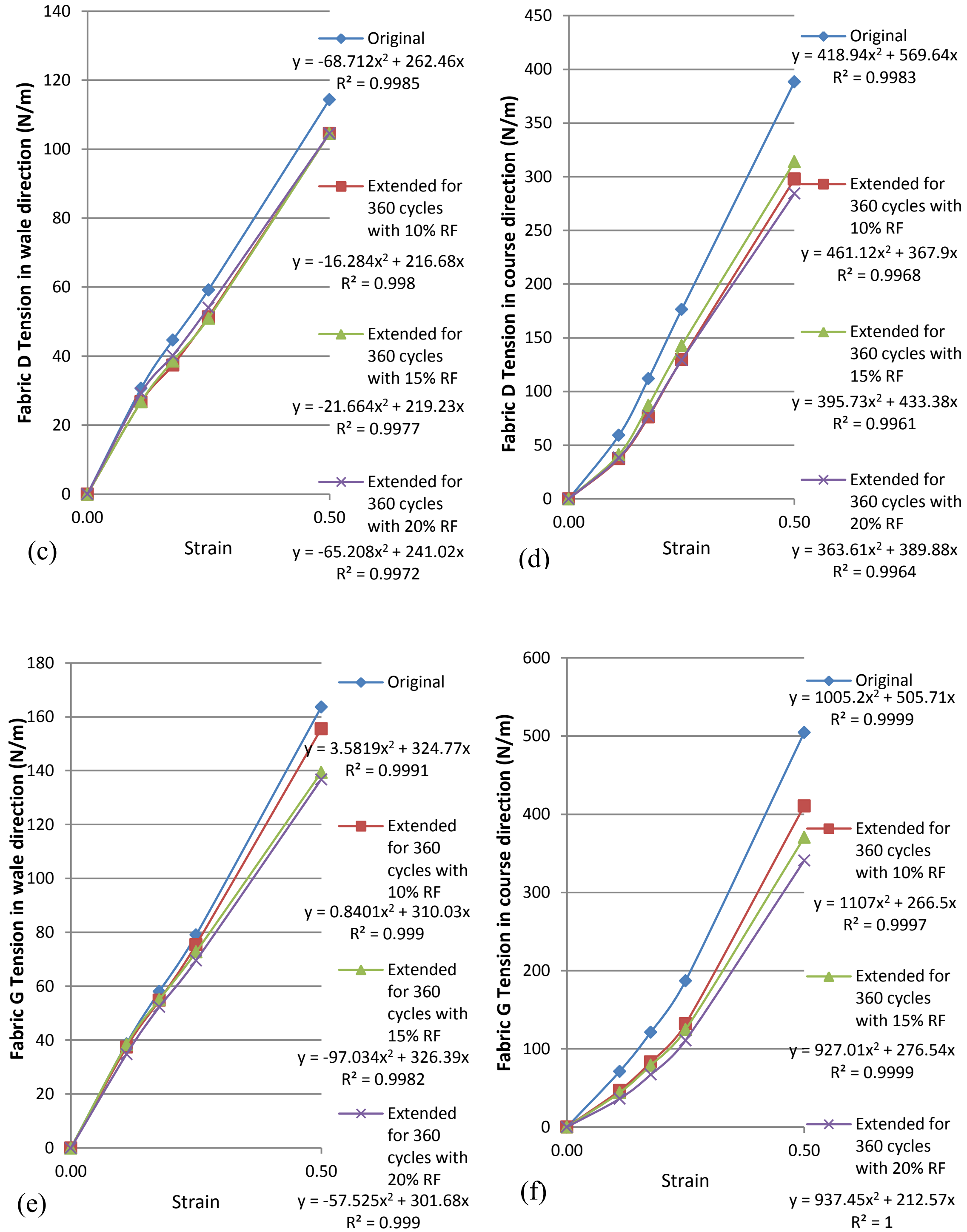


Figure 5.10 Stress/strain curves of (a) Fabric A in the wale direction, (b) Fabric A in the course direction, (c) Fabric D in the wale direction, (d) Fabric D in the course direction, (e) Fabric G in the wale direction, and (f) Fabric G in the course direction.

The results also reveal that there is no apparent influence from the RFs used in this study on the fabric decay for most of the fabrics. In order to understand the impact of the fabric structural properties and RFs on fabric tension decay, a statistical analysis was implemented by using SPSS. The statistical significance level was set at 0.05. A multiple linear regression analysis was conducted to examine the influence of six independent variables, including the (1) RF, (2) strain, (3) fabric thickness, (4) fabric direction (course/wale), (5) fabric weight, and (6) initial fabric tension on the dependent variable which is fabric tension decay percentage after 360 cycles of extension. An informal analysis of the data with the use of histograms and scatterplots (Figures 5.11 and 5.12) revealed no serious threats to the assumption of linearity or the underlying distributional assumptions of the residuals of the dependent variable.

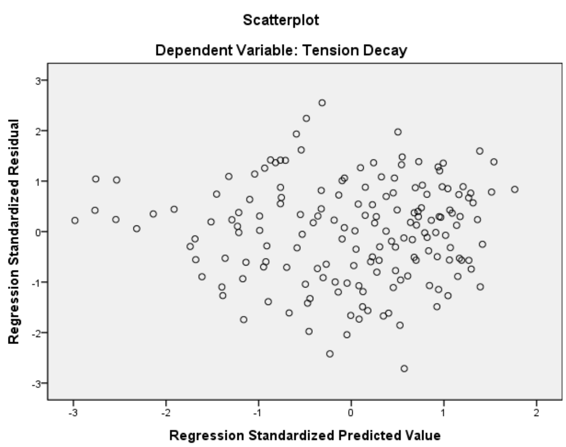


Figure 5.11 Scatterplot of the residuals and predicted scores

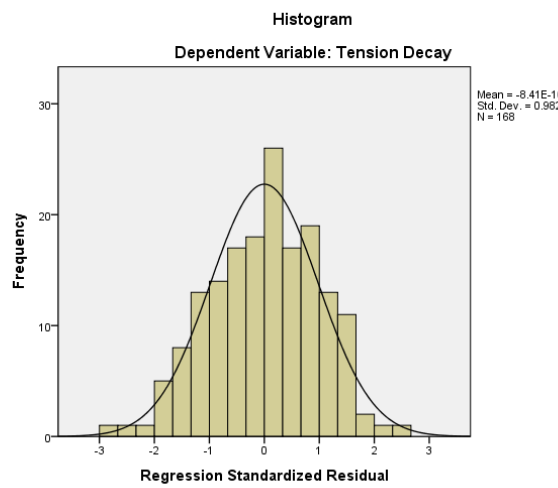


Figure 5.12 Histogram of the residuals

The result of the multiple linear regression analysis showed the overall linear significance of all six independent variables to fabric tension decay. The coefficient of determination (R^2) equals to 0.402 which means that about 40.2% of the variance in fabric tension decay is explained by the six independent variables that were examined.

The regression equation coefficient results show that except for the RF (*p*=0.057 >0.05) and fabric weight (*p*=0.059 >0.05), the other four independent variables; strain (*p*=0.000 <0.05), fabric thickness (*p*=0.011 <0.05), fabric direction (*p*=0.002 <0.05) and original fabric tension (*p*=0.000 <0.05), have a significant linear relationship with fabric tension decay. The results imply that an RF of 10%, 15% or 20% applied in the pattern development process has no significant influence on the resultant fabric tension decay. This result complies with the work by Ng and Hui in predicting the compression pressure of elastic fabrics [66]. As the relationship of RF and fabric weight with fabric tension decay was not significant, the analysis was re-run by removing these two variables. Only the four independent variables that were significant were included in the regression model. The new regression equation is shown as follows:

$$\text{Fabric tension decay} = 56.305 + (-0.740)\ \text{Strain} + (28.128)\ \text{Fabric Thickness} + (-4.715)\ \text{Fabric Direction}^{*} + (1.392)\ \text{Initial Fabric Tension} \qquad (5.6)$$

*taking wale direction as 1 and course direction as 2

This regression model has an overall significant linear relationship and each independent variable has a significant linear relationship with fabric tension decay. The R^2 is 0.375 which is only reduced by 0.027 after the removal of the RF variable from the model. The strain used, fabric thickness, fabric direction and the initial fabric tension are identified as the key factors that affect the percentage of tension decay in the development of pressure therapy gloves.

5.3.2 Glove-skin Interfacial Pressure (Step 3)

Figure 5.13 shows the results of the measured glove interfacial pressures for various hand postures at the six locations. Consistent with the findings of Giele et al.,[71] the geometry of anatomical zones and the radius of anatomic curvatures have major impacts on the interfacial pressures generated by the pressure garments. The glove pressures obtained at P1 are consistently higher than those obtained at the other locations, due to the large curvatures and pointy geometry of P1. The metacarpal position of P1, which is a bony and rigid surface, also bears most of the tension force induced by the glove and hence resulted in high glove-skin interfacial pressure.

The magnitudes of the glove-skin interfacial pressures also varied with changes in hand posture. When a hand is performing different actions, the strain placed onto the fabric also changes, which directly affects the fabric tension and hence the converted glove pressure. The lowest glove pressures are obtained when the hand is relaxed and resting on a table, with a mean pressure of 3.4 kPa at the six locations. When the hand is clenched into a fist, the glove is considerably stretched, thus inducing a higher mean pressure of 9.78 kPa and an extremely high mean pressure of 36.51 kPa at P1. The increase of glove-skin interfacial pressure when a cylinder is held and the hand is made into a clenched fist at P1 is greater than that obtained from the other measurement locations. Hand postures and their range of movements, which lead to substantial geometry shape changes in the metacarpal site, result in major changes in the glove pressure. In the case of locations P2, P3, P4 and P5, the increase in glove pressure with various hand postures is not apparent. These locations are situated on relatively flat areas and their curvatures change very minimally with different hand postures and movements. The curvature on the middle finger is higher than that obtained from the centre of the back of the hand and changes more apparently with different hand postures. Therefore, the interfacial pressure triggered at P6 is consistently higher than the measurements obtained from P2, P3, P4 and P5. On the other hand, the mean interfacial pressure at the metacarpal or P1, readily increased from 5.93 kPa (at rest) to 15.62 kPa when the hand was holding a cylinder. The interfacial pressure further increased to 36.51 kPa when the hand was clenched into a fist. It was also noted that the greatest interfacial pressure was 47.11 kPa at P1 when the hand was clenched into a fist, which is much greater than 3.33 kPa, the effective pressure for treating hypertrophic scars. However, it should be noted that a mean garment pressure of 8.7 kPa could have a major influence on the skin oxygen pressure, which could lead to ischemia, and prolonged clenching with the use of the pressure gloves may result in bruises, ischemic injury, and the development of pressure ulcers on patients. Therefore, even though the pressure induced by a pressure therapy glove is at a safe level when the hand of the wearer is relaxed, it could nevertheless reach high levels with dangerous consequences during various hand movements.

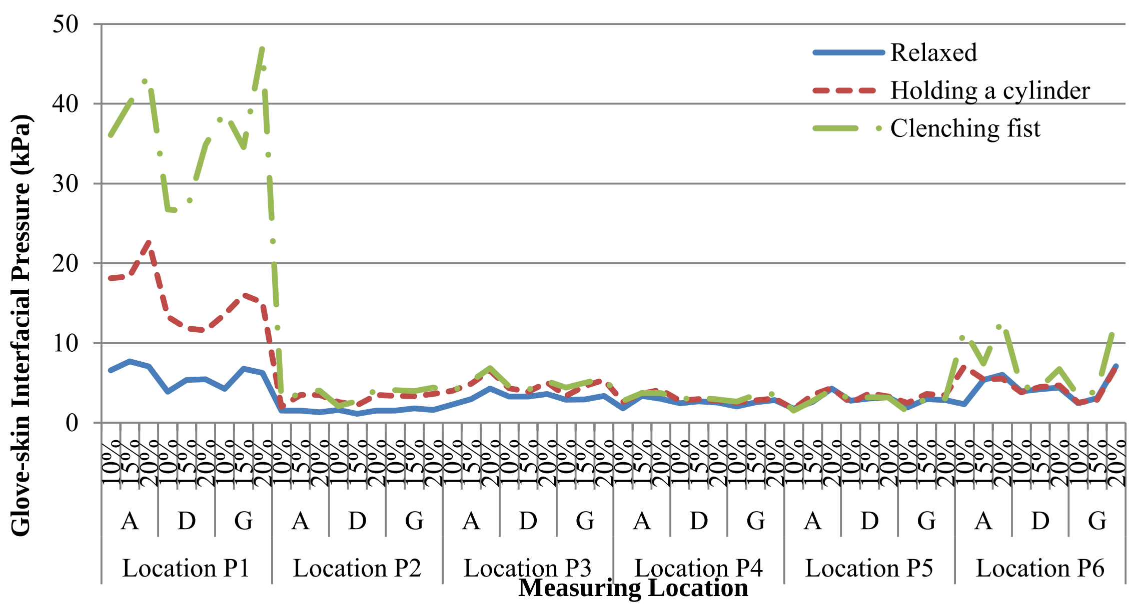


Figure 5.13 Glove-skin interfacial pressures measured during 3 types of hand motions

5.3.3 Hand Curvatures and Predicted Glove-skin Interfacial Pressures (Steps 4 and 5)

The curvatures of the six points of measurement in both the vertical and horizontal directions were determined for each subject. Figure 5.14 shows the box plots of each measurement point in the vertical and horizontal directions. Amongst the six points of measurement, the hand curvatures in the horizontal direction are consistently greater and show greater variation in magnitude than the corresponding vertical direction, with a mean difference of 55.24 m^{-1}. The largest curvature variation between the horizontal and vertical directions is found at P6, with a mean difference of 88.40 m^{-1}. The curvatures at P1 and P6 are relatively greater than those measured at P2, P3, P4 and P5 in both the horizontal and vertical directions. The anatomic curvature variations of the measured locations indicate the potential pressure differences on various hand regions induced by the pressure therapy glove.

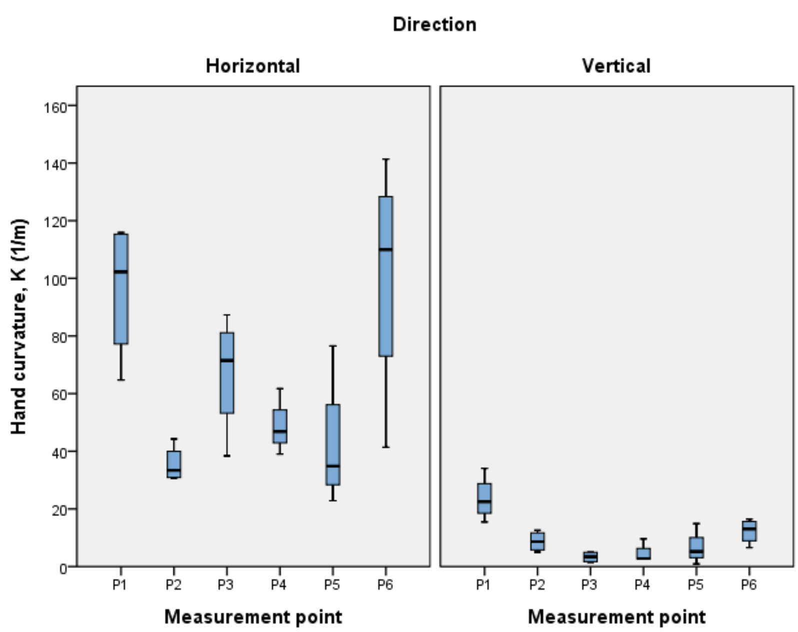


Figure 5.14 Box plots that show hand curvatures of four subjects measured at different points of pressure

On the basis of the dimensional changes of the grid squares on the gloves, fabric strains that were induced by the pressure gloves on the points of measurement were calculated and the corresponding glove tensions were determined. As shown in Table 5.3, the glove strains substantially increase with an increase in the RF for all three fabrics (A, D and G) in the horizontal direction. A larger RF leads to higher glove-skin interfacial pressure when the gloves are worn. The strain exerted in the horizontal direction is consistently higher than that in the vertical direction. In glove pattern development, the RF is only applied in the cross-wise measurements of the hand but not length-wise. Therefore, the hand mainly stretches the glove in the horizontal direction during wearing which induces a higher strain.

Table 5.3 Glove strain at the six locations of measurement when worn with hand relaxed on table

Fabric	RF%	Glove Strain											
		Horizontal						Vertical					
		P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
A	10	8.82%	5.39%	6.03%	4.28%	5.94%	5.77%	4.30%	5.30%	5.06%	4.15%	4.06%	2.75%
	15	9.07%	9.97%	7.08%	7.25%	7.15%	6.97%	6.34%	9.31%	5.46%	6.55%	6.04%	3.43%
	20	15.86%	12.49%	7.38%	10.52%	8.97%	20.86%	9.33%	7.77%	5.87%	3.97%	1.73%	3.47%
D	10	9.06%	6.41%	6.02%	4.88%	3.69%	10.37%	8.30%	6.14%	5.71%	4.26%	3.07%	9.15%
	15	15.88%	8.33%	6.94%	4.94%	10.51%	10.59%	9.92%	7.92%	5.71%	4.81%	5.20%	9.47%
	20	20.83%	10.85%	8.13%	10.09%	11.33%	15.69%	8.13%	9.89%	7.35%	4.83%	4.12%	10.11%
G	10	9.86%	6.58%	6.84%	6.88%	5.61%	4.68%	3.29%	4.37%	4.74%	2.05%	3.94%	4.60%
	15	16.57%	10.13%	6.95%	8.00%	6.70%	8.77%	9.79%	8.73%	6.94%	5.98%	4.52%	5.81%
	20	18.55%	12.32%	9.69%	13.35%	12.26%	24.46%	8.27%	11.17%	9.19%	6.05%	5.17%	9.74%

The magnitudes of the glove-skin interfacial pressure at the six points of pressure measurement were calculated by using Equation (2.2). The predicted and the measured glove pressures obtained from the 3 types of fabrics (Fabrics A, D and G) and the 3 RFs

(10%, 15% and 20%) in 3 different postures are presented in Figure 5.15. The paired sample t-test shows that the difference between the measured and predicted pressure is not statistically different in comparison to the scenario where the hand is holding a cylindrical bottle ($p=0.963 > 0.05$). However, there is a significant difference observed when the hand is relaxed on the table ($p=0.017 < 0.05$) versus a clenched fist ($p=0.000 < 0.05$). It is worth noting that minor muscle contractions and/or hand posture changes have significant impacts on hand curvature, which affect the resultant glove tension and interfacial pressure. When the hand is relaxed on the table, the difference between the measured and predicted values is the smallest at P2 with an RMSE of 0.70 kPa while it is the largest at P6 with an RMSE of 2.25 kPa. The RMSE of the other four points range from 1.14 kPa (P4) to 1.51 kPa (P3). The relatively large difference between the measured and predicted values of P6 is probably due to the small circumference of the middle finger which may affect the accuracy of the sensor and lead to deviations.

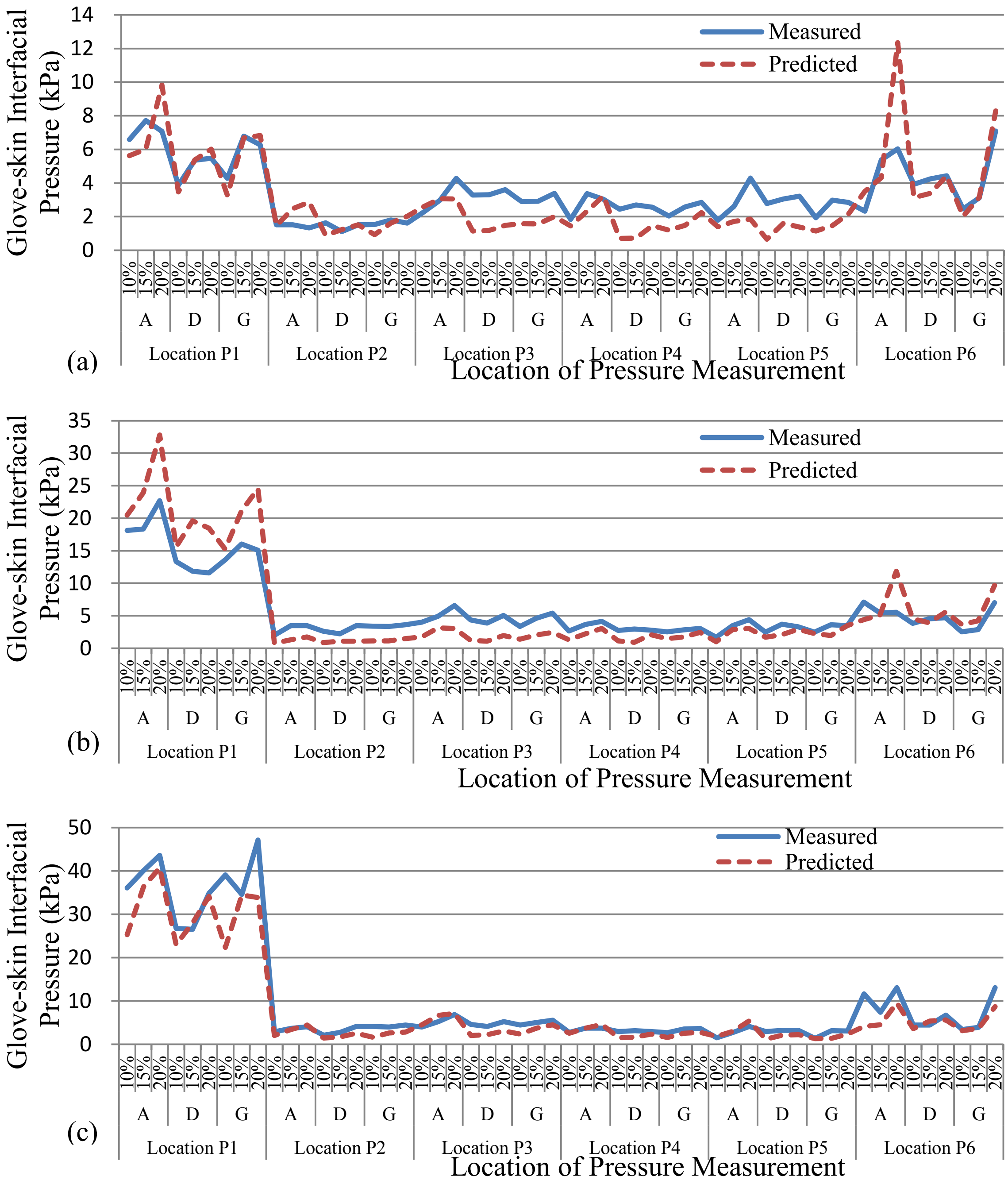


Figure 5.15 Measured and predicted glove skin interfacial pressures (a) when hand is relaxed on table, (b) when hand is holding a cylinder and (c) when hand is made into a clenched fist.

5.3.4 Verification of Pressure Prediction Model (Step 6)

As fabric tensions are significantly reduced upon repeated extensions for all of the 7 types of fabrics studied, this indicates that the predicted glove pressures would be significantly decreased over the course of the treatment. The changes in the glove-skin interfacial pressures after repeated extensions could therefore be determined by the measured fabric tension decay and hand curvature. The results were compared against the actual glove pressures measured. The predicted and measured glove pressures at P1 and P2, which represent two distinctive types of structures, are shown in Figure 5.16. It can be seen from the results that the location of pressure measurement has a major impact on the loss of glove pressure over repeated use. The glove pressure is quite reduced at P1 for all of the pressure gloves, regardless of their fabrication and/or RFs. Continuous changes in the curvature and geometry of the metacarpal (P1) caused by different hand motions during daily activities triggered a reduction of the fabric tension. At P1, the glove fabric was subjected to more extension and contraction than at P2, and therefore could not maintain adequate pressure during the wear cycles. The amount of pressure decay at P2 is minimal as the skin surface here is flat and smooth, and the fabric is therefore less deformed during hand motions.

Even though a previous research study [37] revealed that pressure garments constructed by using higher RFs have greater tension loss during repeated use, the impact of the RFs used in this study (10%, 15% and 20%) on the decay of glove pressure is not apparent. As shown in Figure 5.15, the gloves show a continuous reduction in pressure after 80 hours of the wear trial, regardless of the changes in the RFs and glove dimensions. To some extent, a similar trend of pressure degradation was also observed from the predicted glove pressures. The results revealed that an empirical model that predicts glove pressure based on the measured fabric tension decay and hand curvatures can reliably determine the effectiveness of pressure therapy garments over the course of the treatment.

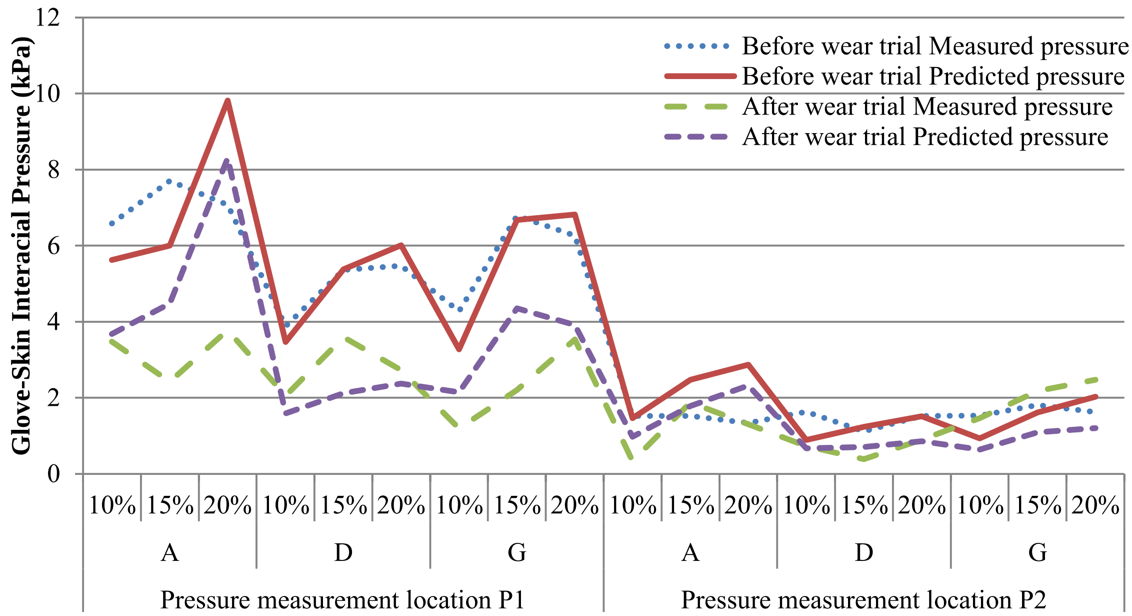


Figure 5.16 Predicted and measured glove-skin interfacial pressures before and after wear trial

5.4 Summary

In this chapter, the curvatures of the locations of pressure measurements are determined based on the 3D hand images of the subjects. In consideration of the nonlinearity of the fabric properties upon repeated use, the nonlinear tensile properties of different materials are determined by using a fabric extender. Along with fabric elongation when the gloves are worn, the skin pressure at any particular point of measurement could be determined by the fabric tension and body curvature. The results are compared against the experimental values of the pressure obtained by using a pressure sensor (Novel Pliance-X system, Germany). No statistical difference is found between the predicted and the measured glove pressures when the hand is holding a cylindrical bottle. The empirical model for predicting garment pressure from fabric tension and hand curvature is found to be satisfactory and useful for accurately evaluating the compression performance of pressure garments. In addition to the evaluation of scar conditions and healing wounds, the tension and decay performance of fabrics used in relation to their structure and RF% are vital components for determining a suitable treatment programme that would adjust the fit of pressure garments. In this chapter, fabric tension decay is found to be influenced by fabric strain, thickness, direction and initial fabric tension. The variations in the RFs in the range of 10% to 20% appear to have less impact on pressure glove tension decay as opposed to the fabric structural properties. Fabrics with a high initial tension have significant tension loss and pressure decay. Regardless of the fabric used and RF applied, high levels of pressure are found at the metacarpal joint due to its large curvature. Unlike pressure sleeves, the pressure delivered by the pressure therapy glove is not evenly distributed over the hand. The measuring of pressure at certain locations is therefore crucial for prescribing an adequate and effective pressure glove to a patient. On the other hand, the study shows that glove-skin interfacial pressure is greatly influenced by hand posture. Although there is a suitable pressure for treating hypertrophic scars on a relaxed hand, the pressure glove can nevertheless reach a pressure level that causes harm to the patient when s/he clenches his/her hand. Therefore, traditional pressure evaluation methods have seemingly underestimated the perceived magnitude of glove-skin pressures in practical use. Hand postures and the range of hand movements, which lead to substantial shape geometry changes of the metacarpal joints, should also be carefully considered in the development of pressure therapy gloves in order to maintain adequate and consistent interfacial pressures onto scars.

Chapter 6 Physiological and Psychophysical Effects of Pressure Therapy Gloves on Humans

6.1 Introduction

The literature has shown that garment pressure can physiologically affect humans. The wearing of gloves can also impact hand dexterity and muscle activity. It is therefore important to determine how pressure therapy gloves which need to be continuously worn for a long period of time affect the physical human body. Besides that, the discomfort caused by pressure gloves is one of the main reasons for poor compliance. There is the need to understand the roots of the discomfort and address them. In this chapter, the aim is to determine if pressure gloves have any negative physiological and psychophysical effects on the human body. The impact of the gloves on the HR, BP, glove-skin microclimate, hand performance, forearm muscle activity, grip strength and psychophysical response are investigated. The key factors of the pressure therapy gloves which have a significant influence on the body of wearers and their perceived comfort sensations are identified so as to determine an approach that will manage glove wearing comfort without sacrificing the effectiveness of the pressure therapy.

6.2 Experimental

The physiological and psychophysical impacts of the pressure gloves were investigated in two phases of the wear trial. In Wear Trial-I, the effects of the fabric properties and RF on hand and finger dexterity, HR, BP, glove-skin microclimate and psychophysical response were examined. In Wear Trial-II, the effects on muscle activity and grip strength in relation to glove tension were examined. The tasks involved in the wear trials were designed to represent the routine hand tasks and difficulties experienced during daily life activities as reported by burn rehabilitation patients.

6.2.1 Participants

Ten healthy participants aged 20 to 38 (mean: 25, SD: 6.1), including five males and five females, were recruited for Wear Trial-I. They had an average height of 164.9 cm (SD: 8.5 cm), and average weight of 56.34 kg (SD: 5.7). Another ten healthy participants, five males and five females, were recruited for Wear Trial-II. Their age ranged from 18 to 29 years old (mean: 22.5, SD: 3.9), with an average height of 168.3 cm (SD: 8.8 cm), and average weight of 59.66 kg (SD: 13.3). All of the participants were right hand dominant, healthy and had no musculoskeletal problems in the upper extremities, and no history of hand or arm injury. Healthy participates were recruited in order to highlight the effect of the glove tightness and avoid the interference of scars or hand disabilities. They had never worn a pressure glove before so their experience with the sensation of the pressure induced by the glove is similar to that of inexperienced patients who first receive the therapy and have many concerns and issues about their pressure glove. The anthropometric data measured from the right hand of the participants are presented in Table 6.1.

Table 6.1Hand anthropometric information of participants

	Participants of Wear Trial-I (n=10)		Participants of Wear Trial-II (n=10)	
Dimension (cm)	Mean	SD	Mean	SD
Middle finger distal interphalangeal joint circumference	5.2	0.42	5	0.29
Middle finger root circumference	6.16	0.53	6.03	0.51
Hand length	18.08	0.74	18.65	0.96
Palm length	10.27	0.44	10.87	0.68
Palm circumference	19.05	1.39	19.49	1.6
Wrist circumference	15.645	1.26	15.77	1.36
Forearm length	N/A	N/A	24.93	1.72
Forearm circumference	N/A	N/A	23.19	2.67

6.2.2 Materials

Fabrics A, B, D and G were selected for the study. Details of these four types of fabrics are provided in Chapter 5. All four types of fabrics were used in Wear Trial-I. These fabrics have different fabric structures and tensile behaviours, and are commonly used by hospitals to make pressure therapy garments. The gloves were custom-made based on the hand dimensions of each subject. For each type of fabric, three pressure gloves were made with applied RFs of 10%, 15% and 20%. All of the gloves had the same design with open fingertips. The length of the fingers reached the distal interphalangeal (DIP) joint and the length of the thumb reached the thumb nail. The zipper was on the ulnar side of the hand (Figure 6.1). The open fingertip design was adopted as it is typically used in clinical practice to improve tactile sensation [88]. Based on the results obtained from Wear Trial-I, the most desirable fabric and RF for hand and finger dexterity and best in terms of psychophysical response can be identified. This fabric was then used to produce a series of pressure gloves with different RFs to examine the impact of glove tightness on muscle activity and grip strength in Wear Trial-II.

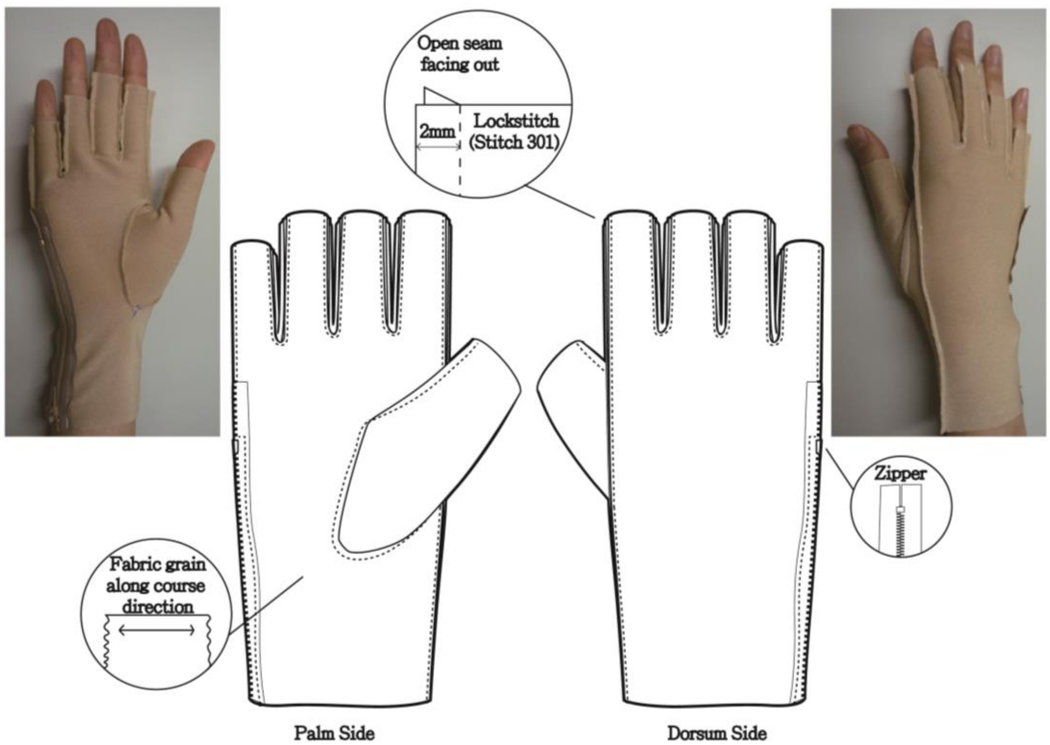


Figure 6.1 Pressure therapy gloves

6.2.3 Physical tests on fabrics and glove samples

The hand feel of fabrics can be determined by the surface roughness. The surface roughness (SMD) of the four fabrics was measured by the Kawabata Standard Evaluation System (KES) (Kato Tech Co., Ltd., Japan) with a KES-FB4 automatic surface tester. The softness of fabric can be assessed by understanding the bending properties. The bending rigidity was therefore measured by a KES-FB2 pure bending tester. The comfort given by fabric is closely related to thermal conductivity, air permeability and moisture retention and transmission. A KES-Thermo Labo II was employed to measure thermal conductivity. Air permeability was measured by a KES-F8-API air permeability tester. The moisture retention % and the drying time of the fabrics were measured in accordance with The American Association of Textile Chemists and Colorists (AATCC) test method 199-2011. The drying rate of the fabrics reported in this study is regarded as the amount of water loss from the saturated weight after 1 hour. The WVTR was measured in accordance with the upright cup method in ASTM E96. The pressure of the centre point of the hand dorsum on each glove was measured with a pressure sensor (Pliance X system, Novel, Germany). The sensor was placed between the glove and the hand dorsum. The participants were asked to perform three hand motions, which were the same as those in Chapter 5, including relaxing the hand on a table, holding a cylinder of 6.3 cm in diameter and clenching the hand into a fist when the interfacial pressure was measured.

6.2.4 Physiological and psychophysical responses toward pressure glove

6.2.4.1 Wear Trial-I – Examination of hand and finger dexterity, HR, BP, glove-skin microclimate and psychophysical response

The experimental schedule of Wear Trial-I is shown in Figure 6.2. The experiment started with four types of daily activities to examine the HR, BR, skin temperature and humidity in the gloves and the perception of comfort. The four activities involved (a) resting in a sitting position for 20 min, (b) hand-copying a standardised essay for 15 min, (c) putting on a shirt, and (d) transporting books (Figure 6.3). Each participant had to wear the glove for 15 minutes before starting the activities. After that, there was 15 minutes of rest followed by the hand function tests. The hand functions were assessed with three standard tests that are commonly used by clinicians. The hand function tests were carried out in the following sequence: (1) testing of the active range of motion (AROM) of the finger, (2) testing of tactile sensitivity and (3) testing of finger dexterity. The experiment was carried out under room conditions. The participants were asked to wear a shirt, trousers, socks, shoes, jacket, and short-sleeve underwear with clothing insulation equal to 1 clo. The testing equipment and procedures were reviewed with the participants and any questions raised were answered by the researcher. In order to familiarise the subjects with the experiment, each test was demonstrated to them before the actual testing was carried out. There were 13 experimental sessions for each subject including the tests with the 12 pressure therapy gloves made of the 4 different types of fabric, each with 3 different RFs, as well as in a bare hand condition. Each subject participated in the 13 sessions over 13 consecutive weeks.

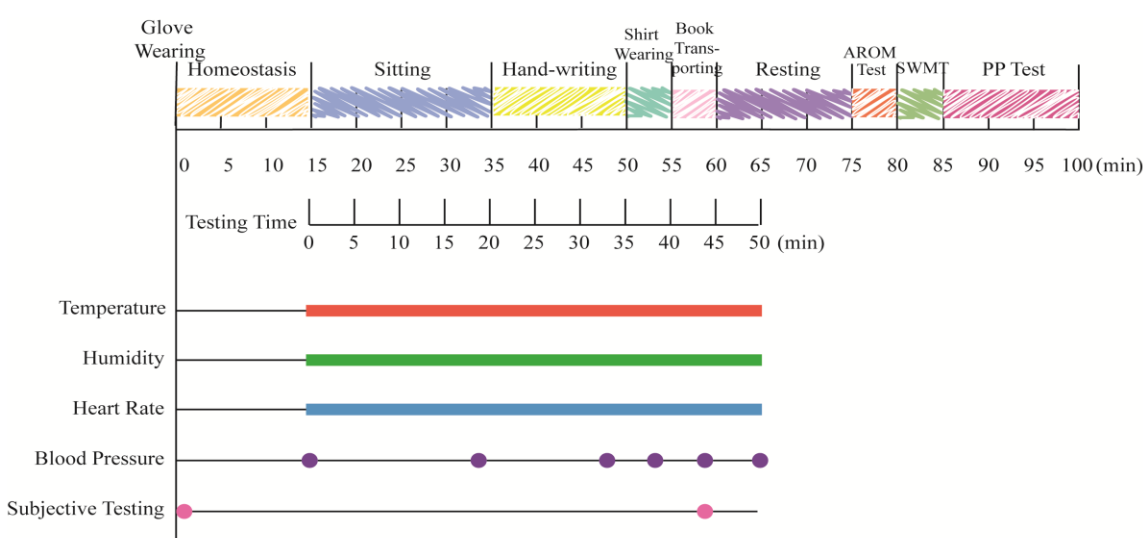


Figure 6.2 Experimental schedule for Wear Trial-I

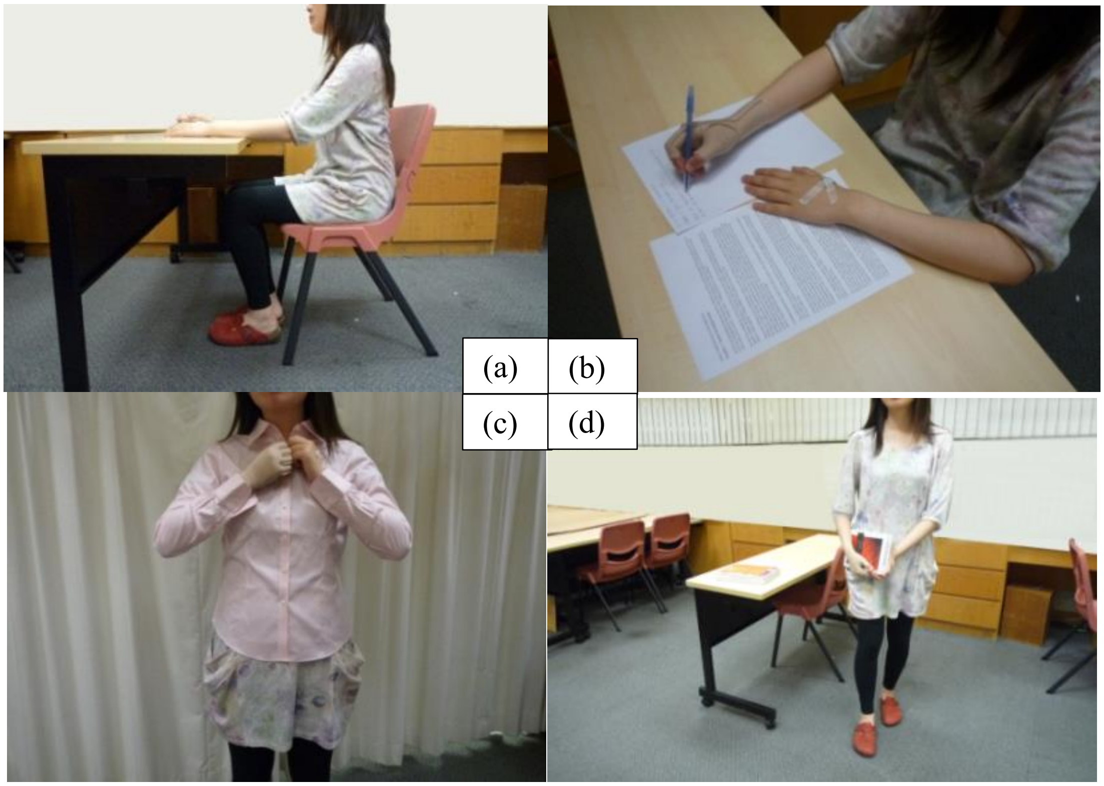


Figure 6.3 Four main tasks of the wear trial, including (a) resting in a sitting position, (b) hand-copying a standardised essay, (c) putting on a shirt, and (d) transporting books

The HR was measured throughout the four activities with a heart rate monitor (RS800CX, Polar Electro). The BP was measured on the right arm before and after each activity with a blood pressure monitor (T5, OMRON Healthcare). The temperature and humidity of the micro-environment conditions of the pressure therapy glove were recorded by placing a sensor (Thermocrons HC, OnSolution) underneath the glove surface at around the thumb-index finger web area. Another sensor was placed on the other hand, and attached with surgical tape to act as the control as illustrated in Figure 6.4. The sensor with diameter of 17.35 mm and thickness of 5.89mm recorded the temperature and humidity at every minute. The two sensors were calibrated beforehand and the differences in the temperature and humidity recorded under the same conditions were within 0.1℃ and 1%, respectively.

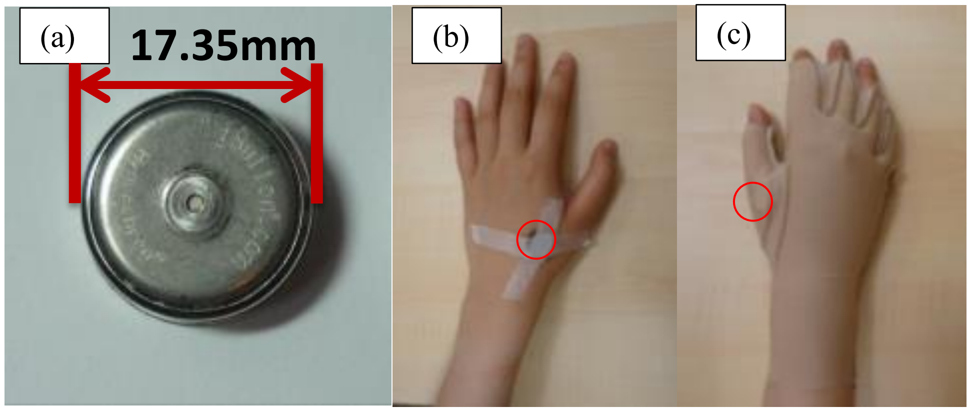


Figure 6.4 (a) Temperature and humidity sensor, (b) placement of the sensor on control hand, (c) placement of the sensor inside gloved hand

Four subjective scales were used to determine the perceived exertion [156], thermal perception [157], perception of comfort, and humidity sensation of the participant towards the pressure therapy glove (Figure 6.5). The ratings for each scale were provided by the participants at the beginning of the glove wearing and after 1 hour of wearing.

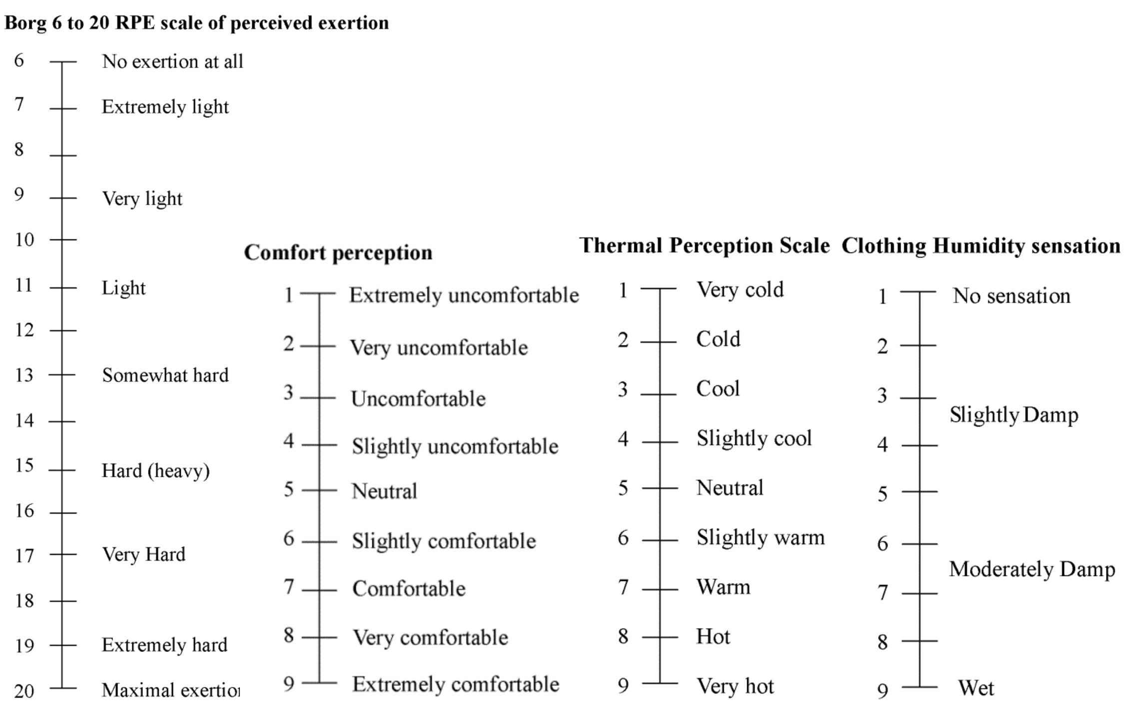


Figure 6.5 Rating scales of subjective sensation

In order to understand the effects of wearing a pressure glove in daily life, the speed of two activities, handwriting and putting on a shirt, were recorded. In the handwriting activity, the subjects were required to use a pen (Stabilo Liner 808F) to copy a standard essay onto a piece of single lined paper for 15 minutes. The writing pace was measured by counting the number of words written. In putting on a shirt, the subjects were requested to don and button up a dress-shirt and then take it off. The total time for completing the whole process was recorded. The shirts used were a size 4 with a button size of 16 ligne for the female subjects and a size 12 with a button size of 18 ligne for the male subjects. The dress shirts were of a regular type with seven buttons on the front placket and one button on each sleeve.

Then, the hand functions were assessed with three standard tests that are commonly used by clinicians. In the first test, a calibrated metal goniometer was used to measure the AROM of the proximal interphalangeal (PIP) joint of each finger and the interphalangeal (IP) joint of the thumb [158, 159]. The measurements were taken on the dorsal aspects of each joint as instructed in Adams and Keyserling [158], which is the measuring method preferred by most hand surgeons and therapists [160]. The subjects were asked to prop their elbows onto a table, hold their arms straight, and clench their hands into fists when measuring the PIP joint of each finger, and bend their thumbs when measuring the IP joint of the thumb (Figure 6.6a). The sum of the AROM of the five digits was treated as the overall finger AROM and used for further analysis.

Then, the second test was a Semmes-Weinstein monofilament test (SWMT) (set of five: 2.83, 3.61, 4.31, 4.56, 6.65), which was employed to examine the tactile sensitivity of the fingertips [161] [162-165]. Monofilaments were vertically applied to the centre of the fingertips which were not covered by the glove (Figure 6.6b). Force was slowly applied onto the skin until the monofilaments started to buckle. The number on each monofilament indicates the amount of force delivered, which is expressed as $\log_{10}$ (10 x Force [mg]). The subjects were asked to close their eyes to occlude their vision and respond when they felt the stimulus. The test began with the finest monofilament of 2.83 which was applied twice on each fingertip. If the subjects did not respond to the stimulus, the test would continue with progressively thicker filaments until a positive response was received in the testing zone.

Finally, in the third test, the Purdue Pegboard (PP), which is a pin insertion test, was adopted to test the dexterity of the fingers in handling small objects (Figure 6.6c) [74, 83, 166]. The test measures fine motor dexterity skills that involve both one- and two-handed tests. As only right-handed gloves were available, modifications to the standardised procedure for administering the PP test [167] were made to fit the experiment. The subtests for the dominant hand (the right hand) (i.e. the unimanual, bimanual and assembly components of the PP test) remained unchanged while the subtest of the non-dominant hand (the left hand) was abandoned. An additional assembly test, which only involved the right hand, was added, following the three standard subtests. The right-hand subtest involved the placement of as many pegs (cylindrical pins 3 cm in length and 0.1 cm in diameter) as possible into a column of holes in 30 seconds. In the bimanual subtest, the dominant and non-dominant hands were simultaneously used to place the pegs into two separate columns in 30 seconds. The assembly subtest dealt with the construction of assembled pegs, washers and collars by using both hands for 60 seconds. The added assembly test was essentially the same as the standard assembly test except that only the right hand was used. The subjects were asked to complete the tests as quickly as possible. In order to standardise the tests and avoid any learning effects, each subject practiced on the pegboard before the task began. The total number of pegs and assemblies completed in the four subtests were added together and regarded as the measure of fine finger dexterity.

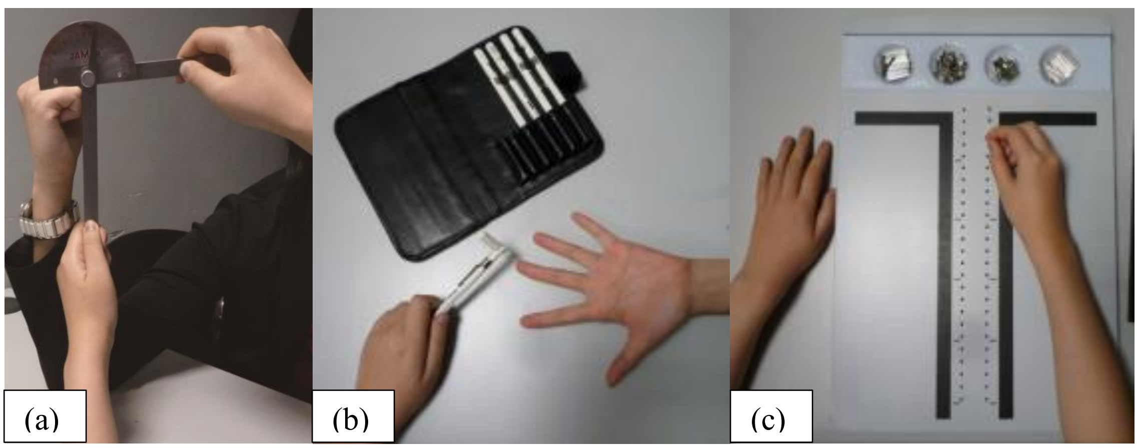


Figure 6.6 Hand functions tests, including (a) testing of AROM, (b) testing of SWMT and (c) PP test

6.2.4.2 Wear Trial-II –effects on muscle activity

In Wear Trial-II, the normalised SEMG of the three forearm muscles, grip strength and psychophysical perception toward the wearing comfort of the glove, ease of hand motion and perceived exertion of the hand during the wearing of the glove, were assessed. Four conditions were tested: three levels of glove tightness (with RFs of 10%, 15% and 20%) and the bare hand.

Disposable Ag/AgCl surface electrodes were used in the SEMG to measure the forearm activity, and positioned on the belly of three muscles on the right forearm, including the flexor pollicis longus (FPL), extensor digitorum (ED), and flexor digitorum superficialis (FDS). The FPL muscle helps to control thumb IP flexion. The contraction of the FDS muscle leads to the flexion of the metacarpophalangeal (MP), PIP and DIP joints of the fingers while the contraction of the ED muscle results in the extension and abduction of the MP, PIP and DIP joints. These muscles are involved in tasks that require gripping, pinching and typing, and hence are representative of the demands required of the hands during the experimental activities and activities of daily life [116, 117]. Before applying the electrodes, the hairs on the overlying skin area were shaved and the skin was abraded to remove dead epidermal cells and then cleaned with alcohol. The raw SEMG signals of each muscle were collected at a rate of 2048 samples/second, amplified (1000X), band-pass filtered (20-500 Hz) and 14 bits A/D converted through an SEMG system, the FlexComp Infiniti (Thought Technology Ltd, Canada). Maximum voluntary contraction (MVC) trials in accordance with the functional characteristics of the three muscles in the bare hand condition were performed to obtain the maximum voluntary electrical activation (MVE) of the three muscles for normalisation purposes. The MVC trials included maximum grip action, resisted thumb IP flexion and isometric wrist extension and flexion [168]. Each trial was carried out four times. Each trial had a length of 8 seconds with at least 2 mins of rest in between the trials [169].

For the SEMG signal processing, all of the EMG signals were high-pass filtered at 20 Hz by using a 4^{th} order Butterworth IIR filter to remove artefacts and a 60 Hz notch filter to remove power-line noise. Then the root mean square (RMS) amplitude of the

SEMG signal ($SEMG_{RMS\mu V}$) was computed with a 50 ms sliding window [170, 171]. The maximum RMS value of 1000 ms across all of the MVC trials for each muscle was regarded as the MVE ($MVE_{RMS\mu V}$) and used as the reference value to normalise the signals [172]. The normalisation was carried out according to the following equation: %MVE = ($SEMG_{RMS\mu V}/MVE_{RMS\mu V}$) x 100 [169]. The amplitude probability distribution function (APDF) of the normalised signal was calculated for further analysis. The static (P10), median (P50) and peak (P90) levels of the APDF indicate the %MVE levels at which 10%, 50% and 90% of the recording time were spent respectively [173, 174].

After the SEMG sensors were positioned and before the start of the wear trial, several MVC trials were performed on the right hand for normalisation purposes. The time taken in the wear trial for each of the hand conditions was around 30 mins and the schedule is shown in Figure 6.7. At the beginning of the wear trial, the participants were asked to put on one of the gloves and rate their perception of the glove by using the subjective scales. Then they were to grip a dynamometer, move 30 marbles, button up a shirt and type an essay for 15 mins. Two minutes of rest was allowed between each activity. At the end of the tasks, the participants were asked to use the scales to subjectively rate their perception again. The wear trial had to be carried out four times by each participant to test the four hand conditions in randomised order. All of the wear trials carried out by the same participant were completed on the same day and there was at least 30 mins of rest between each wear trial. A demonstration of the wear trial procedures was given to the participants. Prior to the start of the wear trials, the participants were allowed to practise and become accustomed to the assigned four tasks so as to achieve a regular pace and rhythm during the given tasks. During the wear trial of the pressure gloves, the participants were also given time for a short practise before the start of each task.

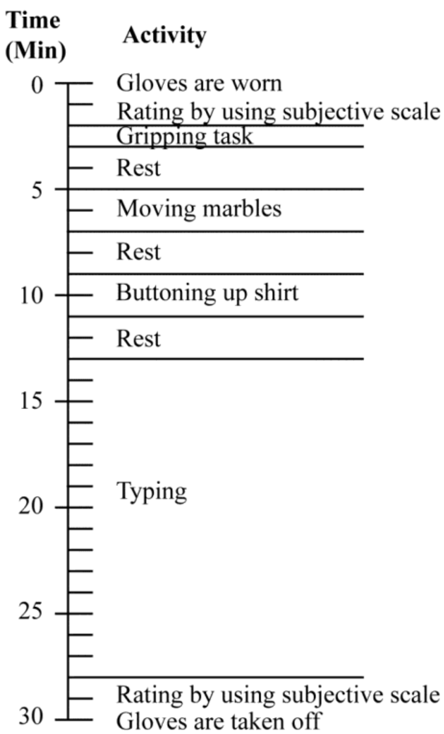


Figure 6.7 Experimental schedule for Wear Trial-II


Figure 6.8 Dynamometer for gripping task

The grip strength of the hand was measured with a JAMAR hand dynamometer which has been reported as a highly reliable and valid tool [175-178]. The dynamometer was set to the second handle position (4.8 cm grip span) for all of the testing and placed onto a table (Figure 6.8). The participant was asked to hold the dynamometer with a straight wrist and elbow angle of about 90°. The participants had to exert maximal gripping effort onto the dynamometer for five seconds within which the one second averaging window with the highest SEMG amplitude was extracted for the EMG data. The gripping task was performed once for each condition.

The test that involved the moving of marbles was designed to examine the ability of the hand to hold and handle a smooth, round object. The marbles were 2 cm in diameter. Two boxes which were 31 cm apart from each other were placed in front of the participant. There were 30 marbles inside the box on the right. The participant was asked to transport all 30 marbles, one at a time, to the box on the left by only using his/her right hand. The participants were allowed to complete the task at their own pace and comfort, and asked to keep this pace throughout the entire wear trial. The SEMG data of the first and last three seconds were excluded from the data analysis.

The participants were then requested to button up all of the buttons on the front placket of a dress-shirt that was laid flat on a table. The shirt used was a regular female dress shirt in US size 4, with seven buttons sized 16 ligne on the front placket. Similar to the marble moving task, the participants were allowed to complete the task at their own pace and comfort, and asked to keep this pace throughout the entire wear trial. The SEMG data of the first and last three seconds were excluded from the data analysis.

Then, in the typing activity, a notebook computer (Precision M4700, Dell, USA) was prepared for the participants to type a standard essay for 15 minutes. The essay was presented as a softcopy in Microsoft Word and shown on the left side of the computer screen. Another blank Microsoft Word window was opened on the right side of the screen for the participants to type the essay. The participants were requested to complete the task at their normal typing speed and keep their pace constant throughout the typing task. They were allowed to correct typing errors as in usual practice. The SEMG data were extracted from three time frames, which were at 1 to 1.5 minutes (Period 1), 7 to 7.5 minutes (Period 2) and the 14 to 14.5 minutes (Period 3).

Finally, the psychophysical assessment was carried out. Apart from using the Borg 6 to 20 ratings for the perceived exertion and wear comfort scales as in Wear Trial-I, the participants were asked to rate on ease of hand motion of each glove (Figure 6.9). The rating for each scale was reported right after the glove was put on, and after the completion of all the tasks.

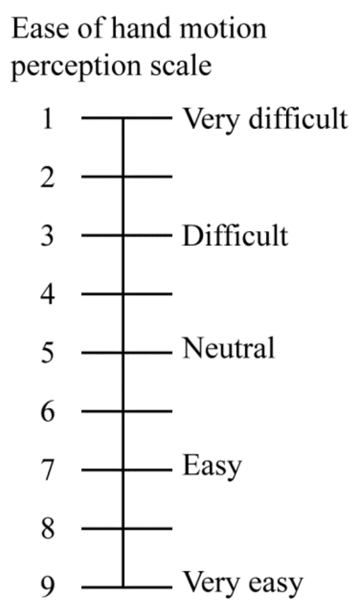


Figure 6.9 Rating scale for ease of hand motion

6.3 Results and Discussions

6.3.1 Physical properties of fabrics and pressure therapy gloves

The physical properties of the four types of fabrics are presented in Table 6.2. The values shown for air permeability is the permeating resistance which is the amount of pressure lost when a stream of air flows through the fabric. The powernet structure fabrics (Fabrics A and B) have relatively higher air permeability with a permeating resistance of 0.013kPa · s/m. The weftlock fabric (Fabric G) is the least air permeable amongst the four fabrics with a permeating resistance of 0.482kPa · s/m. The thermal conductivities of Fabrics A, B and G have very similar values, which are between 0.062–0.063 w/mK while that of Fabric D is comparatively somewhat poor at only 0.056 w/mK. All of the fabrics have a similar WVTR which ranges from 43.04-47.79 g/hr m^2. Fabric G, which has cotton content, has the highest water absorbance, but the slowest rate of drying amongst the fabrics. Fabric D has the highest moisture retention amongst the three types of nylon/spandex blended fabrics. Fabric D also has the lowest surface roughness in the course direction. Fabric G has the highest bending rigidity in the course direction.

Table 6.2 Physical properties of fabric studied

Fabric	Air permeability	Thermal conductivity	Water vapour transmission rate	Moisture Retention	Drying rate	Surface roughness		Bending rigidity	
						wale	course	wale	course
	kPa s/m	w/mK	g/hr m^2	%	%	SMD		10^{-4} Nm/m	
A	0.013	0.062	47.79	79.53	76.39	2.717	20.000	0.064	0.020
B	0.013	0.063	43.04	73.55	74.30	2.290	19.423	0.059	0.019
D	0.019	0.056	45.25	137.86	62.97	8.350	4.908	0.020	0.021
G	0.482	0.063	43.91	153.77	52.06	1.998	13.350	0.057	0.067

*Moisture Retention = % change in weight at wet, Drying rate = % change in weight of water after 1 hour

The interfacial pressure measurements obtained from the 12 glove samples are shown in Figure 6.10. The overall average pressures for all 12 gloves in terms of the 3 hand postures for Fabrics A, B, D and G are 3.22, 3.44, 2.49 and 3.44kPa, respectively. No substantial pressure differences can be observed amongst the gloves made of Fabrics A, B and G. The interfacial pressures obtained from gloves made of Fabric D are consistently lower than those of the other fabrics, regardless of the RF and hand posture. The fabric stress-strain behaviour is highly related to the glove pressure. Fabric D exhibits the least amount of stress of 22.2, 33.93 and 47.68 N/m in the wale direction for strains of 11%, 17.7% and 25% respectively, which therefore provides the lowest glove-skin pressure.

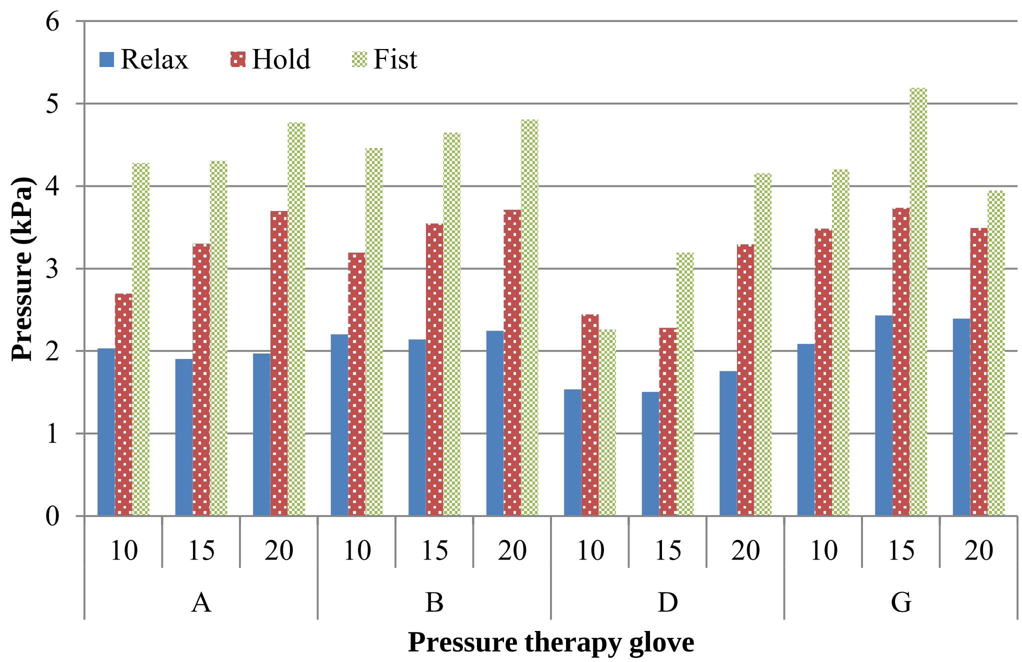


Figure 6.10 Glove-skin interfacial pressure

6.3.2 Heart rate and blood pressure responses

The variation in the HRs due to fabric type and RFs during the wear trial of different gloves shares a similar trend as shown in Figure 6.11. In view of the BP, the mean systolic BP of the wear trials for each glove fluctuates at a range of 106.4 to 116.1 mmHg throughout the testing period except at the moment after the books were transported which shows a considerable increase with a range of 113.9 to 120.9 mmHg (Figure 6.12). Repeated-measures ANOVA was then carried out. The result showed that the wearing of pressure gloves does not significantly change the HR and BP of the wearers. In order to further evaluate the impact of the pressure therapy gloves on the HR and systolic BP of the wearers, a factorial ANOVA was carried out. As shown in Table 6.3, an overall significant difference in the HR and BP is found amongst the activities carried out by the participants during the wear trial, which accounts for 34.9% and 7.4% of the variance in the HR and BP respectively. The effects of the glove fabric and RF on the HR and BP are somewhat subtle.

Table 6.3 Results of factorial ANOVA on heart rate and blood pressure

Independent variable	Dependent variable					
	Heart rate			Blood Pressure		
	F	Sig.	Partial Eta Squared	F	Sig.	Partial Eta Squared
Fabric	1.950	.120	.011	2.425	.065	.013
RF	6.189	.002	.022	.566	.568	.002
Activities	72.485	.000	.349	10.863	.000	.074
Fabric * RF	2.525	.020	.027	.366	.901	.004
Fabric * Activities	.415	.958	.009	.292	.991	.006
RF * Activities	.382	.930	.006	.462	.883	.007
Fabric * RF * Activities	.171	1.000	.008	.409	.995	.018

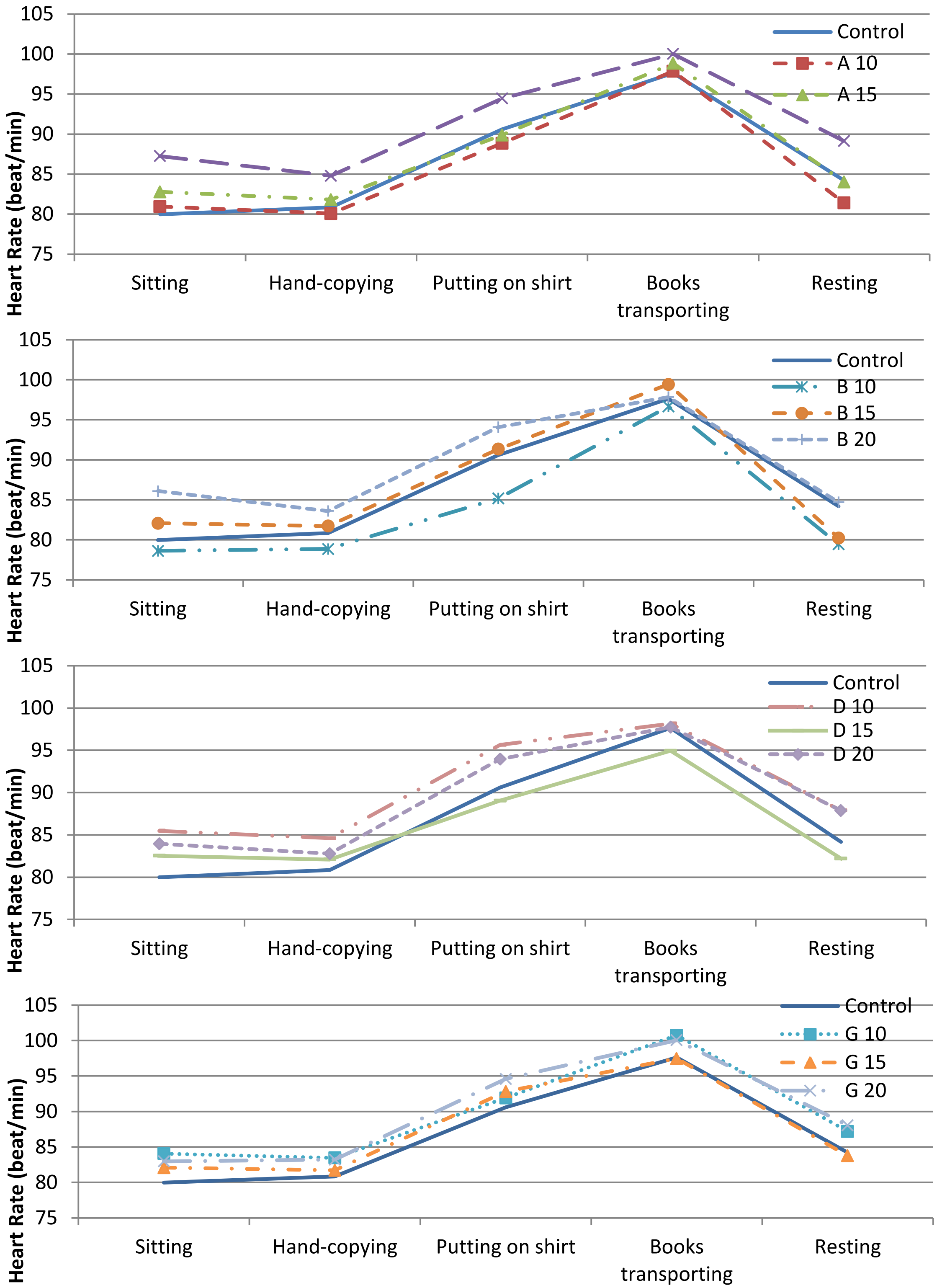


Figure 6.11 Comparison of mean heart rate between the four types of fabrics (A, B, D and G) and three RFs (10%, 15% and 20%) for each glove sample when carrying out different tasks

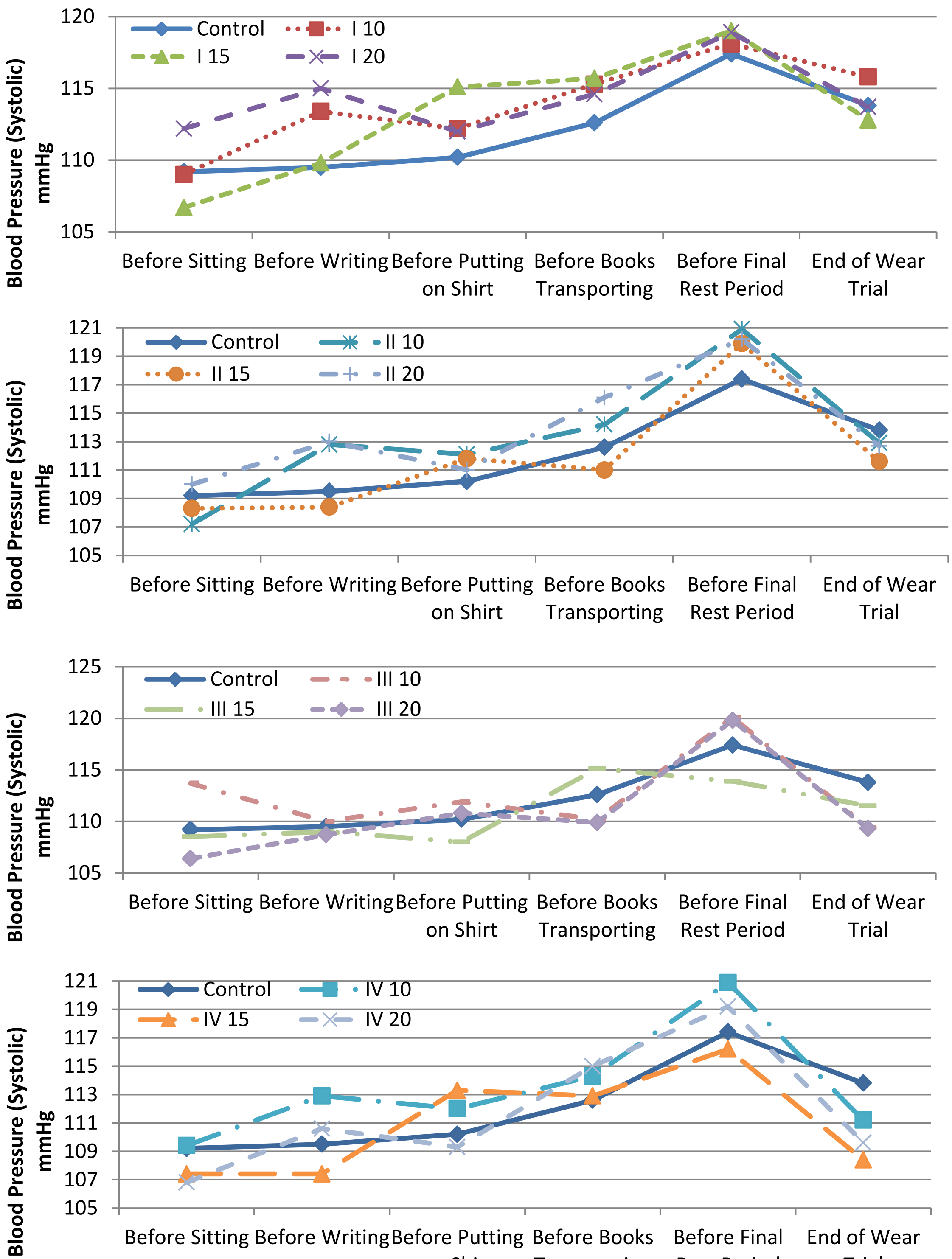


Figure 6.12 Comparison of mean blood pressure between four types of fabrics (A, B, D and G) and three RFs (10%, 15% and 20%) for each glove sample in between different tasks

6.3.3 Microclimate conditions between skin and pressure glove

The temperature and humidity recorded from the environment are 23.14± 1.29℃ and 55.85± 8.94% respectively. Figures 6.13 and 6.14 reveal the changes in hand skin temperature and humidity throughout the wear trial, respectively. A significant difference ($p<0.05$) can be observed between the pressure gloves and the control condition in both skin temperature and humidity by using t-tests. The glove-skin temperature (overall mean of all types of gloves is 31.32± 0.67℃) is consistently higher than that under the control condition (29.80± 0.70℃). This indicates that the use of pressure therapy gloves can trap heat and lower the rate of heat loss. The change in the skin temperature under the glove is eminent for different tasks. There is a remarkable increase when continuous contraction of the hand is required during the hand-copying exercise. The high skin temperature triggers perspiration to reduce heat. The relatively large movements of the hand when the shirt is being put on and books are being transported facilitate the hand to lose heat by convection. The pressure therapy gloves also contribute to an increase in humidity. The mean humidity of the hand skin under the control condition throughout the testing period does not show any notable increase or decline, but fluctuates at a range of 71.22% to 73.94%. With the use of the pressure therapy gloves, the humidity continues to increase from 68.9% at the start of the testing to a peak of 75.73% during the book transporting activity. The humidity when the gloves are worn is lower than that of bare hands at the beginning of the testing as the amount of moisture on the skin surface is absorbed by the glove fabric. An increase in the temperature of the microclimate when the glove is worn triggers the human thermal regulatory system to react in order to control the body temperature. Sweat is generated on the local area under the glove surface and hence the humidity recorded continued to increase. There was a slight drop in the last ten minutes of the testing because the moisture absorbed by the gloves had evaporated.

The temperature and humidity variations during the wear trial of different gloves and the corresponding control can be found on Appendixes IV and V respectively. The RMSE between the pressure gloves and the control condition for the hand skin temperature and humidity was determined (Table 6.4). With the lowest air permeability and drying rate but the highest moisture retention, gloves made of Fabric G were found to bring about the largest changes to the skin temperature and humidity when compared with the other gloves. Fabrics A and B have similar performances in moisture retention and drying rate; thus they have a similar influence on the skin humidity.

When the gloves are increased in RF, the RMSE of the temperature between the two RFs decreases while that of humidity increases which means gloves with tighter pressure induce less change in the temperature of the hand skin, but a greater change in humidity. This is because a tighter glove means that more energy is needed for hand movement, and a larger amount of heat is generated by the muscle actions and hence sweating might occur more vigorously to reduce the heat.

Table 6.4 Root mean square error between the gloved and control conditions

	RMSE between gloved and control conditions											
Fabric	A			B			D			G		
Temperature (℃)	1.65			1.84			1.67			1.91		
Humidity (%)	3.24			3.27			2.37			4.29		
RF	10%				15%				20%			
Temperature (℃)	1.84				1.78				1.69			
Humidity (%)	2.92				3.10				3.97			
Glove	A10%	A15%	A20%	B10%	B15%	B20%	D10%	D15%	D20%	G10%	G15%	G20%
Temperature (℃)	1.52	1.80	1.61	2.31	1.52	1.59	1.33	1.83	1.79	2.04	1.93	1.74
Humidity (%)	3.51	3.18	3.02	3.03	2.97	3.75	1.04	3.47	1.92	3.41	2.72	6.02

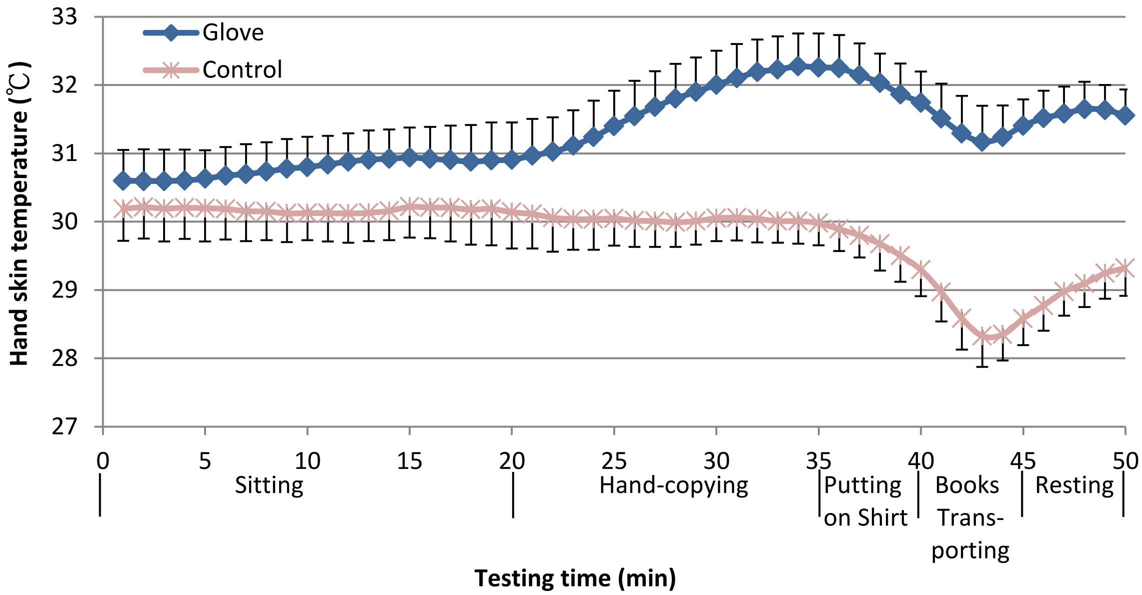


Figure 6.13 Overall hand skin temperature when pressure gloves are worn in the control condition (n=120, mean ± SD)

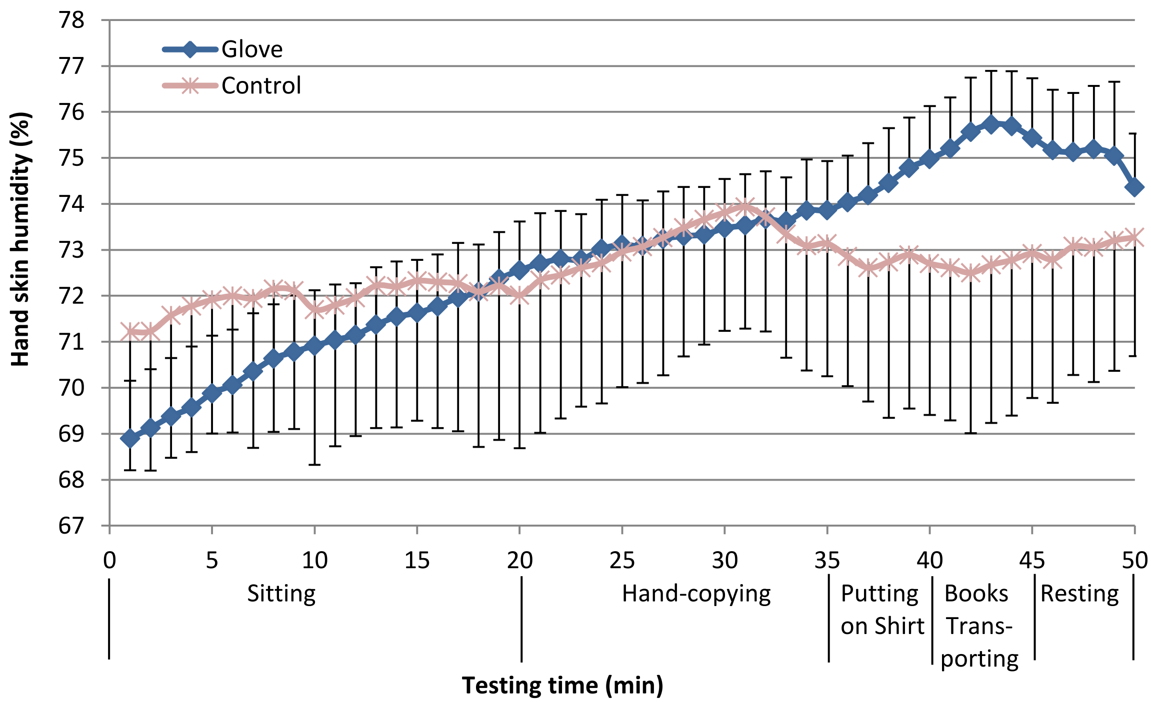


Figure 6.14 Overall hand skin humidity when the pressure gloves are worn in the control condition (n=120, mean ± SD)

6.3.4 Psychophysical responses

6.3.4.1 Impact after1 hour of wearing

Figure 6.15 presents the subjective ratings for each glove at the start and the end of the wear trial. Paired-sample t-testing was carried out. The perceived exertion and thermal perception do not have significant changes ($p>0.05$) after the wear trial. Upon the completion of the wear trial, the perception of comfort for all of the pressure therapy gloves, except the one made of Fabric B with 20% RF, is reduced, which indicates that the gloves can bring further discomfort to the wearer from time to time. A significant increase in the perception of humidity after the wear trial is consistent with the increase in the skin-glove humidity measured.

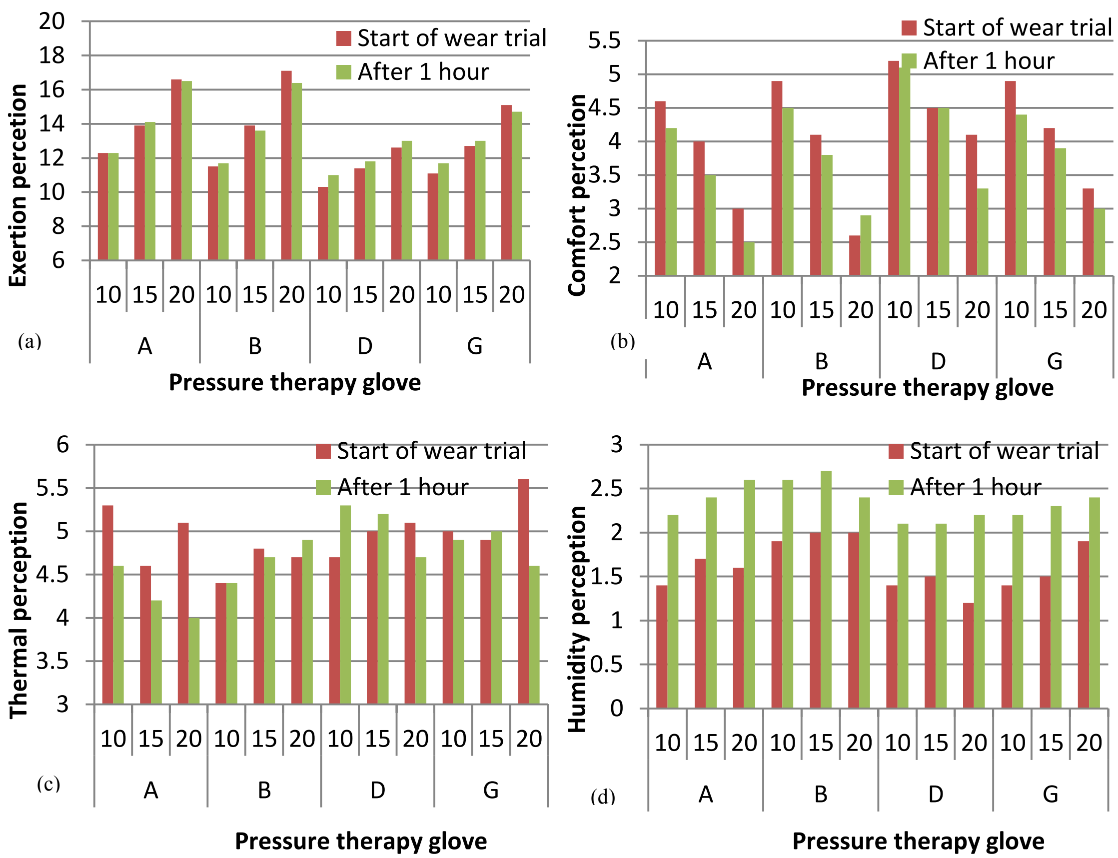


Figure 6.15 Subjective ratings of (a) perceived exertion, (b) comfort perception, (c) thermal perception, (d) humidity perception of pressure gloves made of different fabrics and with different RFs before and after wear trial

6.3.4.2 Impacts of fabric type and reduction factor

A 2-way ANOVA was adopted to investigate the potential impacts, if any, of the different fabric types and RFs on the four psychological perceptions. The results are presented in Table 6.5. The impact of the fabric itself is significant for perceived exertion, and perception of comfort and humidity, but not thermal perception. The variation in skin temperature under the micro-environment of different gloves worn does not vary enough to bring about a significant difference to the thermal perception of the wearers. On the other hand, the RFs have a significant difference on perceived exertion and perception of comfort, but not thermal and humidity perceptions. The perception of humidity was found to be the greatest for gloves made of Fabric B (mean: initial rating= 1.97, final rating= 2.57) and lowest for Fabric D (mean: initial rating= 1.37, final rating= 2.13). The relatively high moisture retention (137.86%) and moderate drying rate (62.97%) of Fabric D allow for quick absorption of sweat from the skin onto the glove and evaporation of moisture from the glove into the environment, thus keeping the hand dry. As the moisture retention of Fabric B is the lowest with a 73.55% change in weight in wet conditions, the moisture on the skin surface cannot be fully absorbed and results in the perception of a high amount of humidity. However, it has good air permeability and hence was rated as lower in thermal perception than Fabrics D and G. The humidity perception of the glove made with Fabric G is even lower than that of Fabric B. This is because the thick fabric and the high moisture retention promote the absorption of moisture. However, Fabric G was rated as relatively high in thermal perception due to its thick structure which resulted in the lowest air permeability, WVTR and drying rate.

Amongst the four fabrics, Fabric D was rated as having the lowest mean perceived exertion, which ranged from 10.3 to 13, while Fabric A was rated as having the greatest perceived exertion, which ranged from 12.3 to 16.6. According to the interfacial pressure measured, gloves made of Fabric D give the lowest amount of interfacial pressure to the wearers, ranging from 1.53 to 4.15 kPa at various RFs and hand postures while that of the other three fabrics ranged from 1.91 to 5.19 kPa. A pressure glove with a higher RF can increase the perceived exertion when working with the hands. The interfacial pressure given by gloves made of Fabrics A, B and G is similar, but the perceived exertion from the glove made of Fabric G is slightly lower. The amount of pressure delivered by the gloves is not the only factor that affects perceived exertion. The human nervous system receives complicated psychological responses which could be correlated to many different human sensations. As shown in Table 6.6, the perceived exertion is negatively correlated to the perception of comfort ($r=-0.741$, $p< 0.01$). However, the correlation between the perception of comfort and thermal and humidity perceptions is merely significant. As the perception of comfort is correlated to the perceived exertion, a better comfort rating for Fabric G could influence the perceived exertion.

Table 6.5 Result of 2-way ANOVA on psychological responses

Independent variable	Dependent variable: Perception											
	Exertion			Comfort			Thermal			Humidity		
	F	Sig.	Partial Eta Squared	F	Sig.	Partial Eta Squared	F	Sig.	Partial Eta Squared	F	Sig.	Partial Eta Squared
Fabric	30.261	.000	.285	7.900	.000	.094	1.811	.146	.023	3.062	.029	.039
RF	103.586	.000	.476	57.561	.000	.336	.021	.980	.000	.522	.594	.005
RF * Fabric	2.967	.008	.072	.296	.938	.008	.678	.668	.018	.327	.922	.009

Table 6.6 Pearson correlation coefficient (R) between subjective ratings

		Perceived exertion	Comfort perception	Thermal perception	Humidity perception
Perceived exertion	**R**	**1.000**	**-0.741**	**0.012**	**0.138**
	sig.	-	0.000	0.858	0.033
Comfort perception	**R**	**-0.741**	**1.000**	**0.158**	**-0.140**
	sig.	0.000	-	0.014	0.030
Thermal perception	**R**	**0.012**	**0.158**	**1.000**	**-0.174**
	sig.	0.858	0.014	-	0.007
Humidity perception	**R**	**0.138**	**-0.140**	**-0.174**	**1.000**
	sig.	0.033	0.030	0.07	-

Gloves made of Fabric D were rated the highest for comfort but relatively lower in interfacial pressure amongst the four fabrics. Therefore, Fabric D is suitable for the treatment of hypertrophic scars that are sufficiently stable and the treatment pressure requirements are not overly demanding, so that better comfort can be provided for the hand. Fabric G was perceived as a comfortable fabric in comparison to Fabrics A and B, which induced similar magnitudes of pressure onto the hand. This is because other than the thermal and moisture properties, hand-feel also affects the perception of clothing comfort. The cotton content of Fabric G provides a soft and smooth hand-feel, and has minimum friction between the hand and fabric, thus giving the sensation that it is more comfortable to the wearers. As a result, Fabric G is considered as a suitable fabric for pressure gloves in the initial or interim stages of treatment when the scars are relatively delicate and a sufficient high pressure provided by the glove is essential to suppress the growth of scars. Fabrics A and B are relatively thin fabrics and have relatively higher air permeability and lower moisture retention. They also have higher fabric tension in the wale direction for providing the required amount of treatment pressure. They can be a suitable choice for providing better comfort in prolonged wearing during hot and humid weather.

Based on the results of the wear trial which tested the four most common types of fabrics adopted in pressure therapy, it can observed that a fabric that has good moisture retention ability and drying rate, and is soft with a smooth hand-feel can give a better perception of comfort to wearers. The comfort sensation of pressure therapy gloves has a major influence on treatment compliance, and thus, this adversely affects the effectiveness and progression of the treatment. Hence, apart from fabric stress-strain properties, fabric properties such as moisture management, comfort and hand-feel should be taken into consideration.

The RFs adopted by the pressure therapy gloves determine the tightness and amount of pressure applied onto the hand. Different RFs, therefore, affect comfort and perceived exertion in different ways. As shown in Figure 6.15, a higher RF used results in a tighter glove, and is associated with higher perceived exertion and discomfort. The RFs adopted by occupational therapists in making pressure therapy gloves are mostly dependent on their experiential judgment without taking into consideration the fabric properties [38, 47]. However, the fabric properties not only determine the amount of pressure applied onto the skin, but also the perceived exertion and perception of comfort which are related to the compliance and the outcomes of scar treatments. Other than the size and the interfacial pressure delivered, the fabric properties should therefore also be considered in the production of pressure therapy gloves for minimizing discomfort and improving compliance rate.

6.3.5 Impact on hand and finger dexterity

The results of the five hand function tests (AROM, SWMT, PP test, putting on a shirt, and handwriting an essay) on hand and finger dexterity are shown in Figure 6.16. The results of the AROM and SWMT tests are presented as the sum of the results of the five digits. In comparing the test results on the bare hand (control experiment), a general decrease in hand performance could be observed after wearing the pressure therapy glove regardless of the fabric type or RF adopted. The AROM with the presence of the glove (446.66±34.1°) decreased by 39.4° in comparison to that of the bare hand (486±33.4°). The total number of pegs and assemblies completed in the PP test was also reduced from 53.2±7.7 pieces when the hand was bare to 47.3±5.2 pieces when the hand was gloved. When wearing the glove, the writing speed decreased from 456.1±69.4 to 403.925±65.7 words/15 mins and the time needed for putting on the shirt increased from 71.6±21.1 to 87.9±28.2 s. However, there was little effect on tactile sensitivity caused by the presence of the glove with minimal sensible force increased by 0.63 mg for the sum of all five fingers.

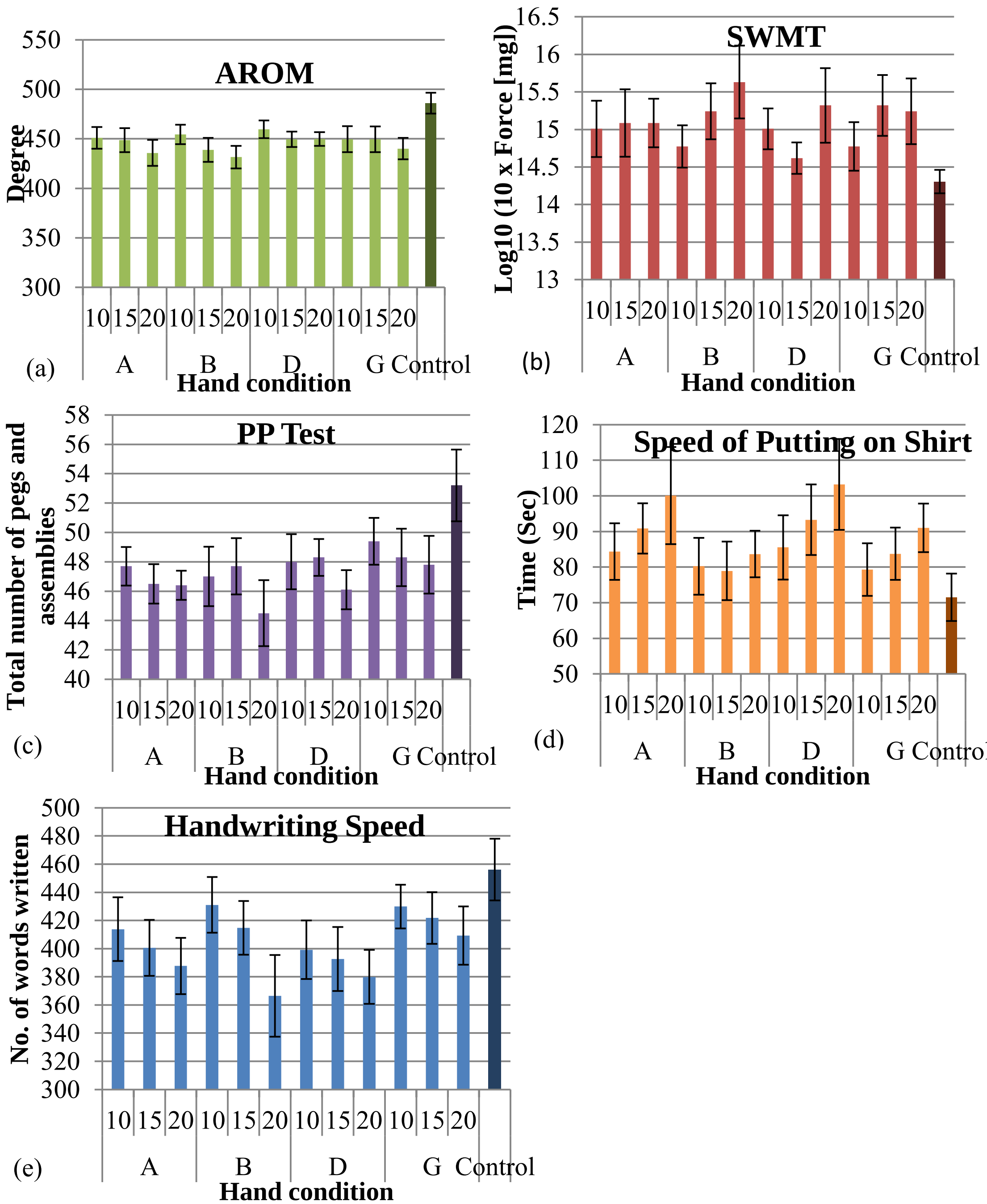


Figure 6.16 Effect of the condition of the hand on different hand performance capabilities while performing the (a) AROM test, (b) SWMT, (c) PP test, (d) handwriting task, (e) task of putting on a shirt (Error bars indicate ± standard errors)

In order to understand the impact of the fabric type and RF of the pressure gloves on hand function, the test results were evaluated by using Friedman testing and repeated-measures MANOVA. The results showed overall significant differences caused by fabric type ($p=0.002 < 0.05$) and RF ($p=0.000 < 0.05$), but not by the interaction between fabric type and RF ($p=0.682 > 0.05$). The results of the analysis of each hand function test are shown in Table 6.7. The results show that there is no significant difference in the hand function tests when wearing the gloves made of different fabric types. The AROM and finger dexterity, time to carry out the handwritten task and time for shirt donning are significantly affected by the RF of the pressure glove. No significant difference could be found in the tactile sensitivity between the wearing of the glove made of different fabric types and the RFs. This indicates that the fabric type (i.e. powernet, satinet and weftlock) and standard RFs of 10%, 15% and 20% used in this study do not affect the tactile sensation of fingers.

The RF used for pressure gloves is the main factor in restraining hand performance, which is closely correlated to the glove-skin interfacial pressure. Tight-fitting therapy gloves continuously apply tensile forces onto the hands, thus hindering finger flexion and extension. Therefore, the gloves made with higher RFs induce increased tensile force and therefore require a greater counteracting force to allow free movement of the hands and fingers as compared to the gloves made with lower RFs. When the fingers bend, the glove fabric on the joint areas is stretched and extra pressure is delivered. Hence, additional force is needed for gripping, flexing and/or bending, thus resulting in retardation of the AROM and finger dexterity. Writing and donning on clothing are two simple and common tasks in daily life, but require hands to have certain degree of dexterity for successful completion. The performance of handwriting and shirt donning are also affected when wearing pressure gloves with higher RFs. According to the test results, the hand performance is not severely affected. This amount of reduced hand function may not be large enough to hold wearers back from performing daily activities but may limit their efficiency, thus resulting in substantial inconvenience. Patients commonly complain about the added mobility restriction caused by pressure garments [8]. This restriction may reduce treatment adherence [73]. Clinicians should therefore be aware of the impact of pressure gloves on hand functions and prepared to openly discuss this issue with patients to improve their treatment adherence [36].

Table 6.7 Summary of Friedman test and repeated-measures MANOVA on hand functions amongst the various types of pressure therapy gloves

Measure	p(sig.)[a]		
	Fabric	RF	Fabric x RF
AROM (°)	0.252	0.035	0.337
SWMT (Handle marking)	0.938	0.081	-
PP Test (No. of pegs and assemblies)	0.338	0.031	0.428
Handwriting speed (words/15 mins)	0.095	0.001	0.122
Speed of putting on a shirt (sec)	0.137	0.002	0.764

[a]SWMT measures are analysed with a non-parametric Friedman test. The other measures are analysed with repeated-measures MANOVA. Variables with p value highlighted are significant (p <0.05)

The post-hoc Sidak pairwise comparisons between each fabric type and the RF of the pressure gloves are shown in Table 6.8. With respect to the RFs, no significant difference can be found between the gloves with an RF of 10% and 15% for all of the hand function tests. Significant differences are found between gloves with an RF of 10% and 20% for the SWMT, writing speed and shirt donning; and between gloves with an RF of 15% and 20% for all of the hand function tests except for the SWMT. This indicates that when a high RF of 20% is selected for pressure therapy gloves, hand performance will be affected. The force applied onto the fingers and hands with a glove that has a 20% RF reaches a level where the wearer needs to provide a high reaction force to cancel out the force from the glove so as to facilitate movement at the expense of finger dexterity. Therefore, it is suggested that occupational therapists should carefully consider whether a high RF (>15%) should be adopted in the making of pressure gloves.

Table 6.8 Summary of pairwise comparisons between each fabric type and RF on hand functions

	p(sig.)[a]								
	Fabric						RF		
Measure	A and B	A and D	A and G	B and D	B and G	D and G	10% and 15%	10% and 20%	15% and 20%
AROM (°)	.982	.854	.999	.527	.895	.925	.356	.092	.024
SWMT (Handle marking)	.436	.803	.863	.385	.737	.723	.369	.030	.178
PP Test (No. of pegs and assemblies)	1.000	.997	.632	.985	.234	.928	.905	.121	.016
Handwriting speed (words/15 mins)	1.000	.976	.675	.836	.490	.093	.288	.013	.009
Speed of putting on a shirt (sec)	.125	1.000	.893	.245	.664	.372	.446	.012	.020

[a]Adjustment for multiple comparisons: Sidak. SWMT measures are analysed with non-parametric Wilcoxon test. . Variables with p value highlighted are significant (p <0.05)

6.3.6 Impact on muscle activity and grip strength

As the impact of the four types of fabrics on hand performance is not significant, the evaluation of the muscle activity focuses on the RFs, and the pressure gloves made of only one type of fabric, Fabric B, were tested in Wear Trial-II. Fabric B can provide a suitable level of pressure and allows for better control on interfacial pressure delivery with different RFs. The %MVE of the three muscles at P10, P50 and P90 of the APDF during the different tasks of the wear trial and the results of the repeated-measures ANOVA amongst the four hand conditions are presented in Figure 6.17 and Table 6.9 respectively.

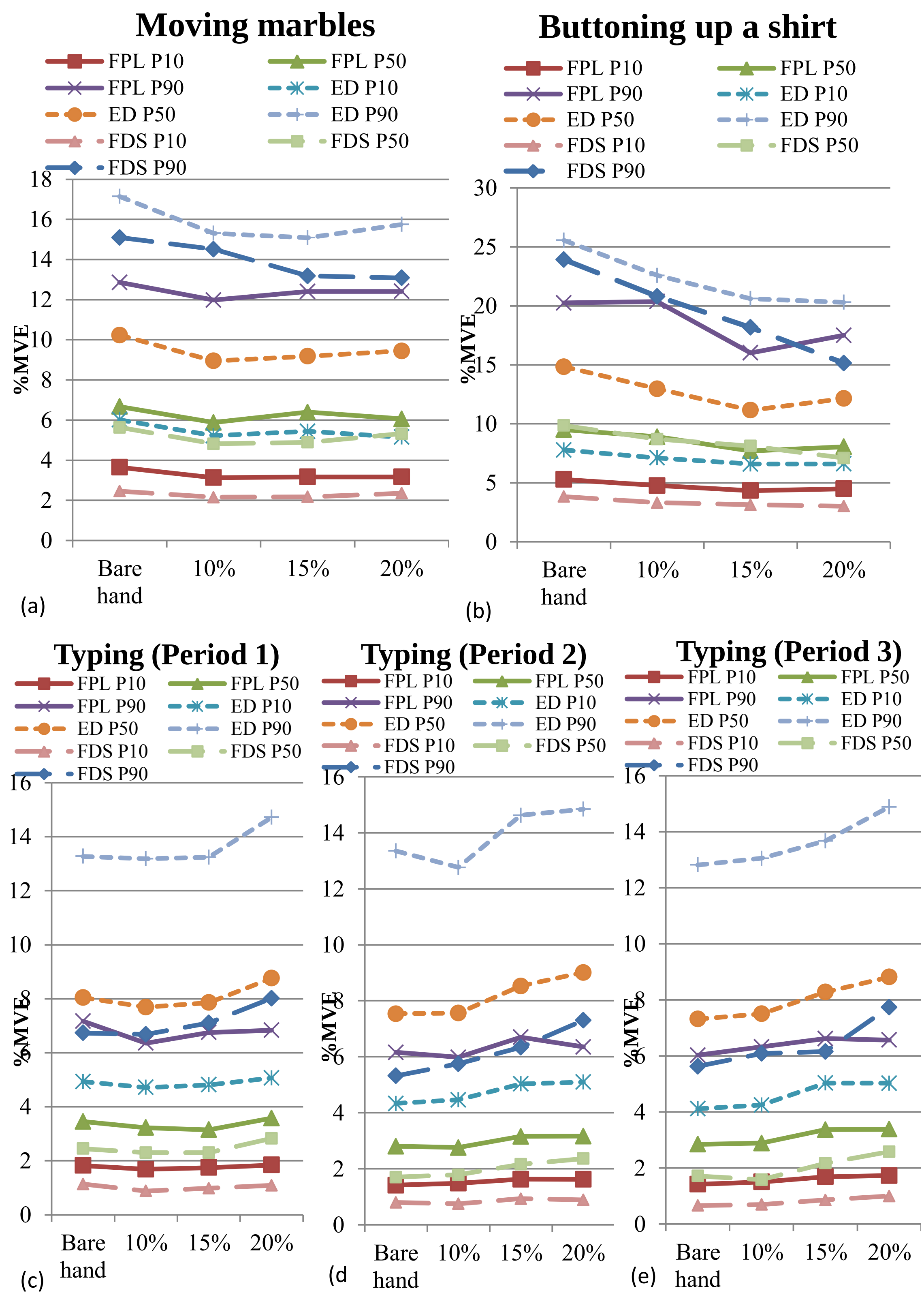


Figure 6.17 APDFs of muscle activity (%MVE) of FPL, ED and FDS at P10, P50 and P90 during (a) moving of marbles, (b) buttoning up of a shirt and typing in (c) Period 1, (d) Period 2 and (e) Period 3 under different hand conditions

Table 6.9 Repeated-measures ANOVA results of the effect of hand conditions on the FPL, ED and FDS muscles at P10, P50 and P90 of the APDFs during different tasks

	p (sig.)								
	FPL			ED			FDS		
Task	P10	P50	P90	P10	P50	P90	P10	P50	P90
Gripping	0.215	0.112	0.437	0.044	0.061	0.076	0.060	0.057	0.090
Moving marbles	0.214	0.622	0.813	0.219	0.210	0.117	0.669	0.603	0.565
Buttoning a shirt	0.001	0.006	0.002	0.030	0.000	0.000	0.093	0.009	0.014
Typing task Period 1	0.398	0.368	0.455	0.942	0.560	0.804	0.177	0.623	0.137
Typing task Period 2	0.205	0.337	0.581	0.115	0.116	0.245	0.574	0.025	0.065
Typing task Period 3	0.299	0.113	0.616	0.024	0.029	0.216	0.201	0.025	0.018

*FPL = Flexor pollicis longus, ED = Extensor digitorum, FDS = Flexors digitorum superficialis

In the task that involved the buttoning up of a shirt, significant differences were found for the APDF of the FPL and ED at P10 and for the APDF of all three muscles at P50 and P90 amongst the four hand conditions. For each muscle, the APDF (except for FPL at P90) of the bare hand condition was at the highest level amongst the four hand conditions and that of the FDS decreased as the RF increased. From the results of the Bonferroni pairwise comparison, the FPL showed significant differences in the pairing of the bare hand condition with the glove that had an RF of 15% in the APDFs at P10, P50 and P90, and in the pairing of the glove with an RF of 10% and that with an RF of 15% in the APDF at P90. For the ED, a significant difference was also found between the pairing of the gloves with RFs of 10% and 15% in the APDF at P50. In addition, a pairwise comparison of each condition with the bare hand condition showed significant differences at different levels of the APDF. Significant differences were found for the APDF of the FDS at P90 in the pairwise comparisons between the bare hand condition and the glove with an RF of 15% and between the bare hand condition and the glove with an RF of 20%. For buttoning up a shirt, muscle effort is required not only to hold the buttons but also to pass them through the small button holes, thus resulting in higher overall forearm muscle activity than the act of moving marbles. The hand dexterity and the range of finger motion required become more demanding in the handling of smaller objects. With the pressure glove, the muscle activity of the FPL, ED and FDS during the buttoning up of the shirt decreased in comparison to the barehanded condition. In the current study, the presence of the glove and its tightness could have led to a change in muscle utilisation patterns during fine and dexterity demanding hand activities, such as buttoning a shirt.

The APDF of the three muscles showed a similar trend amongst the three timeframes of the typing task. During Period 3, the APDF of the ED at P10 and P50 and the APDF of FDS at P50 and P90 had significant differences amongst the four hand conditions. Even though the APDF of these two muscles showed an increase in % MVE with the RF, only the difference between the bare hand condition and a glove with an RF of 20% was found to be significant in the pairwise comparisons. No significant difference was found in the APDF of the three muscles at P10, P50 and P90 in Periods 1 and 2 of the typing task. The participants may need an acclimation period to become accustomed to the typing motion when the pressure glove is worn. The levels of the APDF are relatively low during typing (APDF of FPL at P50< 3.57 %MVE) as compared with other assigned tasks such as buttoning up a shirt (APDF of FPL at P50> 7.7 %MVE) and moving marbles (APDF of FPL at P50> 5.88%MVE). The anticipated finger force during typing and pressing on the keyboard is relatively small. The muscle activity requirements for typing are not as high as the tasks that involve a grip action. However, the typing action involves a higher frequency of finger, hand and wrist combined movements [179]. An increase in the level of forearm muscle activity with a glove that has a higher RF showed that more muscle effort is put forth by the participants to complete the typing task. Additional muscle effort may be needed to work against the pressure delivered by a tighter glove. The presence of a pressure glove with a high RF of 20% could bring about an increase in the muscle demand for typing which involves higher frequency of motion, but with low force intensity. The adjustment of muscle utilisation in completing the buttoning task or the increase in muscle demand for typing induced by the pressure therapy glove could be one of the factors that lead to a negative perception on comfort, ease of motion and perceived exertion.

There was no significant difference found in muscle activity during the task of moving marbles. This activity required the participants to grasp, hold and release 30 marbles by using their fingers and moving their forearms to carry the marbles. It was observed that the presence of the pressure glove and its tightness do not significantly affect the patterns of muscle activity that are monitored in this study.

The maximum grip force under different hand conditions and the corresponding APDF at P90 are presented in Figure 6.18. The hand condition has no significant effect on the activity of the three muscles. The participants showed a high level of compliance to the experiment and provided maximum grip under all hand conditions by using a similar muscle activity level which is agreement with the finding by Kovacs [113]. However, an overall significant difference was found for the maximum grip force between the bare hand and the three gloved conditions (p=0.03). The maximum grip force across all of the participants was 37.2±8.6 kg in the bare hand condition, whilst it decreased by 3.4-4.4 kg in the gloved conditions. The hand conditions affect the force output during the action of gripping. The participants put forth similar muscle activity, but with a difference in the force output under different hand conditions. Muscle activation is not the major factor that drives a reduced maximum grip force. As indicated by Dianat, Haslegrave & Stedmon [180], the effect on hand grip strength could be due to the reduction in friction at the glove-object or hand-glove interface and hence increases the likelihood of slippage. The friction and the tightness of the gloves may be the contributing factors for the change in force output between the bare hand and gloved conditions. As some of the force was used against the pressure delivered by the pressure glove, the grip strength recorded showed a significant decrease.

However, no significant difference was found in the pairwise comparison which indicates the RF of the pressure gloves did not contribute to the force output during gripping. The difference in pressure delivered to the hand among the different RFs was not large enough to make a difference to the maximum grip strength measured. This means that with the use of a pressure glove, the maximum grip strength can be affected, but the impact caused by an RF between 10-20% is not obvious. Hence, to preserve the maximum grip strength, clinicians should not only focus on the amount of RF and the tightness of the glove, but also the fabrication of the glove, such as the fabric surface properties.

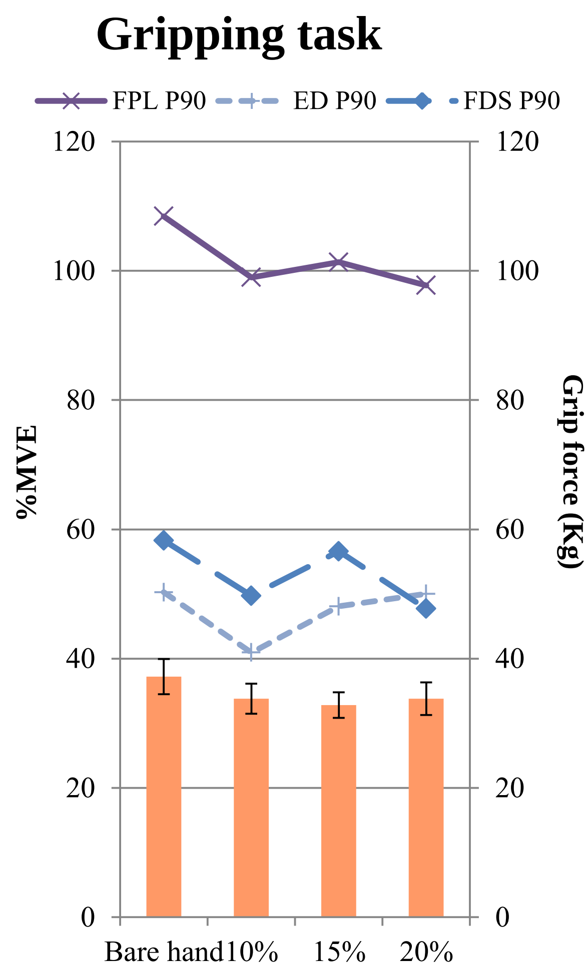


Figure 6.18 Grip force and APDFs of FPL, ED and FDS at P90 during gripping under different hand conditions (Error bars indicate ± standard errors)

Finally, a psychophysical assessment was conducted in Wear Trial-II. No significant difference was found between the ratings at the beginning and end of the wear trial except for the rating on the motion perception of the glove with an RF of 10%. The results obtained at the end of the wear trial are shown in Figure 6.19. The results of the repeated-measures ANOVA amongst the four hand conditions showed a significant difference for all of the three perceptions measured (Table 6.10). This is consistent with the results on the perceived exertion and the comfort perception in Wear Trial-I. The increase in glove tightness (from an RF of 10% to 20%) adversely affects the perceived exertion, glove comfort and ease of motion. The corresponding pairwise comparisons showed that significant differences are evident in a comparison between the gloves with RFs of 10% and 20% in terms of all three different types of perceived sensations and between the gloves with RFs of 15% and 20% in terms of the perceived ease of motion. There is a significant negative impact on these sensations when the glove tightness changed from 10% to 20%. Apart from the reduction in hand grip strength and the change in muscle activity of the forearm, the increased glove tightness also contributes to a reduction in perceived comfort and ease of motion.

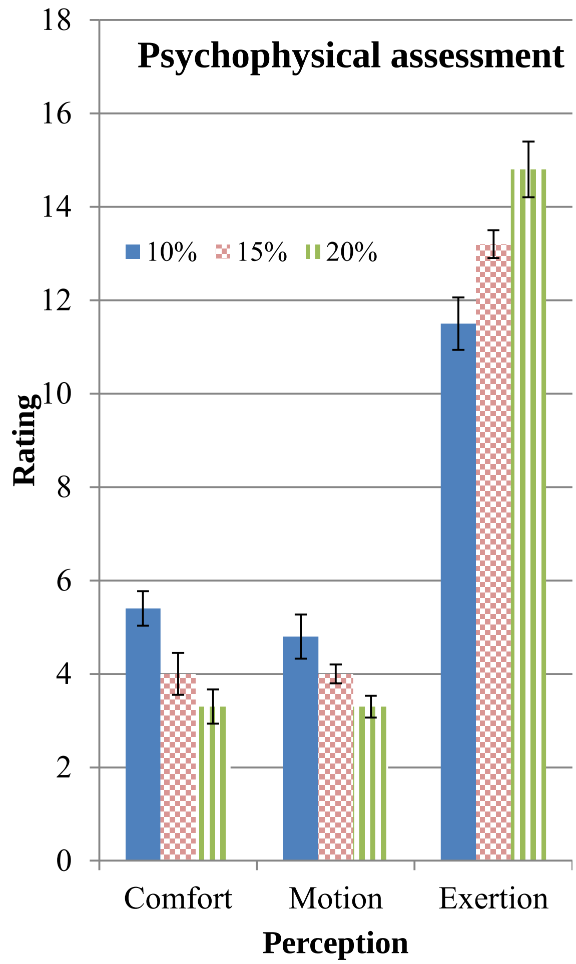


Figure 6.19 Psychophysical assessment at the end of wear trial (Error bars indicate ± standard errors)

Table 6.10 Result of repeated-measures ANOVA for the effect of RF on subjective perception at the end of wear trial

	Comfort	Motion	Exertion
		p (sig.)	
Repeated-measures ANOVA	0.001	0.006	0.002
Pairwise comparison between 10% and 15%	0.052	0.11	0.066
Pairwise comparison between 15% and 20 %	0.332	0.029	0.122
Pairwise comparison between 10% and 20%	0.008	0.027	0.025

* Bonferroni pairwise comparison

6.4 Summary

The use of pressure gloves has no significant impact on the HR and BP. However, the gloves have a significant influence on the microclimate conditions found between the gloves and skin surface. Fabric properties in term of air permeability, water absorbency and drying rate affect the skin-glove temperature and should be taken into account in pressure glove fabrication. The use of pressure gloves results in a remarkable increase of the humidity in the glove micro-environment. Daily activities and/or hand movements can even bring an additional increase to the skin-glove temperature and humidity. The fabric of the pressure glove can also have a significant impact on comfort perception which may adversely influence the rate of patient compliance during the course of the treatment.

The use of pressure therapy gloves has considerable impact on hand dexterity in carrying out of normal daily activities, and this impact is strongly associated with the tightness or RFs of the gloves. The gloves with RFs greater than 15% deliver high pressure onto the hand of the wearer, thus leading to a negative impact on hand performance and comfort performance. When a pressure glove is worn, the muscle activity is affected in different ways throughout the performing of different tasks. When pressure gloves with an RF of 15% and 20% are worn, the muscle activity of the ED and FDS shows a significant decrease in comparison with buttoning up a shirt with bare hands. Future research that includes sampling of additional muscles would be required to explain which muscles are in use and the extent that they are used. In terms of typing, the activity of these two said muscles are increased with a pressure glove that has an RF of 20%. Pressure glove tightness also negatively affects hand grip force.

Delivering a suitable amount of pressure is always the first concern in the production of pressure therapy garments. The comfort sensation of the therapy garment which is the main factor that affects treatment compliance is easily neglected by therapists during the course of a treatment. In this chapter, the results of the study have revealed that the fabric properties and value of the RF not only control the amount of interfacial pressure delivered by the pressure gloves, but also the microclimate conditions inside the gloves, hand performance, forearm muscle activity and perception of comfort by the wearers. Therefore, these factors should be taken into consideration in the prescription of pressure therapy glove to increase acceptance of the treatment and compliance, and hence, better prohibit the growth of scars.

Chapter 7 Development of New Pressure Glove

7.1 Introduction

As reported by practitioners and patients in the clinical study of this research work, fit and comfort are considered to be the major factors that affect the effectiveness and treatment quality of pressure glove therapy. Nevertheless, the current glove making process fails to provide patterns that properly fit the hand geometry, thus leading to inadequate pressure exerted onto the scar region, particularly in the finger web area. The focus in this chapter is therefore on the development of a new pressure glove with improved fit and comfort. A new approach that considers the finger web in the process of the glove production pattern development is proposed to advance the fit of pressure gloves in this area. To enhance the comfort of pressure glove therapy, a potential insert material is also suggested in this chapter.

Recently, the use of spacer fabrics has gained a great deal of attention. Spacer fabrics are widely used in mattresses, automotives (car seats), medical and sports textiles (running shoes, hiking backpacks), foundation garments and other industries (composites) [181, 182]. There are many studies on the unique structure of spacer fabrics and their physical and mechanical properties [183-186]. The 3D fabric structure of spacer fabrics consists of two surface layers and a connection layer (Figure 7.1). The surface layers are connected by pile yarns or filaments which use tuck stitches to form the connection layer. Spacer fabrics exhibit good compression ability and create a moisture free environment with high breathability. A recent study on the development of functional fabrics for pressure ulcer prevention indicated that the superior wicking ability of channelled polyester makes it ideal for the warp, pile and the top weft in the spacer structure, whilst cotton fibres are used as the bottom weft to improve fabric comfort by trapping the moisture delivered from the top layer [187]. A spacer fabric with suitable thickness and compression resistance can be a potential material for the inserts in pressure therapy.

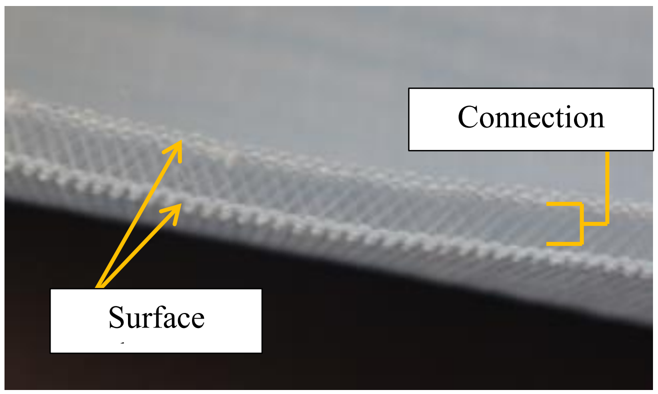


Figure 7.1 Spacer fabric

However, inserts can be easily displaced during wear. Therefore, the use of thermoplastic adhesive tape is also suggested in this study to improve the wearing convenience by addressing the displacement problem. Adhesive tape made of thermoplastic is widely used in the clothing industry as an alternative to the sewing process with needle and thread for the production of seamless apparel [188]. Thermoplastics can be moulded above a specific temperature and solidify upon cooling. They can be act as an adhesive in a heat bonding process. For instance, taped seams can be found in lingerie where flat and smooth seams are desired. Therefore, the smoothness of taped seams renders them a potential means to attach an insert onto the pressure garment as a whole to solve the displacement problem.

7.2 New gusset design for finger web space of pressure glove

7.2.1 Experimental

In this part of study, the angle of the finger web slants of 79 individuals are measured and evaluated by using a 3D scanning method. The angle of the dorsal slant of the web space is then measured for the development of the gusset pattern. Glove prototypes that take into consideration the finger web slants are then developed and assessed through a wear trial with 10 participants.

7.2.1.1 Participants

Seventy-nine participants (36 males and 43 females) who did not have any scars or observable injuries on both of their hands were invited to take part in 3D hand scanning to obtain the slope measurement of their finger webs. Their age range was from 27 to 65 (mean: 50.9, SD: 7.4) years old. Another 10 healthy participants (5 males and 5 females) were invited to take part in a wear trial of the glove samples to assess the fit and comfort. They were all right-handed and healthy with no history of upper limb injuries. Their ages ranged from 18 to 29 (mean: 22.5, SD: 3.9) years old.

7.2.1.2 Finger web slope measurement

Both hands of the 79 participants and the right hand of the 10 participants were scanned by a 3D laser scanner (NextEngine Inc.) with the use of Method IM-III; see Chapter 4 for details. From the 3D images, the cross-section of the finger web was extracted by using RapidForm 2004 software (INUS Technology Inc.). The angle of the dorsal slant of the web space was therefore obtained (Figure 7.2). The finger webs in three locations of the hand were measured; that is, between the index (D2) and the middle fingers (D3), D3 and the ring finger (D4), and D4 and the little finger (D5). The finger webs between D2 and D3, D3 and D4, and D4 and D5 were labelled as W2, W3 and W4 respectively. A measuring tape was used to obtain the other hand dimensions needed for the fabrication of the pressure gloves.

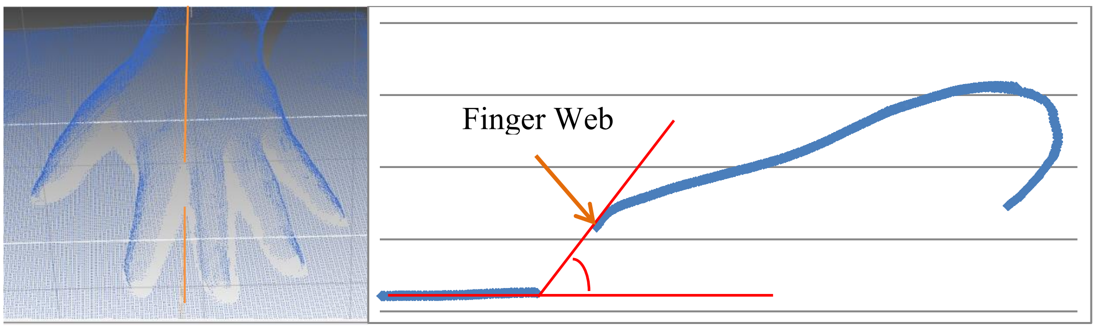


Figure 7.2 Slope measurement of W1 taken from 3D image

7.2.1.3 Glove prototype

It was discussed in Chapter 6 that Fabric B, a powernet fabric, can provide better control on interfacial pressure delivery with different RFs and it has good air permeability. Therefore, Fabric B was used to develop the glove prototypes. The pressure therapy gloves were custom-made for each of the 10 participants with a 10% size reduction in the circumference dimensions of their hand. Three pressure glove samples (Gloves X, Y and Z) were made for each participant. Glove X was based on an original pressure glove pattern currently used by a Hong Kong hospital. Glove Y was made by modifying the currently used glove pattern in accordance with the angle of each of the finger web slant obtained from the 3D scanning imaging. Glove Z was made by using 45° as the standard angle of all the finger web slants. The pattern pieces of the palm and thumb were first made (Figure 7.3). The design of the finger gusset pieces (Figure 7.4) was then made based on the angle of the slants of the finger webs with a width of 1 cm. The web space of the dorsal piece of the pattern (Figure 7.5) was also modified. The finger web panels of Gloves X and Z are shown in Figure 7.6.

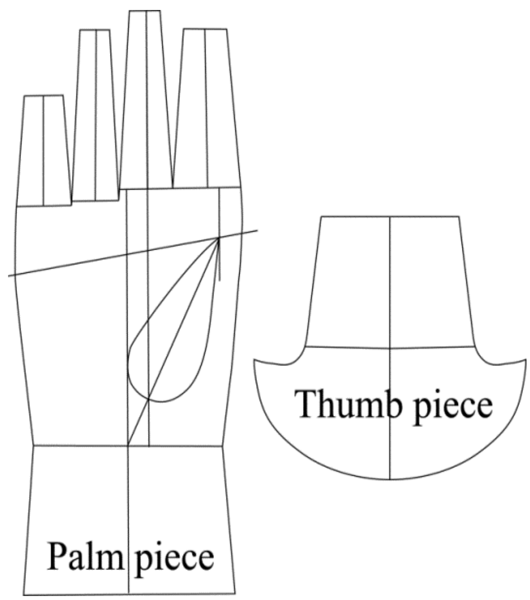


Figure 7.3 Pattern pieces of palm and thumb

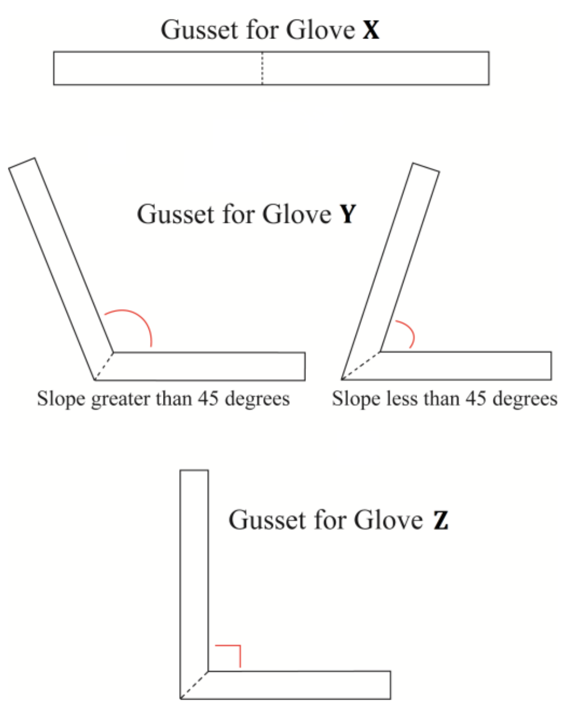


Figure 7.4 Pattern piece of gusset

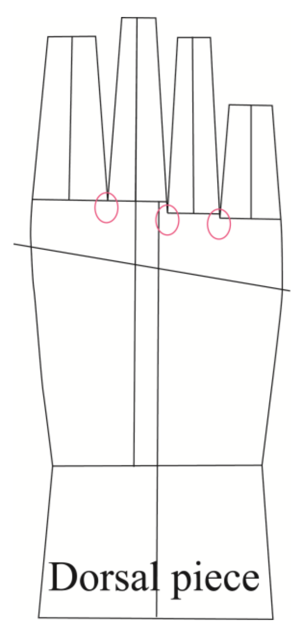


Figure 7.5 Pattern piece of dorsal

Figure 7.6 Finger web panels of Glove X (with sharp finger web angle) and Glove Z (with widened finger web angle)

7.2.1.4 Glove fit assessment

The 10 participants were given the 3 different gloves. They tried on the gloves, rated the glove performance in terms of fit, ease of hand motion and comfort perception respectively by using 11-point subjective scales, as shown in Figure 7.7 and ranked the 3 gloves in order by best fit and comfort. They were allowed to try on the gloves as many times as they wanted to do so and freely move their fingers and hands as they wished. The participants were not told about the differences in the three gloves. The time and number of trials taken for each glove were not restricted. In general, the participants spent an average of 15 minutes to rate the gloves.

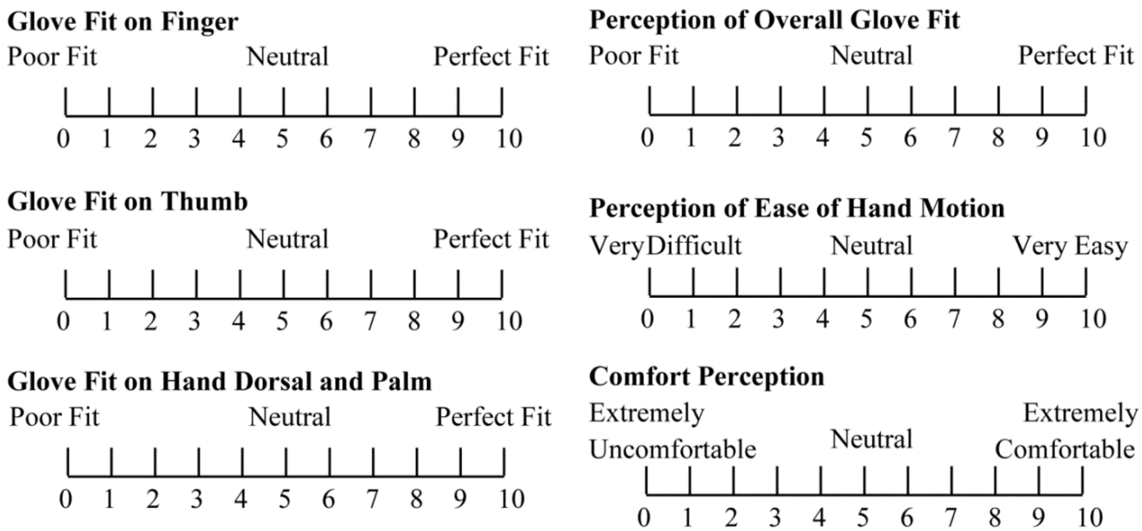


Figure 7.7 Subjective rating scale on the fit, ease of motion and comfort of pressure glove

7.2.2 Results and Discussions

The dorsal slant angles of the finger webs of both hands of the79 participants are shown in Figure 7.8. Due to the quality of the 3D images, some of the web space slants with uncompleted shapes were eliminated. The number of successful finger web measurements was 435. The overall mean, mode and median of the dorsal slant angle of the web spaces were 46.86° $\pm$ 7.02°, 48 and 47.43 respectively. A 3-way ANOVA was conducted to investigate the potential impacts of (1) gender, (2) left/right hand, and (3) location of the finger web on the angle of the finger web slants. The significant level was set at 0.05. The results showed that gender and the location of the finger web have significant effects on the angle of the finger web slants. The angle of W2 is 6.6° greater than that of W3 and 3.02° greater than that of W4 on average. Females have greater finger web slant angles than males on average by 2.15°. However, the effect between the left and right hands is not significant and there is no interaction effect between the three factors. This result reveals that the angle of the finger web slants varies between males and females, and between different fingers of a person. To improve the fit and comfort of pressure gloves, the angle of the finger web slants should be measured and taken into account in the process of glove pattern design and development. This finding was taken into consideration with the development of Glove Y. Glove Y was constructed by taking into consideration the interior angle of each finger web for the gusset on the basis of the angle of the finger web slant measured from the 3D hand image. To simplify the process of the 3D hand image analysis in measuring the finger web of the wearers for pattern development, a standard right angle gusset pattern was adopted in Glove Z where the angle of the finger web slants was assumed to be 45°.

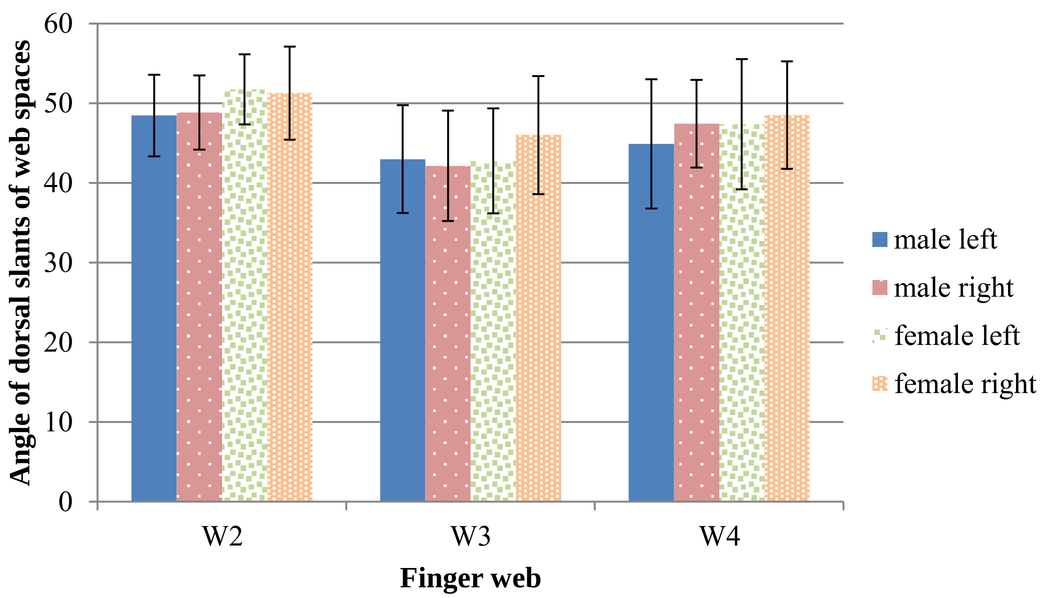


Figure 7.8 Angle of finger web slant of 79 individuals (Error bars indicate ± SD)

The finger slant angles of the 10 participants in the wear trial of the gloves were all within the first and the third quartiles of those of the 79 participants. The results of the subjective ratings are presented in Figure 7.9. It can be seen that Glove Z has the highest rating in all the subjective scales, thus revealing that Glove Z gives the best fit, ease of hand motion and comfort amongst the three gloves. Seven out of the 10 participants rated Glove Z as having the best fit and comfort. This shows an improvement in fit in comparison to Glove X. Four participants rated Glove Y as having the worst fit and being the least comfortable, while five participants indicated Glove X as so. Glove Y, which was developed in accordance with the angle of the finger web slants obtained from the 3D hand images of the participants, received an average rating that is even lower than that of Glove X. This is because the slants of the web space change with hand motions. The angle of the slants measured from the 3D images can therefore only represent the slant of the web space when the hand is widely opened and spread apart, but not when the hand is carrying out other hand motions. Besides that, the gussets for the finger webs were made with different interior angles and the dorsal piece of the glove had to be cut to match the gussets. These increased the difficulty in the fabrication and sewing of the pressure gloves. Thus, that is why Glove Y was rated with an unsatisfactory fit and not considered to be comfortable. On the other hand, the construction of Glove Z was relatively simple and standardised. The finger web slants of Glove Z were standardised as 45° which is 4% below the mean and 5% below the mode of the angle of the finger web slants of the 79 participants. There were 73% of the finger web slants of the 10 participants with angles greater than 45°. However, because of this slight reduction, the glove can better come into contact with the finger webs and received a better rating in the perception of glove fit, comfort and ease of motion. In the fabrication of pressure gloves, an RF is applied to the circumferential dimensions of the hand to provide a certain amount of pressure for scar treatment. Therefore, the application of a certain amount of reduction to the actual angle of the finger web slants in making the gussets not only increases the fit and contact of the glove to the finger webs, but also delivers pressure to treat scars. To balance the priority given to fabrication and the improvement in the fit of the glove, the use of a right angle gusset (Glove Z) can be a possible way to improve the fit of pressure gloves in the finger web area.

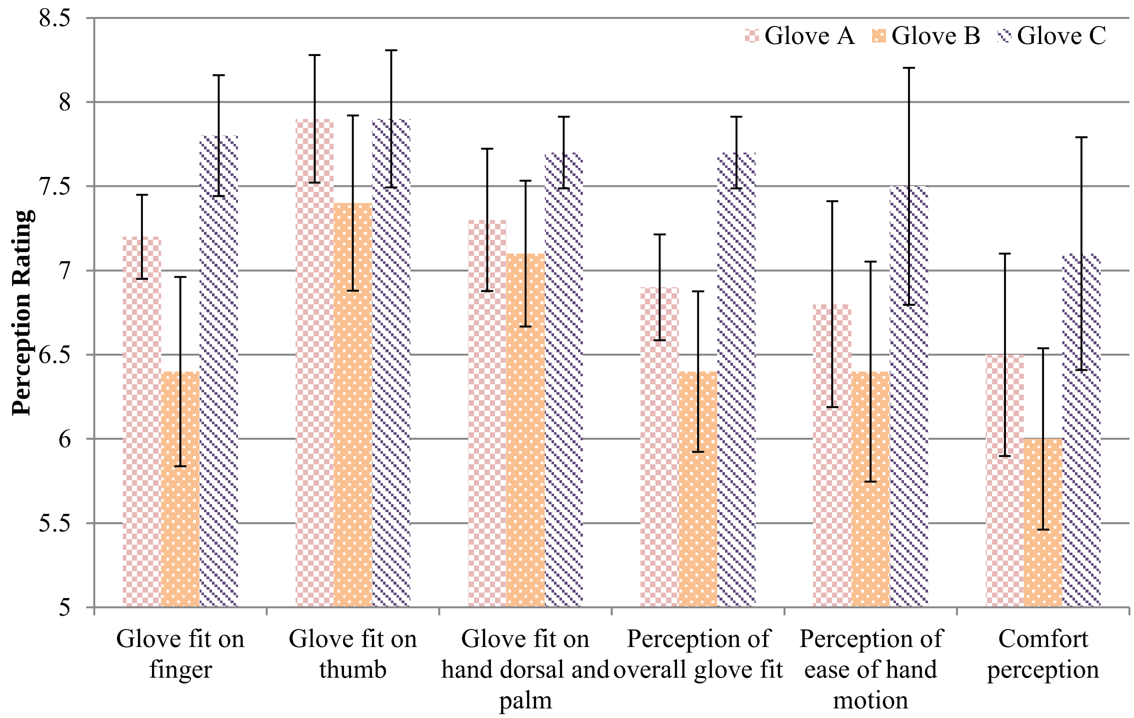


Figure 7.9 Results of the subjective ratings for the three types of pressure gloves (Error bars indicate ± SD)

7.3 Functional performance and clinical uses of textile inserts

7.3.1 Experimental

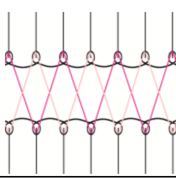
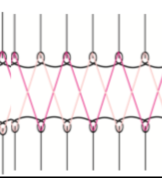
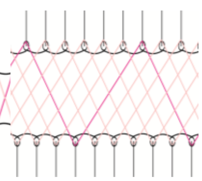
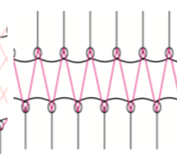
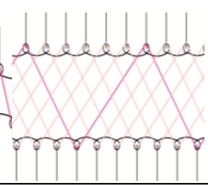
In this part of study, spacer fabric is proposed as a potential insert material to increase the comfort of pressure therapy gloves. However, currently used insert materials for increasing local pressure are barely breathable and quite uncomfortable. As optimal glove-skin interfacial pressure is an important prerequisite of treatment whilst anticipated comfort perception has been proven to be highly associated with treatment adherence and ultimately treatment outcome, the following will be evaluated: the physical and mechanical properties of textile inserts, their corresponding insert-skin pressure, as well as perceived comfort. The effectiveness of textile inserts on the management of hypertrophic scars will also be investigated through a 24-week clinical study.

7.3.1.1 Samples of spacer inserts

Insert materials placed inside the pressure gloves have to be thin enough for insertion purposes, but also have good compression strength to deliver a sufficient amount of pressure and a smooth surface for contact with the scars. The knitting structure of the two surface layers and the choice of using monofilaments as the vertical spacer yarns to connect the two layers have a major effect on fabric thickness and compressive behaviour. In this work, a total of 5 types of single jersey weft-knitted spacer fabrics with different monofilaments that form the connection layer have been studied. Amongst the 5 types of fabrics, Spacers W1 and W2 were relatively thin and commercially sourced from the local industry. Spacers S1, S2 and S3 were fabricated by using a flat knitting machine STOLL CMS822 of gauge 14 in the laboratory. The outer layers of Spacers S1, S2 and S3 were made from the same polyester (150D) and nylon/spandex (70D/20D) yarns. Spacers S1 and S2 were made of the same materials but with different knit structures in the fabrication of the connection layer. The connection layers of

Spacers S1 and S3 were fabricated with the same knit pattern and made of monofilaments with the same diameter of 0.08 mm but different in material (polyester or nylon). A summary of the fabric specifications is presented in Table 7.1. A traditional insert made of Plastazote® with a thickness of 3 mm was also used in the study.

Table 7.1 Specifications of spacer fabric samples

	Spacer W1	Spacer W2	Spacer S1	Spacer S2	Spacer S3
Composition of the outer layers	Polyester	Polyester	Polyester, Nylon/Spandex	Polyester, Nylon/Spandex	Polyester, Nylon/Spandex
Spacer yarn composition	Polyester	Polyester	Polyester	Polyester	Nylon
Spacer yarn diameter (mm)	0.06	0.06	0.08	0.08	0.08
Fabric thickness (mm)	3.08	2.98	5.08	3.7	4.47
Wale wise density (wale/cm)	22	19	16	16	16
Course wise density (course/cm)	18	18	8	8	8
Knit pattern					

Fabric B is used to make the pressure glove samples for this part of the study. For details on fabric specification and physical testing results of Fabric B, see Chapters 5 and 6 respectively. Three pressure therapy gloves with different RFs were custom-made for each subject based on their actual hand dimensions. Based on the finding in Chapter 6; that a high RF (e.g. 20%) in a pressure therapy glove can affect finger dexterity and wear comfort [189], low RFs of 5%, 10% and 15% were therefore applied in the pattern construction to evaluate the effect of insert materials on pressure delivery. All of the gloves had the same design which is the same as the one used in Chapter 6 as shown in

Figure 6.1. A 4 cm x 4 cm square was marked on the hand dorsal side of each glove to identify the location for placing the insert and measuring the interfacial pressure (Figure 7.10).

7.3.1.2 Physical and mechanical properties testing

Physical properties, such as the WVTR, air permeability and surface properties of insert materials are proven to have significant impacts on wearing comfort [38, 190, 191], whilst fabric compression properties contribute to the pressure delivering ability and thus affect treatment efficacy. The WVTR was measured in accordance with the ASTM E96 upright cup method. The air permeability, and surface and compression properties were measured by using KES-F8-API, KES-FB4 and KES-FB3 respectively. The compression testing was carried at a speed of 0.08 mm/sec with a maximum compression stress of 250 gf/cm^2. The compression stress (ε_c) is defined as the load applied divided by the area. The strain (σ_c) is defined as the difference between the current and the original specimen thickness divided by the original specimen thickness. The compression strength therefore corresponds to the points on the stress-strain curve (ε_c, σ_c). The maximum compression force for the standard measurement of normal fabric is 50 gf/cm^2. As spacer fabric and Plastazote® are much thicker than a normal single layer fabric, a higher compression force is needed to determine their compression strength.

7.3.1.3 Interfacial pressure measurement

Ten participants, composed of five men and five women, were recruited to take part in the interfacial pressure measurement of the pressure glove and insert materials. The age range of the participants was from 18 to 29 (mean: 22, SD: 3.3), their average height was 167 cm (SD: 9.4 cm), and average weight was 58.86 kg (SD: 13.8). All were right hand dominant, healthy and had no musculoskeletal problems in the upper extremities, and no history of hand or arm injury. The pressure delivery of each of the three pressure gloves inserted with the 5 different types of spacer fabrics and Plastazote® as well as that of a control (pressure glove only) was measured. The insert materials were prepared as a 4 cm x 4 cm square and placed in between the hand of the subjects and pressure glove under the marked location. A pressure sensor (Pliance X system, Novel, Germany) was used to measure the pressure delivered by the glove and the insert materials in 7 locations (Figure 7.10). The pressure measurement method of Chapter 5 was followed, and so the subjects were asked to perform three hand motions which included resting their hand on a table, holding a cylindrical water bottle and clenching their hand into a fist.

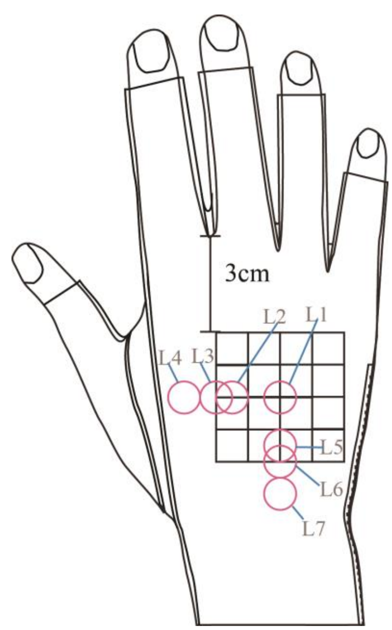


Figure 7.10 Interfacial pressure measurement locations

7.3.1.4 Clinical study

A clinical wear trial of an insert made with one of the spacer fabrics was carried out to examine its effectiveness on scar healing and the subjective feelings of the wearers toward the insert. A 24 week study on each subject was carried out. Three patients with hypertrophic scars in the age range of 48 to 54 (SD: 3.21) were recruited for the study to provide a total of 4 hand samples. Written consent form (See Appendix I) was signed by each participant and the procedure of the study was fully explained with an information sheet (See Appendix VI) prior to the study. They had been wearing pressure gloves with original treatment modality (sponge or Plastazote® inserts) for at least one month. The pressure gloves were first prescribed by an occupational therapist at the hospital. Based on the experimental results of the testing of the material properties and measurement of pressure delivery, a spacer fabric was selected and developed into the textile inserts (Table 7.2). The participants were asked to wear the pressure gloves together with the textile inserts for 24 hours a day except for hygiene purposes. By following the clinical practice, the deformation of gloves and inserts, and scar conditions were regularly monitored every 4 weeks during the study period. Renewal and modifications of the gloves and inserts were provided when necessary.

Table 7.2 Original modality and the use of textile insert in the treatment of hypertrophic scars

Scars at baseline	Original modality		Spacer fabric insert	
				
				

The participants were first requested to rate their original treatment modality on their perception of the fit, breathability, comfort and effectiveness of the insert, as well as their willingness to wear the inserts and perception of ease of hand motion by using a 11-point Likert scale (Figure 7.11). At every 4 weeks of the clinical study, scar conditions were assessed in terms of pigmentation, vascularity, pliability and height in accordance with the VSS (Figure 2.2) conducted by the same occupational therapist. Assessments by the patients on pain and itchiness caused by the scars were also recorded. After 24 weeks of treatment with the spacer fabric insert, the participants were further invited to give a rating for the textile inserts. Additionally, the occupational therapist who participated in the present study was also invited to assess the functional performance of the Plastazote® and spacer fabric inserts, see Figure 7.12.

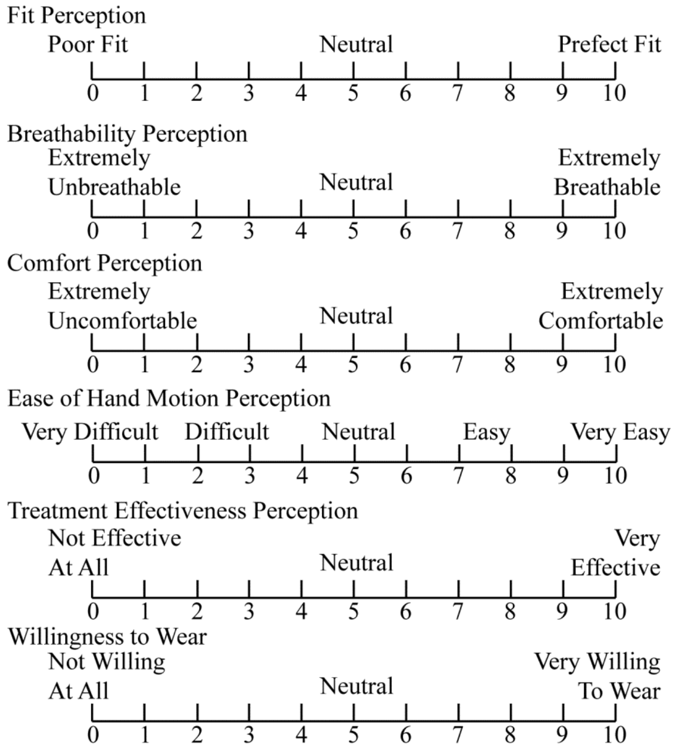


Figure 7.11 Perception scales for hypertrophic scar patients to rate use of inserts inside pressure therapy gloves

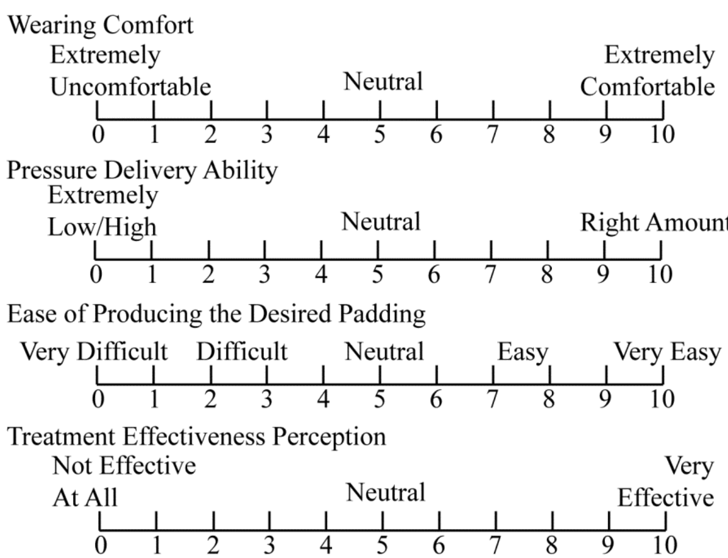


Figure 7.12 Perception scales for occupational therapist to rate Plastazote® and spacer fabric inserts

7.3.2 Results and Discussion

7.3.2.1 Physical and mechanical properties of spacer fabrics

The comfort of the spacer fabrics was evaluated in term of the air permeability, WVTR and surface friction and roughness. The test results are presented in Table 7.3.

In pressure therapy, an insert that exhibits good air permeability can promote ventilation in the micro-climate under a pressure garment. The air permeating resistance of the 5 types of spacer fabrics ranges from 0.05 to 0.12 kPa s/m which excel the non-air permeable Plastazote® in terms of air permeability. Amongst the 5 types of spacer fabrics, Spacer W1 has the lowest air permeability. Spacers S1 and S3 are relatively thick fabrics with the same fabric structure, thus giving the best air permeability, even though they have different yarn connections in their composition. Spacer S2, which differs from Spacer S1 only in the structure of the connection layer and fabric thickness, has lower air permeability than Spacer S1.

With a high WVTR, heat and moisture can be transported away from the skin, thus improving the wearing comfort, especially in hot and humid weather. Spacer W1 has the highest WVTR of 102.39 $g/h{\cdot}m^2$. Even Spacer S1, which has the lowest WVTR, can transmit moisture at 34.35 $g/h{\cdot}m^2$ whereas the WVTR of Plastazote® is only 2.57 $g/h{\cdot}m^2$. Since Spacer 2 is a thinner fabric, its WVTR is better than Spacer S1. The WVTR of the spacer fabric that uses nylon monofilaments (Spacer S3) as the connection yarn is higher than that which uses polyester (Spacer S1).

If the insert materials have a soft and smooth surface, this would provide a more comfortable feeling when the insert comes into contact with the hand and avoids inflicting pain onto the surface of delicate scars during wearing. The surface friction and roughness of Spacers W1 and W2 are relatively lower. The surface roughness of Spacers S1, S2 and S3, especially in the course direction, is much higher. Spacers W1 and W2 have a higher fabric density and their connection layers are made of finer monofilaments, and the surface roughness caused by the tuck stitches of the connection layers is reduced. These two fabrics thus have a smoother surface but some of the air permeability is sacrificed. With reference to Spacers S1 and S3, the surface roughness is also decreased due to the use of nylon monofilaments. Spacer S2 has a higher surface roughness in the wale direction and surface friction in both directions as opposed to Spacer S1.

In comparison, Plastazote®, which is one of the most commonly used insert materials, has good surface smoothness, but is nearly non-air permeable with a very low WVTR. The spacer fabrics that are recommended in the present study as a replacement have much better air permeability and WVTR when compared with Plastazote®. The spacer fabrics can provide good moisture transmission and air permeability to transport away moisture, sweat and heat from the skin so as to provide better wearing comfort.

Table 7.3 Physical properties of spacer fabrics and Plastazote®

Material	Air permeating resistance	KES Surface Test*						WVTR
		MIU		MMD		SMD		
	kPa s/m	wale	course	wale	course	wale	course	g/h·m2
Spacer W1	0.12	1.21	1.51	0.59	0.88	2.46	6.29	102.39
Spacer W2	0.10	1.19	1.34	0.75	0.66	1.43	2.69	52.26
Spacer S1	0.05	1.48	2.01	0.89	4.23	3.22	19.51	34.35
Spacer S2	0.09	1.61	2.21	1.98	2.23	6.15	15.27	42.28
Spacer S3	0.05	1.54	2.22	1.91	1.83	2.79	10.72	48.30
Plastazote®	N/A	0.52	0.50	0.02	0.02	3.36	2.01	2.57

*MIU= Mean coefficient of friction, MMD= Mean deviation of MIU, SMD= surface roughness

7.3.2.2 Compression behaviour of spacer fabrics

The inserts were placed inside the pressure therapy gloves and bore the compression force applied by the gloves. Fabrics with higher compression strength can thus better support the thickness of the inserts and the amount of pressure delivery. From the compression stress-strain curves shown in Figure 7.13, Spacer S3 gives the best compression strength amongst the 5 types of spacer fabrics at a compression stress less than 50 gf/cm^2. During the compression of the fabric at a force up to 250 gf/cm^2, Spacer S3 shows stress-strain behaviour that has a typical compression performance for a spacer fabric. A gentler slope is observed in the initial stage of compression. In a spacer fabric, the outer and the connection layers are not tightly constrained against each other. The initial change of the fabric strain is caused by tightening the loosely compacted layers. When the compression further increases, the slope of the curve becomes steep, thus showing a stiffer behaviour. The monofilaments and the crossing structure of the connection layer form a support against the compression force. A large increase of stress is needed to buckle the monofilaments for further compression. The stress-strain curve of Spacer S3 reaches the plateau stage at a stress of 160 gf/cm^2. The nearly constant compression stress is caused by the shearing and shifting of the monofilaments in the connection layer, which result in a great reduction in thickness and the collapse of the connection layer. At the end of this stage, more than half of the thickness of Spacer S3 is reduced. After that, the stress rapidly increases again for the compression of the surface fabric layers and the monofilaments of the collapsed connection layer. The other 4 types of spacer fabrics do not reach the plateau stage until a compression stress of 250 gf/cm^2. Spacer S3 was fabricated by using the same machine setting, fabric structure and surface layer yarns as those of Spacer S1. The only difference was the use of the monofilaments to compose the connection layer. Spacer S3 used nylon monofilaments with the same diameter. The compression property was thus altered. With the use of nylon monofilaments, Spacer S3 gives a good compression strength at a low force of compression, but the connection layer collapses at the lowest compression stress amongst the 5 types of fabrics.

With regard to the other 4 types of spacer fabrics, Spacer S2 has the lowest compression strength. Since it is a thicker fabric and used monofilaments with a large diameter, Spacer S2 shows a compression strength that is even lower than that of Spacers W1 and W2. One of the reasons could be its lower course and wale fabric densities. A higher fabric density allows a denser composition of the monofilaments in the connection layer, so as to provide strong support against compression. The compression property of spacer fabrics is related to the fabric density. Apart from this, the connection structure of Spacer S2 is formed by the tuck stitch in every needle of the rib gaiting and hence involves only one monofilament in the formation of each fabric course. Spacers W1 and

W2 are produced by interlock gaiting and involve two monofilaments in the formation of each fabric course. This structural difference can also affect the compression behaviour of the spacer fabric. Spacer S1 used thicker monofilaments for the connection layer and a connection structure formed by tuck stitches that shifted a distance of three needles, and was thus composed of six connection monofilaments in the formation of each course of the fabric. It is the thickest and exhibits the steepest compression stress-strain curve amongst the 5 types of spacer fabrics, thus showing good compression strength. The connection structure not only affects the thickness, but also the compression strength of a fabric.

Plastazote® is stiff and has high compression strength. The stress-strain curve for Plastazote® is the steepest with the smallest hysteresis loop, which indicates a small dissipation of energy during the compression/recovery cycle. Spacers S1 and W2 have better compression strength than Plastazote® at a compression of 150 gf/cm^2. For compressions up to 250 gf/cm^2, Spacer S1 still has higher compression strength than Plastazote®.

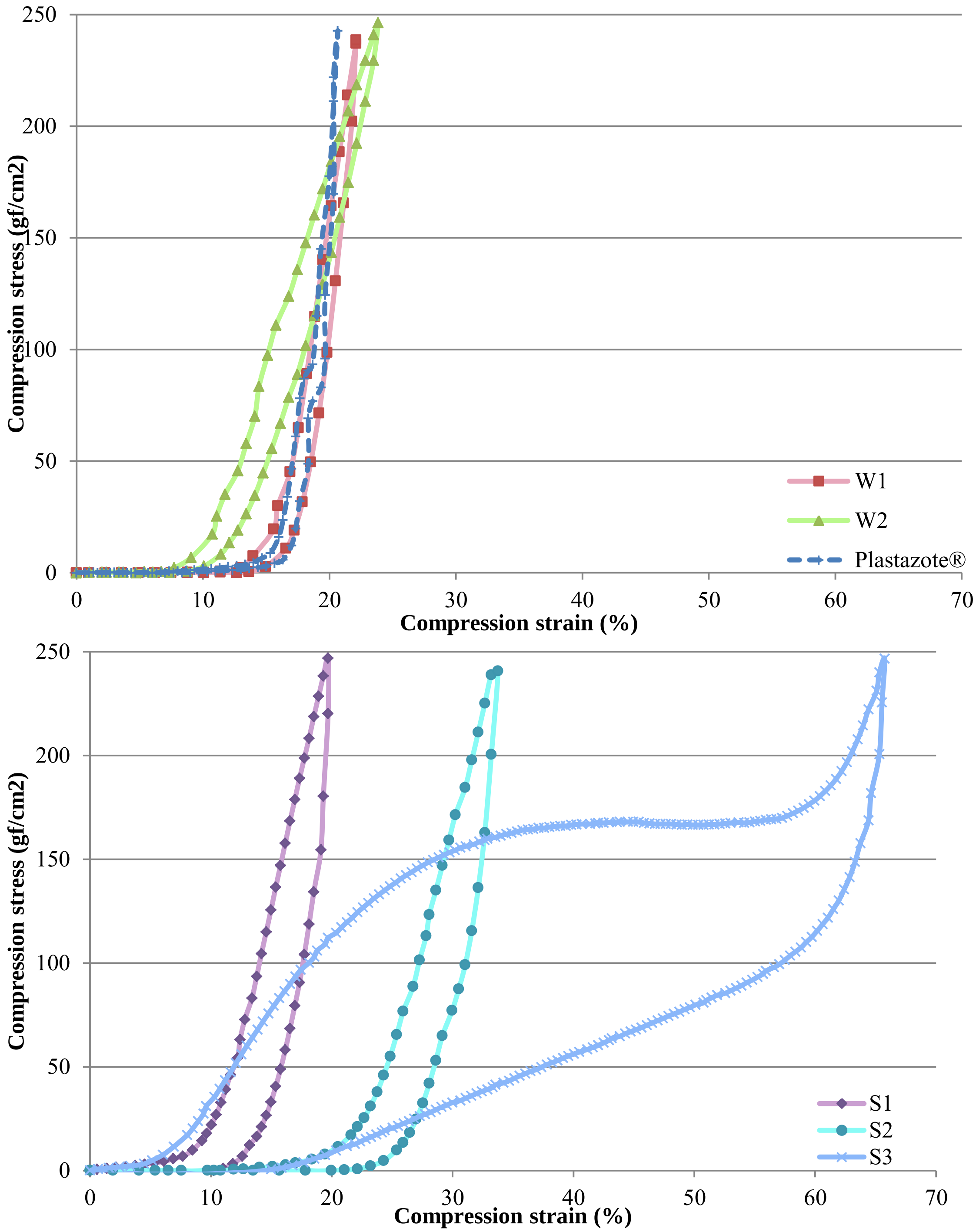


Figure 7.13 Compression stress-strain curves of the five types of spacer fabrics and Plastazote®

7.3.2.3 Pressure delivering ability of spacer fabrics

The amount of pressure applied onto hypertrophic scars directly affects the outcomes of treatment. From the experimental results, it was found that the pressure glove samples alone cannot provide a pressure that reaches 25 mmHg (3.33 kPa) at the locations that were measured. When the hand was lying flat, the pressure gloves with 5%, 10% and 15% RFs could only provide a pressure of 0.11-0.29, 0.39-0.7 and 0.87-1.37 kPa respectively at the seven locations. With reference to Chapter 5, the amount of pressure delivered onto the hand is related to the fabric tension and the curvature of the body. Higher body curvature means higher pressure delivered with the same fabric tension. The pressure applied by the gloves to the areas with a flat surface is relatively lower. Insert materials are therefore needed to assist the pressure garment in the treatment of the scars.

Plastazote® is commonly used by clinicians and occupational therapists as insert materials. Clinicians often shape Plastazote® and sometimes combine several layers to make the desired insert. However, spacer fabrics not only can be easily cut into the desired shape, but their flexibility and softness also match the contour of the hand dorsum. In this study, the 5 types of spacer fabrics have a thickness that ranges from 2.98 to 5.08 mm. A 3 mm Plastazote® was selected for comparison of pressure delivery ability with the 5 types of spacer fabrics. The interfacial pressure given by the gloves and inserts showed a similar trend for three RFs. The interfacial pressure increased when a cylinder was held and when the hand was clenched, which is consistent with the finding of Chapter 5. The pressure delivery from the different inserts also showed a similar trend for the three hand motions. The horizontal locations of L2, L3 and L4 also showed a similar trend in pressure delivery with the corresponding locations (L5, L6 and L7) in the vertical direction. The results from the four locations when holding a cylinder are selected for illustration purposes in Figure 7.14. The pressure measurement on all the 7 locations with the glove made of the 3 different RFs can be found on Appendix VII. A repeated-measures ANOVA (significance at 0.05) was carried to understand the effect of the six inserts on the interfacial pressure. Significant differences caused by the six inserts were found on more than one type of glove or hand motion at the different measurement locations except for L4 and L7. Spacer S1 gives the highest pressure at L1 and L2, which are fully covered by the inserts, followed by Plastazote®, then Spacer S3, and finally Spacer S2. L3 is on the left edge of the inserts. Spacer S1 and Plastazote® continue to deliver relatively high pressure while Spacer S3 gives the lowest pressure increment amongst the six types of insert materials. L4 is somewhat next to the edge of the insert. It can be observed that the control condition can give a pressure that is even higher than that with an insert at these locations. This is because the insert slightly lifts up the glove in the area just next to it, which results in lower contact pressure. Amongst the 5 types of spacer fabrics, Spacer S1 can deliver a pressure that is comparable to that of the 3 mm Plastazote®, which makes it a potential insert material for pressure therapy. Although Spacer 1 induced slightly higher interfacial pressures than Plastazote® in some of the measurement locations, the amplitude of the pressure can still be controlled within the effective pressure range of 25-40 mmHg for scar treatment. By using the same machine gauge for knitting and with the same surface layer structure and fibre contents, Spacer S1 can still deliver a pressure that is higher than Spacer S2. This is because the connection structure can affect the thickness and stiffness of the spacer fabric and hence the amount of pressure delivery when used as inserts. Although the other spacer fabrics cannot provide an increase in local pressure as much as that of Spacer S1 and Plastazote®, they still can give a certain amount of pressure increment. Therefore, the large variety of fabric structure and properties of spacer fabrics can help to increase the flexibility of treatment to suit the requirements of different hypertrophic scars.

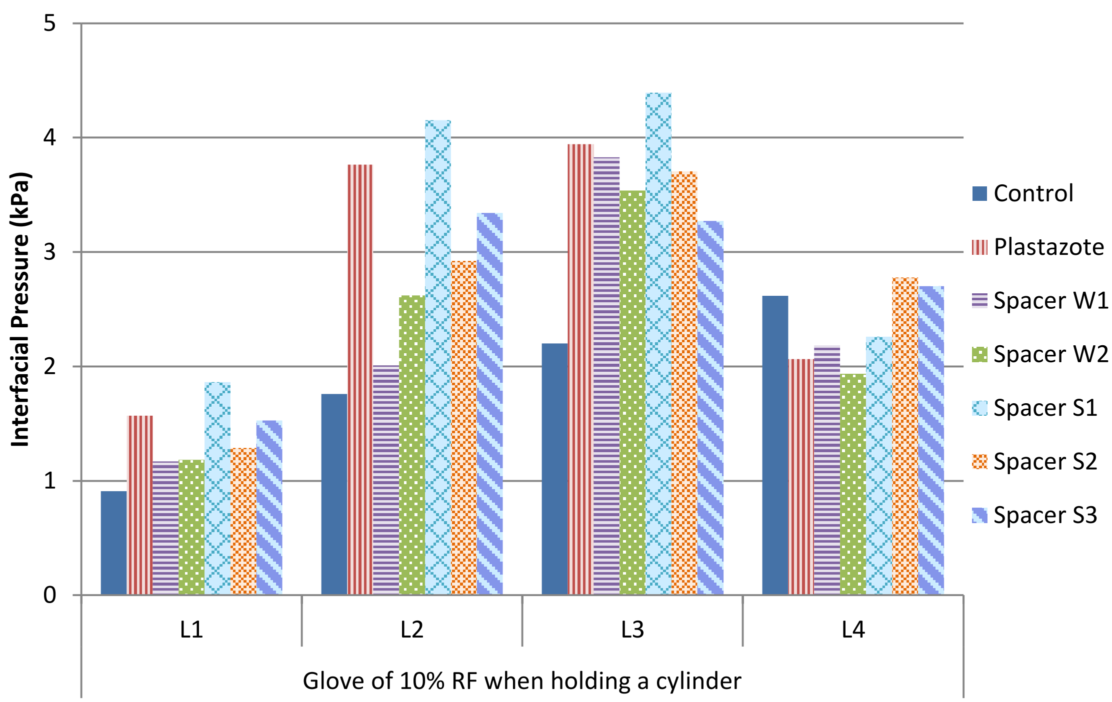


Figure 7.14 Interfacial pressures at 4 locations on the dorsum of the hand between the hand and the pressure gloves with 10% RF that have different inserts when the subject is holding a cylinder

7.3.2.4 Clinical study - Impact on hypertrophic scar treatment

In order to understand the improvement in comfort with the use of spacer fabric as an insert and the effectiveness in suppressing the growth of scars, a study on patients with hypertrophic scars was conducted. With a relatively better air permeability, pressure delivery ability and compression strength, Spacer S1 was selected to produce the inserts in the clinical study. The scarred hands of three participants are shown in Figure 7.15. As shown, there is an observable improvement in the conditions of the scars after 24 weeks of pressure therapy with the use of the spacer fabric insert. The VSS record presented in Table 7.4 also indicates certain improvements in scar conditions after 24 weeks of pressure glove treatment with the use of spacer fabric inserts. The insert made of this type of spacer fabric can thus be an effective modality in treating hypertrophic scars.

Figure 7.15 Photos of hypertrophic scars at the beginning of the clinical study and after wearing the pressure glove and spacer fabric insert for 24 weeks

Table 7.4 VSS record of participants

	Subject 1		Subject 2		Subject 3	
Time point	Baseline	After 24 weeks	Baseline	After 24 weeks	Baseline	After 24 weeks
Pigmentation (0-2)	2	2	0	0	1-2 **	2
Vascularity (0-3)	2	1	2	2	2	2
Pliability (0-5)	2	1	2+ *	2	2	1-2 **
Thickness (0-3)	1	1	2	2	1	1
Pain (0-2)	1	1	0	0	0	0
Itchiness (0-2)	1	1	0	0	0	0

* rating of 2+ means the condition is higher than 2 but has not reached 3
** rating between 1-2 means certain scars have a rating of 1 and certain scars have a rating of 2

The results of the subjective ratings provided by the patients and the occupational therapist on the inserts made of Spacer 1 and Plastazote® are presented in Figures 7.16 and 7.17 respectively. The spacer fabric insert is perceived as a better insert material with consistently higher ratings than the Plastazote® insert by all 3 patients in terms of fit, breathability, comfort, treatment effectiveness, willingness to wear and ease of hand motion. From the viewpoint of the occupational therapist, the spacer fabric insert is somewhat lower in treatment effectiveness (rating of 7) and pressure delivery ability (rating of 9) when compared to the performance of the Plastazote® insert (ratings of 9 and 10 respectively). Nevertheless, the occupational therapist indicated a problem with the spacer fabric insert which is the ease of production of a desirable insert. Protruding monofilaments were found on the edges so that additional edge finishing needed to be carried out on the insert, thus increasing complications in the production. However, in considering the outstanding wear comfort of the spacer fabric inserts, the spacer fabric is suggested as an alternative insert material for patients who find it difficult to accommodate a Plastazote® insert.

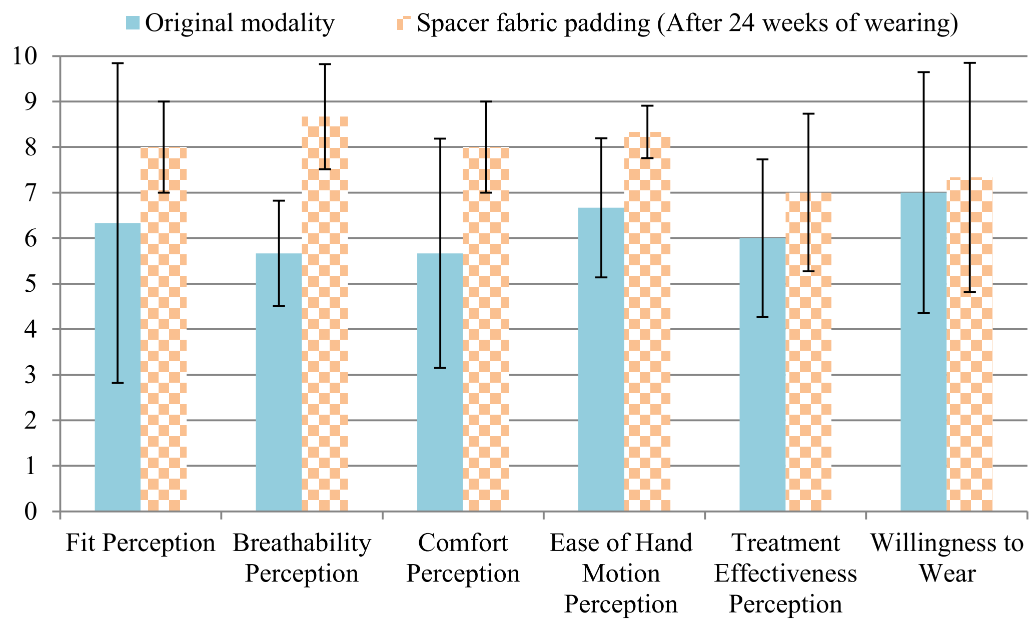


Figure 7.16 Subjective ratings given by hypertrophic scar patients on the original insert made of sponge or Plastazote®, and on the spacer fabric insert (Error bars indicate SD)

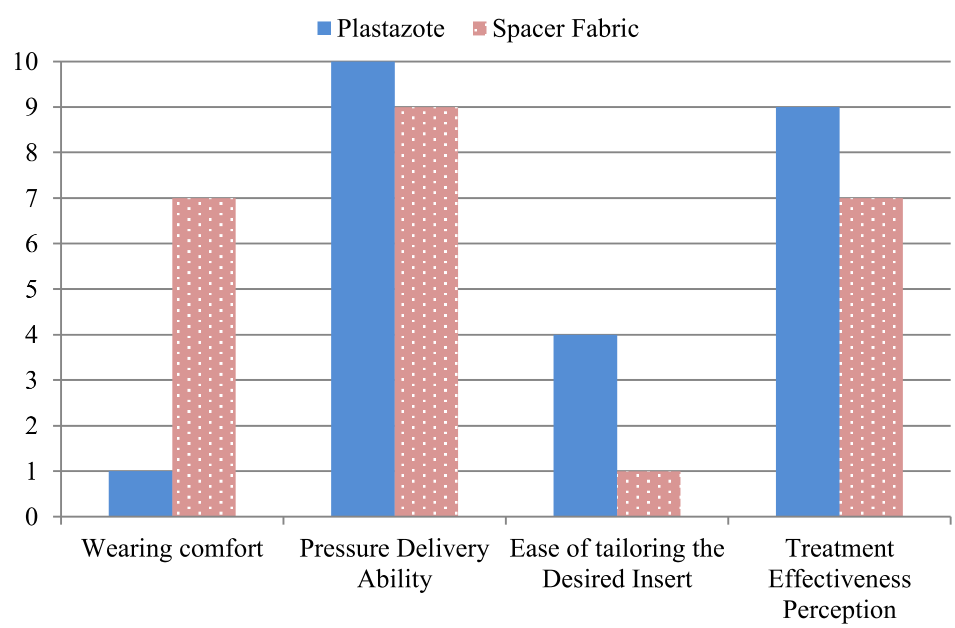


Figure 7.17 Subjective ratings given by the occupational therapist on inserts made of Plastazote® and spacer fabric

7.4 Attachment of inserts with thermoplastic adhesive tape

7.4.1 Experimental

Body movements during daily activities can result in frequent displacement and repositioning of the inserts, thus affecting their contact with the pressure therapy gloves. The use of thermoplastic adhesive tape is suggested for securing inserts onto the pressure gloves to prevent displacement and improve wearing convenience.

The five types of spacer fabrics and the pressure therapy glove sample, as described in Section 7.3.1.1, are used in this part of the study. The five types of spacer fabrics were cut into squares of 4 cm x 4 cm and attached to the pressure therapy glove as a whole by using Bemis adhesive tape (Tape 3918, Bemis, USA). The attachment method is illustrated on Figure 7.18. In order to neatly bind the edges of the spacer fabric during the attachment process, 3 mm of the perimeter of the layer that would be attached onto the glove was cut off. Thermal plastic adhesive tape was then attached onto the perimeter by using an iron with a temperature of 130°C. The film of the adhesive tape was removed and the fabric sample was then attached onto the glove by ironing the adhesive taped area. After the attachment, the 10 subjects who participated in the interfacial pressure measurement with the insert materials put on the glove samples again and repeated the interfacial pressure measurements per Section 7.3.1.3 in order to determine the impact of the attachment on pressure delivery.

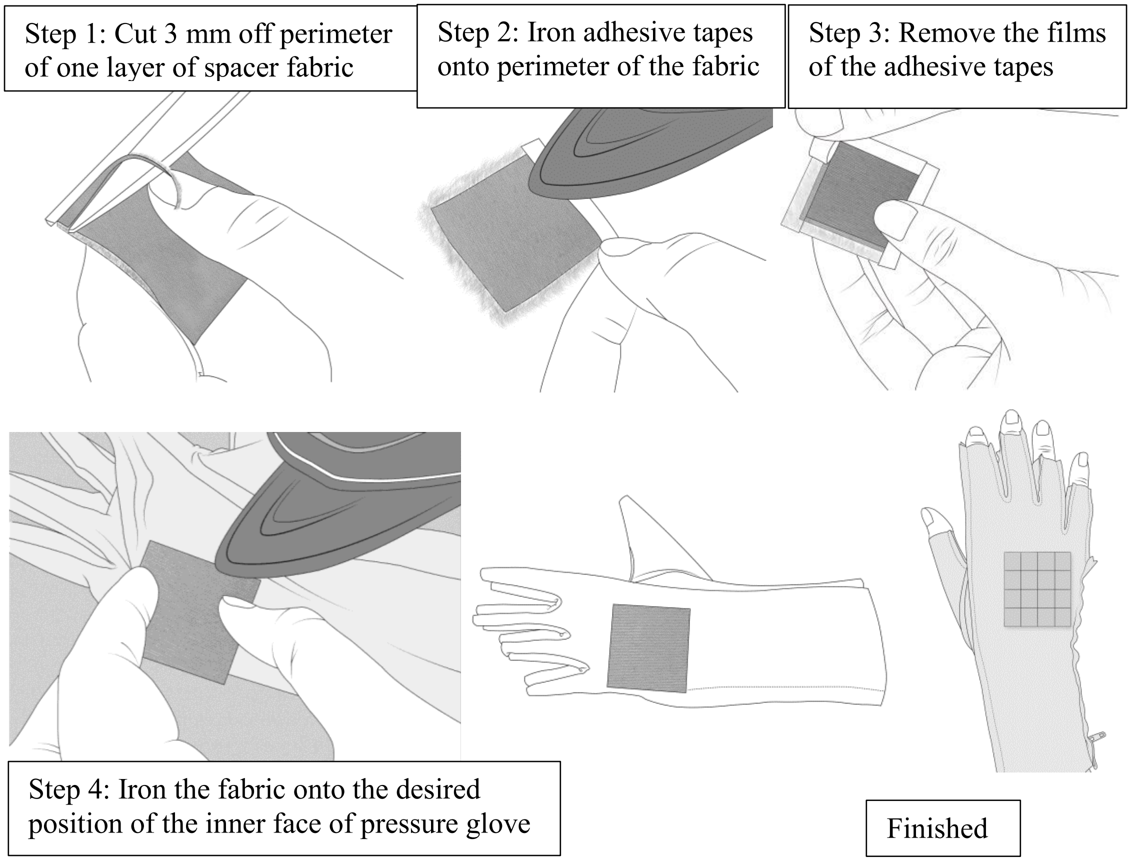


Figure 7.18 Attachment of spacer fabric onto a pressure glove

7.4.2 Results and Discussion

With the use of adhesive bonding, the spacer fabric can be attached onto the pressure garment as a whole which can increase the wear convenience of inserts and prevent displacement. If the insert is sewn onto the pressure garment, it can be difficult to remove for adjustment purposes to suit the progress of the scar treatment. The sewn seam can also affect comfort. Elastic thermoplastic adhesive tape has good stretching strength and the peeling strength can be maintained at a moderate level by controlling the temperature and time of the heat setting. Adhesive tape allows the insert to be firmly attached onto the pressure garment during use and hand laundering, but at the same time, can be peeled off from the pressure garment relatively easily for adjustment. Moreover, the seams of the attachment are smooth and neat and hence minimise the discomfort caused. On the other hand, it is also important to understand the impact of the application of adhesive tape on the interfacial pressure given by the pressure garment and inserts.

The interfacial pressure differences measured from the pressure glove with a spacer insert attached by using adhesive tape showed a similar trend on the glove with different RFs. The results can be found on Appendix VIII. The pressure differences on the glove with 10% RF were selected as an example, see Figure 7.19. The interfacial pressure at L1, L2, L4, L5 and L7 mostly increases after the attachment of the spacer fabric insert with the use of adhesive tape. L1, L3 and L5 are fully covered by the insert. The adhesive tape restricts the extension of the glove fabric onto the insert area and imposes a further increase in the local pressure under the insert. L4 and L7 are located just next to the spacer insert. The attachment brings an increase in pressure at these two locations but still maintains a pressure level similar to that without the use of an insert. The interfacial pressure at L3 and L6 decreases when the insert attached with adhesive tape is used. This is because the edges are cut for the attachment of the adhesive tape. When the insert material is simply placed inside glove without use of any attachment means, the thickness of the insert materials would cause the glove fabric to lift up in the area just next to the insert and result in additional pressure induced onto the perimeter of the insert.

A RF controls the overall tightness of pressure garment while an insert aims to give an extra pressure targeting on the scar areas. The ideal pressure distribution of the pressure therapy aims to strategically exert suitable pressure that reach the treatment pressure level on the specified scar area, but minimal pressure on other areas without scar. In the current practice, inserts are usually made to be somewhat larger in size than the hypertrophic scars so as to consider its displacement during wearing and ensure that the scar can be entirely covered all of the time. The high pressure induced onto the perimeter of the insert is therefore unnecessary and can even bring about discomfort. With the use of adhesive tape for attachment, not only will the local pressure delivered by the insert increase but also the unnecessary pressure onto the perimeter is reduced. The attaching of the insert onto the glove as a whole can ease the wearing process and the delivery of pressure can be more efficient and effective.

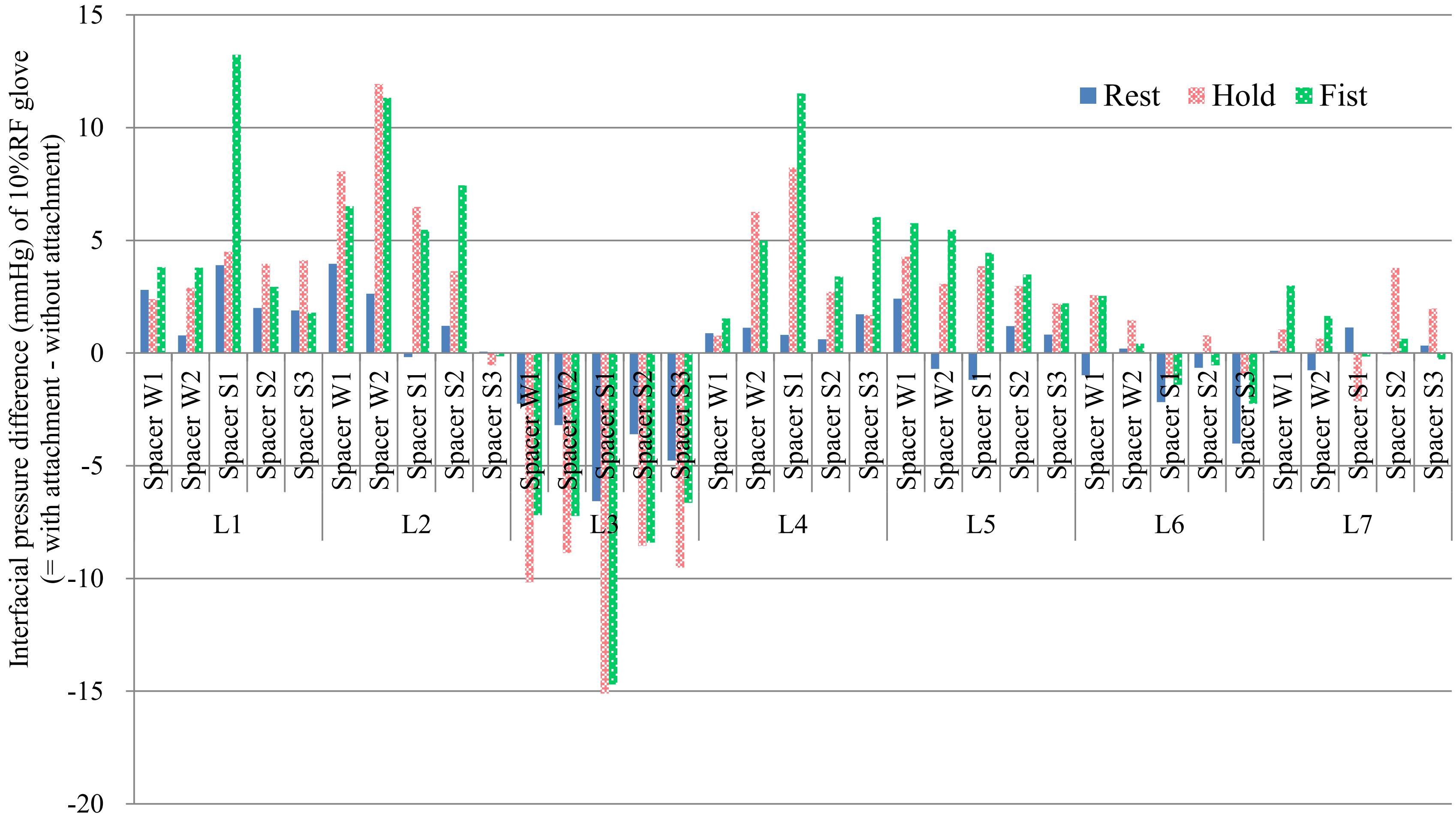


Figure 7.19 Difference between the glove-skin interfacial pressures of a 10% RF glove that has spacer fabric insert attached with adhesive tape and one without insert attachment

7.5 Summary

A production pattern has been modified in this study to improve the fit of pressure therapy gloves in the finger web area. However, the glove with gusset dimensions that are custom-made based on the interior angle of each finger web of the wearer does not provide a satisfying fit and comfort. Instead, the glove made with a gusset pattern that has a standard right angle not only results in a good perception of the glove-skin contact in terms of fit, comfort and ease of hand motion, but also eliminates the complex process of 3D hand image analysis for measuring the finger web slants. The new pattern making approach of pressure therapy gloves proposed in this study therefore provides a practical and effective solution to improve the glove fit in the finger web area. The approach may also be applied to custom-made gloves required by certain sports that need to perfectly fit the hands of players and professionals so as to achieve better performance and provide better means of protection.

To address the concern of comfort, spacer fabrics are proposed as a possible material for inserts in pressure therapy. Spacer fabric can be produced from a normal knitting machine at a relatively low cost. Compared with traditional insert materials like Plastazote®, spacer fabric is more flexible and its physical and mechanical properties can be easily adjusted by altering the yarn and filaments used or the connection structure [192]. The spacer fabrics used in this study are made of polyester, nylon and spandex which are the same as the materials usually used for making pressure garments with good biocompatibility. The spacer fabrics show outstanding air permeability and WVTR when compared with the Plastazote® insert material that is currently used. The softness of spacer fabrics can help to increase the glove-skin interfacial pressure on some of the concave areas of the hand dorsum. As an insert placed inside a pressure garment, the spacer fabric can improve the wearing comfort without sacrificing much the level of local pressure increment. From a 24 week clinical study on the scarred hands of four individuals, the use of an insert made of spacer fabric is found to be effective in treating their scars. With improvement in wearing comfort, the pressure treatment acceptance and compliance would consequently increase. A spacer fabric insert that is attached onto the pressure garment by using thermoplastic adhesive tape has also been suggested in this study. This method can address the insert displacement problems and the delivery of pressure can be more efficient and effective, and ultimately improve the treatment quality.

Chapter 8 Formulation of Pressure Simulation Model by FEM

8.1 Introduction

On the basis of Laplace's law, a mathematical pressure prediction model has been successfully developed (see Chapter 5) to estimate the amount of pressure delivered by a pressure glove with the curvature of hand and fabric tensile behaviour taken into account. With the advancement of computer technology, FEM provides an opportunity to investigate multiple glove prescription parameters (e.g. fabric type and tension) from biomechanical aspects in accordance with the design and fabrication materials of pressure gloves, specific treatment requirements and/or scar conditions of the patients. In this chapter, a 3D biomechanical model will be developed to numerically simulate the glove-skin interfacial pressure by using FEM. In this model, the shape geometry of the hand, the mechanical properties of the glove and human body tissues are incorporated in the numerical stress analyses. The corresponding pressure magnitudes and distribution over the hand dorsum can thus be simulated. On the basis of the simulation model, the pressure distribution given by the pressure therapy glove in relation to the hand geometry, prescribed RF, fabric choice, scar conditions and skin pliability can be accurately predicted and controlled during the course of treatment.

8.2 Finite element model building

A commercial FEM software, ABAQUS/CAE 6.10-1 (Dassault Systémes SA, France), was used to carry out the simulation. The interfacial pressure simulation model mainly consists of two materials: a hand and glove fabric. First, geometrical models of the hand and glove fabric were created. Secondly, the appropriate element type and material properties were defined. After meshing, the numerical processing of the wearing of the glove fabric on a hand was carried out by defining the initial and boundary conditions and displacement loading of the glove fabric to obtain the numerical solution. Then, the results were post-processed and validated.

8.2.1 Geometric model of hand and glove fabric

8.2.1.1 Construction of hand contour model

In order to study the pressure distribution on the hand dorsum, it is essential to develop a 3D hand geometric model. Many previous studies have used MRI images that show the cross-sections of body parts to develop geometric models for the conducting of simulation by FEM [150, 193, 194]. However, the equipment for taking MRI images is large in size, and the cost is very high. In order to suit the clinical situation for pressure therapy, it is proposed that a simpler and more practical method to obtain 3D surface images is from a 3D laser scanner. Three dimensional scanners are portable which eliminate the location restriction of image capturing. The 3D images can also provide the means for continuous monitoring of the scar conditions. The simulation model developed in this study also mainly takes into consideration the contour of the hand and not the cross-section components, thus 3D images are adequate enough to provide the necessary information.

The right hand of a healthy Chinese female, age 25, with a height of 173 cm and weight of 53 kg, was used. The 3D laser scanning method, Method IM-II, as outlined in Chapter 4, can help to obtain a precise 3D hand image that has major hand dimensions with no significant differences from measurements that are manually taken by hand. Therefore, a plaster model of the hand was made and scanned by using Method IM-II to create the 3D model (Figure 8.1a). The thumb of the 3D hand model was eliminated so as to simplify the pressure simulation model (Figure 8.1b).

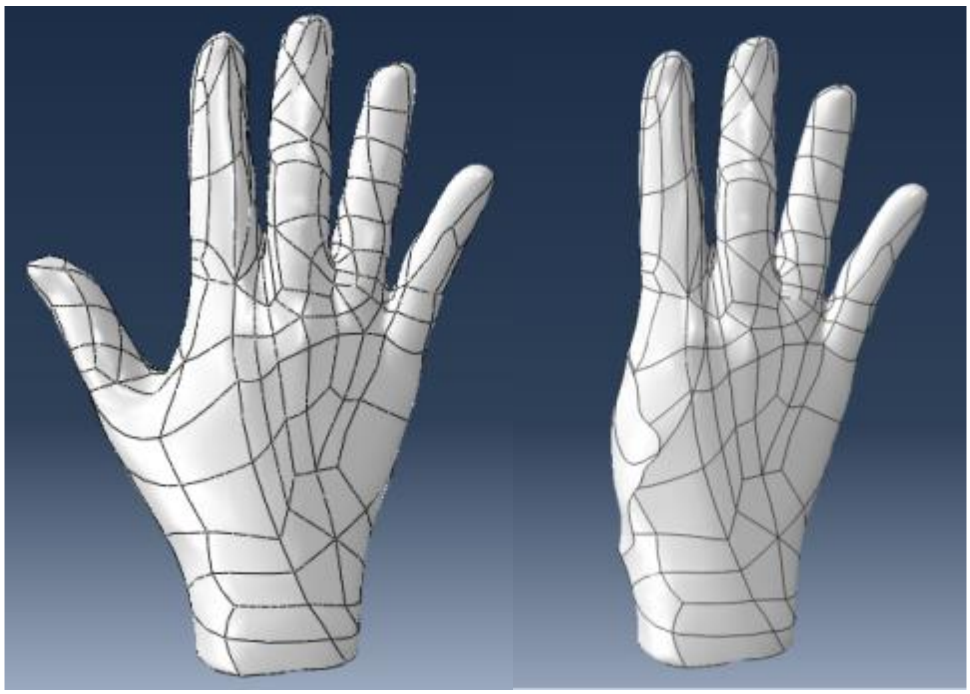


Figure 8.1 (a)Hand geometric model obtained from 3D scanning and (b)hand geometric model with thumb removed for use in pressure prediction model

8.2.1.2 Development of glove fabric model

A production pattern for making a 10% RF pressure therapy glove was custom-made for the hand. In the face of danger, people tend to clench their hand into a fist or use their hand to protect themselves, which leads to hand burns or scald wounds that are mostly found on the dorsal part of the hand. The model developed by the FEM would then mainly focus on the prediction of the interfacial pressure on the hand dorsum. The design of the palm and dorsum pattern pieces is therefore carried out separately from the thumb piece in the glove pattern development. To simplify the pressure simulation model, only the palm and dorsum were extracted whilst the thumb was neglected. The dorsal and the palm pattern pieces were joined as a single glove fabric geometric model to produce a pressure glove with a 10% RF (Figure 8.2).

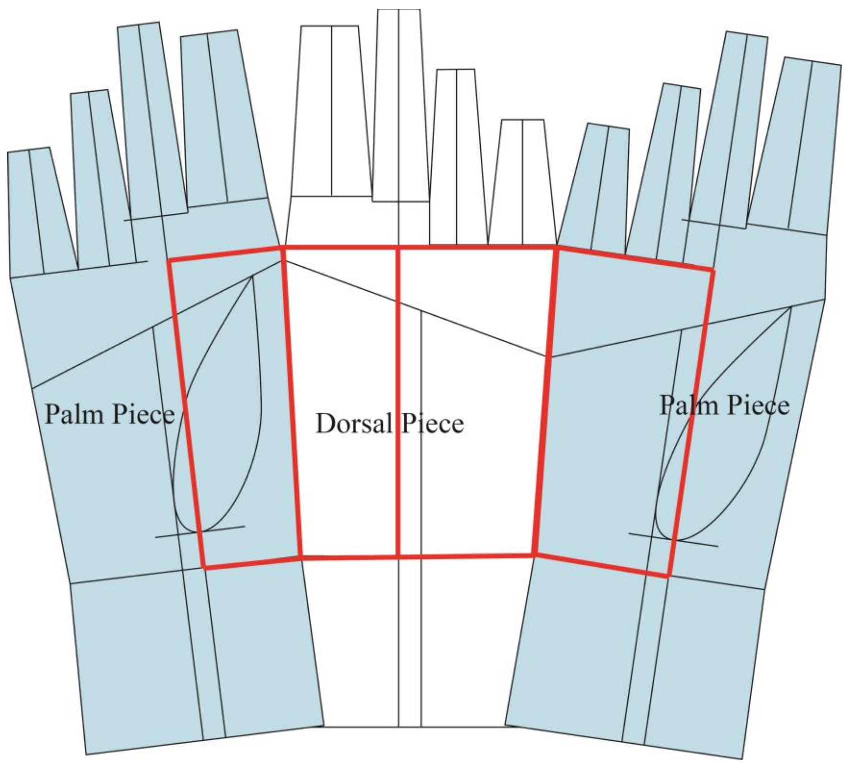


Figure 8.2 Part of glove pattern (red in colour) extracted for finite element analysis

8.2.2 Defining material properties

In this study, the simulation model has two material models: the hand and fabric. The hand was assumed to be homogeneous, isotropic and linearly elastic. Skin and dermis elasticity changes with age, gender and living conditions. With the presence of hypertrophic scars, the surface properties of the hand can be altered and largely vary from scar to scar. Hypertrophic scars are usually harder and more rigid than normal skin. Two simulations were conducted with one that characterised the hand model with the properties of human bone while another with the properties of human skin. Based on previous works on mechanical properties of the human body, the Young's modulus (*E*) and Poisson's ratio (*v*) of bone were defined as 17 GPa and 0.3 respectively [195-197]. With a proper treatment, the condition of hypertrophic scars can be better controlled with low pliability and to be soft as normal skin. The use of bone properties (e.g. *E* = 17 GPa) in the prediction model may possibly overestimate the pressure delivery. Therefore, the hand model with properties of human skin was also adopted in the simulation. Skin is much softer and assumed to have a much lower Young's modulus of 177 kPa [197-200]. Skin is incompressible and the Poisson's ratio was therefore assumed to be 0.4 [195].

A powernet fabric, Fabric B, and a satinnet fabric, Fabric D, were selected as the glove fabrics in the simulation. With reference to Chapter 6, these two fabrics not only represent different structures but also provide different levels of pressure delivery. The tensile property of each of the glove fabric was examined by using a tensile tester (Model 5566, Instron). The elasticity of each fabric was measured in accordance with British Standard BS EN 14704-1:2005. Each fabric sample was extended up to 30% elongation for five cycles. The Young's modulus of the fabric was determined from the stress-strain curve of the fifth extension. The Young's modulus is defined as the ratio of the tensile stress to the extensional strain and can be obtained from Equation (8.1).

$$E = \frac{\sigma}{\varepsilon} = \frac{\frac{f}{w\ t}}{\frac{(l_1 - l_0)}{l_0}} = \frac{f\ l_0}{w\ \ t\ (l_1 - l_0)} \qquad (8.1)$$

where *E* = Young's modulus (MPa), σ = engineering stress (N/mm^2), ε = engineering strain, f =tensile force applied to the fabric in the tensile test (N), w = fabric width of the testing sample (mm), t = fabric thickness (mm), l_0 = initial length of fabric (mm), and l_1 =elongated length of fabric (mm).

In order to determine the Poisson's ratio of the fabric, uniaxial tensile testing was conducted (Figure 8.3). The fabric samples were drawn into 5×5 mm grid squares. Each fabric sample was extended up to 100% elongation during which the change of fabric dimensions were recorded at every 10% interval by using a camera. The transverse and axial strains of the fabric during the extension can therefore be measured from the photos taken. The Poisson's ratio is the negative ratio of the transverse strain to the axial strain in the direction of the applied load and can be calculated as Equation (8.2).

$$\nu = -\frac{\varepsilon_{trans}}{\varepsilon_{axial}} \quad (8.2)$$

where ν = Poisson's ratio, ε_{trans} = transverse strain, and ε_{axial} = axial strain.

Figure 8.3 Experimental setting for determining the Poisson's ratio of a fabric

The amount of size reduction in the circumferential dimension of a pressure glove induces the pressure delivered onto the hand. Hence, the amount of pressure is mainly related to the fabric stress-strain behaviour in the horizontal direction of the glove during actual glove wear. The effect in the vertical direction is negligible. By following the traditional glove making process in hospitals, the pressure glove fabric was cut with the fabric grain along the course direction. The fabric model was assumed to be isotropic and the tensile properties of the fabric in the wale direction were taken into consideration. In terms of the tensile stress-strain curves of the two fabrics in the wale direction, they are linear in the application strain range from 0 to 30% (Figure 8.4). In the simulation model, the fabrics were also assumed to be linear elastic and the material properties are shown in Table 8.1.

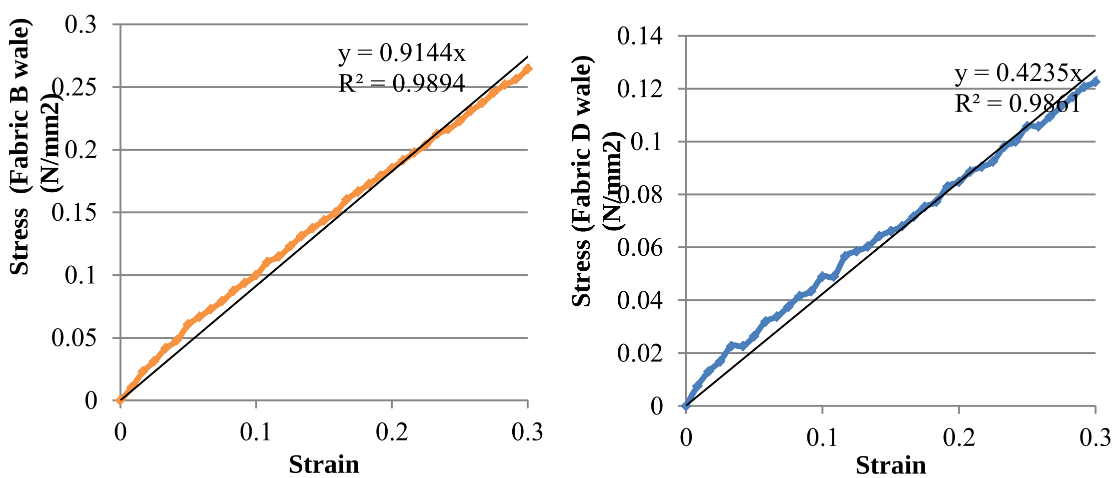


Figure 8.4 Tensile stress-strain curves of wale direction of Fabrics B and D

Table 8.1 Material properties of glove fabric

Fabric	Structure	*E* (N/mm2)	*v*	Thickness(mm)
B	Powernet	0.9144	0.2292	0.43
D	Satinnet	0.4235	0.244	0.474

E: Young's modulus in wale direction of fabric, *v*: Poisson's ratio

8.2.3 Defining mesh element type

The mesh is generated by top-down free meshing. The mesh element used for the hand model was a four-node linear tetrahedron element with three degrees of freedom at each node (C3D4) (Figure 8.5a). The hand model consisted of 220194 elements with a minimum mesh size of 2.3 mm. The mesh element used for the glove fabric model was a three-node triangular general-purpose shell with finite membrane strains (S3) (Figure 8.5b). There were 2940 elements in the glove fabric model with a minimum mesh size of 3 mm.

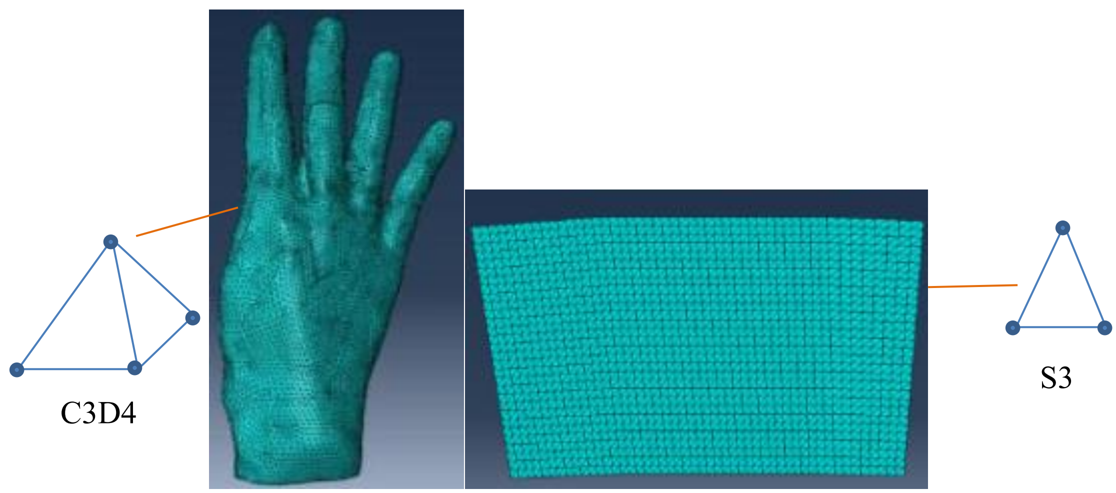


Figure 8.5 Meshed model of (a) hand and (b) glove fabric

8.2.4 Glove wearing process in the simulation model

In actual pressure glove wear, the glove is first applied onto the fingers, passed through the hand and then zipped up. The pressure glove is stretched and a treatment pressure is applied to the hand once the glove is zipped up and fully enclosed, and in contact with the hand. In the glove wear in the simulation model, the glove fabric is stretched so that it is fully enclosed around the hand and in contact with the hand so as to simulate the pressure applied by a pressure glove on the hand dorsum.

In the simulation model of the initial stage of wear, the hand and the fabric were separated without any contact in between the two (Figure 8.6). Both the hand and the glove fabric were taken to be elastic bodies that occupied domains Ω^1 and Ω^2 respectively. Surface-to-surface contact was applied to simulate the inter-surface interactions between the two components. The impact condition was set to hard contact which assumes that the two impact surfaces instantaneously acquire the same velocity in the direction of the impact. The hard contact relationship allowed no penetration of the slave surface into the master surface at the constraint locations and did not allow the transfer of tensile stress across the interface. When the surfaces were in contact, any contact pressure could be transmitted between them with no limit to the magnitude.

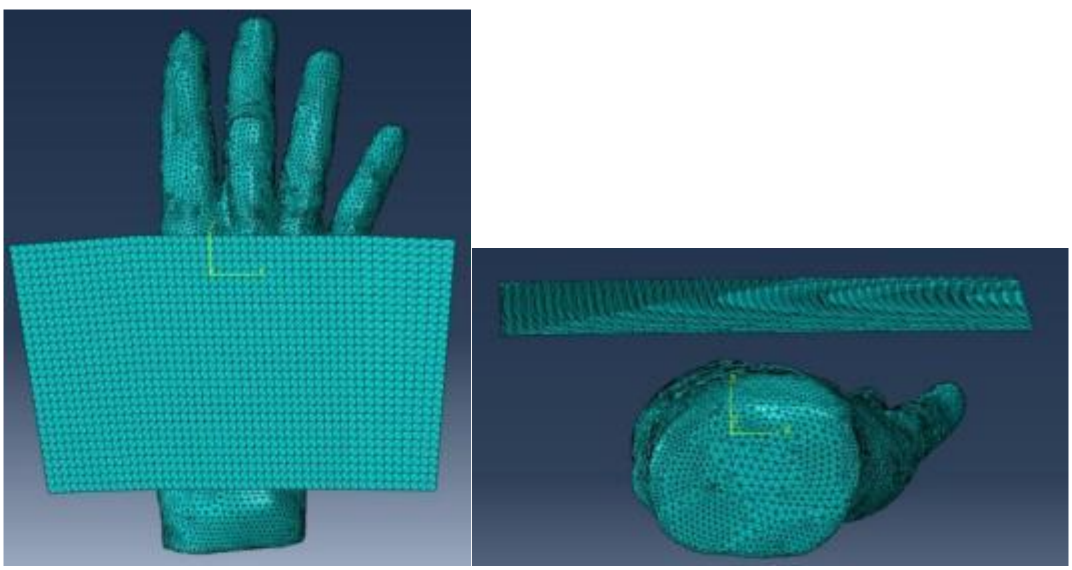


Figure 8.6 Assembly of the hand and the glove models

When domain Ω^1 is in contact with domain Ω^2, the boundaries of Ω^1 and Ω^2 which are denoted by Γ^1 and Γ^2 respectively consist of three parts:

$$\Gamma^p = \Gamma_d^p \cup \Gamma_\sigma^p \cup \Gamma_c^p \qquad p=1,2 \qquad (8.3)$$

where Γ_d is a prescribed displacement, Γ_σ is a prescribed surface load and Γ_c is the contact boundary when contact occurs[150].

Boundary point x_1 on the hand is in contact with boundary point x_2 on the glove fabric. The inequality constraint of the non-penetrated condition is defined as:

$$g_N = x_2 - x_1 \geq 0 \quad (8.4)$$

where g_N is the normal gap between the two points.

The boundary points (x_1,x_2) and the associated normal vectors ($N^1{}_1$, $N^2{}_1$) and tangential vectors ($N^1{}_2$, $N^1{}_3$, $N^2{}_2$, $N^2{}_3$) are shown in Figure 8.7. The component of the contact force $F_c{}^p$ in the direction of $N^p{}_i$ is defined as

$$F^p_{ci} = F^p_c N^p_i \qquad p=1, 2, i=1 \text{ to } 3 \quad (8.5)$$

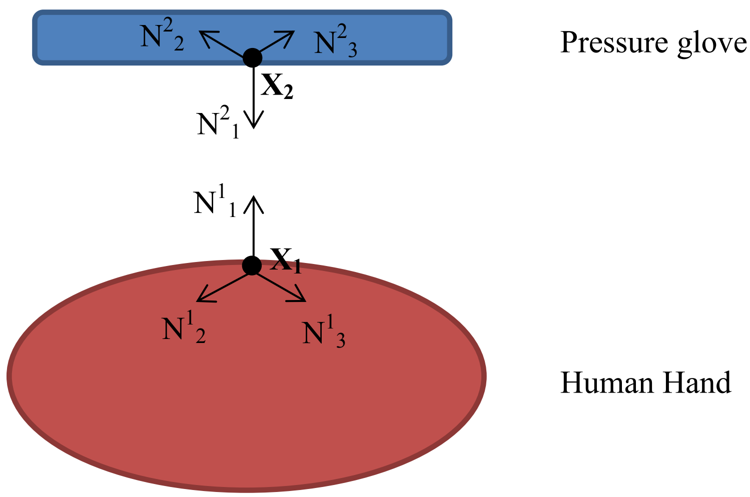


Figure 8.7 Two boundary points and its associated normal and tangential vectors on pressure glove and human hand

In the present study, the friction between the hand and the glove fabric was neglected. By denoting the contact force at x^p by $F_c{}^p{}_1$ and by Newton's third law,

$$F^1_{c1} = -F^2_{c1} \qquad \text{on } \Gamma_c{}^1 \cap \Gamma_c{}^2 \quad (8.6)$$

The interactive force is exerted on the pressure glove or the hand against its normal direction of contact points. The fabric was selected as master surface while the hand was taken as slave surface. The two deformable surfaces underwent mechanical finite-sliding with a penalty contact algorithm to enforce contact constraints. The surface to surface discretization method was used and no surface smoothing was allowed. The wrist cross-section of the hand was assumed to be aptotic with zero displacements in the x, y and z directions of the global coordinates in the boundary. The wearing process started with the two sides of fabric moving towards and surrounding the hand (Figure 8.8). As stresses were applied onto the left and right sides of the fabric to pull them together, the stress distribution on the two sides were not in equilibrium (Figure 8.9). Therefore, constraints were added on every corresponding pair of nodes on the left and right sides to sew them together. After that, the uneven stresses of the fabric on the two sides were allowed to release over the whole glove fabric (Figure 8.10). The hand was then tightly surrounded by the glove fabric tube and hence the contact pressure distribution on the hand could be simulated.

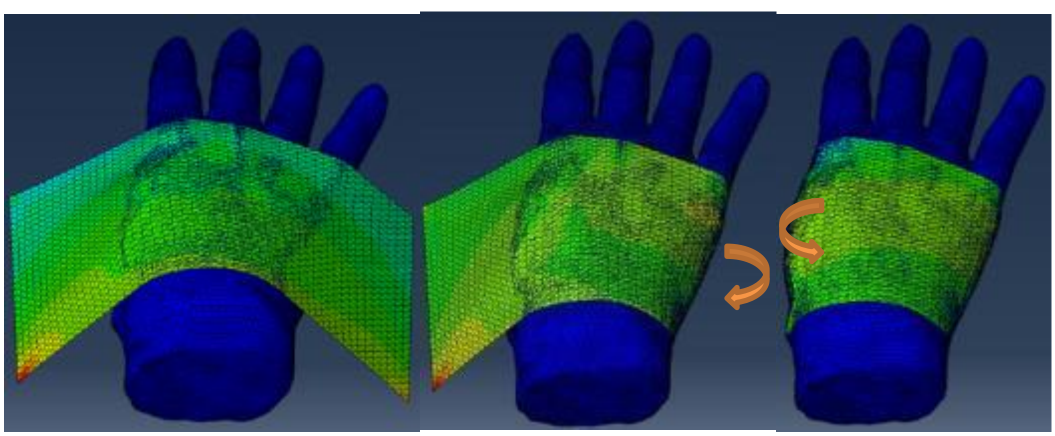


Figure 8.8 Moving the fabric towards and surrounding the hand

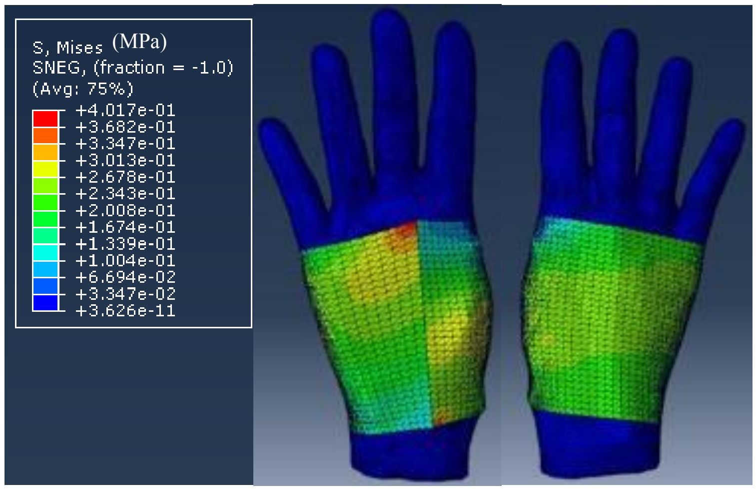


Figure 8.9 Stress distribution on the glove fabric after fully surrounding the hand

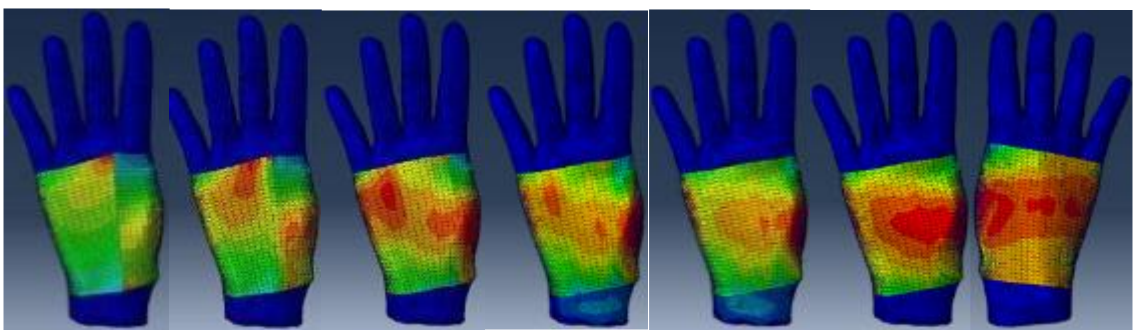


Figure 8.10 Adding constraints to sew the left and right sides of the fabric and allowing pressure to reach the equilibrium stage

8.2.5 Validation

To verify the pressure predicted by the simulation, the garment pressure that was exerted onto the plaster and the human hands were measured and compared with that predicted by the FEM. The hand dorsal side of the glove was fully drawn with 1×1 cm grid squares (Figure 8.11). The glove was then worn by the plaster hand and the real hand. The pressure under each grid square was measured by using a pressure sensor (Novel Pliance X system, Germany). In order to locate the measurement points from the simulation model, the hand with contact pressure distribution obtained from the FEM was superimposed with the picture of the plaster hand with the pressure glove. As shown in Figure 8.12, the notation of every column of grids is composed of alphabets while that of every row is composed of numbers, i.e. the grids that run down from the top of the first left column are named A1, A2, A3…to A7, and the grids of the first row from the left to the right are A1, B1, C1…to G1. In the simulation model, the predicted pressure of each grid was regarded as the average of the contact pressures given by the glove fabric in the normal direction onto the elements within the grid. The values obtained from the pressure sensor measurement were compared with the prediction values by the FEM at the corresponding locations.

Figure 8.11 Grid marks on pressure therapy glove

Figure 8.12 Superimposing of the plaster hand with pressure glove and the hand with contact pressure simulation from FEM

8.3 Results and Discussion

Validation of the simulation model was carried out by comparing the predicted pressure value with the actual measurement. The results of the pressure simulation and the sensor measurements at different locations over the hand dorsum given by the gloves made of Fabrics B and D are shown in Figures 8.13 and 8.14 respectively. The simulation pressure values provided by the FEM show a similar trend with the measured values for both the real and plaster hands. The simulation that assigned the hand with bone material properties shows pressure values close to the measured values on the plaster hand (RMSE = 1.99 kPa) while the simulation that assigned the hand with skin material properties gives pressure values that are more similar to the measured pressure on the real hand (RMSE = 0.47 kPa). The differences between the predicted pressure from the simulation that considers bone material properties and the pressure measured on the plaster hand are within 20% for at least half of the locations. Plaster is relatively hard and rigid in comparison with a real hand and thus has a higher interfacial pressure with the use of pressure gloves. The high Young's modulus of bone implies a high stiffness and the predicted glove pressure from the model that assigned bone properties to the hand can give values that are similar to the interfacial pressure on the plaster hand. A real human hand consists of different components, including skin, muscles, bones, tendons, blood vessels, nerves, etc. Each component has different material properties and varies from person to person. Due to pliability, the interfacial pressure between the gloves and real hands is much lower. The differences between the predicted pressure from the simulation model that assigned the hand with skin properties and the pressure measured on the real hand are within 20% for almost half of the locations (22 locations for both fabrics). The hand model in the simulation has a certain elasticity which allows the prediction of pressure values that are closer to the interfacial pressure between the gloves and the real hand. In the simulation models, the material properties assigned to hand model is not exactly that of the plaster hand and the real hand sample used for validation. Therefore, it is reasonable to find differences (20% values) between the measured and predicted pressure. More importantly, on the basis of the proposed simulation model, therapists can better understand the properties and pressure performance of pressure therapy gloves, such as identifying the locations with insufficient or excessive high pressure, thus prescribing suitable rehabilitation treatment for patients with hypertrophic scar and hence facilitating the effectiveness of pressure therapy.

The predicted values on column A and column G areas show certain variation with the measured values. Column A is on the cutting edge of thumb of the hand model. The cutting edge slightly affects the hand geometry around that area and result in the variation of the predicted values. Around the column G area, a zipper is sewn in the glove used in pressure measurement. The presence of zipper and sewing workmanship that affecting the pressure delivery has been neglected in the simulation model. But for the other location points, the predicted and measured interfacial pressure shows a similar trend. Therefore, the simulation model developed by the FEM can be regarded as good accuracy in predicting the glove-skin interfacial between the pressure glove and the hand.

The simulation model developed by using FEM shows the contact pressure distribution on the hand given by the different glove fabrics, that is, Fabrics B and D. The pressure given by the Fabric B glove as shown in Figure 8.15 is higher than that by Fabric D glove as shown in Figure 8.16. Fabric D has higher elasticity and thus the pressure delivered to the hand by a glove made of this fabric is relatively lower. The result is consistent with the interfacial pressure measured on the plaster and real hands during validation and also the measurement results from Chapter 6. By looking at the pressure distribution pattern over the hand dorsum, the pressure increases with hand curvature. For instance, the pressure is relatively higher on grids B1, B2 and D1 (8.27-11.23 kPa for Fabric B on the hand model with bone properties) where the tendons of the ED are present and shown as raised on the hand dorsal surface. Due to the higher curvature, high pressure is also observed on the area near the lateral parts of the hand on columns A and G. The pressure distribution pattern parallels the pressure prediction model formulated in Chapter 5 in that the curvature of the hand surface directly affects the pressure delivered by the pressure glove. The change in the material properties of the hand model in terms of human bone (a harder material) vs. skin (a softer material) can lead to a decrease in the whole pressure level distributed over the hand dorsum. This implies that the skin and scar condition which lead to a variation in stiffness and pliability can affect the pressure received from the pressure glove. Practitioners therefore should pay more attention to fabric properties and scar stiffness in pressure glove prescription, and particularly that daily hand movements will also increase glove-skin interfacial pressures.

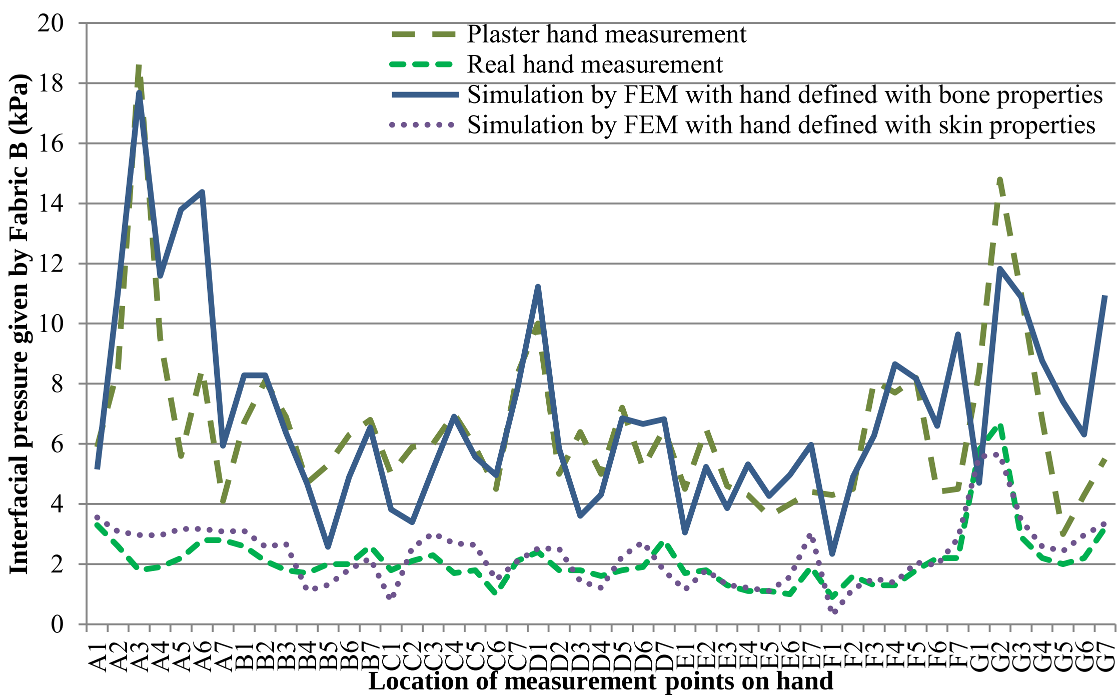


Figure 8.13 Comparison of simulated pressure from FEM and sensor measured pressure on plaster and real hands induced by glove made of Fabric B

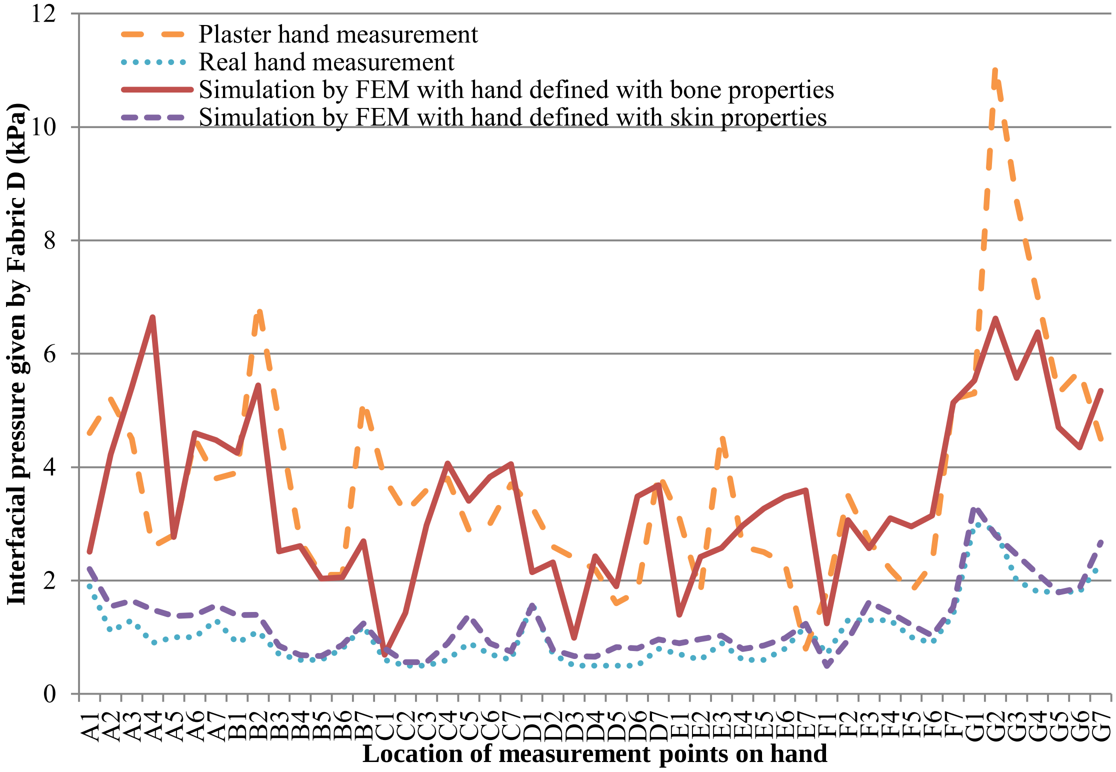


Figure 8.14 Comparison of simulated pressure from FEM and sensor measured pressure on plaster and real hands induced by glove made of Fabric D

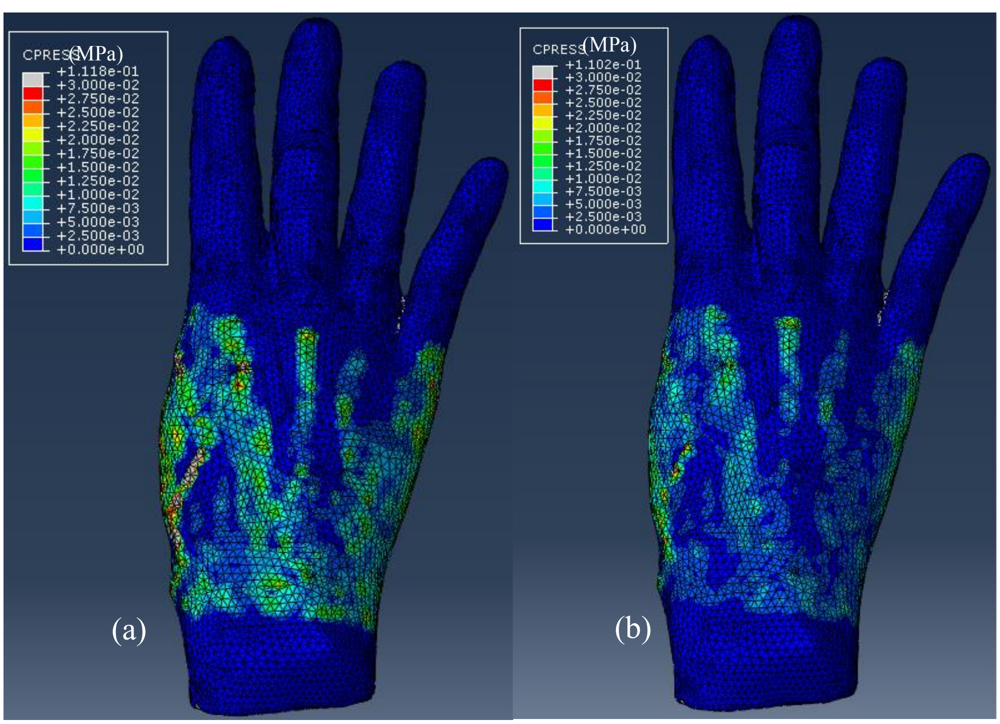


Figure 8.15 Simulation of contact pressure distribution by glove made of Fabric B on hand defined with properties of (a) bone and (b) skin

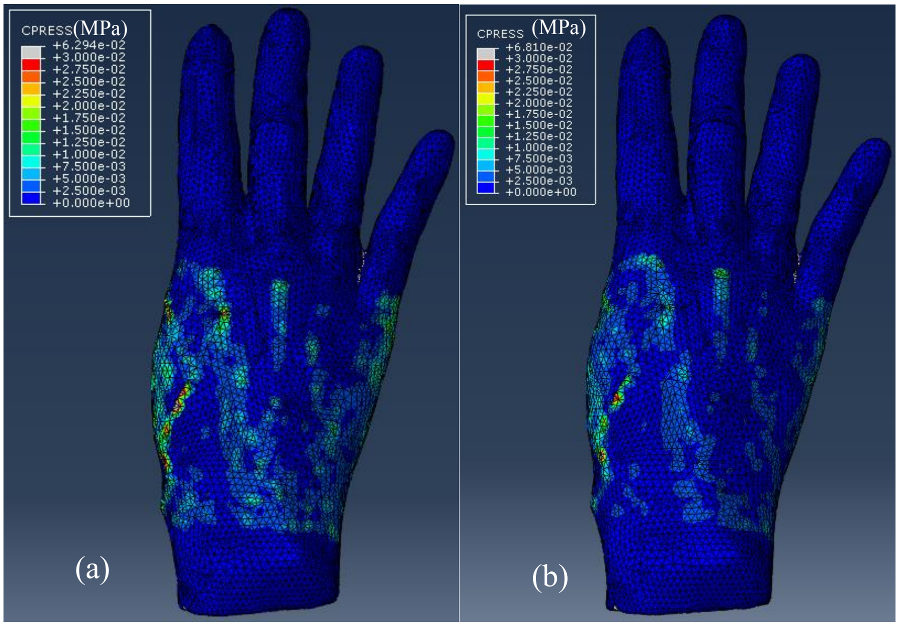


Figure 8.16 Simulation of contact pressure distribution by glove made of Fabric D on hand defined with properties of (a) bone and (b) skin

8.4 Summary

A simulation model for predicting the interfacial pressure given by pressure gloves on a human hand was developed by using FEM. The simulation model can predict the trend of pressure distribution when the glove is worn. By considering the properties of bone and skin in the hand model for the simulation, the pressure predicted is close to the pressure measured when the glove is worn on plaster and real hands respectively. The model shows reasonable accuracy in the prediction and can help to determine the overall contact pressure distribution over the hand dorsum. With the use of the simulation model, the pressure distribution given by pressure gloves can be determined by obtaining a 3D image of the hand of a patient. The time required, pain and discomfort caused by pressure measurement can therefore be eliminated. By changing the material properties of the fabric model, the pressure distribution on the hand given by different fabrics can be obtained. This can assist clinicians in selecting a suitable fabric for making a pressure glove.

Chapter 9 Conclusion and Recommendations for Future Work

9.1 Conclusion

Pressure therapy gloves are the mainstay of treatment for hypertrophic scars on hands. Nevertheless, the amount of pressure given by these gloves to treat the scars cannot be efficiently controlled and treatment compliance is lacking due to issues with comfort and restriction of movement. The aims of this thesis are to fill the knowledge gaps in the traditional pressure glove prescription practice through the development of a new hand measuring approach, understanding of glove fabric tensile properties and tension decay, investigating of the physiological and psychophysical effects induced by these gloves on human responses, producing of a new pressure glove prototype and development of a simulation model by FEM for contact pressure prediction. The objectives listed in Section 1.3 have been realised and the achievements of the work are summarised as follows.

1) The research work started with an 18 week clinical study on 5 patients to observe current clinical practices. The hypertrophic scar conditions, interfacial pressure, temperature and humidity between pressure therapy gloves and the skin at different times are recorded and analysed. Interviews have also been carried out to understand the feelings of the patients towards pressure therapy. The influence of the pressure gloves on work and daily activities, feelings of being hot, moisture and poor breathability are identified as the problems associated with pressure gloves and also the reasons for taking off the gloves. Poor compliance and uncertainty on the amount of interfacial pressure for pressure therapy gloves are identified as the two major aspects that need to

be improved for higher quality pressure therapy and better treatment outcome.

2) In the research, 2D and 3D image analysis methods are developed as the measurement means of hand anthropometry by using a domestic colour scanner and a 3D laser scanner respectively. Both image analysis methods do not require direct contact with the hand of the subjects throughout the entire process and hence minimise the discomfort of the patients during the measurement taking process. The anthropometric measurements, morphology and curvature of the hands, thumbs, fingers and related joints have been analysed. The 3D image analysis method is able to obtain results that are close to those of direct measurements. The analysis results show that 3D image analysis can provide hand measurements that have no significant differences from manual hand measurements, including the hand and finger circumferences, length and breadth dimensions, and offers high precision and good repeatability during the course of treatment. It therefore provides precise hand measurements for developing optimal fitting pressure therapy gloves.

3) The research work has demonstrated the impact of hand surface contour, hand posture, fabric properties and RF of pressure gloves on glove-skin interfacial pressure and glove tension decay. The positions where the pressure is measured and their corresponding curvature and geometry changes caused by hand movements and postures are closely associated with the glove-skin interfacial pressure. Continuous fabric extension and contraction due to hand movements and different postures during daily activities are closely associated with the significant loss of glove pressure over repeated use. Fabrics with a high initial tension have a large amount of tension loss and pressure

decay. A mathematical interfacial pressure prediction model based on Laplace's equation has been formulated to determine if there is any statistical difference between the predicted and the measured glove pressures, but none is found. With this simple mathematical model, the glove-skin interfacial pressure can therefore be predicted from the fabric tension behaviour, strain of the glove and hand curvatures.

4) In the research, the physiological and psychological effects of pressure gloves, glove fabric and RF on human response are explored. The effects on the HR, BP, glove-skin microclimate, hand performance, forearm muscle activity, grip strength and subjective sensory perception have been investigated in a series of wear trials. There is no significant impact on the HR, BP and finger tactile sensitivity caused by the pressure gloves with a reduction of 10-20% in the circumference dimensions from the actual hand measurement. However, there is a noticeable influence in the skin-glove microclimate. The fabric properties of the glove, including air permeability, moisture retention and drying rate are found to be correlated to the skin-glove temperature. The AROM of the finger, dexterity in carrying out daily tasks, maximum gripping force, and comfort sensation and perceived ease of hand motion are also negatively affected. In certain daily activities that require fine motor skills, the results also reveal that the forearm muscles activities are greatly affected by the tightness of the glove. The negative impact becomes more significant when a high RF of 20% is used for the pressure glove.

5) Feasible modifications to the development of pressure therapy gloves are proposed. A

modification to the glove production pattern in the finger web areas can improve the fit and better control scar growth in those areas. Also, textile inserts made of spacer fabric can be used as a substitute for conventional Plastazote® inserts to provide better comfort and breathability, and effectively increase the local pressure for scar treatment. The use of thermoplastic adhesive tape is also suggested as a feasible method to affix a textile insert onto a pressure garment to address the long standing problem of displacement during wearing. With the new pressure glove design, adequate pressure can therefore be exerted onto hands for hypertrophic scar treatment, the physiological comfort of patients will be improved and flexible and continuous use of the gloves is facilitated.

6) The research demonstrates the prediction of contact pressure distributed over the hand dorsum through a biomechanical simulation model by using FEM. Both the geometrical and mechanical properties of the glove and human body tissues are taken into consideration in the pressure simulation model. By taking into account the different mechanical properties of human tissue, the optimal skin pressure can be precisely predicted and controlled in relation to the glove pattern design, fabric mechanical properties, curvature of the anatomic sites, etc. This could effectively optimise the quality and performance of the treatment process, and hence the outcomes of the scar treatment.

9.2 Limitations of the study

There are some limitations to this study that restrict the generalisation of the results.

1) In the series of wear trials for understanding the physiological and psychophysical effects of pressure therapy gloves on human responses, the participants are not suffering from hypertrophic scars. It is reasonable to deduce that the presence of hypertrophic scars may further restrict hand performance and a different level of discomfort can result. However, there are many kinds of scars that can mask the effects of pressure therapy gloves on hand functions and comfort perception. Apart from psychophysical sensations, the pain caused by the scars can be another important concern in the treatment of burn rehabilitation. An examination of the impact of the pressure gloves on hands with these types of scars is essential to reflect real life scenarios. The findings from this study have only highlighted the impact of fabric type and RF, so as to provide reference for clinicians so that they can find a balance between the tightness of the gloves and hindering of hand functions and comfort perception during the development of the pressure glove. Moreover, the wear trials are carried under room conditions. The impact of pressure therapy gloves at different temperatures and humidities is not investigated, but could be useful for identifying a suitable fabric for different seasons and regions.

2) A textile insert method by using thermoplastic adhesive tape for seaming has been proposed in this study. However, due to the difficulties in recruiting suitable individuals with hypertrophic scars and also limitation of time, the practical use and comfort of the insert have not been fully evaluated. However, this proposed method can be a possible means to simplify the glove prescription and replacement processes, thus improving the treatment quality and adding a new design and dimension to pressure thermal garments. Further and more in depth investigations on the attachment method would be needed.

3) The hand geometric model used in the FEM is a normal hand without hypertrophic scars. Hypertrophic scars can develop with a wide range of different sizes, shapes, colours and softness in accordance with the condition of the wound of the injury, personal healing system, treatment received, etc. To enhance the practical use of the simulation model, it is important to develop a model that considers the geometry of the hypertrophic scars and their mechanical properties. The simulation model developed in the present study can act as a preliminary means for further development and improvement of the model.

9.3 Recommendations for future work

Based on the established research findings, the following recommendations are made:

1) after investigating the impact of fabric type and RF on human response, it is recommended that the study be extended to patients with hypertrophic scars to evaluate the combined effect of pressure gloves and hypertrophic scars on hand functions, and

2) further development on the measurement method of geometrical parameter of hypertrophic scars in term of thickness, dimensions, etc. with the use of 3D image analysis to provide an objective quantitative scar condition measurement method, and

3) a pressure prediction model that adopts a hand geometric model with the presence of hypertrophic scars can help to further evaluate the feasibility of the prediction by using FEM for implementation in clinical practice. A comprehensive database of the mechanical properties of different body tissues and hypertrophic scars (such as hardness) can considerably improve the accuracy of pressure simulation and hence, the quality and efficacy of treatment.

Appendix I Consent to participate in research

Participate Consent Form

Title of Project: Development of pressure therapy gloves for hypertrophic scar treatment

Name of researcher: Dr. Kit-lun YICK, Miss Amelia Ying-fan CHAN, Dr. Sun-pui NG, Dr. Yiu-wan YIP and Prof. Xin ZHANG

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. The results will be published in referred medical and textile journals. All information collected will be kept confidential.

4. 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

<<Chinese version>>

參與研究項目同意書

研究主題: 發展用於增生性瘢痕復康治療的壓力手套

研究員: Dr. Kit-lun YICK, Miss Amelia Ying-fan CHAN, Dr. Sun-pui NG, Dr. Yiu-wan YIP and Prof. Xin ZHANG

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. 研究結果將會發報在醫學和紡織設計刊物內。其他的資料一概保密

4. 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

Appendix II Information sheet for clinical study participant

Development of pressure therapy glove for hypertrophic scar

Information sheet

Name:________________ Gender: ☐M ☐F Date of Birth:_______________

Record Period:____________________________~____________________________

Research program process:

The whole research study lasts for 6 months. You are required to come back to hospital 6 times for assessment including:

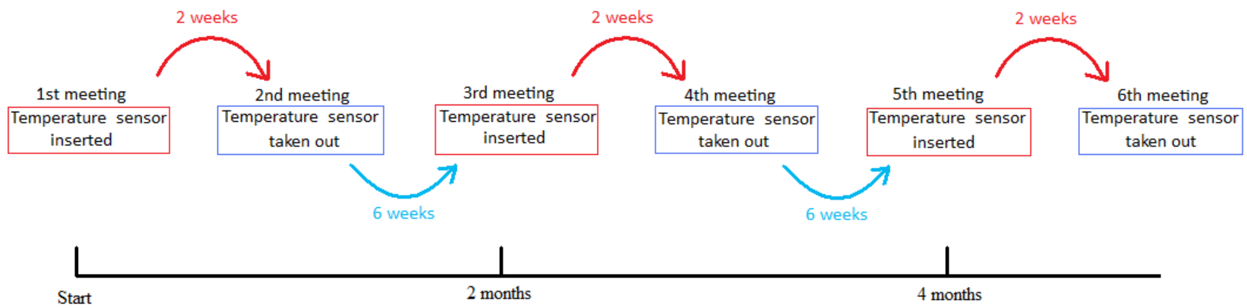
(1) An interview to understand your life and work, scar condition and feedback of the pressure garment.

(2) Pressure sensing to measure the pressure apply on your hand by the pressure therapy glove.

(3) Inserting 2 temperature sensors to your pressure glove and padding on the first, third and fifth meeting as well as taking them out on the second, fourth and sixth meeting. The temperature sensors will record your hands temperature and humidity for 14 consecutive days. During the period of the sensors wearing, you need to fill in the sensor wearing time record table every day.

The whole assessment will take around 30 minutes.

The schedule for the 6 meetings would be as follow:



In order to show our thanks, a $200 cash coupon will be given once finished the 14 days temperature and humidity sensing, sensor wearing record form and questionnaire and the bi-monthly assessment.

Care Instructions:

-The pressure glove should be used together with the padding and other treatment modality

-The pressure glove should be wash by water.

-The temperature sensor on the glove **needed to be taken out** and put onto another cleaned pressure glove for the glove washing.

-Unless for normal cleaning, the temperature sensor on the padding **should NOT be taken out.**

-Please make sure the sensors are in touch with the skin.

-Please do not put the sensor under water.

-Please do not throw away, open or break the sensor.

Contact information:

If the sensor is lost or damaged, please immediately call Dr Yick Kit Lun on 2766-6551 or Ms Chan Ying Fan, Amelia on 2632 . You are also welcome to contact us if you have any questions or would like to withdraw from the research.

Temperature sensor wearing time record table

	Date	Please put a ✓		Temperature sensor wearing time (Please put a ✓ on the box below the time when the temperature sensor is wore during the whole period of time)																							
		Work day	Day-off	A.M.												P.M.											
				00:00 ~ 1:00	1:00 ~ 2:00	2:00 ~ 3:00	3:00 ~ 4:00	4:00 ~ 5:00	5:00 ~ 6:00	6:00 ~ 7:00	7:00 ~ 8:00	8:00 ~ 9:00	9:00 ~ 10:00	10:00 ~ 11:00	11:00 ~ 12:00	12:00 ~ 1:00	1:00 ~ 2:00	2:00 ~ 3:00	3:00 ~ 4:00	4:00 ~ 5:00	5:00 ~ 6:00	6:00 ~ 7:00	7:00 ~ 8:00	8:00 ~ 9:00	9:00 ~ 10:00	10:00 ~ 11:00	11:00 ~ 00:00
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<<Chinese Version>>

發展用於增生性瘢痕復康治療的壓力手套

參與者須知

姓名:__________________ 性別: □M □F 出生日期:______________

紀錄時段:__________________________~__________________________

研究計劃過程:

整個監測為期六個月。你須要回到醫院七次以進行跟進及詳細檢查，其包括:

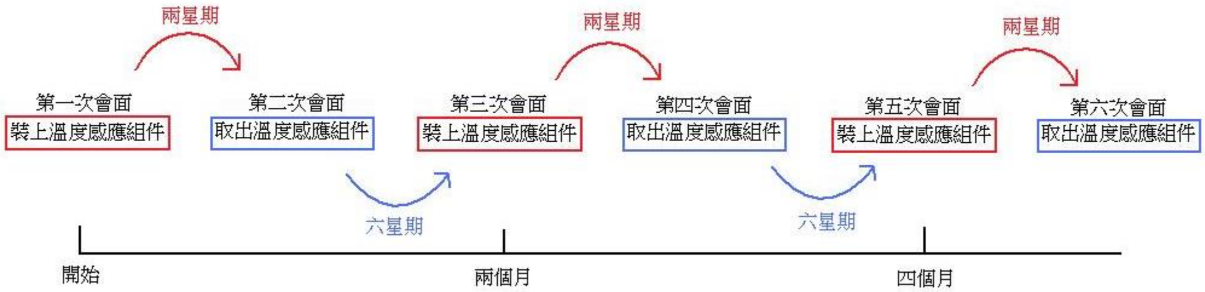
(1) 進行會面，從而了解你的日常生活、工作、瘢痕的狀況及對於壓力手套的反應。

(2 使用感應器材，從而量度配戴壓力手套後，你手部瘢痕皮膚的壓力分佈。

(3) 於第一、三、五次會面時，在你的壓力手套及壓力墊內裝上兩個溫度感應組件，並於第二、四、六次會面時取出。該溫度感應組件會於連續十四天之中，記錄你的手部溫度和濕度變化。於配戴感應組件的期間，你需要每天填寫配戴感應組件之時間記錄表。

整個會面過程約需三十分鐘。

六次會面的安排如下:



為表謝意，每完成為期十四天的溫度及溫度監測、配戴感應組件之時間記錄表和問卷及兩個月的詳細檢查，我們會送上港幣二百元的現金購物券。

<u>保養指示:</u>

-請把壓力手套與其壓力墊及其他配件一併使用。

-請使用水或清潔劑清洗壓力手套。

-在日常清洗前，請先**拆下**壓力手套中的溫度感應組件，並於另一手套裝上。

-除日常清洗外，**切勿取出**壓力墊中的溫度感應組件。

-請確保感應器材接觸到皮膚。

-請勿使感應器材與水接觸。

-請勿丟棄、打開或壓碎感應器材。

<u>聯絡資料:</u>

如遺失或損壞感應器材，請立即致電予 27666551 易潔倫博士或 2632 陳映芬小姐。如有任何疑問，你亦可致電以上電話。

配戴感應組件之時間記錄表

	日期	請填上✓		溫度感應器材的配戴時間 請於配戴溫度感應器的相應時間方格填上✓(需於整段時間配戴方可填上✓)																							
		上班	假期	A.M.												P.M.											
				00:00 ~ 1:00	1:00 ~ 2:00	2:00 ~ 3:00	3:00 ~ 4:00	4:00 ~ 5:00	5:00 ~ 6:00	6:00 ~ 7:00	7:00 ~ 8:00	8:00 ~ 9:00	9:00 ~ 10:00	10:00 ~ 11:00	11:00 ~ 12:00	12:00 ~ 1:00	1:00 ~ 2:00	2:00 ~ 3:00	3:00 ~ 4:00	4:00 ~ 5:00	5:00 ~ 6:00	6:00 ~ 7:00	7:00 ~ 8:00	8:00 ~ 9:00	9:00 ~ 10:00	10:00 ~ 11:00	11:00 ~ 00:00
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Appendix III Interview questions of clinical study

<u>Interview</u>

Name: ________________
Date: ________________

Part 1

Understand the habit, attitude and adherence towards the pressure therapy scar treatment:

1. How often do you change the pressure glove?

2. How many hours a day do you wear the pressure therapy gloves on average?

3. Apart from hygienic purposes or laundry, why did you take off the gloves?

☐ fabric discomfort	☐ too hot & perspiration	☐ too tight
☐ seam discomfort	☐ poor fitting	☐ pressure too high
☐ aesthetic problem	☐ restrain daily activities	☐ change of dimensions
☐ pressure decay of gloves	☐ others, please specify______________________________	

4. Do you face any difficulties in wearing the pressure glove?

5. Other than the pressure glove, there are other accessories likes, paddings, need to wear for treating the scar. Do you face any problem with this?

6. Do you follow occupational therapist instruction to wear and handle the pressure glove?

7. Do you think you have enough communication with occupational therapist in expressing your feeling and sensation on the pressure glove? Will you opinion being adopted and make the pressure glove fit you more?

8. How often you put on ointment or oil endorsed by doctor?

9. Do you often do massage on the scar?

10. Do you seek for other ways to treat the scar, like eating something or applying something on the scar?

Part 2 Understand the subjective feelings on the efficiency of the pressure therapy treatment:

	Strongly Disagree ←- - - - - - - - - - - - - - - - -						→Strongly Agree
The pressure glove is effective.	1	2	3	4	5	6	7
The scar is becoming smooth after wearing the pressure glove.	1	2	3	4	5	6	7
The glove can help to control the growth of scar.	1	2	3	4	5	6	7
.The scar is becoming smaller after wearing the pressure glove.	1	2	3	4	5	6	7

Part 3

Understand the problems associated with wearing the pressure garment

1. How the pressure glove affects your daily life?

2. How the pressure glove affects your work?

Which part/parts of the pressure garment make you feel bad?

☐Hand feel ☐Breathability ☐Strength ☐Durability
☐Pressure decay after wearing and washing ☐Pressure exert on hand/fingers
☐Ease of putting on/taking off ☐Uncomfortable
☐Restrain hand/fingers movement ☐Design ☐Fitting
☐Displacement of gloves ☐Aesthetic Appearance
☐Limit work/daily life ☐Lowers working efficiency
☐Others, please specify: ____

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問卷

姓名:__________________

日期:__________________

第一部分

了解患者對於壓力治療的習慣，態度和堅持度

1. 您多久更換一次壓力手套？

2. 您平均一天使用壓力手套幾個小時？

3. 除了考慮到衛生因素和為了洗滌手套，您還會在什麼情況下摘下手套？

☐ 布料不舒適　☐ 感到太熱或有手汗產生　☐ 感到手套太緊

☐ 對縫合部份感到不適　☐ 手套不合不符合自己的手型　☐ 手套壓力過大

☐ 美觀原因　☐ 影響手部的日常活動　☐ 手套使用後產生的變形

☐ 手套壓力效果的減退　☐ 其他原因，請列舉____________________________

4. 在佩戴手套時，您有遇到什麼困難嗎？

5. 在您佩戴其他輔助治癒工具，比如填充墊時，您有遇到什麼困難嗎？

6. 您是否遵循專業治療師的指導去穿戴和保管壓力手套？

7. 您是否將佩帶手套時的感受和感覺與專業治療師進行足夠的溝通？您的意見是否將被採用去製作更符合您的手套？

8. 您多久會使用一次醫生處方的藥膏和藥油？

9. 您多久會對傷疤進行按摩？

10. 為了治癒傷疤，您有否尋找其他方法。比如，吃特殊食品等等？

第二部分

了解患者是否認為壓力療法有益於疤痕的痊癒

完全不同意 ←------------------→完全同意							
壓力手套是有效的	1	2	3	4	5	6	7
在佩戴壓力手套後，患部變得光滑	1	2	3	4	5	6	7
壓力手套可以幫助控制疤痕的生長	1	2	3	4	5	6	7
.T 在佩戴壓力手套後，疤痕變得小了	1	2	3	4	5	6	7

第三部分

了解患者在佩戴手套時所遇到的問題

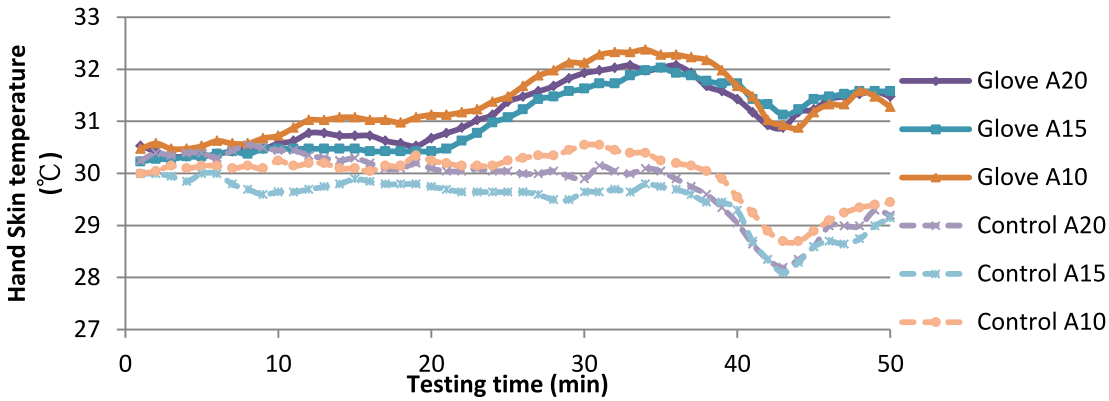
1. 佩戴壓力手套會怎樣影響您的日常生活？

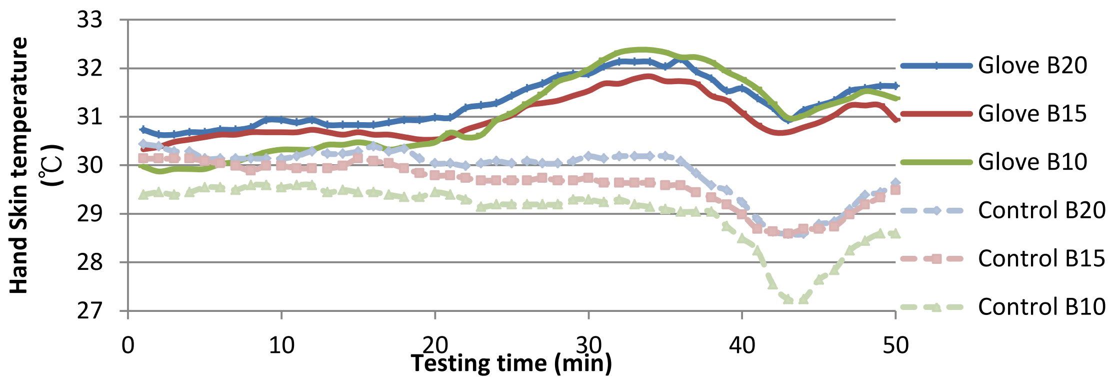
2. 佩戴壓力手套會怎樣影響您的工作？

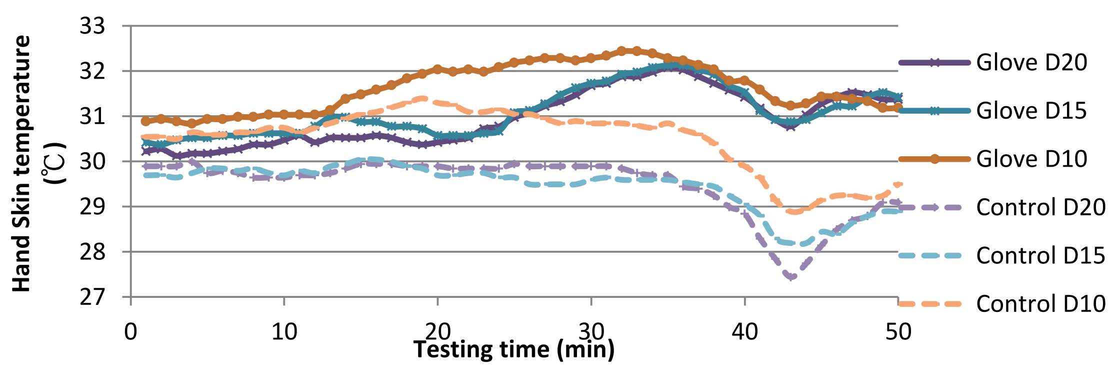
3. 什麼因素讓您對手套感到不滿？

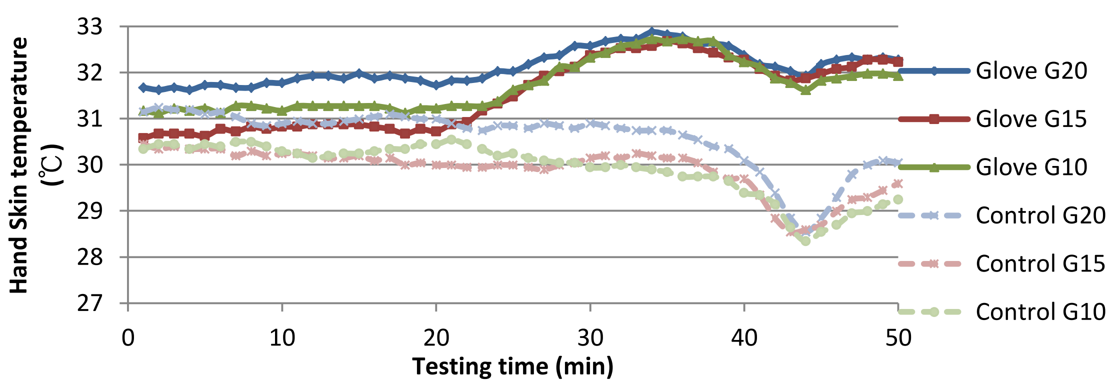
☐ 手感 ☐ 透氣性 ☐ 強度
☐ 耐用性 ☐ 使用和洗滌後壓力減弱 ☐ 帶給手部和手指的壓著感
☐ 佩帶或摘下輕易度 ☐ 不舒適 ☐ 影響手或手指的移動
☐ 手套的功能設計 ☐ 合身度 ☐ 佩戴時手套或填充墊移動
☐ 外觀和審美性 ☐對工作和日常生活的限制 ☐ 降低工作效率
☐ 其他因素，請列舉______________________________

Appendix IV Temperature under different glove sample during wear trial

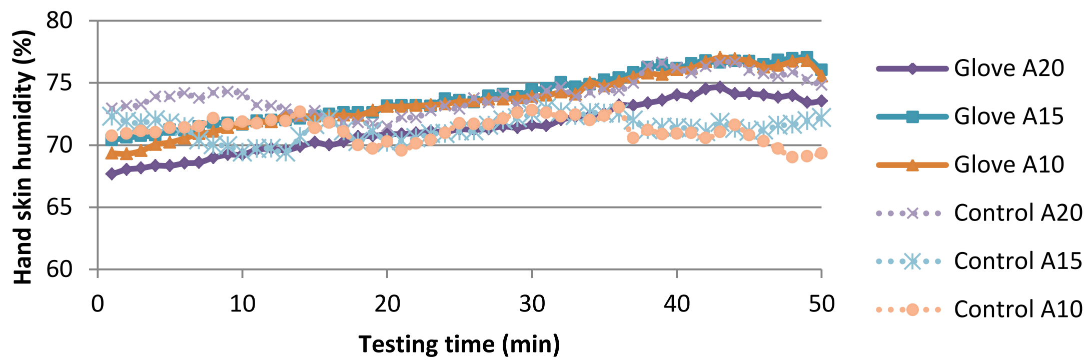


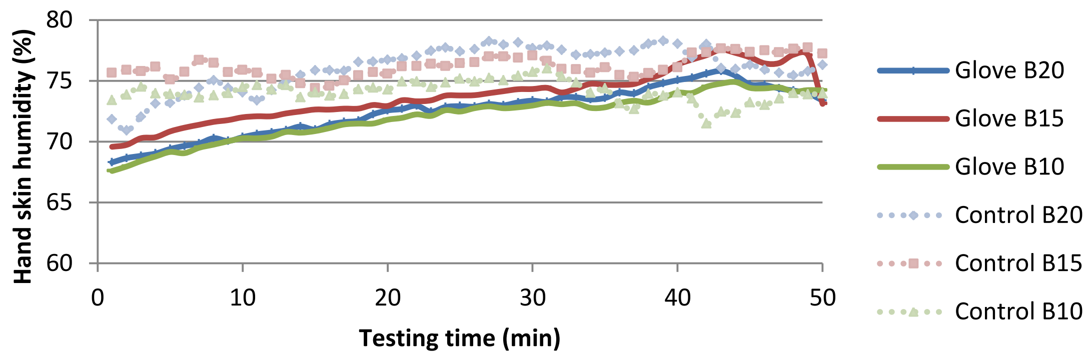


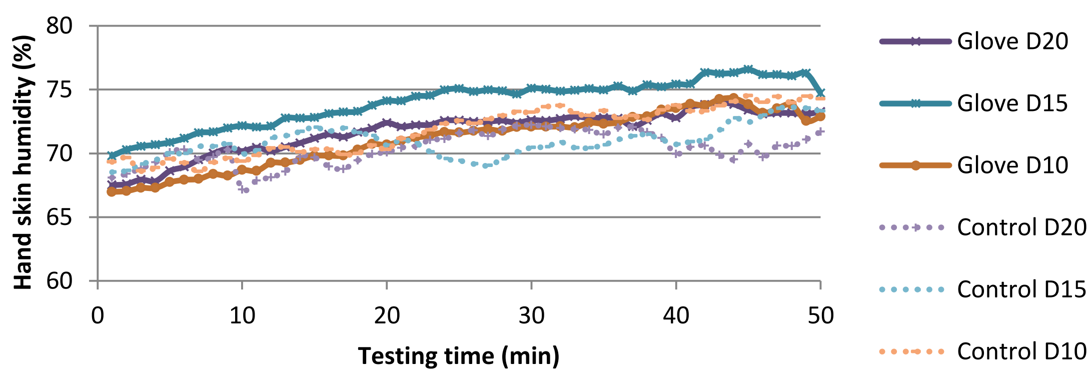


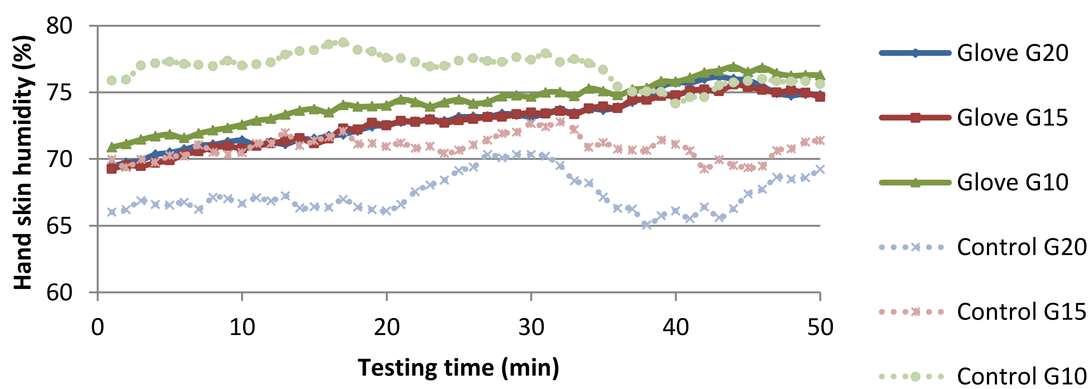


Appendix V Humidity under different glove sample during wear trial









Appendix VI Information sheet for spacer fabric insert wear trial

Development of pressure therapy glove for hypertrophic scar treatment
Information Sheet

We would like to invite you to participate in a research study of Development of pressure therapy glove for hypertrophic scar treatment. This research is conducted by Dr. Yick Kit Lun, associate professor of Institute of Textiles and Clothing, The Hong Kong Polytechnic University and Ms. Chan Ameila, occupational therapist of The Prince of Wales Hospital. Please take time to read the following information carefully and discuss it with friends and relatives 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 and mode of activities

This project aims to bring improvement to the currently using pressure therapy glove for hypertrophic scar treatment based on clinical study and scientific analysis. The new developed pressure therapy glove made of new functional materials and well fitted to wearers' hands, so as to provide better wearing comfort and treatment efficiency. Participants of this study will be offered with a wear trial of the new designed pressure therapy glove. The hand dimensions measurement of the participants, the comfort perception, pressure distribution given by this pressure glove and all others responses would be recorded and utilised for further development of pressure therapy glove.

How is the developing pressure therapy glove?

In Hong Kong, pressure therapy garments and gloves are commonly used in hypertrophic scars treatment. The pressure garments required to be well fitted to the body of patient and worn for 24 hours per day. The pressure garments deliver a suitable pressure to inhibit the growth of scars and prevent contracture formation and enhance cosmetic appearance. However, the currently using materials for the fabrication and the fitting of pressure garments bring certain degree of uncomfortable and resistant to movement to the wearers and hence affecting the treatment adherence and effectiveness. The problem is even more significant in summer. Therefore, we would like to use new functional materials in new cutting pressure glove to improve the comfort and efficacy of pressure therapy glove treatment.

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. Your decision would not affect any therapy you received from the hospital.

What will happen if you decide to take part?

Apart from the normal checkup procedures, new designed pressure therapy glove will be custom-made to the participant based on the condition of the hypertrophic scars for conducting a 6 months wear trial and monitoring. During the wear trial period, participants have to come for a visit 5 times at the 2nd, 4th, 8th, 12th and 24th weeks for a detail checkup of the scar condition and the treatment progress which including:

1. Take hand measurements by using measuring tape, photo-taking and 3D scanning method to precisely understand the scan recovery progress. The measurement takes around 20 minutes.
2. Measure hand dexterity by using a goniometer. The measurement takes around 5 minutes.
3. Measure interfacial pressure delivered by the pressure glove by using a pressure sensor. The measurement takes around 5 minutes.
4. Carry a short interview to understand your perception and opinions toward the pressure glove. The interview takes around 5 minutes.

All equipment adopted in the study is non-invasive. In order to show our thanks, a $50 cash coupon* will be given once finished.

*Participants have to sign a receipt and personal information and ID number have to be recorded to receive the cask coupon.

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 are the benefits of taking part?

Though this study, we hope to develop a pressure therapy glove with optimal fit and comfort. The potential benefit is to provide valuable experimental data for scientific analysis to achieve the purpose of study which is good for the hypertrophic scars recovery.

What are the risks of taking part?

The materials used for producing pressure therapy glove are all tested and can provide a suitable pressure for inhibit the growth of hypertrophic scars. Particular participant may show a light allergic response or discomfort with the treatment pressure. However, the materials have been investigated and used for a period of time. Besides, all measuring equipment including the measuring tape, 3D scanning and goniometer induce no risks to health. Therefore, it is expected this study would not bring any serious problem to the participants.

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 (c/o M1303, Human Resources Office of the University) or Hospital Authority, New Territories East Cluster Clinical Research Ethics Committee in person or in writing.

What will happen to the results of the research study?

The results will be published in referred medical, burns care and textiles journals.

Who is organizing and funding the research?

The research is organized by Institute of Textiles and Clothing, The Hong Kong Polytechnic University and Occupational Therapy Services, Prince of Wales Hospital. It is funded by Research Committee Internal Grant and the Departmental Grant of the 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 and Hospital Authority, New Territories East Cluster Clinical Research Ethics Committee.

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. Yick Kit Lun at 27666551 or Ms. Amelia Chan at 2632 . Thank you very much for your participation in this valuable research activity. We value highly your contribution to the improvement of therapy.

<<Chinese Version>>

用於增生性瘢痕復康治療的壓力手套的開發研究

參與者須知

我們誠意邀請閣下一同參與《用於增生性瘢痕復康治療的壓力手套的開發》的研究，本項研究由香港理工大學紡織及製衣學系副教授易潔倫博士及威爾斯親王醫院職業治療部一級職業治療師陳映芬小姐共同籌劃。請詳細閱讀以下資料，並且可與親友商量或向醫護人員諮詢。若有不明之處或需要更多資料，請隨時與我們聯繫。

研究目的及活動形式

本項研究的目的是根據臨床及科學分析，對目前用於臨床的增生性瘢痕復康治療的壓力手套進行改良。新的壓力手套將採用功能物料，配合病人手部的尺碼，達到改善生理舒適及提高其康復的功能。參與本項研究的患者將有機會試用新設計的壓力手套，我們將記錄參加者的手部尺寸、使用此壓力手套時的舒適度與壓力分佈、以及臨床反應，所有資料將被用於新手套的開發。

開發中的「壓力手套」究竟是怎樣的?

在香港，壓力衣物及手套常用於增生性瘢痕及燒傷復康治療，其衣物的設計必須完全配合病者的身型縫製，並全日二十四小時使用，利用物料在傷處加上適當的壓力，從而防止或減輕後遺瘢痕攣縮或變形等情況。然而，現時的壓力衣物因選料不當及貼身程度等問題，亦會為病者帶來一定程度的不舒適或阻礙，因而影響壓力衣物的使用率及效用，其中尤以夏季為甚。因此，我們希望能以功能物料，配合新式量裁方法，加強燒傷復康治療壓力手套的效用以及舒適度。

是否一定要參加?

這完全由您決定。如果您決定參加,請保留這資料篇，我們會同您簽署一份同意書。你參與後有權隨時退出而且不需要任何理由。您是否參加本研究亦不會影響您在醫院內所接受的任何康復服務。

決定參加後，需要做什麼?

除了一般的復康檢查，我們會根據參加者瘢痕的情況為其訂造新設計的壓力手套，並進行為期六個月的試戴及監測。在這期間參加者須回到醫院，進行共五次的跟進及詳細檢查，時間為開始配戴該手套後第二，第四，第八，第十二和第二十四星期，檢查的具體內容包括：

一. 使用量尺、立體素描及攝影方法，測量您手部的尺碼，從而更準確地瞭解您手部的瘢痕皮膚的復康進度。量度時間須約二十分鐘。

二. 使用測角器量度您手部的靈活度。量度時間須約五分鐘。

三.利用壓力感應器材，在您戴上復康治療壓力手套時，測量您的手部瘢痕皮膚的壓力分佈。測量時間須約五分鐘。
四. 進行一次簡短的面談，瞭解您對新手套的意見。面談時間須約五分鐘。
我們不會使用任何侵入性測試。為表謝意，每完成一次的詳細檢查我們會為您贈送價值港幣五十元的購物券*。
*領取購物券時須簽收，並登記參加者的個人資料及身份証號碼。

參與這項研究的資料是否保密?
凡是有關參加者的資料均會被保密，所有資料及資料將僅限於用於本研究。

參加此研究有什麼實際益處?
我們希望通過本項研究可以開發出有利於患者康復的具有貼身及舒適性的壓力手套。您的大力參與將為本研究提供寶貴的臨床資料，有益於您和其他患者的早日康復。

參與此研究有風險嗎?
新設計的手套所使用的物料經過測試，能提供適當的壓力去抑制瘢痕的增長，個別參加者或有輕微的皮膚敏感或因物料壓力而產生不適。然而，由於在以往的壓力手套的設計及生產過程中，該物料已被研究並被使用了一段時間。另外，手型量度，立體素描，測角器均無危險性。因此，我們預期這項研究計劃並不會在參加者身上引起任何特別不適。

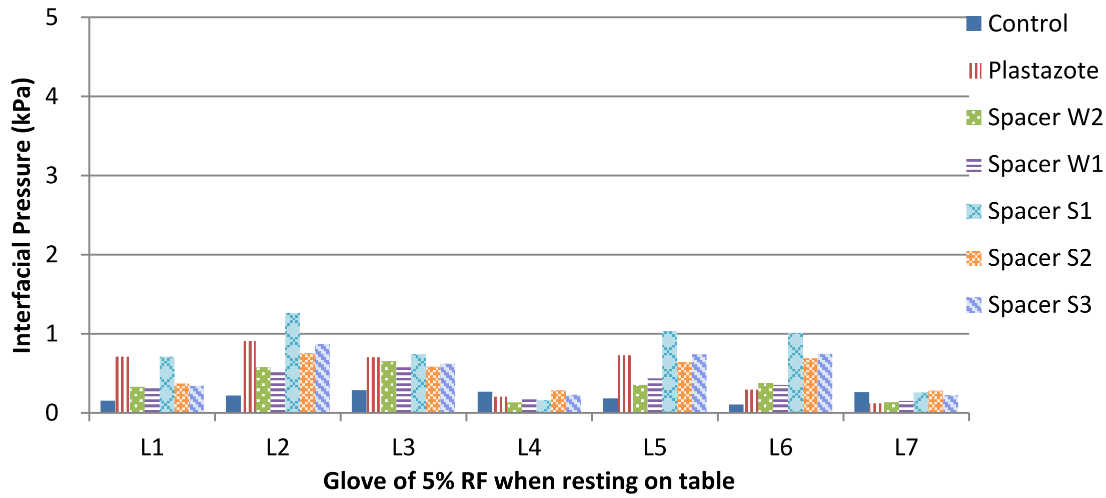
參加此項研究，有甚麼補償?
本研究對參加者沒有提供補償安排。如果您在參與中對這項研究有任何不滿，您可以親自或者以書面形式聯絡香港理工大學人事倫理委員會秘書(地址：香港理工大學人力資源辦公室M1303室轉交)及／或醫院管理局新界東醫院聯網臨床研究倫理委員會。

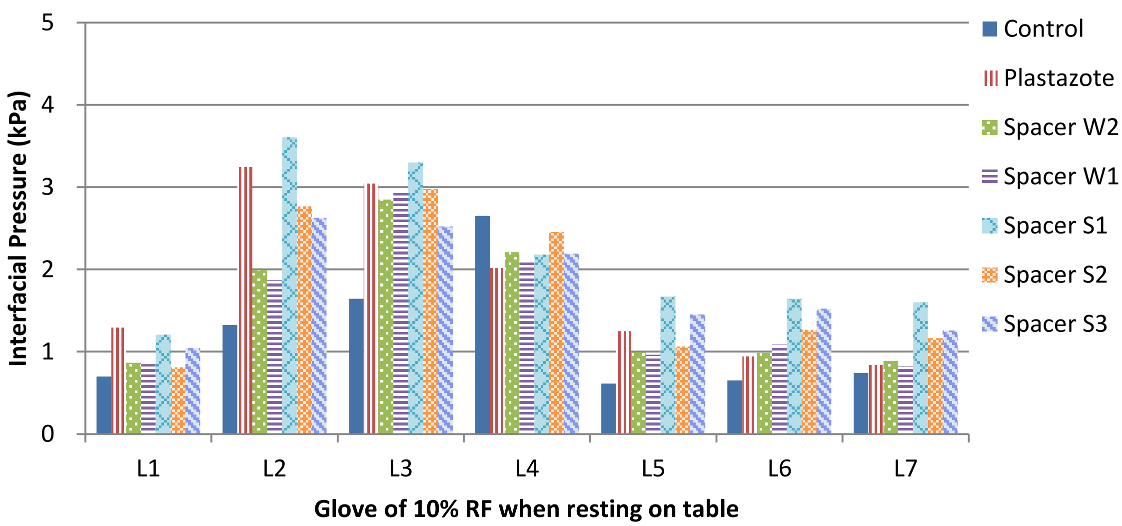
研究結果將被怎樣利用?
我們會把結果發報在醫學、燒傷護理和紡織設計刊物等。

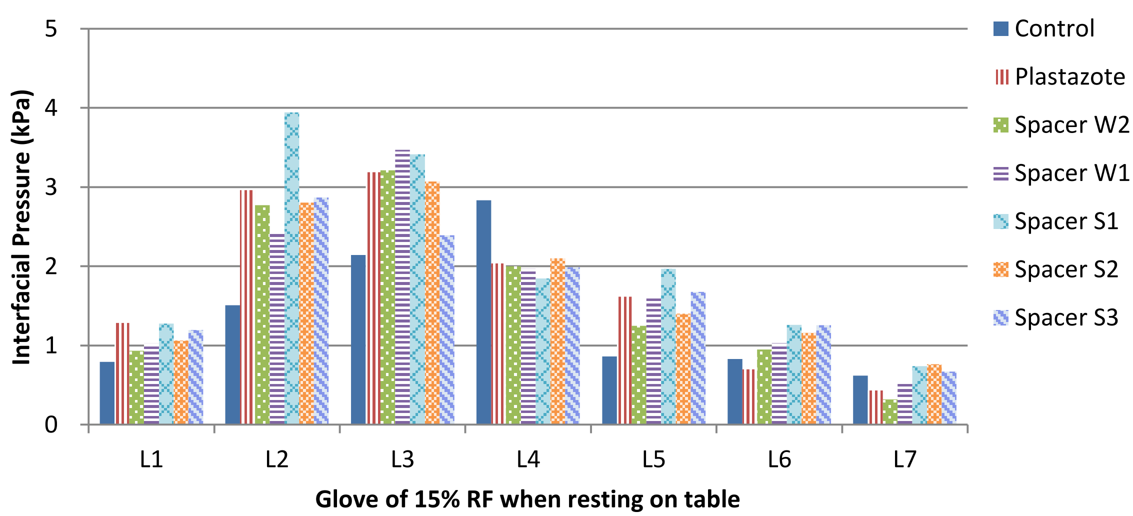
是誰統籌和資助此研究?
本項研究是由香港理工大學紡織及製衣學系和威爾斯親王醫院職業治療部聯合統籌，由大學研究基金資助。

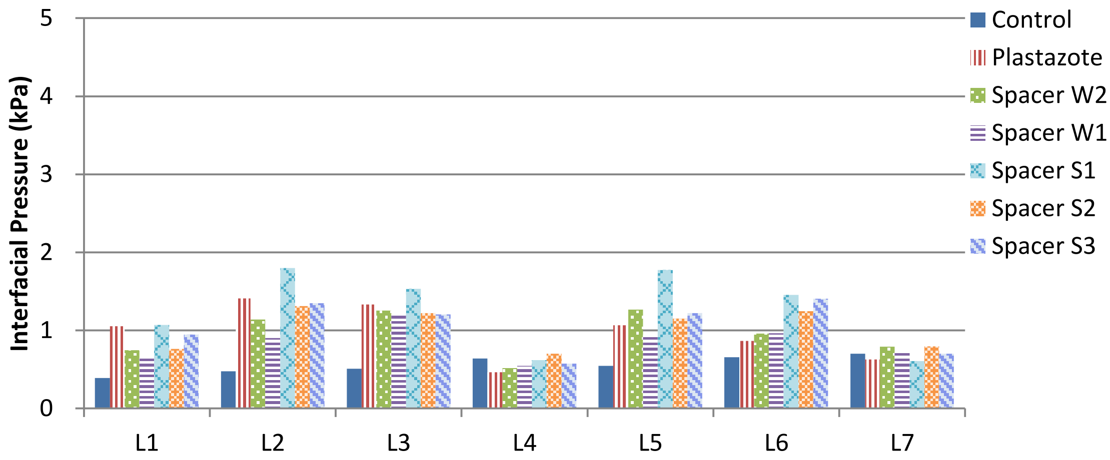
誰審核過此研究?
香港理工大學紡織及製衣學系研究委員會及醫院管理局新界東醫院聯網臨床研究倫理委員會。
請保存這份資料和同意書用作日後參考。如有疑問，請至電27666551易潔倫博士或2632　　陳映芬小姐查詢。再次感謝您的關注，閣下的支持定能對將來改善醫院病人的服務有莫大的幫助

Appendix VII Interfacial pressure given by different insert materials

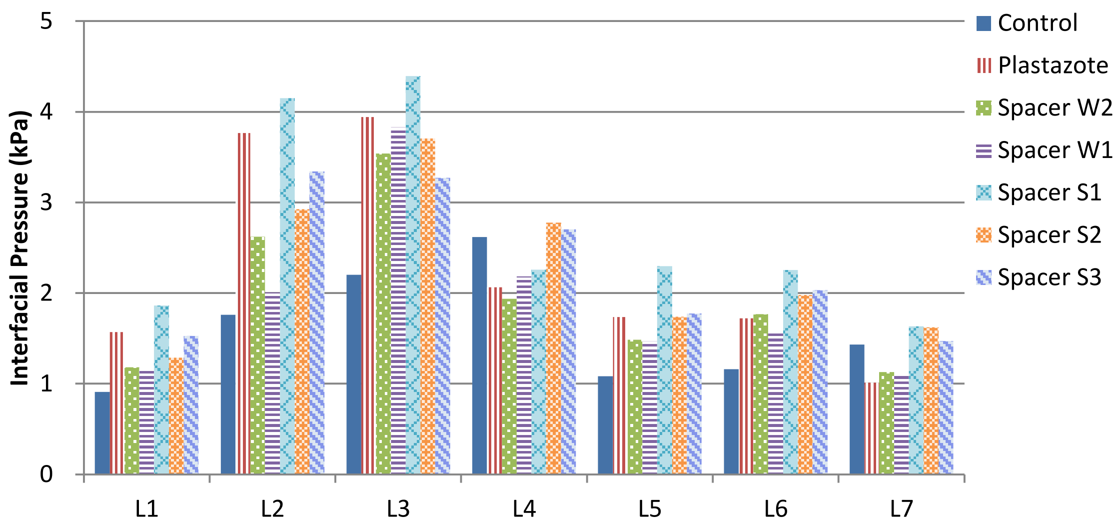




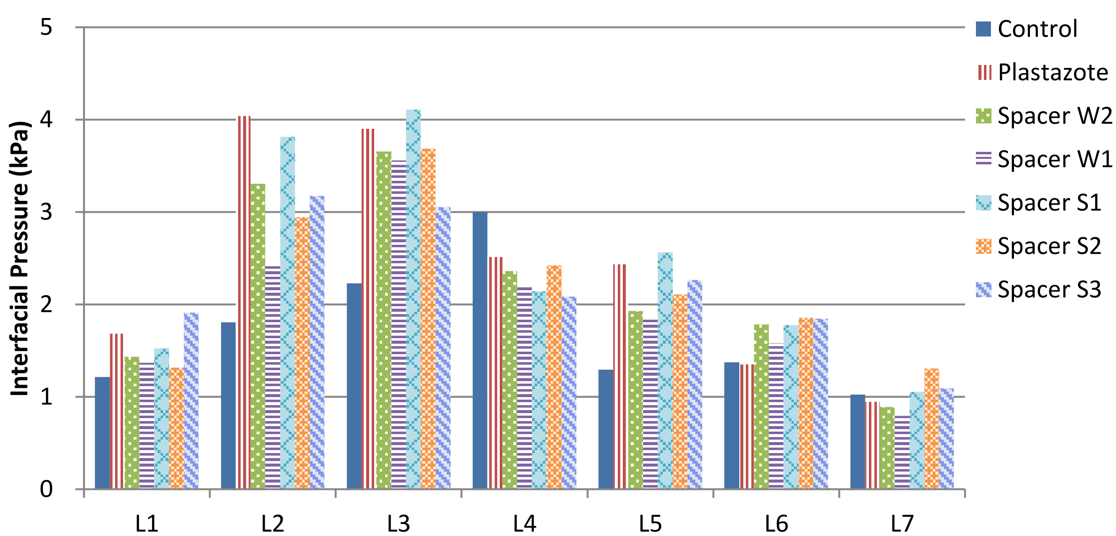




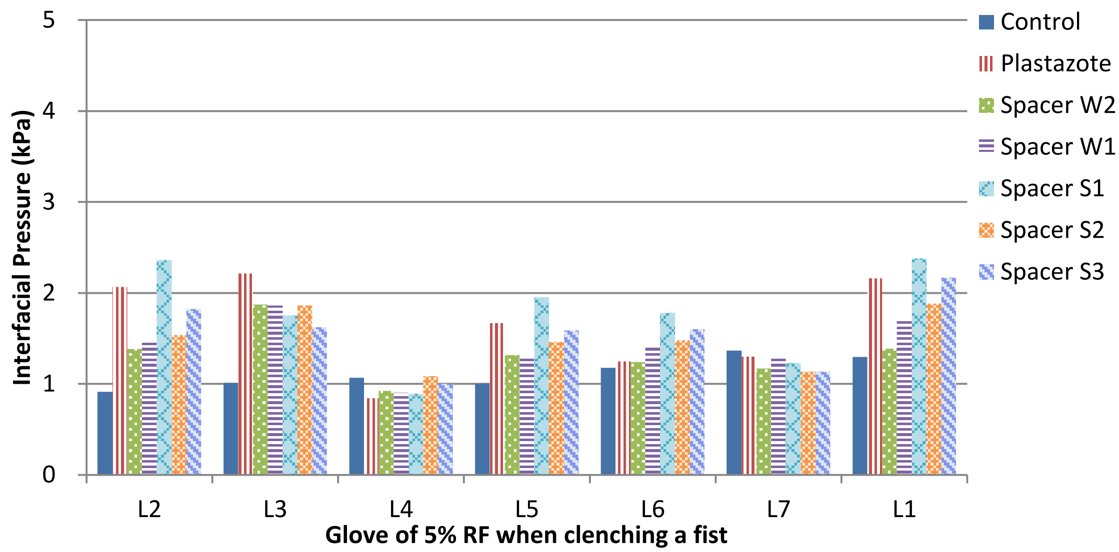
Glove of 5% RF when holding a cylinder

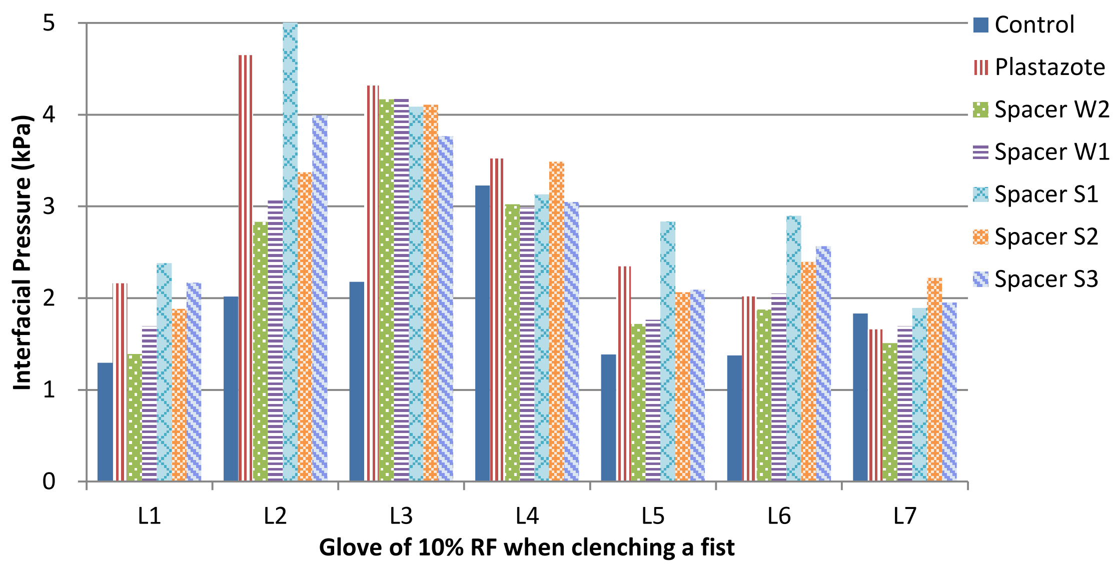


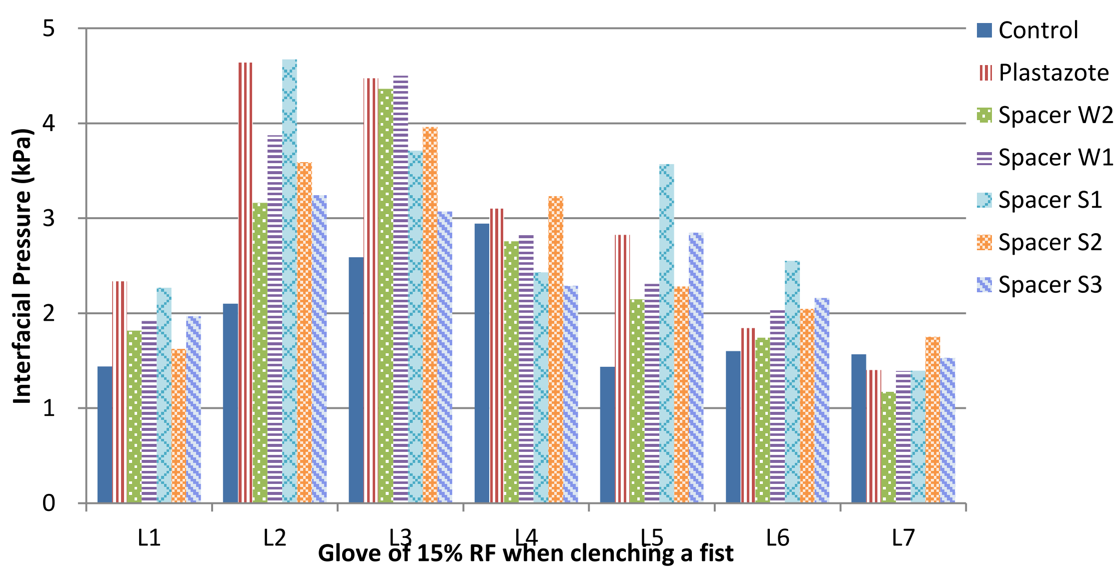
Glove of 10% RF when holding a cylinder



Glove of 15% RF when holding a cylinder


Interfacial Pressure (kPa)
0
1
2
3
4
5
L2
L3
L4
L5
L6
L7
L1
Glove of 5% RF when clenching a fist
Control
Plastazote
Spacer W2
Spacer W1
Spacer S1
Spacer S2
Spacer S3


Interfacial Pressure (kPa)
0
1
2
3
4
5
L1
L2
L3
L4
L5
L6
L7
Glove of 10% RF when clenching a fist
Control
Plastazote
Spacer W2
Spacer W1
Spacer S1
Spacer S2
Spacer S3


Interfacial Pressure (kPa)
0
1
2
3
4
5
L1
L2
L3
L4
L5
L6
L7
Glove of 15% RF when clenching a fist
Control
Plastazote
Spacer W2
Spacer W1
Spacer S1
Spacer S2
Spacer S3

Appendix VIII The difference between the glove-skin interfacial pressure given by the spacer fabric attached

Location	Padding	Interfacial pressure difference (mmHg) (= with attachment - without attachment) 5% Rest	5% Hold	5% Fist	10% Rest	10% Hold	10% Fist	15% Rest	15% Hold	15% Fist
L1	Spacer W1	1.11	0.39	4.62	2.81	2.40	3.82	2.86	2.85	5.18
	Spacer W2	0.64	2.03	4.19	0.78	2.90	3.79	2.84	6.54	5.52
	Spacer S1	2.83	6.51	10.97	3.90	4.50	13.24	3.09	4.69	5.93
	Spacer S2	2.69	3.91	3.46	2.01	3.97	2.93	2.13	6.06	7.20
	Spacer S3	3.59	3.72	6.44	1.89	4.11	1.79	4.81	2.36	8.82
L2	Spacer W1	0.84	2.27	2.13	3.96	8.07	6.52	1.83	2.45	-4.84
	Spacer W2	1.47	7.27	8.58	2.64	11.94	11.32	2.34	7.70	2.85
	Spacer S1	0.59	1.61	1.12	-0.17	6.49	5.48	0.54	-0.48	-1.29
	Spacer S2	1.18	2.05	2.55	1.21	3.64	7.44	3.81	6.47	4.21
	Spacer S3	0.86	-0.46	2.72	0.07	-0.55	-0.15	2.55	-1.61	3.81
L3	Spacer W1	-1.14	-6.93	-9.42	-2.25	-10.17	-7.19	-4.16	-10.07	-12.60
	Spacer W2	-1.68	-6.86	-3.88	-3.20	-8.87	-7.23	-4.27	-8.89	-5.46
	Spacer S1	-4.41	-13.59	-12.45	-6.57	-15.11	-14.71	-4.90	-11.65	-7.41
	Spacer S2	-2.57	-7.51	-6.39	-3.61	-8.56	-8.40	-5.51	-6.32	-4.43
	Spacer S3	-2.08	-7.49	-3.63	-4.77	-9.52	-6.65	-4.86	-9.45	-3.54
L4	Spacer W1	0.38	1.41	5.04	0.88	0.77	1.54	0.69	1.77	3.29
	Spacer W2	0.96	5.00	6.51	1.12	6.27	4.99	1.59	3.79	7.06
	Spacer S1	0.53	4.89	9.54	0.81	8.24	11.52	2.32	5.05	8.03
	Spacer S2	-0.29	3.28	4.97	0.62	2.72	3.40	1.01	3.22	6.48
	Spacer S3	0.54	6.45	7.66	1.72	1.69	6.03	2.41	1.98	7.78
L5	Spacer W1	0.74	2.18	-0.93	2.42	4.28	5.77	4.21	4.60	6.47
	Spacer W2	1.72	1.97	1.49	-0.70	3.07	5.47	3.31	7.01	10.03
	Spacer S1	0.91	0.86	-0.29	-1.19	3.86	4.45	2.30	5.84	4.79
	Spacer S2	0.67	3.55	1.57	1.20	2.97	3.49	1.53	3.30	6.70
	Spacer S3	0.14	0.47	-2.91	0.81	2.20	2.21	0.46	4.02	3.82
L6	Spacer W1	-0.27	1.13	-1.67	-0.98	2.58	2.53	0.33	3.60	1.93
	Spacer W2	0.20	0.57	2.84	0.20	1.46	0.42	-0.21	2.92	1.99
	Spacer S1	-4.07	-2.73	-2.80	-2.18	-1.13	-1.41	-3.48	-3.24	-3.34
	Spacer S2	-1.46	0.17	-1.89	-0.66	0.78	-0.54	0.00	0.41	6.64
	Spacer S3	-2.32	-3.01	-2.13	-4.01	-0.91	-2.24	-3.02	-1.15	-1.94
L7	Spacer W1	0.93	0.55	0.08	0.10	1.05	3.00	-0.74	-1.91	-1.44
	Spacer W2	0.33	0.59	2.47	-0.77	0.65	1.64	-0.43	0.37	2.12
	Spacer S1	1.22	-2.27	-0.28	1.13	-2.15	-0.15	-0.55	0.62	-0.66
	Spacer S2	1.00	-0.27	0.53	-0.04	3.78	0.63	0.27	1.51	-0.15
	Spacer S3	1.67	1.48	2.01	0.34	1.98	-0.28	0.80	0.08	-0.92

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