



Therapeutic gloves for patients with arthritis

A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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List of Publications and Award

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2. **Nasir, S H**, Troynikov, O and Watson, C. Skin deformation behavior during hand movements and their impact on functional sports glove design, *Procedia Engineering*, 2015; Vol. 112: pp. 92–97.
3. **Nasir, S H**, Troynikov, O and Massy-Westropp, N. Therapy gloves for patients with rheumatoid arthritis: A review. *Therapeutic Advances in Musculoskeletal Disease*. 2014; Vol. 6 (6): pp. 226–237.
4. **Nasir, S H**, Troynikov, O. Elastic attributes of fabrics suitable for therapeutic compression gloves. *Advanced Materials Research*. 2014; Vol. 1048: pp. 21–25.

Conference Proceedings

1. **Nasir, S H**, Troynikov, O. The effect of elastic strain on tribological characteristics of fabrics suitable for therapeutic gloves. *The 13th Asian Textile Conference*. 3–6 November; Geelong, Australia 2015; pp. 924-927.
2. Troynikov, O, **Nasir, S H**, Bafekrpour, E and Interface pressure generated by sports gloves to the hand of the wearer and its impact on sports gloves engineering. *21st European College of Sport Science (ECSS) Congress*. 6–9 July; Vienna, Austria 2016.

Award

1. 2016 RMIT Prize for Research Impact – Higher Degree by Research (Design).

Abbreviations

ANOVA	Analysis of variance
AOTI	Accumulative one-way transport index
ARb	Absorption rate bottom surface
ARt	Absorption rate top surface
CMC	Carpometacarpal
DIP	Distal interphalangeal
FEA	Functional-Expressive-Aesthetic
MCP	Metacarpophalangeal
MIU	Coefficient of friction
MMT	Moisture management tester
MWRb	Maximum wetted radius bottom surface
MWRt	Maximum wetted radius top surface
OA	Osteoarthritis
OMMC	Overall moisture management capability
PEDro	Physiotherapy evidence database
PIP	Proximal interphalangeal
RA	Rheumatoid arthritis
R_{ct}	Thermal resistance
R_{et}	Water vapour resistance

ROM	Range of motion
SD	Standard deviation
Sec	Seconds
SMD	Surface roughness mean deviation
SPSS	Statistical Package for the Social Sciences
SSb	Spreading speed bottom surface
SSt	Spreading speed top surface
WTb	Wetting time bottom surface
WTt	Wetting time top surface

Abstract

Therapeutic gloves are an intervention widely recommended and prescribed by rheumatologists and occupational therapists for the management and treatment of hand osteoarthritis (OA) and rheumatoid arthritis (RA). At least a dozen different models of therapeutic gloves are available, with varying design, construction and materials. However, there is no systematic classification for therapeutic gloves and their effectiveness has not been well established. In addition, little research has addressed the issue of material choice on glove performance. The aim of this research was to fill these knowledge gaps and establish a framework for the design and engineering of functional and comfortable therapeutic gloves. To achieve that aim, the author undertook a series of integrated theoretical, experiential, physical and mechanical investigations.

The research began with a review of existing evidence about the effectiveness of therapeutic gloves for people with hand OA and RA. Then, 30 people with hand OA and RA were surveyed, using a purpose-designed questionnaire, to gain insights into their experiences and perceptions of currently available therapeutic gloves. Six commercially available therapeutic gloves were tested on three aspects: physical parameters, tensile attributes, and properties relevant to physiological comfort.

The next stage of this research was a comprehensive investigation of the impact of hand movements on skin deformation and the resultant glove–skin interfacial pressure. The metacarpal region showed significantly higher skin deformation and glove–skin interfacial pressure than other regions. It was also found that the corresponding geometry and the curvature caused by hand movements impact the skin deformation

and glove-skin interfacial pressures. The results were translated into regional hand mapping design concept.

Individuals vary in their sensitivity towards different types of therapies, thus it is important in glove design to consider a range of levels of sensitivity towards pressure and thermal stimuli to improve wearer comfort and optimal therapy effectiveness. The pressure and thermal discomfort thresholds of 13 arthritis patients, recruited from local libraries, community centres, campuses of universities and local clinics were examined. Significant variations in pressure, cold and heat discomfort thresholds were found between patients, and sensitivities were significantly different at different locations of the hand. The results obtained were again translated into regional hand mapping design concept.

The results from the literature review, survey study, objective material tests and physical testing were combined with the regional hand mapping design concept to produce a novel, evidence-based theoretical framework for the design and engineering of functional and comfortable therapeutic gloves. The methodologies employed and the framework established in this research significantly advance knowledge in this field, and provide a robust foundation for the design and engineering of therapeutic gloves and other user-centric therapeutic garments.

Chapter 1 Introduction

1.1 Prevalence and significant of arthritis

Arthritis is a chronic musculoskeletal condition causing disability, mobility limitation, and pain, affecting 52.5 million adults worldwide (Centers for disease control and prevention, 2015; Klocke, 2000). It is a form of joint disorder that involves inflammation of one or more joints (Klocke, 2000; Moriyama & Bagchi, 2011; Syngle, 2006), and most frequently involves joints of the hands (Wilder et al., 2006). The symptoms of arthritis of the hand are swelling, stiffness and pain in the affected joints. There are more than 100 types of arthritis; the most common are osteoarthritis (OA) and rheumatoid arthritis (RA) (Access Economics, 2007; Syngle, 2006).

Estimates published in 2012 report 6.1 million cases of arthritis and other musculoskeletal conditions in Australia with 1.9 million people with OA and 0.5 million people with RA (Arthritis and Osteoporosis Victoria, 2013). According to Arthritis and Osteoporosis Victoria (2013), over 50% of Australians with arthritis are between the ages of 25 and 64 years; in their prime working age. The prevalence of arthritis increases with age, from less than 1% of people below 25 years of age to 52.1% of people aged 75 years and over. The prevalence of arthritis is also associated with sex, with women are more likely to have arthritis than men. In particular, at ages 75 years and over, 59.9% of women were reported to have arthritis, as compared to 42.3% of men (Australian Bureau of Statistics, 2012; Jenkins, 2011). With the ageing of 'baby boomers' population, the prevalence of arthritis cases will substantially rise, with projections that the number of arthritis cases in Australia will double by 2032 (Arthritis and Osteoporosis Victoria, 2013; Australian Bureau of Statistics, 2012).

The high prevalence of the disease and its effect on disability significantly contribute on individuals and on society. The risk of physical impairment and activity limitation (defined as needing help in performing daily activities), attributed to arthritis of the hand, markedly reduces the quality of individuals' lives and productivity (Wong et al., 2010).

1.2 Therapeutic gloves

Management and intervention for patients with hand arthritis aim to reduce pain, improve hand function, maintain independent daily living and promote active participation in their chosen occupations, while simultaneously prevent joint damage and functional disability (Hammond et al., 2016; Malcus-Johnson et al., 2005; Reese, 2013; Vlieland, 2003). One of the interventions recommended and prescribed by rheumatologists and occupational therapists in routine clinical care is wearing of therapeutic gloves (Corcoran et al., 2010; Kavuncu & Evcik, 2004; Oosterveld & Rasker, 1990; Prior & Hammond, 2015).

A therapeutic glove may be prescribed to relieve pain and improve hand function in arthritis, manage hypertrophic scarring after a burn injury, and reduce swelling in lymphedema (Dewey et al., 2007; Macintyre et al., 2004). People with hand arthritis typically buy off-the-shelf gloves based on recommendations from therapists, consumer websites, and pharmacists who sell these gloves (Cherney, 2016). Therapeutic gloves for people with hand arthritis are available in various designs, constructions, and materials. Manufacturers claim they provide therapeutic effects, applying pressure to underlying hand tissue and skin (compression), warmth, and support (Hammond et al., 2016; Nasir et al., 2014; Weiss, 2013); however, research on the effects and comfort of the gloves is scarce.

1.3 Outline of thesis

The thesis is divided into ten distinct chapters to report the research and outputs of this study. Chapter 1 briefly introduces the research background and the outline of the thesis. Chapter 2 presents an extensive literature review on relevant disciplinary areas to provide background information involved in the research area and to identify the knowledge gaps for this study. Chapter 3, 5–8 are presented in a publication format with relevant methodology, results, discussion and conclusion sections presented in each chapter. Introduction parts for these chapters are contained in Chapter 2 - Literature Review, to avoid repetition. Where the Chapters have been published or are under peer review at the time of submission for examination, this information is noted in the introduction for each of such Chapter.

Chapter 3 presents the review of the evidence for whether therapeutic gloves improve hand function and reduce hand symptoms in people with hand OA and RA. Chapter 4 outlines the research objectives, research questions, the significance and value of this research and the research design used in this study.

Chapter 5 describes the experience and attitudes of 30 arthritis patients who used therapeutic gloves as part of their rehabilitation treatment. Chapter 6 investigates and compares the physical, tensile and comfort properties of six benchmark therapeutic glove fabrics. Chapter 7 presents the skin deformation behaviour and the glove-skin interfacial pressure during hand movements. Chapter 8 presents the pressure and thermal discomfort thresholds of arthritis patients at different parts of the hand.

Chapter 9 presents an evidence-based design framework for design and engineering of therapeutic gloves. Finally, Chapter 10 summarizes the findings of chapters 3, 5–9 and makes recommendations for future research.

References and appendices are presented at the end of the thesis. Ethical approvals from RMIT University Human Research Ethics Committee were granted prior to data collection for the studies involving participants that are presented in this thesis.

Chapter 2 Literature Review

Introduction

The first part of this chapter discusses the definitions, symptoms, prevalence, cost and management of arthritis. Next, different existing designs and materials used for the construction of therapeutic gloves are investigated. This chapter also includes a review of literature on clothing comfort, the relationship between hand physiology and comfort as well as the functional design framework in garment design. Finally, gaps in the existing knowledge are highlighted and the content of the chapter is summarised.

2.1 Arthritis

The term 'arthritis' is derived from two Greek words: 'arthron', meaning 'joint', and 'itis', meaning 'inflammation'. Hence, arthritis refers to a joint disorder that involves inflammation of one or more joints (Klocke, 2000; Moriyama & Bagchi, 2011; Syngle, 2006). There are more than 100 types of arthritis, including OA, RA, gout, psoriatic arthritis, systemic lupus erythematosus and scleroderma, but the most common are OA and RA, thus the majority of the reviewed literature discusses these forms of arthritis. Both OA and RA commonly affect the joints of the hand (Access Economics, 2007; Boscheinen-Morrin & Conolly, 2001; Moriyama & Bagchi, 2011).

Osteoarthritis is the most common type of arthritis, causing impaired mobility and disability (Manno, 2012). It is often called 'wear and tear' arthritis due to its onset following the breakdown of cartilage, usually as a result of trauma and ageing (Arden & Nevitt, 2006; Welzein, 2003). Cartilage is the part of the joint that cushions the ends of the bones and allows easy movement of joints. The breakdown of cartilage causes the bones to rub against each other and causes inflammation. The inflamed bone can be

stimulated to produce new bone called bone spurs (Figure 2.1). Osteoarthritis gradually worsens with time, and no currently available treatments to cure the disease. Existing oral supplements for OA assist in cartilage rebuilding and reduction of inflammation, which can slow the progression of the disease, relieve pain and improve joint function (Sofat & Kuttapitiya, 2014).

There is no specific cause of OA, but certain factors such as ageing, obesity, joint injury, repeated overuse of certain joints, nerve injury or genetics might increase the risk of developing OA, or worsen existing OA (Access Economics, 2007; Arden & Nevitt, 2006; Beasley, 2012; Hubele, 2006). Gender is also a well-recognised risk factor for OA: the incidence of hand OA is higher in women, while hip OA occurs more commonly in men (Manno, 2012).

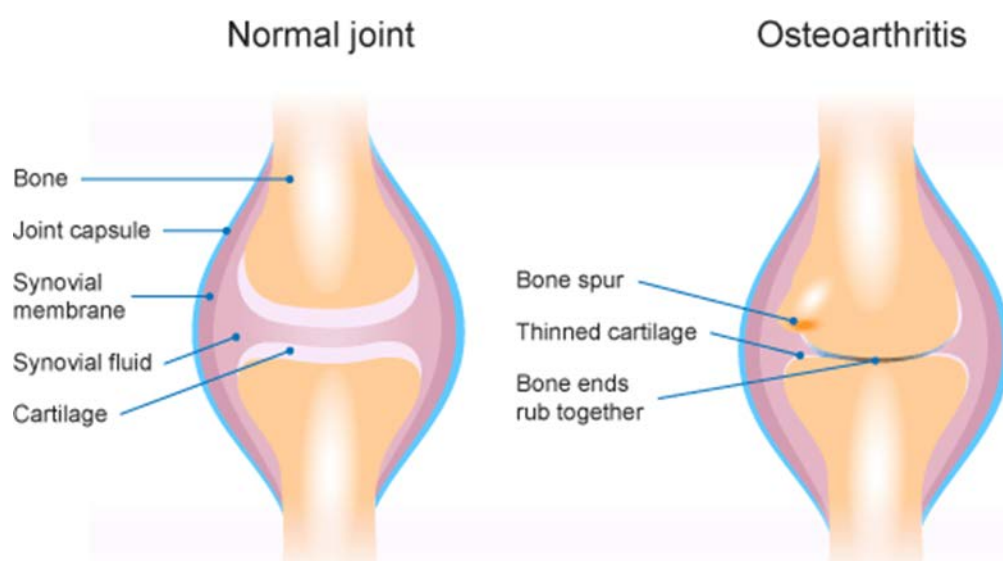


Figure 2.1: Cartilage thinning and bone damage in osteoarthritis (Australian Institute of Health and Welfare, 2016)

Rheumatoid arthritis causes the immune system to attack the lining of joints (the synovium), causing painful swelling that can eventually result in bone erosion, joint damage and loss of function (Lee, 2000). It is a chronic, progressive, systemic

inflammatory disease that influences a patient's life in many ways (Malcus-Johnson et al., 2005). Rheumatoid arthritis is the second most common form of arthritis and the most common autoimmune disease in Australia (Access Economics, 2007). It progresses in three stages (Figure 2.2). In the early stage, the immune system attacks the synovium, causing pain, swelling and stiffness of the joints. In the intermediate stage, the rapid division and growth of cells cause the synovium to thicken. In the late or advanced stage, the inflamed cells release enzymes that may digest bone and cartilage, often causing the joint to lose its shape and alignment, resulting in loss of movement (Lacroix, 2015; Quan, 2011; Syngle, 2006).

The specific cause of RA is unknown, but infection, autoimmunity, hormonal, genetic, and environmental factors such as smoking are risk factors for the development of the disease (Choy, 2012; Lee, 2000; Lester, 2009; Quan, 2011). Although there is no cure, the progression of the disease can be slowed with early detection and oral medication that suppresses the immune system (Aletaha, 2015; Dieckmann, 2005; Kourilovitch et al., 2014; Quan, 2011). If the disease is left untreated, the rate of mortality is twice that of unaffected people the same age (Bingham, 2013).

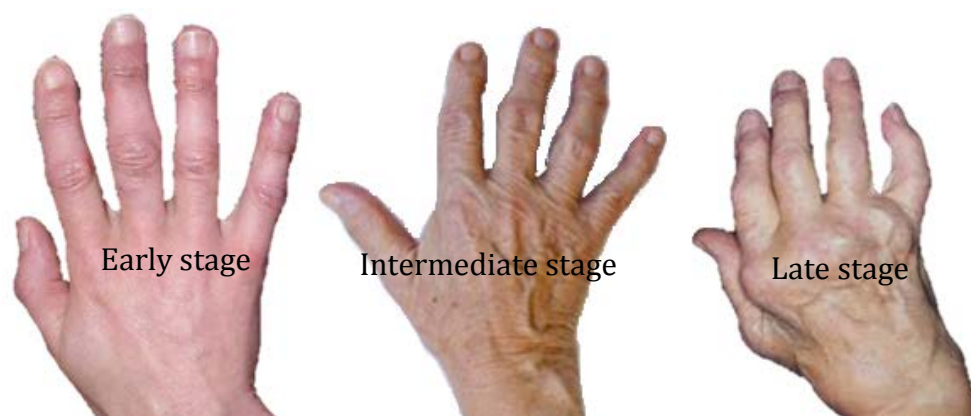


Figure 2.2: Stages of rheumatoid arthritis, showing early inflammation and later development of joint deformity

2.1.1 Symptoms, classification and epidemiology

The early symptoms of OA are stiffness in the morning (lasting less than 30 minutes) and localised joint pain that worsens with activity (Manno, 2012). These symptoms are the result of progressive synovial thickening, narrowing of the joint space, and wear of the joint cartilage (Arden & Nevitt, 2006; Moskowitz et al., 2007; Welzein, 2003).

The distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints of the hand have been identified as the joints most commonly affected by OA (Figure 2.3). However, they are not likely to be symptomatic in the early stage (Arden & Nevitt, 2006; Manno, 2012). The base of the thumb can be affected by OA as well, with symptoms of tenderness and swelling (Manno, 2012). The bony deformity referred to as Heberden's nodes and Bouchard's node are the symptoms of joints affected by OA. The bony deformity is a result of the bone spurs in that joint. Heberden's node is observed as a bump at the end of the finger closest to the nail, and Bouchard's node is a bump located in the middle of joints in the finger (Klocke, 2000).



Figure 2.3: Osteoarthritis of the hand, involving the proximal (PIP) and distal interphalangeal (DIP) joints (Cedars-Sinai, 2016)

The diagnosis of OA relies mainly on clinical examination (symptoms) and radiographic investigation. The most widely used diagnostic criteria was developed by the American College of Rheumatology and is shown in Table 2.1 (Altman et al., 1990).

Table 2.1: American College of Rheumatology criteria for osteoarthritis of the hand

Clinical symptoms	OA is present if the patient has symptoms:
1. Hand pain, aching or stiffness for most days or prior month	1,2,3 & 4 or 1,2,3 & 5
2. Hard tissue enlargement of two or more of the ten selected hand joints	
3. Metacarpophalangeal (MCP) swelling in two or more joints	
4. Hard tissue enlargement of two or more DIP joints	
5. Deformity of one or more of 10 selected hand joints	

Symptoms of RA vary from person to person. The most common symptoms are swelling, tenderness, pain and stiffness at the impaired joints (Malcus-Johnson et al., 2005; Newman & Matzko, 2007), which are usually worse in the morning or after prolonged inactivity (Cooney et al., 2011). Unlike in OA, morning stiffness in RA can last for several hours (Ruffing & Bingham, 2016).

In the early stages of RA the smaller joints in the hands and feet are usually affected, but as it progresses, damage can occur in almost all peripheral joints (Combe, 2007; Lee, 2000; McNeal, 1990; Quan, 2011; Rindfleisch & Muller, 2005). The joint involved most frequently are the PIP and MCP joints of the hands (Figure 2.4), the wrists, and small joints of the feet including the metatarsophalangeal joints (Ruffing & Bingham, 2016). Swelling in one or two joints is another characteristic of RA. The swelling may last for a few days or weeks, then go away completely and later return in

the same or other joints, with severity increasing over time (McNeal, 1990; Ruffing & Bingham, 2016). Inflammation, structural deformity, or both may limit the range of motion (ROM) of the joint. Over time, some patients with RA develop deformities in the hands or feet; especially those in late stages (Figure 2.2).

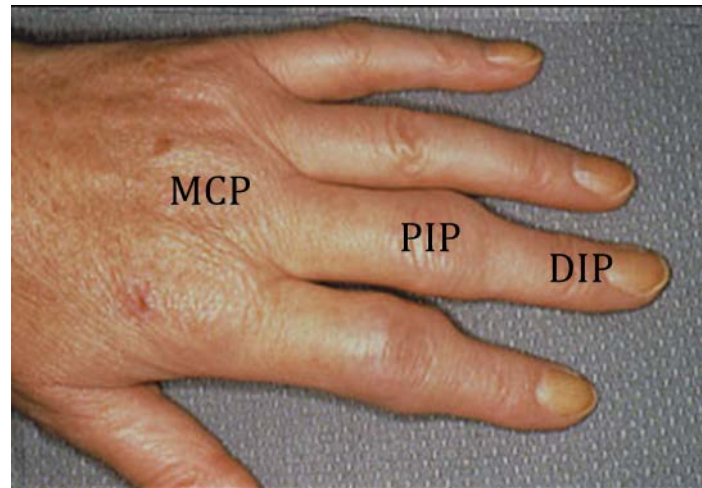


Figure 2.4: Swelling of the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of the hands in rheumatoid arthritis (Ruffing & Bingham, 2016)

The classification criteria for RA were first proposed by the American College of Rheumatology and the European League against Rheumatism in 1987, and then revised in 2010. The 2010 criteria comprise a scoring system that considers the number and distribution of the affected joints, serology, duration of symptoms, and acute phase reactants. A patient is classified as having 'definite RA' if a score of six or greater is attained using the 2010 criteria (Aletaha, 2015; Aletaha et al., 2010).

Rheumatoid arthritis diminishes a person's capability to perform daily activities such as grooming, brushing teeth, opening a door, turning a key or holding a cup. However, the impact of RA on each person varies. In some individuals, symptoms of RA will appear, flare up and remit, but in some cases, the symptoms are active most of the

time, last for many years and lead to serious joint damage and disability (Merritt, 2012; Steultjens et al., 2004).

Arthritis primarily affects adults, especially the older age groups. It is the leading cause of disability in Australia and other developed countries (Arthritis and Osteoporosis Victoria, 2013; Kourilovitch et al., 2014; Reese, 2013). Approximately 3.3 million Australians currently have some form of arthritis, with 2.4 million of those with arthritis being of working age (25–64 years) (Arthritis and Osteoporosis Victoria, 2013; Australian Bureau of Statistics, 2012). It is predicted that arthritis prevalence will increase with age to the point where half of Australians aged over 80 have some form of arthritis (Access Economics, 2007). Individuals over 55 years of age will account for the greatest increase in the number of people affected by arthritis because of the ageing of the 'baby boomers' population (Hunter et al., 2014).

The incidence and prevalence rates of OA in specific joints vary widely, due to differences in the case definition of OA (Manno, 2012). In most epidemiological studies, the incidence for hand OA is reported at around 100 per 100,000 person-years (Arden & Nevitt, 2006; Oliveria et al., 1995). The incidence of OA increases sharply with age, especially in the joints of the hand (Arthritis and Osteoporosis Victoria, 2013; Merritt, 2012), with one study reported the incidence in the elderly population was as high as 80% (Merritt, 2012). Population surveys have reported prevalence of hand OA of more than 75% in older women (Helmick et al., 2008; van Saase et al., 1989). It is projected that the number of people with OA disease in Australia will increase to three million by 2032 (Arthritis and Osteoporosis Victoria, 2013).

The incidence rate of RA is significantly lower than of OA, at about 30–40 per 100,000 person-years (Riise et al., 2000; Viatte et al., 2013). Over 90% of patients with

RA have hand involvement (Dellhag & Burckhardt, 1995). The disease is three times more common in women than in men, and the prevalence increases with age, especially over 65 years (Jenkins, 2011; Ruffing & Bingham, 2016). Arthritis and Osteoporosis Victoria (2013) reported that the prevalence of RA was 6.8% in Australian women aged 65–74 in 2012. Some studies have implied that RA has a non-uniform geographical distribution; the disease is more common in Northern Europe and North America compared with West Africa and Asian countries (Lacroix, 2015; Silman & Pearson, 2002).

The increasing prevalence of arthritis puts economic stress on society (Reese, 2013). The disease has a major effect on productivity and places an enormous burden on the health care system (Hunter et al., 2014). The disease burden of arthritis is typically measured in direct and indirect costs, and also in intangible costs such as pain and reduced quality of life (Arthritis and Osteoporosis Victoria, 2013; Callander & Schofield, 2016). It has been estimated that the total cost of arthritis and other musculoskeletal conditions in Australia was \$55.1 billion in 2012 with \$9.2 billion in direct health costs (Arthritis and Osteoporosis Victoria, 2013). According to March and Bachmeier (1997), pharmaceutical costs account for 10% of the total direct costs of OA. The direct costs of OA are mostly attributed to hospital stays and surgery with health professional visits and diagnostic procedures accounting for small proportions (Hunter et al., 2014).

The indirect costs associated with loss of productivity and labour force participation are usually larger than the direct medical costs. These costs are mainly attributed to reduced employment, as well as significant costs associated with lost of superannuation and absenteeism (Arthritis and Osteoporosis Victoria, 2013; Hunter et

al., 2014). Workforce absenteeism has been reported to comprise a substantial proportion of the burden of OA in numerous countries, including Canada and the United States (Hunter et al., 2014; Schofield et al., 2014). With the ageing of national populations and the increasing prevalence of OA with age, OA is a growing source of absenteeism (Hunter et al., 2014).

The direct and indirect costs of arthritis underscore the importance of making the rehabilitation process of arthritis more effective. Rehabilitation intervention approaches enable people to lead full and active lives and maintain workforce participation, and reduce the health care and social care costs (Access Economics, 2007; Centre for Rehabilitation Research in Oxford, 2014; Lee, 2000). In other words, a way to reduce the cost of arthritis is to reduce the disability associated with arthritis (Access Economics, 2007).

2.1.2 Management of arthritis

The management of arthritis has changed considerably in the past few years, and the treatments used have become more efficient. As previously stated, there are currently no treatments that are known to cure the disease (Sofat & Kuttapitiya, 2014). The goals of rehabilitation of both OA and RA are to relieve pain and maintain the independent performance of daily living, and simultaneously prevent joint damage and functional disability (Reese, 2013). As the incidence of arthritis continues to rise in an ageing population worldwide, there is a need to develop new treatments for arthritis that target relief of symptoms and improve patients' quality of life. There are several options for treating arthritis, both invasive and non-invasive. Some treatments are more appropriate for particular patients; the most suitable approach depends on the severity of the disease and information gained from X-rays and magnetic resonance imaging

(MRI) (Ye et al., 2011). There are several non-invasive approaches to arthritis management which involve medication and conservative treatments or combination of both treatments. The treatment depends on severity of the disease, age, gender, weight, lifestyle and individual's functionality. Surgery, such as joint replacement, is the last option if all other treatments have failed to prevent joint damage, pain and deformity (Merritt, 2012).

Conservative or rehabilitative treatments are recommended to reduce pain and maintain or regain ability to perform daily activities. These include physical agent modalities, energy conservation, exercise therapy, joint protection and orthoses (Merritt, 2012).

Physical agent modalities are therapeutic intervention techniques involving heat or cold applications, electricity, sound, or pressure therapy (Kawate et al., 2011). Physical agent modalities are mostly used as supplementary therapy for other treatment – such as exercise – for maximum benefit (Kavuncu & Evcik, 2004). Heat relaxes muscles and increases blood circulation in specific areas. Heat therapies include paraffin baths, heat packs, fluid therapy or warm water soaks. Cold therapy is most helpful when a person is experiencing an arthritic 'flare-up' because it can reduce inflammation by lowering the temperature of the skin, and the superficial and deeper tissues (Kavuncu & Evcik, 2004; Vlieland, 2003).

Energy conservation techniques are used to decrease fatigue and conserve energy. According to Cooper (2007), "energy conservation consists of simplifying tasks or activities to minimize the amount of energy use" (p.9). This may include planning ahead, setting priorities, eliminating unnecessary tasks and regular rest. Taking breaks and

resting can be an effective way to reduce inflammation and pain (Kavuncu & Evcik, 2004; Zhang et al., 2002).

Exercise therapy is an integral tool in arthritis rehabilitation (Moriyama & Bagchi, 2011). A systematic review reported that aerobic and strengthening exercises for three times a week for 30 to 60 minutes in patients with RA improved muscle function and fitness (Stenstrom & Minor, 2003). Low-impact activities such as walking, bicycling and yoga are recommended, whereas high-impact activities that may contribute to joint inflammation in patients with either OA or RA are not (Beasley, 2012).

The purpose of initiating joint protection treatment in the early stages of OA and RA disease is to decrease joint stress and damage through altered work methods, and to educate patients on proper joint alignment and the use of adaptive equipment. There are several principles of joint management used to create joint protection programs such as respect pain, balance rest and activity, exercise in a pain-free range, avoid positions of deformity, reduce effort and force, and use stronger joints (Beasley, 2012; Brink & Sumpmann, 2012; Vlieland, 2003).

Orthoses or splints are externally applied devices designed to support or immobilise joints. In OA and RA patients, orthoses are used to decrease pain, minimise deformities, decrease inflammation, decrease stress on joints, provide support for increased function, and assist with joint stability (Bani et al., 2013; Murphy, 1996; Vlieland, 2003). Systematic review reported that long-term use of splints was associated with reduction of pain. Another review, by Steultjens et al. (2002) found that the use of orthosis could decrease pain and improve the strength of one's grip; although it may decrease hand movement. In a longitudinal study of 168 patients with RA, using either ready-to-wear or custom-made orthoses was reported as the second most frequent

intervention prescribed to patients by occupational therapists (Malcus-Johnson et al., 2005). Although orthosis is common practice in the clinic for management of arthritis, more research is required in order to validate its benefits (Beasley, 2012). Static orthosis offer immobilisation of a joint and/or tissue which can reduce pain and allow comfortable rest of the hand. Figure 2.5 is an example of a static orthosis used to rest the hand.



Figure 2.5: Plastic, custom-made static resting orthosis worn with a compression glove
(HubPages., 2014)

A therapeutic glove is a type of dynamic orthoses, claimed to help alleviate pain, stiffness and swelling (Boscheinen-Morrin & Conolly, 2001; Kavuncu & Evcik, 2004). The next section focuses on types, materials and construction of therapeutic gloves.

2.2 Therapeutic gloves

Medical garments are apparel designed for people with medical conditions. These garments can be divided into three main functional categories: protective, treatment and caring. Therapeutic gloves are garments that belong in the treatment function domain, along with pressure garments, compression stockings and wet dressings (Sau-Fun et al., 2011).

Most therapeutic gloves are tight-fitting gloves made from elastic materials. They are available either as ready-to-wear or custom-made. Ready-to-wear gloves are available from several commercial companies, and costs in the range of AUD20–50. People with hand OA or RA typically buy these gloves based on clinical recommendations from therapists, consumer websites (Cherney, 2016; Hammond et al., 2016) as well as recommendations from friends and families.

The following section describes the classifications and functions of therapeutic gloves, as well as the materials used in construction of therapeutic gloves. The evidence for whether therapeutic gloves improve the hand function and hand symptoms in people with hand OA and RA have been reviewed in Chapter 3.

2.2.1 Classification and functions

Although the effectiveness of therapeutic gloves has not been proven scientifically, therapeutic gloves of various designs, constructions and materials are claimed to provide therapeutic effects by applying pressure to underlying hand tissue and skin (compression), warmth and support. No information relating to design criteria for therapeutic gloves is available. This, and the epidemiology of arthritis outlined earlier, underlines the urgent need for scientifically established classification and categorisation of therapeutic gloves. Such classification is essential to enable medical practitioners and product engineers to focus clearly on the design of gloves and select appropriate materials for specific functions.

Therapeutic gloves designed for people with hand arthritis can be classified based on two key specific functions: improvement of hand function and reduction of hand symptoms (Figure 2.6). Hand function is defined as “the ability to use the hand in every activity” which involves dexterity, manipulative skills and task performance skills

(Dellhag & Bjelle, 1999; Lin et al., 2013). As mentioned previously, patients affected by OA and RA usually suffer from hand symptoms such as pain, stiffness and swelling especially in the joints. Designs for improvement of hand function usually consist of straps, padding, elastic materials and rubber bands or silicone beads, which act to improve grip, enhance dexterity and strengthen the hand. Gloves designed for reduction of arthritic hand symptoms are usually designed to apply pressure to underlying hand tissue and skin and use high thermal resistance materials; aims of such gloves are to reduce swelling and provide pain relief.

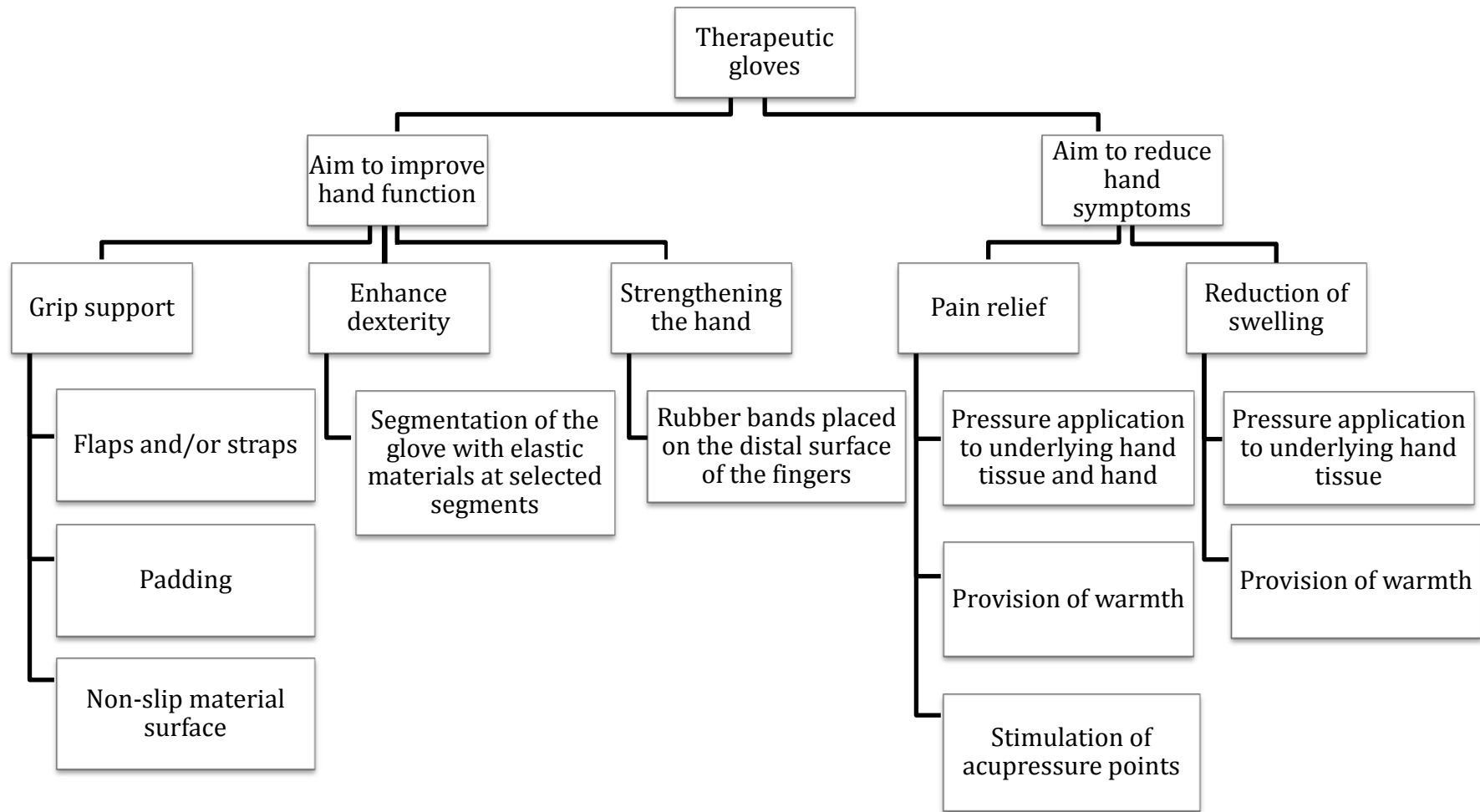


Figure 2.6: Classifications of therapeutic gloves

2.2.1.1 Improvement of hand function

Individuals with arthritis in their hands often have difficulty in gripping and holding objects securely, so unable to perform activities that require holding objects for an extended period. Therapeutic gloves which are designed for grip assistance are widely used as sports gloves for individuals with arthritis. For example, these gloves are useful in assisting persons to control sports equipment such as golf clubs. Gloves in this category are claimed to improve the user's grip strength – defined as the amount of static force that the hand can squeeze – without the need for the wearer to grip harder (Bedell, 2002; Bionic Gloves™, 2014a; Marando, 2000). This permits the same grip to be retained on an item with less flexing of the fingers, which is especially important for individuals who experience pain when flexing their fingers. Several additional innovative elements designed to enhance grip strength are described below.

Some patented sports gloves incorporate additional flaps (Figure 2.7) or straps to them to enhance grip. A flap or strap is usually positioned in the thumb section in order to wrap around the base of the thumb and hold the fingers securely around an object (Bedell, 2002; Carothers, 2001; Godson, 2008; Hydock, 1967; Marando, 2000; Yu, 2011a).

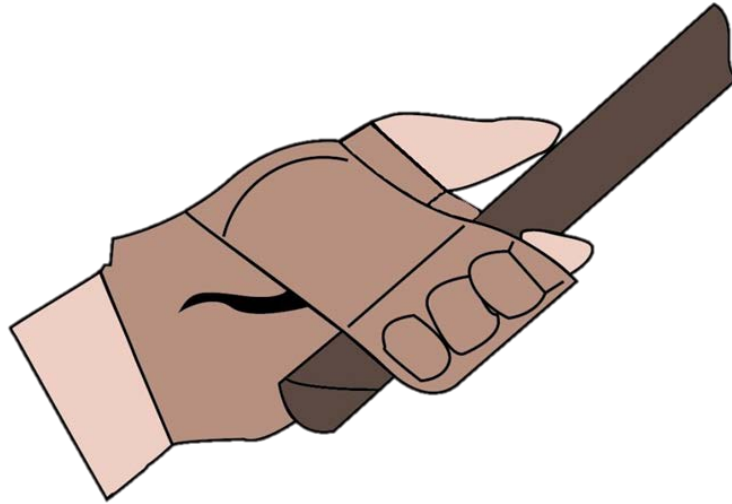


Figure 2.7: Designs of therapeutic gloves with flap

Padding is usually placed at the palm surface of a therapeutic glove (Figure 2.8) and is meant to increase the relative diameter of an item grasped by the user (Marando, 2000; Ville, 1997). Commercially available therapeutic golfing gloves have been constructed with pads placed on the gloves to eliminate the curvature of the hand surface (Bionic Gloves™, 2014a). Bionic Gloves™ claim their designs improve grip strength without the need to grip harder and reduce hand fatigue. The company also claims that experimental results from its independent study show that grip and pinch strength, and torque force are improved with the use of their gloves as compared to bare hands. However, no explanation was given by the company as to how different hand sizes and structures fit into their designs (Bionic Gloves™, 2014a).

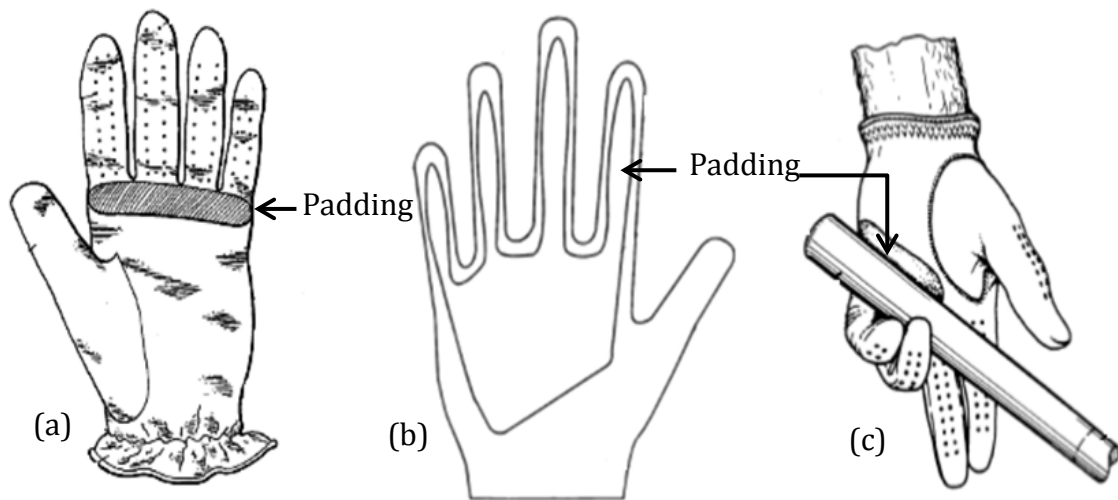


Figure 2.8: Designs of therapeutic gloves with padding by (a) Ville (1997), (b) Marando (2000) and (c) Lappley (1993)

Non-slip material is frequently incorporated into the palm surface of therapeutic gloves to enhance grip. Bowers (1992) patented a glove consisting a thin layer of silicone sealant applied on the palm surface which is intended to provide a better grip. Dewey et al. (2007) developed and tested five different designs of grip enhancement gloves for burn patients where rubber and silicone were incorporated into the palmar surface of the gloves in various patterns: rectangular rubber tabs, honeycomb pattern silicone, wave pattern silicone and silicone beads. The experimental results concluded that addition of grip enhancement material to the palmar surface of gloves improved patients' grip strength (Dewey et al., 2007).

Therapeutic gloves claiming to provide grip enhancement are commercially available under the brand name of Thermoskin®. The outer layer of the gloves is textured by using silicone beads in order to provide additional grip support and prevent slip when holding an item. Figure 2.9 shows the typical placement of non-slip materials for added grip support.

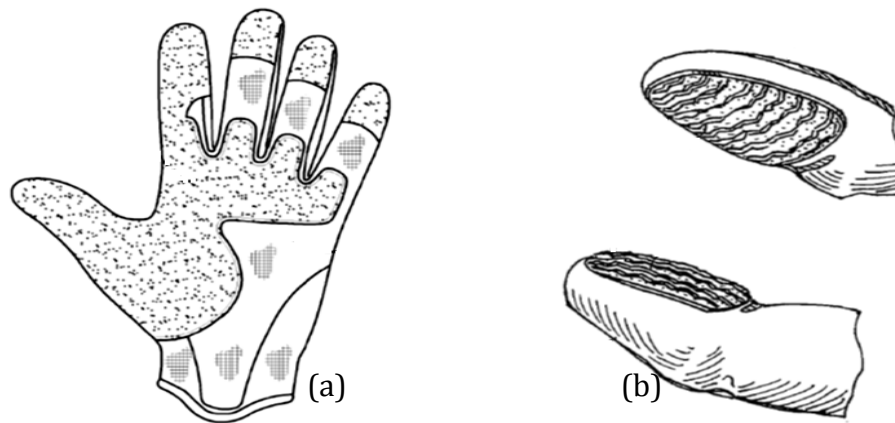


Figure 2.9: (a) Palm and finger surface applied with elastomeric materials, Gellis (2010) and (b) fingers area applied with corrugated surfaces, (Schroeder, 1978)

Many variations in glove that purport to allow greater movement of the hand have been designed, and many have been patented. Besides adding elastic materials over the knuckles and between the fingers, some designers also add elastic materials at the dorsal side of the hand. These modifications are claimed to provide greater dexterity and flexibility to the wearer, thus reducing hand fatigue (Bionic Gloves™, 2014a). Bionic™'s therapeutic gloves feature designs which include stretchable materials at the dorsal side of the hand and between the fingers. Elastic materials are located at the knuckles and around the bony areas of the hand to allow greater movement, especially at the places where the skin stretches the most (Figure 2.10).



Figure 2.10: Bionic Gloves Women's ReliefGrip™ (Bionic Gloves™, 2014b)

Hand therapy can be a time-consuming process which requires considerable commitment from a patient. To alleviate this problem, some gloves have been developed as therapeutic devices to assist patients to improve their hand function (Scaff, 2013). A typical aspect of glove design intended to exercise the hands and fingers is placement of a set of straps at the back of the hand to resist the motions of fingers during fisting. Movement of fingers helps strengthen weak muscles in the hand and forearm (Balint & Szebenyi, 1997; Vlieland, 2003).

Villepique (1996) patented exercise therapeutic glove which incorporates a set of spring-loaded cables running along the finger portion. The spring-loaded cables resist the motions of the fingers during fisting to strengthen the user's hand. The adjustable tension of the cables is an advantage of this invention. Many other variations have been invented to improve the functionality of exercise gloves. Wiggins (1997) and Scaff (2013), patented gloves that incorporate rubber bands on their backs. The principle is the same as that of Villepique's gloves, in that the rubber bands restrict the movement of the hand and strengthen it as a result. Figure 2.11 shows the gloves patented by Wiggins (1997) and Scaff (2013).

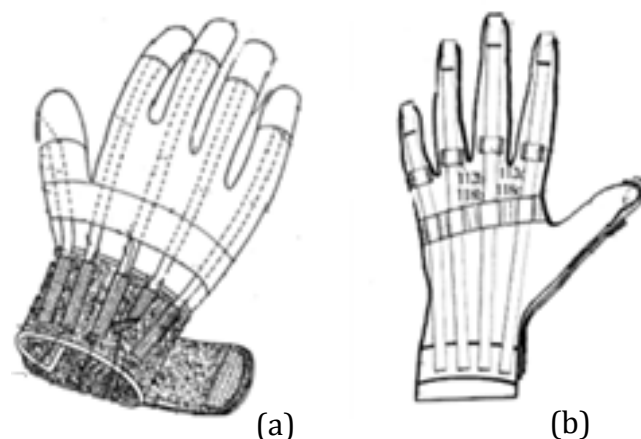


Figure 2.11: Gloves for hand strengthening: (a) Wiggins (1997) and (b) Scaff (2013)

2.2.1.2 Reduction of hand symptoms

Various therapeutic glove designs have been created to relieve pain, lessen the finger swelling and prevent further damage to the joint tissues. Several innovative elements designed to relieve pain and lessen the finger swelling are described below.

Widely varying amounts of pressure applied using therapeutic gloves have been reported in studies to date. Swezey et al's (1979) 'pressure gradient gloves' were reported to generate 10 mmHg at the wrist, 15 mmHg at the hands, 20 mmHg at the knuckles and 28 mmHg at the fingers. In another study by Culic et al. (1979), the pressure at the fingers was 12 mmHg. However, no clinical evidence exists to indicate the ideal pressure for therapeutic gloves for people with arthritis. Recommendations are often borrowed from other types of pressure garments such as in pressure gloves or compression stockings used in the treatment of hypertrophic scar or lymphedema. Pressure garments is widely used in the treatment of lymphedema with interstitial pressure of more than 40 mmHg is claimed to improve the fluid exchange from the blood and thus preventing extracellular fluid accumulation (swelling) (Krimmel, 2009). According to Krimmel (2009), the hand usually correspond to a lower compression levels than those of lower limb pressure garment; this is mainly due to lower blood pressure and the force of gravity as well as differences in the anatomical and physiological construction of the arms and hands.

Very few manufacturers of commercial therapeutic gloves provide information on how much pressure their gloves apply. Isotoner® gloves are claim to apply 23 to 32mmHg of pressure at the MCP joints, and Norco™ gloves to apply 15mmHg (Hammond et al., 2016). Figure 2.12 shows the IMAK® arthritis gloves, a currently available therapeutic glove, which claims to provide mild compression resulting in

decrease of joint swelling (Brownmed, 2010). However, the amount of pressure exerted to the hand by the glove is not given.



Figure 2.12: IMAK® arthritis gloves, with open fingertips to provide sensation during hand function and allow the wearer to observe the colour of their skin and therefore assess the circulation in their fingers (Brownmed, 2010)

Heat therapy is a therapeutic intervention commonly used to reduce pain and swelling. The heat is said to relax muscles and increase blood circulation in the specific targeted area (Kawate et al., 2011; Vlieland, 2003). The increase in blood circulation promotes supply of oxygenated blood and nutrients to the inflamed tissues and therefore reduces swelling and leads to pain relief (Sluka et al., 1999b). Swezey et al. (1979) noted a significant elevation of skin temperature in the hand while wearing 'pressure gradient gloves', in comparison to the skin temperature of an ungloved hand. The researchers claimed that their gloves provided warmth (heat therapy) to the wearer that led to pain relief, as did Oosterveld et al. (1990).

Materials with high thermal resistance (insulation) can be incorporated into a glove in order to increase warmth at the hand. Gordon (1988) suggested that

developing a glove from a thermally insulating material could enhance the treatment of arthritic inflammation; where thermally insulating material not only provides warmth to the joints but reduces the possibility of joints being exposed to rapid cooling.

Acupressure therapy is an alternative medicine technique similar in principle to acupuncture. This treatment has been claimed to be a safe and cost-effective alternative for individuals seeking a non-drug approach to pain relief (Rowe-Lanzisera & Lanzisera, 1995). Most of the acupressure therapy devices or apparatus available involve electrical stimulation; however Rowe-Lanzisera and Lanzisera (1995) patented a glove that enabled self-application of acupressure therapy using direct pressure to the hands, wrists and fingers. The glove is fitted with nodules in its interior surface area which are positioned over acupressure points of the hand, wrist and fingers. The user can apply direct pressure to these points, using the information guide supplied by the manufacturer, to stimulate acupressure points and relieve pain.

2.2.2 Materials

As mentioned previously, therapeutic gloves are tight-fitting garments that are intended to induce pressure onto the underlying tissues of the hand. They are constructed to have a negative fit; where the size of the unworn glove is smaller than the actual anthropometric measurements of the hand. The patterns of the gloves are normally constructed with 10%–20% reduction in hand circumference in accordance with the fabric's extensibility (Anand et al., 2013; Macintyre & Baird, 2006; Yu et al., 2013a).

Most therapeutic gloves are composed of elastic fabrics. The proportion and weight of the elastane in the fabric determines its potential tension (Krimmel, 2009; Sau-Fun et al., 2011). Warp-knitted fabrics prepared from blends of cotton and

polyamide are commonly used and provide reasonable durability and comfort (Sau-Fun et al., 2011). To create a therapeutic glove that provides warmth, the fabrics are often laminated with neoprene. However, neoprene-laminated fabric has been shown to have poor breathability, which can lead to an uncomfortable amount of sweating within the glove (Kennedy, 2003). Appropriate fabric is important to maintain the physiological comfort of the wearer (Ho et al., 2009a). Sau-Fun et al. (2011) argued that all medical garments should be breathable, non-abrasive, durable and comfortable to wear irrespective of the fabric of which they are constructed.

Different levels of elasticity and tensile strength provide varying degrees of fabric tension, thus inducing different degrees of pressure on the users (Sau-Fun et al., 2011). The amount of pressure generated by gloves are influenced by the construction and fit of the glove, the structure and physical properties of its materials, the size and shape of the hand, and the nature of the hand activity undertaken. However, when fabrics are subjected to prolonged stress (during donning and wearing), some of their initial tension will be reduced and thus the interfacial pressure between the skin and the garment will be lowered (Troynikov et al., 2011; Yildiz, 2007; Yip, 1994). The rate of tension decay in the fabric depends on its properties, as well as the amount and direction of stretch applied. Deterioration of fabrics elasticity will affect the fit, the amount of pressure generated on the hand, and ultimately the clinical effectiveness of the gloves. Therefore, it is essential for the fabrics to be durable and not stretch out of shape during application or after repeated wear (Yu et al., 2013a).

According to Ng-Yip (1993), the average life expectancy of a pressure garment is about two to three months; a glove may last about six weeks. Van den Kerckhove et al. (2007) reported that the overall pressure loss after wearing pressure gloves for 23

hours a day for one month was 2.13 mmHg. Loss of durability of pressure garments can be attributed to factors such as donning procedures, care, movements and environmental factors (Macintyre & Baird, 2006; Ng-Yip, 1993). Ng-Yip (1993) stated that the tension of fabric is time-dependent; therefore slackening is bound to occur in pressure garments after a period of wear. According to Macintyre (2007) and Yu et al. (2013b), pressure garments which are designed to exert higher pressures tend to have higher pressure loss with repeated extension and use.

2.3 Mechanisms of clothing comfort

Therapeutic gloves are worn during the day and/or at night to relieve symptoms and improve hand function in arthritis patients. Therefore, it is important for the gloves to be comfortable to wear. Hatch (1993) defined comfort as 'freedom from pain and discomfort'. Other researchers have defined comfort as a state of physiological, psychological and physical harmony between a human being and the environment. People would feel uncomfortable if any one of the three aspects is absent (Das & Alagirusamy, 2010b; Slater, 1986a). Comfort in the context of clothing means a neutral sensation – the wearer is physiologically and psychologically unaware of the clothing (Li & Dai, 2006). There are two major types of discomfort sensation: physiological discomfort and psychological discomfort. Physiological discomfort is when the body feels uncomfortable such as itchy, too cold, or too tight, whereas psychological comfort is when the clothing feels inappropriate or a person is not confident with the appearance (Fan, 2009; Fan & Hunter, 2009; Li & Dai, 2006).

There are four main elements of comfort that all clothes have to meet: thermo-physiological, ergonomic, sensorial and psychological comfort. Thermo-physiological comfort relates to the interaction between the body's thermoregulation and its clothing.

Ergonomic comfort is concerned with the fit of the clothing, the ease of movement within it, and how it is donned. Sensorial comfort is related to the feeling of the fabric next-to-skin. Psychological comfort as discussed earlier is affected by the attitude of the wearer towards the brand image, colour, pattern, material and production (Bartels, 2011; Fan, 2009; Wardiningsih, 2009).

It is clear that aspects of comfort related to therapeutic gloves are multidimensional and interrelated. Given the lack of scientific research on wearer's sensation of comfort while using a therapeutic glove, a comprehensive knowledge framework needs to be established for scientific engineering design and development of therapeutic gloves. The following section describes the four main aspects of clothing comfort, which represent the foundation of the research described in this thesis.

2.3.1 Thermo-physiological comfort

Thermo-physiological comfort is one of the most important components that affect the overall comfort of clothing. It is related to the heat and moisture transport properties of clothing (Bartels, 2011; Higgins & Anand, 2003). The body constantly generates heat from the metabolism of food and muscle activity and loses this heat to the environment; therefore, a balance must be maintained between the rates of heat production and heat loss. The body is in a state of comfort when the skin temperature is around 33–35°C (Li & Dai, 2006).

The thermo-physiological comfort of clothing depends on the rates of thermal and water vapour transport, moisture content and the speed of moisture movement across the fabrics (Fan & Hunter, 2009; Onofrei et al., 2011). The ability of fabrics to absorb moisture and the speed at which they absorb are very important in determining the comfort factor of gloves, especially in the palm area. Some wear trials reported that

therapeutic gloves were 'too hot' to wear, and that this could adversely influence patients' adherence (McKnight & Kwoh, 1992; Oosterveld & Rasker, 1990). Yu (2015) stated that heat and perspiration could be major sources of discomfort or even cause blistering and ulceration when wearing pressure therapy garments for hypertrophic scarring, particularly in warm weather. Investigation of the microclimatic conditions under clothing is important for understanding their influence on human physiological responses and comfort sensation.

2.3.2 Ergonomic comfort

Hu et al. (2007) stated that ergonomic clothing should fulfil the requirements of human mechanics. Ergonomic comfort influences freedom of movement and body thermoregulation (Wang, 2011). The fit of the design, fabric elasticity, and pattern construction are the most important factors in ergonomic comfort (Ashdown, 2011; Manshahia & Das, 2014; Sau-Fun et al., 2011; Wang, 2011). Mehta and Narrasimham (1987) stated that no matter how well clothing is engineered for optimum values of heat or moisture transport, it cannot be regarded as comfortable if it does not fit properly.

A well-designed and engineered garment must not interfere, impede, or restrict body movement relative to the end use for which it is intended (Ashdown, 2011; Troynikov & Watson, 2015). Hence, during the design and engineering process, it is important to consider how the garment fits and the way it integrates with the natural form of the relevant human body. The ability of clothing to provide the required freedom of movement is related to factors such as the garment fit, the properties of its fabrics and materials, and garment design (Jones & Rioux, 1997). The fit of a glove directly influences the hand function of the wearer and resultant ergonomic comfort

(Torrens et al., 2012). According to Gompers (2004), a glove that does not fit or is uncomfortable will be discarded by the user, regardless of its technical qualities. To optimise the effectiveness of therapeutic gloves and adherence to their wearing and practical application, accurate and efficient measurement of wearers' hand dimensions and characteristics – especially those influencing hand function and wear comfort – are crucial.

Ashdown (2011) highlighted that measurements for most garments are made in a standing or other static position, although most of the time the wearer is moving. Body dimensions change during movement, especially in areas surrounding the joints in the human body; for instance, elbows and knees are critical strain areas (Ashdown, 2011; Choi & Ashdown, 2011; Li, 2001). Allowing for wearing ease in garment construction permits unrestricted movement of the wearer's body, thus improving ergonomic comfort (Wang et al., 2011b). Ease of movement of the hand is critical in handwear design due to the hand's complexity and high number and density of joints in comparison to the rest of the human body.

Restriction of hand movement when wearing a glove will generate high glove-skin interfacial pressure, which may apart from discomfort, lead to abrasion and bruising of underlying tissues, especially if the glove fits tightly and its materials are of low elasticity and bending modulus (Das & Alagirusamy, 2010a; Dianat et al., 2014). Therefore, to achieve a good fit and resultant ergonomic comfort, a glove structure should be designed based on the hand's dimensions and characteristics not only in static relaxed posture but dynamic postures, adequately representing critical points in hand movement. Hand anthropometric research to date has tended to focus on measurement of hand dimensions in static relaxed posture, with few investigations into

these measurements relevant to dynamic postures. To date, only a few researchers working on ergonomic hand tool design and military hand wear design (Harih & Dolšak, 2013; Torrens et al., 2012; Williams, 2007) have considered dynamic posture measurement in the design and engineering process.

According to Williams (2007), additional material (up to 16%) may be required at the dorsal side of a hand to accommodate the change in skin strain and the hand dimensions when a fist is formed (Figure 2.13). For example, on a size nine hand, an increase of 31 mm from an original length of 191 mm can be observed when changing from a relaxed hand posture to a power grip posture. Other studies have found that excess material around the fingers and thumb significantly influences hand function and performance (Bishu & Klute, 1995; Tremblay-Lutter & Weihrer, 1996; Williams, 2007). To overcome this, in one study the size and construction of a glove were manipulated to shorten its digit length and to proportionally extend the height of the digit crotch (Tremblay-Lutter & Weihrer, 1996). Tremblay-Lutter and Weihrer (1996) also recommended that an ease value of 17.5 mm for palm circumference could be added to improve the fit of a glove, considering the thickness, elasticity and the bending modulus of the material. Although some researchers have considered the influence of hand movements relevant to glove pattern design (Bishu & Klute, 1995; Harih & Dolšak, 2013; Torrens et al., 2012), it remains unclear how different hand movements affect hand dimensions and the distribution of skin strain across the hand, especially in the vertical and horizontal directions.

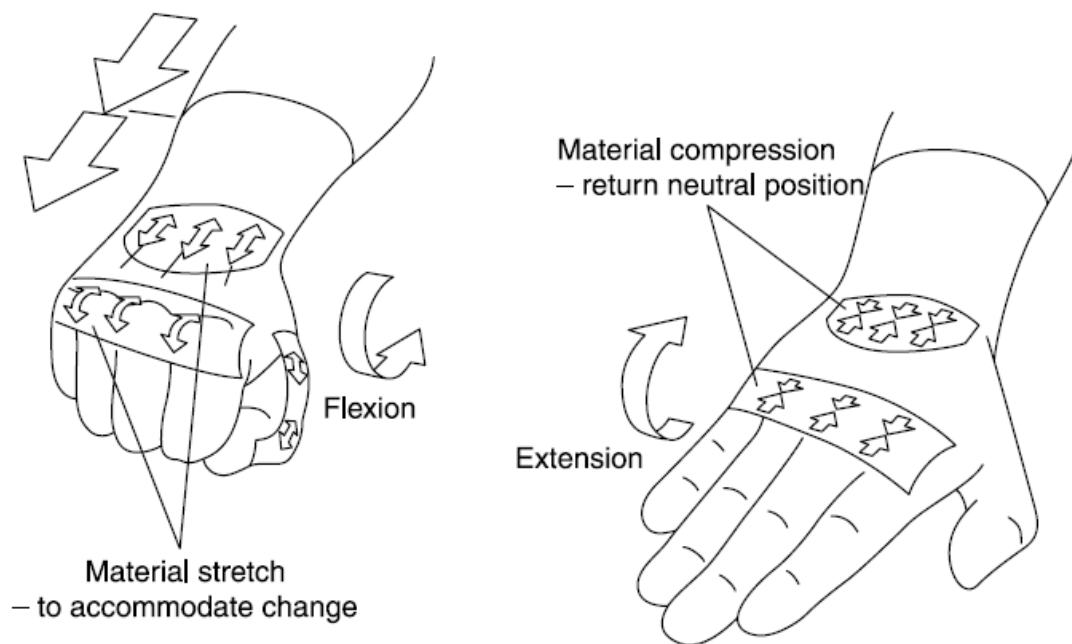


Figure 2.13: Illustration of the movement of material at the dorsal side of the hand
(Williams, 2007)

The magnitudes and distribution induced by pressure garments affect not only psychophysical sensation but other aspects of the human body which could adversely affecting the rate of patient compliance during the treatment (Yu, 2015). Yu et al. (2015a) measured the comfort perceptions of burn patients wearing 'pressure therapy gloves' with three different applied reduction factors - 10%, 15%, and 20%. They found that the comfort performance of the gloves decreased when the reduction factor was increased. The use of pressure gloves with a 20% reduction factor induced a high level of discomfort to patients' hands. They also revealed that the choice of materials and fabric properties such as surface roughness, bending rigidity, thermal conductivity and moisture retention could compromise comfort (Yu et al., 2015a). Similarly, Nakahashi et al. (1998) examined the effect of wearing girdles of various designs, materials, patterns and constructions on users' comfort. They found that when the pressure generated to

the underlying hand tissue and skin of the wearer was more than 40 mmHg, wearers complained of discomfort.

In addition to fabric's properties, anatomical structure, skin stiffness, age and health condition can influence the fabric-skin interface pressure (Rong, 2006; Yu et al., 2013a). To date, changes in glove-skin interface pressure associated with different body movements, anatomical structures and mechanical properties of fabrics have not been established quantitatively.

2.3.3 Sensorial comfort

Therapeutic gloves are worn next-to-skin, so there is a close interaction between the gloves' properties and human hands, which is likely to affect sensorial comfort. Li and Wong (2006) defined sensorial comfort as the elicitation of various neural sensations when fabric comes into contact with skin. Sensorial comfort does not directly involve any temperature balance but is related to the way the person feels when clothing is worn next-to-skin (Wardiningsih, 2009).

Sensation arises through the triggering of sensory receptors in or near the skin surface. The sensations detected by the skin's sensory receptors can be categorised into three groups: touch, thermal and pain sensations. Touch sensations are feelings of smoothness, softness, stiffness and clinginess. Thermal sensations are related to the perception of cold or warmth. The first sensation when fabric touches the skin is usually one of cold. Pain sensations range from relatively mild sensations through to more severe discomfort such as allergic reactions, skin and nasal irritation and skin abrasion (Fan & Hunter, 2009).

Sensorial comfort is mainly determined by fabric surface structure and to some degree by moisture transport and buffering capacity. It is associated with skin contact

sensation and is often expressed as a feeling of softness, smoothness, clamminess, clinginess or prickliness (Das & Alagirusamy, 2010b). These descriptors can be related to specific, measurable mechanical and surface properties of fabric, including the number of surface fibres and contact points, wet cling to a surface, absorptivity, bending stiffness, resistance to shear and tensile forces, and coolness to the touch (Barker, 2002).

Prickliness and itchiness have been identified as the main reason for discomfort resulting from clothing worn next-to-skin (Li & Dai, 2006). Fibre characteristics, fabric thickness, surface roughness, cover factor and finishes influence the itchiness and prickliness sensed from the fabrics (Das & Alagirusamy, 2010b).

Fabric-skin interactions play an important role in maintaining overall physiological comfort. Since therapeutic gloves are worn for up to eight hours a day, it is necessary that they are comfortable to wear for extended periods of time. Fabrics with poor sensorial comfort may lead to skin irritations when worn next-to-skin (Nawaz et al., 2011). Fabric surface roughness and the friction between fabric and the skin are the two most critical components in the evaluation of skin sensorial comfort (Troynikov et al., 2011).

Numerous investigations have been focused on the sensorial wear comfort of sports compression garments and medical compression stockings (Baussan et al., 2013; Troynikov et al., 2011; Van Amber et al., 2015a). However, there is no published research on the sensorial comfort attributes of therapeutic glove fabrics. In addition, when the glove is stretched over the hand, the fabric surface topography changes due to the strain. Thus, it is important to investigate how the topographical changes induced by

varying elastic strain influence the friction at the fabric-skin interface and the fabric surface roughness.

2.3.4 Psychological comfort

Psychological comfort may be defined as 'a pleasant state of psychological harmony between a human being and the environment' (Slater, 1986a). The psychological comfort of clothing is an increasingly important issue in fabric engineering design. Psychological comfort of clothing is a highly subjective matter and relies on individual preference, which is difficult to quantify (Bartels, 2011). The aesthetics in terms of colour, style, shape, material, fitting and finishing can all influence psychological comfort (Fan, 2009).

Some people are strongly resistant to wear any clothing that in some way does not 'look right' to them (Sau-Fun et al., 2011). Many studies of therapeutic garments show that poor construction and appearance makes the wearer feel unhappy, distressed, embarrassed and self-conscious; emotions which lead to poor adherence to the treatment (Ho, 2008; Macintyre & Baird, 2006; Ripper et al., 2009; Yu et al., 2015a). For example, the beige colour which is standard for many therapeutic pressure garments has been reported to have adverse associations with illness and disability; lowering the self-esteem of the wearer (Macintyre & Baird, 2006; Macintyre et al., 1999; Thompson et al., 1992). Thus, a wide range of colours and aesthetic design features are necessary to maintain psychological comfort.

Development of a therapeutic glove that is not only functional and comfortable but aesthetically pleasing to wear requires carefully designed research. Such research must take into consideration wearers' preferences and design features such as the appearance of the gloves and characteristics such as colour, length, and type of closures.

2.4 Physiological comfort maintenance

As arthritis sufferers can spend considerable time wearing therapeutic gloves, it is important to understand their perception of comfort and other sensations during wear. A comprehensive understanding of clothing comfort and accurate prediction of the comfort performance of clothing during wear requires integrated scientific knowledge of the physics, physiology and psychology of comfort.

Physiological comfort sensations is what the glove feels like when it is worn next-to-skin, the microclimate within the glove, and the fit of the glove. The design of the gloves must take into consideration the patient's lifestyle, mobility, ability to apply and remove the glove, stage of arthritis and its severity, tolerance of pressure generated to the underlying hand tissue and skin, and sensitivity towards thermal therapy. These factors together with the aesthetic concerns such as colour selection, fabric handle and overall style contribute to the wearer's sense of well-being and confidence.

When designing the pressure level of the glove, it is important to avoid applying circumferential pressure that may impede the circulation of the hand. It is a tendency of gloves to exert increased pressure over bony protuberances, but the pressure must not exceed that of the patient's capillaries, otherwise blood supply to an area will be restricted, and tissue damage can occur (Yu, 2011b). Thus, careful note should be made to avoid overpressure especially at the bony protuberances of the hand.

Discomfort as a result of over pressure can influence compliance and the overall goal of the treatment. Discomfort and pain thresholds for mechanical forces have been studied quite extensively. Using what is known of sensation and pain from the literature, useful measures can be developed that facilitate achievement of an optimal pressure between the glove and hand. Johansson et al. (1999) found that the discomfort

thresholds for finger and palm were 188 kPa (1410 mmHg) and 200 kPa (1500 mmHg) respectively, and the discomfort thresholds of male and female wearers were significantly different. Chiarotto et al. (2013) found that patients with thumb OA demonstrated widespread hypersensitivity to mechanical pressure stimuli when compared to healthy subjects. These studies shows that physiology varies significantly between individuals, and these differences can affect perceptions of comfort.

For gloves that are designed to keep the hand warm, the moisture management properties of the gloves are important as they allow removal of excessive wetness from the skin. The human body is normally at a stable internal temperature of 37°C, and the average skin temperature is around 33°C without the presence of sweat. It is crucial to determine the optimum skin temperature required for the thermal modality of gloves to be effective and comfortable for the wearer.

The dorsal side of the hand has been reported as having a significantly higher sensitivity to warmth than the palmar area (Wakolbinger et al., 2014). The difference in sensitivity is reportedly due to the thickness of the glabrous skin, which lowers the speed at which temperature changes reach receptors (Defrin et al., 2009; Wakolbinger et al., 2014). Interestingly, sweating has been shown to affect thermal thresholds in the glabrous skin, probably because of the higher density of sweat glands in this area. In the dorsal region of the hand, there are approximately 167 sweat glands per cm², while the sweat glands in the palmar surface are at a density of approximately 307 per cm² (Taylor et al., 2014).

A design prototype which aims to achieve the thermal and biomechanical requirements mentioned above can be created using body mapping concept. Body mapping is a recent and important concept in sport and performance garment design

and engineering (Jinyun, 2013; Smith & Havenith, 2011; Troynikov & Watson, 2015). It takes into consideration the regional variation in the responses of the human body to its activity level and the environment. Regional variations in term of skin deformation, different level of pressure and thermal sensitivity as well as sweat distribution, need to be included in the design of therapeutic gloves to achieve optimal comfort and functionality.

2.5 Functional design framework

Apparel design is a process that requires a mixture of elements in order to create fresh combinations of products. An effective design model greatly increases the chance of success in the design of an apparel product (Luo et al., 2014). The functional design process is widely used by clothing and textile researchers and has also been used to guide researchers in the development of garment design criteria and prototype (Barker, 2007; Ho, 2008). DeJonge (1984), developed a functional design process which included a reflective examination of the end use requirements of a garment, and creative analysis of the methods of development and application of the required criteria. DeJonge's functional design process consists of seven stages, starting with the initial idea and finishing with evaluation of the prototype.

Lamb and Kallal (1992) established an apparel design framework which incorporates a model called Functional-Expressive-Aesthetic (FEA). Their FEA model allows evaluation of the functional needs of the wearer and his or her expressive and aesthetic needs. The functional aspect of the model covers thermal balance, fit, mobility, donning and doffing, comfort, compression, quality and protection. The expression aspect can include self-esteem, values, roles and status, while the aesthetic aspect encompasses style, self-esteem, artistic elements, design principles and the body-

garment relationship (Bye & Hakala, 2005; Gordon & Guttmann, 2013; Lamb & Kallal, 1992; Stokes, 2010). Researchers have established that users are significantly more satisfied with the product if it is aesthetically pleasing and express the user's self (Gordon & Guttmann, 2013; Stokes, 2010; Suh et al., 2010).

Scientific knowledge and a systematic design framework are necessary to guide the design and engineering of a therapeutic glove. The design process of therapeutic gloves is different from that of protective gloves, because the functional requirements of the users are not the same. Researchers have examined the design of functional gloves for industrial, military and gardening purposes (Dianat et al., 2014; Koo et al., 2016; Torrens et al., 2012), but no systematic research has been conducted on the design of a functional therapeutic glove. This research employed the functional design process of DeJonge (1984) and the FEA model developed by Lamb and Kallal (1992), to develop an evidence-based framework for the design and engineering of therapeutic gloves. Details of the design framework are presented in Chapter 9.

2.6 Summary and research gaps

The review of the literature and existing research presented in this chapter explored the key research and state of knowledge about arthritis (particularly hand arthritis), treatment available for management of the disease, different designs and materials of therapeutic gloves, and the main elements of clothing comfort. Although numerous designs of therapeutic gloves have been developed and patented, evidence-based research in this area is scarce. There is no clear systematic classification for therapeutic gloves. Thus, it is hard for the practitioner, as well as for the patient and product engineer, to acquire a comprehensive understanding of glove features and their proposed benefits to the wearer.

The critical design approach to therapeutic gloves – in terms of the materials and construction, the ergonomic interaction between the glove and the hand of the wearer, and the optimum level of pressure and skin temperature required for therapeutic modalities – needs to be studied. These criteria are crucial to the design process, since they not only influence the functional and comfort aspects but users' compliance with the treatment. Accordingly, an understanding of the factors influencing the comfort perception of users, including thermo-physiological comfort, ergonomic comfort, sensorial comfort and psychological comfort, is important to identify ways to develop a better glove.

The objectives of the research and its design are presented in Chapter 4. The outcomes of the research and the degree to which it achieved its objectives are reported in the following chapters.

Chapter 3 The Effect of Therapeutic Gloves on Hand Function and Hand Symptoms: A Review

Introduction

This chapter reviews the evidence for whether therapeutic gloves improve the hand function and hand symptoms in people with hand OA and RA. The chapter is adapted from published paper: **Nasir, S H**, Troynikov, O and Massy-Westropp, N. Therapy gloves for patients with rheumatoid arthritis: A review. *Therapeutic Advances in Musculoskeletal Disease*. 2014; Vol. 6 (6): pp. 226-237, with additional content covering patients with hand OA. The review on patients with hand OA was added to expand the scope, in line with the aims of this research.

3.1 Methods

The term ‘therapeutic gloves’ in this study is used most broadly and all types of gloves were considered, where they aim to deliver various rehabilitative treatments for patients: to control and manage the hand pain, to maintain or restore the patient’s hand function, or to psychologically help to relax or calm the wearer.

3.1.1 Data sources

In order to locate published studies documenting gloves as a treatment for adults with OA and RA, an extensive literature search, irrespective of the year of publication, was conducted using relevant electronic databases: MEDLINE, Physiotherapy Evidence Database (PEDro), Occupational Therapy Systematic Evaluation of Evidence, Wiley online library, ScienceDirect and Cochrane Central Register of Controlled Trial. In addition, a search was also conducted using Google Scholar. The literature search strategy combined the use of two primary keywords: ‘arthritis’ and ‘glove’. These

keywords were combined with other keywords such as 'glove splint', 'orthosis' 'therapy', 'therapeutic', 'compression glove', 'pressure garment', and 'rehabilitation' to explore the related existing research. The literature search was performed over a seven month period, from April 2013 to October 2013, where the databases were accessed multiple times due to difficulty in sourcing some of the relevant sources and for further references. Furthermore, references of relevant studies were examined for additional studies to be included. Only papers written in English were included as the search was not designed to be comprehensive, but to provide a comprehensive overview of the available research evidence.

3.1.2 Study selection and data collection analysis

Retrieved studies were screened independently by the first author using titles of papers and abstracts. Once relevant studies were identified, the full publication was retrieved and reviewed independently by the second author to determine the suitability based on the inclusion and exclusion criteria identified. Any conflicts were resolved through the review conducted by the third author.

For selection criteria, the studies were considered if glove or glove-splint was used as a therapeutic treatment. However, studies using splint only were not considered for this review. Only studies carried out on adults aged 18 years and older were considered. Studies involving patients with any type of arthritis were included if at least one of the participants of the considered study was OA or RA patient. Studies which included at least one measure from the following outcome measures: grip strength, pinch strength, ROM, dexterity, hand pain, finger swelling, joint stiffness were considered for inclusion in this review.

The methodological quality approach was not adopted due to the limited number of studies. This review includes all types of study designs, including uncontrolled studies and case studies. The PEDro methodological quality discussed in the results section was based on the data extracted from the PEDro database.

Studies in the form of abstracts or poster presentations were excluded due to insufficient information for discussion.

3.2 Results

A total of 27 articles were retrieved and after a closer inspection of titles and abstracts, the final number of relevant articles was reduced to eight which consisted of seven clinical trials and one case study. Out of the selected eight studies, four were published in the 1970s, one in 1986, two in the 1990s, and the last one in 2001. Details of the study design and outcome measures from the selected studies are presented in Table 3.1.

Table 3.1: Study design and outcome measures

References	Study design	No of subjects	Concurrent therapies	Trial durations	Follow-up	Outcome Measures
(Oosterveld & Rasker, 1990)	Clinical crossover trial	8 patients	Yes	3 weeks	Weekly	Grip strength, finger swelling, pain and joint stiffness
(Askari et al., 1974)	Clinical crossover trial	23 patients	Not mentioned	Group 1: 20 weeks Group 2: 8-52 weeks	Periodic, every 1 or 2 weeks	Finger swelling, grip strength, ROM, pain and joint stiffness.
(Barbarioli, 2001)	Case study	1 patient	Not mentioned	12 months	Not clearly mentioned	Self-reported hand function
(Culic et al., 1979)	Clinical crossover trial	23 patients	Yes	8 weeks	Weekly	Finger swelling, grip strength, pinch strength, dexterity, pain and joint stiffness, self-reported rating scale on hand symptoms
(Dixon et al., 1986)	Clinical crossover trial	18 patients	Yes	2 weeks	Daily except for Sunday	Finger swelling, grip strength, dexterity, pain and joint stiffness.
(Ehrlich & DiPiero,	Clinical trial	44 patients	Not mentioned	2 weeks	Baseline before treatment	Finger swelling, grip strength, pain and joint stiffness

1971)					Weekly	
(McKnight & Kwoh, 1992)	Clinical trial	39 patients	No	1 week	1 week	Finger swelling, grip strength, ROM, pain and joint stiffness
(Swezey et al., 1979)	Clinical crossover trial	15 patients	Yes	6 weeks	7 visits	Grip strength, finger swelling, ROM, pain, joint stiffness, dexterity

Five out of the eight studies were crossover clinical trials; two were clinical trials, and one was a case study. In four of the studies (Culic et al., 1979; Dixon et al., 1986; Oosterveld & Rasker, 1990; Swezey et al., 1979), treatments for nonsteroidal anti-inflammatory drugs, medication dosages or any therapeutic treatments remained the same. Inversely, in one study, the researchers stopped the use of splints, orthoses and steroid injection treatments for all patients during the trials (McKnight & Kwoh, 1992). Treatment durations ranged from one week to 52 weeks. All studies reported the outcome measures at least once a week except one study (Barbarioli, 2001), which reported the outcome measures after 52 weeks only.

Seven outcome measures were identified from the included studies: grip strength, pinch strength, ROM, dexterity, hand pain, finger swelling and joint stiffness. The outcome measures identified were then classified into two categories; hand function and hand symptoms. Out of the eight studies included, only three studies were found rated by PEDro methodological quality, where the PEDro is based on a quality rating scale which includes 10 criteria. The items are scored as either present (1) or absent (0), and a score out of 10 is obtained by summation (de Morton, 2009). Two studies (McKnight & Kwoh, 1992; Oosterveld & Rasker, 1990) received four out of 10 points and one study (Swezey et al., 1979) received two out of 10 points.

3.2.1 Effect of therapeutic gloves on hand function

Hand function is defined as “the ability to use the hand in every activity” which involves dexterity, manipulative skills and task performance skills (Dellhag & Bjelle, 1999; Lin et al., 2013). Limitation in hand function in patients with OA and RA is related to their quality of joint motion as well as muscle strength (Ouellette, 1991). Although there are various aspects of hand function measures available, it is possible that not all

of these measures can adequately evaluate and reflect the changes in hand function in all patients (Jarus & Poremba, 1993).

Grip strength, pinch strength, and ROM are the most commonly used outcome measures reported in the literature (Lin et al., 2013). There are other outcome measures such as the patient self-reported measures (Björk et al., 2007; Brorsson et al., 2009; Dipietro et al., 2003; Nicolay & Walker, 2005). Obtaining the outcome measures of hand function could be useful for planning of treatment (drug prescription, surgery and conservative therapy), assessment of treatment effectiveness and determination of patients' readiness to use their hands for self-care, work and leisure activities (Dipietro et al., 2003; Fraser et al., 1999; Sollerman & Ejeskär, 1995).

In this review, grip strength, pinch strength, ROM and dexterity were selected as the outcome measures to measure the effectiveness of using therapeutic gloves on hand function in patients with OA and RA. Due to the date of the selected studies, the outcome measures used were traditional measures and thus do not include more recently developed functional measures such as grip ability test, arthritis hand function test, Jebsen hand function test, Sollerman hand function test and disabilities of the arm, shoulder and hand.

3.2.1.1 Grip strength

Grip is critical in many daily activities and because of that it is often used as screening tool in assessing a person's overall health (Nicolay & Walker, 2005). Measurement of grip strength is a widely used measure due to its ease of conduction and reliability (Innes, 1999). Hand grip strength can be evaluated by measuring the amount of static force that the hand can squeeze around a dynamometer. The force is commonly measured in kilograms or pounds, but sometimes it can be measured in

millilitres of mercury or in Newtons (Massy-Westropp et al., 2011). Measurement of grip force provides an objective measure of the strength of a patient's hand in comparison to healthy hand strength and thus the degree of limitation imposed by the patients can be determined (Brorsson et al., 2009; Nicolay & Walker, 2005).

Grip strength was reported improved in RA patients in eight of the included studies (Askari et al., 1974; Barbarioli, 2001; Culic et al., 1979; Dixon et al., 1986; Ehrlich & DiPiero, 1971; McKnight & Kwoh, 1992; Oosterveld & Rasker, 1990; Swezey et al., 1979), however, only two studies demonstrated that the improvement was statistically significant (Table 3.2). McKnight and Kwoh compared two commercially available therapeutic gloves, Isotoner® and Futuro®, which are used at night (McKnight & Kwoh, 1992). The Isotoner® glove is composed of nylon and elastane fibre blend, while the Futuro® consists of a blend of wool and elastane fibres. Although both gloves improved the hand grip strength, the researchers could not identify which glove was superior and similarly what was the mechanism which influences the gloves on improved hand grip strength. The researchers concluded that patient's preference is mainly related to the fit and comfort of gloves, which may ultimately determine the suitability of the gloves to be used (McKnight & Kwoh, 1992). Patients' complaints related to warmth (hot), sensation (scratchy) and fit (tight) should be certainly taken into consideration at the process of glove design. However, the studies did not objectively analyse the glove attributes relevant to its comfort properties.

3.2.1.2 Effect on pinch strength

In the study conducted by Culic et al., the use of a therapeutic glove was compared to a control glove which acted as a placebo (Culic et al., 1979). Each RA patient received a pair of 'compression gloves' and a pair of loosely fitting gloves made of the nylon fibre

(no details on fabric construction were provided). Although patients expressed a preference for the therapeutic gloves over the control gloves with regard to a feeling of improved wellbeing, there was no consistent effect of gloves noted on pinch strength (Table 3.2). As the gloves were all the same size and were not fitted to the patients hand size, it is most likely that the fit of the gloves in some of the patients influenced the hand movement, as well as ROM, which could have affected the resultant pinch strength.

3.2.1.3 Effect on range of motion (ROM)

Range of motion is frequently used as an assessment tool for evaluation of effectiveness of the rehabilitative treatment. Range of motion limitation of hands is a serious problem that is seen in most patients with OA and RA (Lin et al., 2013). Range of motion was commonly measured using composite finger flexion methods where the distance between the distal palmar crease and the tip of the finger is measured using a ruler or a tape to assess the ability of the patient to flex their fingers and make a fist. Distance between the distal palmar crease and the tip of the finger is normally zero for a normal hand.

McKnight and Kwoh (1992) studied the short-term efficacy of wearing two types of 'compression gloves' during night time in 23 RA patients. They reported a significant improvement in ROM by an average of 1.0 to 1.3 cm ($p < 0.05$) (Table 3.2) for each finger (McKnight & Kwoh, 1992). Although both 'compression gloves' improved ROM, there was no detailed information on the 'compression gloves' themselves. The amount of compression exerted by the gloves to the skin, which would significantly influence the hand movement, was not measured.

In the case study conducted by Barbarioli, after 12 months of using glove-splint, the RA patient reported improvement in ROM, especially in managing daily activities

such as meal preparation and washing up. An elastane glove pattern was used as a soft splint. The design of the glove had an opening at the ulnar side seam with a velcro closure, incorporated to permit easy donning and doffing. Although it was reported that the glove-splint was very helpful in contributing towards the independence of the patient, the conclusion made from this statement was based solely on subjective patient's experience, not on any objective measurements. On the other hand, two studies (Askari et al., 1974; Swezey et al., 1979) reported no significant improvement of ROM in OA and RA patients after wearing therapeutic gloves every night. In one of the above studies (Askari et al., 1974), the trial duration for which the gloves were worn, was different for each patient and periodic measurements at one or two weeks' intervals were taken until patients stopped wearing gloves, which was between 2 to 20 weeks. These variations in wear trial protocols would have affected the overall reported ROM results.

Table 3.2: Therapeutic gloves and the effect on hand function

References	Grip strength	Pinch strength	ROM	Dexterity
(Dixon et al., 1986)	p<0.05			+
(McKnight & Kwoh, 1992)	p<0.05		p<0.05	
(Barbarioli, 2001)	+		+	
(Culic et al., 1979)	+	+/-		P<0.05
(Ehrlich & DiPiero, 1971)	+			
(Askari et al., 1974)	+		+	
(Oosterveld & Rasker, 1990)	+			
(Swezey et al., 1979)	+		+	+

P<0.05, improved significantly; +*, improved but no statistical data analysis included;

+/-, no improvement; +, improved but not statistically significant.

3.2.1.4 Effect on dexterity

Dexterity is defined as the ability to perform a specific task, such as pushing, grabbing or pulling an object (Dianat et al., 2012). The effect of wearing therapeutic gloves on hand dexterity was investigated by three studies (Culic et al., 1979; Dixon et al., 1986; Swezey et al., 1979). All three studies reported improvement in dexterity when wearing gloves in comparison to not wearing gloves, however only one study demonstrated that the improvement was statistically significant ($p < 0.05$) (Culic et al., 1979).

3.2.2 Effect of therapeutic gloves on hand symptoms

Patients affected by OA and RA usually suffer from hand symptoms such as pain, stiffness and swelling especially in the joints (Combe, 2007). The use of therapeutic gloves has been widely practiced to reduce hand symptoms in OA and RA (Kavuncu & Evcik, 2004; Oosterveld & Rasker, 1990; Weiss, 2013), however the exact mechanism of symptomatic relief has not been ascertained (Askari et al., 1974; Oosterveld & Rasker,

1990). It was postulated that the pressure of the glove removes extracellular fluid (articular and peri-articular swelling) via the lymphatic system (Hammond et al., 2016). The measurement of symptoms is subjective and usually self-reported using rating scores, questionnaires or interviews, where hand symptoms are measured by assessing finger swelling, hand pain, and joint stiffness. The assessment of the severity of symptoms is very important in monitoring the progression of the disease, measuring the effectiveness of treatment, and maintaining the physical and mental wellbeing of patients (Ouellette, 1991).

3.2.2.1 Effect on finger swelling

The swelling resulting from inflammation of the synovial tissues of the joints and tendons may lead to cartilage destruction, bone erosion and weakening of supporting joint structures (Prosser & Conolly, 2003). For the measurement of finger swelling, the circumference of PIP joints on each finger is taken for evaluation of the difference in the size of fingers (Oosterveld & Rasker, 1990).

Swezey et al. (1979) observed the effect of wearing therapeutic gloves on ten patients with RA and five patients with OA. The study demonstrated that the circumferences of PIP joints in RA patients reduced significantly with $p=0.038$ (Table 3.3) compared when wearing control glove and when not wearing any glove (Swezey et al., 1979). For patients with OA, no improvement in finger swelling was noted following glove wear. The figures supplied by the gloves manufacturer - Jung Company indicate that the expected amount of pressure exerted by the 'pressure gradient gloves' are 28 mmHg at fingers, 20 mmHg at metacarpal, 15 mmHg in hands and 10 mmHg in wrists. However, the actual pressure exerted by these gloves on patient's hands in the above studies was not measured or reported. Similar results were noted in the studies carried

out by McKnight and Kwoh, as well as by Oosterveld and Rasker , with the average circumference of PIP joints reduced by 0.2–0.4 cm and 0.9 cm respectively in RA patients after the used of therapeutic gloves over the period of one week (McKnight & Kwoh, 1992; Oosterveld & Rasker, 1990).

Study conducted by Culic et al. (1979) reported significant improvement in finger swelling in RA patients after the use of therapeutic gloves ($p=0.05$) (Table 3.3). The measurements of swelling of the fingers were taken by measuring the circumferences of PIP joints on each finger, and also by interviewing the patients. The gloves used in this study were ‘compression gloves’ made from nylon and elastane fibre blend and manufactured by Aris group, however, no details of fabric construction or construction of the gloves given.

Ehrlich and DiPiero (1971) reported reduction in circumferences of PIP joints by 0.5cm with the use of ‘nylon knit glove’ and by 1.0cm with use of the ‘spandex/nylon’ glove. Contrariwise to the other six studies discussed above, no significant improvement in finger swelling was noted in the study by Dixon et al. The analysis of the study was restricted to patients with RA, although there were three patients with OA in the trial.

Table 3.3: The effect of therapeutic gloves on hand symptoms

Reference	PIP swelling	Hand pain	Joint stiffness
(Dixon et al., 1986)	P>0.01	P<0.001	P<0.001
(McKnight & Kwoh, 1992)	P<0.05	P<0.05	P<0.05
(Culic et al., 1979)	P=0.05	P=0.01	P=0.01
(Ehrlich & DiPiero, 1971)	Slightly improved*	Improved*	Improved*
(Askari et al., 1974)	Not significant*	Moderate improvement*	Moderate improvement*
(Oosterveld & Rasker, 1990)	P<0.001	P<0.05	P<0.001
(Swezey et al., 1979)	P=0.038	Not significant*	Not significant*

Note: *No statistical indicators reported

3.2.2.2 Effect on hand pain

Pain relief has been reported as a primary goal for therapeutic treatment in OA and RA due to its direct association with increased hand function (McKnight & Kwoh, 1992). The measurement of pain is subjective and is usually self-reported by patients using rating scores, questionnaires or interviews. Six studies reported reduction of pain (Table 3.3) after wearing therapeutic gloves with four studies reported significant improvement $p<0.05$ in nocturnal pain (Culic et al., 1979; Dixon et al., 1986; McKnight & Kwoh, 1992; Oosterveld & Rasker, 1990). Dixon et al studied the effect of wearing 'stretch glove' on 18 female RA patients and found that the use of Isotoner® stretch gloves at night was helpful in decreasing the pain (Dixon et al., 1986). It was hypothesized that the mechanism of glove covering the hand could provide warmth, which led to the reduction of pain (Askari et al., 1974; Oosterveld & Rasker, 1990; Swezey et al., 1979).

Another two studies (Askari et al., 1974; Ehrlich & DiPiero, 1971) also reported improvement in pain reduction in patients with RA at the end of the period of wearing therapeutic gloves; however no statistical indicators were included. These studies used subjective measurement methods such as self-reporting and scale rate of pain levels as 'none', 'mild', 'moderate' and 'severe'. Even though there were improvements in pain reduction in the study conducted by Askari et al., the duration of wearing the gloves between patients were varied (Askari et al., 1974). Periodic measurements at one or two week's interval were taken until patients stopped wearing the gloves, which was between 2 to 20 weeks. The methods of measuring pain were different in all studies (Table 3.4).

Table 3.4: Method used to measure level of pain

Reference	Method to measure level of pain
(Dixon et al., 1986)	Scoring system -2=maximum negative score, -1= deterioration, 0=no change, +1= improvement, +2=maximum positive score
(McKnight & Kwoh, 1992)	10 cm visual analogue scale ranging from "no pain" to "the most intense pain"
(Culic et al., 1979)	A series of question regarding pain
(Ehrlich & DiPiero, 1971)	Self-report by patient
(Askari et al., 1974)	Scale written as none, mild, moderate, severe
(Oosterveld & Rasker, 1990)	Numerical rating scale 0=no pain to 4=worst pain
(Swezey et al., 1979)	Likert scale 0=none, 1=mild, -2=less than usual, 2=usual, +2=more than usual, 3=severe

3.2.2.3 Effect on joint stiffness

Measurement of joint stiffness especially in the morning is nonspecific and difficult to quantify because it wears off gradually with no demonstrable end point (Oosterveld & Rasker, 1990). Measurement of joint stiffness is taken by recording duration of stiffness of the hand in the morning and it is usually self-reported by patients (Ehrlich & DiPiero, 1971; Oosterveld & Rasker, 1990). The effect of wearing different types of therapeutic gloves was investigated in seven of the reviewed studies, where six studies reported improvement in joint stiffness (Table 3.3). In one study (Ehrlich & DiPiero, 1971), joint stiffness in the morning reported lessened to the point of virtual disappearance in almost all patients which consisted 24 RA patients and 18 OA patients. In the study, patients were given two types of 'stretch gloves', as described in section 3.2.2.1 and were instructed to wear the gloves starting from bedtime until morning. The measurement of joint stiffness was taken every morning at the same time over the period of one week. However, no further explanations were given on the mechanism of reduction of joint stiffness through wearing a therapeutic glove every night for one week.

A randomized controlled trial conducted by McKnight and Kwoh, demonstrated that joint stiffness in RA patients improved significantly at $p < 0.05$ (Table 3.3), after using therapeutic gloves for one week (McKnight & Kwoh, 1992). This study compared the short term efficacy of wearing two types of 'compression gloves' every night during sleeping hours. Two methods were used to measure the joint stiffness in this clinical trial: one method was where patients were asked to rate their level of stiffness ranging from 'no stiffness' to 'most intense stiffness' at the end of each treatment. The second method was based on measurement of the rate of finger motion. An automatic counting

device was used to record the number of repetitions of MCP flexion and extension of all four fingers over a set distance during 10 seconds period. Researchers concluded that there were no significant differences between the two types of 'compression gloves', indicating that neither type of the glove was more efficacious than the other in reducing the joint stiffness.

In contrast, one study reported no improvement in joint stiffness in OA and RA patients after using 'pressure gradient gloves' for six weeks (Swezey et al., 1979). The researchers reported that the scale used to measure joint stiffness might be the reason of lacking improvement because patients were unable to differentiate 'mild' or 'moderate' in the scale used to measure joint stiffness.

3.3 Discussion and research gaps

This review revealed very few quality clinical trials with highly rated methodology investigating the effect of therapeutic gloves for the management of hand OA and RA. The methodology quality rating is based on PEDro methodological quality data extracted from PEDro database. Most studies failed to receive high ratings for the reason of no blind subjects, no blind therapists, no adequate follow up, no concealed allocation and many others. The length of time during which the therapeutic gloves influenced outcome measures such as grip strength, pinch strength, swelling, pain and others, were not observed and/or noted; as well as the duration of its effectiveness. Most of the studies mentioned that the gloves were worn during sleeping hours (Culic et al., 1979; Dixon et al., 1986; Ehrlich & DiPiero, 1971; McKnight & Kwok, 1992; Swezey et al., 1979) however, no minimum hours requirement was specified which is important as this would certainly influence the results of the therapy. This can be seen especially in

carried out outcome measurements of hand function, where researchers could not ascertain that the improvement in hand function was due to wearing therapeutic gloves.

In hand OA, only one study reported lessening of morning stiffness in fingers (Ehrlich & DiPiero, 1971). Although patient with hand OA were often recommended to wear therapeutic gloves, not many of the trials included patients with hand OA in the analysis. The evidence on the effect of wearing therapeutic gloves for pain and stiffness in RA patients is strong. However, researchers could not explain or propose the mechanism by which the therapeutic gloves provide symptomatic relief in arthritic hands. It was found that the mechanism of gloves covering the hand is able to provide warmth to the wearer and thus might be the reason for pain relief (Oosterveld & Rasker, 1990). This can also be seen in the study conducted by Swezey and colleagues in which a significant elevation of skin temperature is reported in hands while wearing 'pressure gradient gloves' in comparison to the skin temperature of the ungloved hand (Swezey et al., 1979). The proposed theory behind this is that when the skin and joint temperature increases, blood flow will increase as well. The increase in blood flow reduces pain by effectively supplying oxygenated blood and nutrients to the inflamed tissues, thus providing better healing (Sluka et al., 1999b); and thus having a possible positive effect on the symptoms of pain and swelling.

The researchers could not substantiate that the relief of pain and stiffness is due to compression from the gloves, because there was no correlation between diminished swelling of PIP joints with pain or stiffness. The parameters such as the type of compression needed, the amount of compression generated and the optimum amounts of compression to provide to the wearer were not critically observed or discussed in the reviewed studies. Only two studies included the figures for the amount of compression

exerted by the gloves (Culic et al., 1979; Swezey et al., 1979). It was found that the amount of pressure exerted on each type of gloves is quite different and thus it is not possible to conclude what amount of pressure applied to the wearer's hand would be beneficial.

The results for improvement of hand function in RA patients were inconclusive; except for the grip strength, with few studies reporting improvement and few reporting slightly better. This finding is similar with a more recent systematic review by Hammond et al. (2015), which concluded that evidence on the effects of using therapeutic gloves on hand function is poor and inconclusive. The study also reported that the use of therapeutic gloves at night might have small effect on PIP joint swelling in RA patients. The inconclusive results of hand function might be due to the traditional component measurements used in clinical testing in the reviewed studies. These measurements may not provide enough information about the ability to use the hands by patients for daily living, work and leisure. Self-reporting and performance-based hand function tests such as Jebsen Hand Function Test, Grip Ability Test and Arthritis Hand Function Test should be used to provide the outcome of capacity to perform daily activities. On the other hand, patient's ability to participate in active work or services, if not on pension, should be measured. Early prevention and management of OA and RA could help on a patient's physical, emotional and social functioning (Combe, 2007).

Adherence to recommended treatment such as wearing gloves every day requires high motivation from a patient, so fit and comfort of the therapeutic gloves are paramount, along with the delivery of the necessary amount and distribution of pressure to the hand (Culic et al., 1979; McKnight & Kwoh, 1992; Oosterveld & Rasker, 1990). Only few studies noted complaints of gloves being 'too hot' or 'too tight' to wear,

resulting in few patients' withdrawal from the study (McKnight & Kwoh, 1992; Oosterveld & Rasker, 1990). Glove fitting and design could influence the outcome results measures of hand function because fit can influence wearer's hand movement, sensation and overall comfort. Improper fitting too may lead to hand swelling and burning sensation at night (Ehrlich & DiPiero, 1971). One study described that patient preference in choosing which glove is superior related to fit and comfort rather than glove efficacy. Improving these factors may improve patient satisfaction and enhance patient compliance to prescribed treatment (McKnight & Kwoh, 1992). Furthermore, none of the studies examined the properties relevant to thermo-physiological comfort of the glove. Since therapeutic gloves are recommended to be worn for at least eight hours (sleeping duration), so it is essential that they should be comfortable to wear and not causing physiological discomfort due to excess warmth or sweat production.

3.4 Conclusions

Therapeutic gloves for management of hand RA can lead to substantial improvements in hand symptoms (pain, stiffness and swelling), although the exact mechanisms of their action remain unclear. This suggests that therapeutic gloves can be used to reduce the pain, stiffness and swelling in hand RA. Not many studies included patient of OA in the trials, thus there was not enough evidence to quantify the effectiveness of using the therapeutic gloves in patients with hand OA. This review highlights the need for quality clinical trials to evaluate whether wearing therapeutic gloves could lessen the hand symptoms and improve hand function in people with hand OA and RA in short or long term.

Chapter 4 Research Methodology

4.1 Research objectives

The aim of this research is to establish an evidence-based framework for design and engineering of therapeutic gloves that are functional and comfortable for individuals suffering from hand arthritis. The knowledge gap identified in Chapter 2 and Chapter 3 were combined with the needs and preferences of the patients, design theory and experimentation. The specific research objectives are as follows:

1. To identify and characterise the effectiveness of existing therapeutic gloves in terms of hand function and hand symptoms.
2. To investigate users' perception of effectiveness, comfort and preference when utilising therapeutic gloves.
3. To evaluate the commercial benchmark therapeutic gloves in terms of physical parameters, tensile attributes and properties relevant to physiological comfort of the wearer.
4. To evaluate the effect of hand movements on skin deformation as well as on the interface pressure the gloves impart to the hand of the wearer
5. To evaluate the pressure and thermal discomfort thresholds on the hands of arthritis patients.
6. To propose an evidence-based framework for design and engineering of therapeutic gloves with improved functional attributes as well as improved wear comfort.

4.2 Research questions

The research questions to be addressed are:

1. What are the gloves that are commercially available for arthritis patients, and what is their effectiveness in terms of improving the hand function and reducing the hand symptoms?
2. What are the comfort requirements and preferences of arthritis patients in relation to a therapeutic glove?
3. What are the characteristics and performance attributes of the materials comprising existing therapeutic gloves?
4. How do hand movements impact on skin deformation and on the interface pressure generated by therapeutic glove over the hand of the wearer?
5. Do the pressure and thermal discomfort thresholds significantly varied between patients with hand arthritis? Should the pressure and thermal discomfort thresholds of arthritis patients be taken into considerations in design and engineering of improved therapeutic gloves?
6. What are the best methods for development of therapeutic gloves with improved functional and wear comfort attributes?

4.3 Research significance and value

Therapeutic gloves are widely used as part of conservative treatment for arthritis patients; however, little has been published about their specifications or evaluation. This PhD study goes towards addressing the knowledge gap and develops an evidence-based framework for design and engineering of therapeutic gloves.

The methodologies and the framework established from this research will advance the knowledge in the field and provide a robust foundation for design and

engineering of functional and comfortable therapeutic gloves and other user-centric therapeutic garments.

4.4 Research design

This research adopted the first five stages of DeJonge's (1984) functional design process to develop the framework for design and engineering of therapeutic gloves. Findings gained from the research will allow future research to explore stage six and stage seven of DeJonge's functional design process which is prototype development and prototype evaluation. DeJonge's functional design process is often used by clothing and textile researchers to guide research concerning the development of garment prototype. Examples of previous research that have used the full, or adaptations of DeJonge's design process can be seen in (Barker, 2007; Ho, 2008; McRoberts et al., 2015; Stokes, 2010). The procedures developed specifically in this study are set into five stages; starting with identification of a need for an improved design to a list of design factors for development of evidence-based framework.

1. Initial request

A literature review was completed, summarizing research which concentrated on the therapeutic gloves for people with hand arthritis. The researcher concluded that although numerous therapeutic gloves have been developed and patented, research in this area is very limited. A general objective was determined through informal interviews with hand therapists, patients and manufacturer of therapeutic gloves.

2. Explore design direction

An extensive literature review (summarised in Chapter 2 and Chapter 3) was carried out to understand the disease, its impact on the patients and economy as well as the treatments available for the patients. The different types of therapeutic gloves

available commercially and patented were investigated and classified. The beneficial effect of wearing therapeutic gloves on patients was also reviewed.

Furthermore, user interviews were conducted with a hand therapist and her patients and also with representatives from therapeutic gloves' manufacturers. The hand therapist provided valuable information regarding the symptoms of arthritis, the impacts of arthritis on hand function, and pertinent journals in this area. Aesthetic and expressive information was gained from informal interview with the patients. The manufacturers' representatives provided information about the current market situation and deficiencies of products related to gloves for treating arthritis.

Next, a survey was conducted to investigate the experience of arthritis patients who used therapeutic gloves. The findings from the survey enabled the researcher to identify patients' preferences in therapeutic glove design as well as to benchmark the popular commercial glove brands commonly used.

A market analysis was also carried out via the Internet to determine the types of therapeutic gloves currently available, their design specifications, advantages and disadvantages.

Further literature review was conducted to identify the aspect of clothing comfort and relevant existing research in comfort of therapeutic gloves. From the literature, it is clear that the aspects of comfort in therapeutic gloves are multidimensional and interrelated. It was also established that there is limited scientific research in wearer's sensation of comfort while using a therapeutic glove.

3. Define design goals

The third stage of this research begins with analysis of the information collected from the second stage in order to focus on more specific aspects of the problem under

investigation. The six critical design factors of therapeutic gloves were identified in this stage which were: improvement of hand function, reduction of hand symptoms, thermo-physiological comfort, ergonomic comfort, sensorial comfort and aesthetic comfort.

4. Establish design specification

A series of physical testing were conducted in this stage. The physical parameter, tensile attributes and properties relevant to physiological comfort aspects of wearers for the existing therapeutic benchmark gloves were examined. The effect of hand movements on skin deformation and the interface pressure generated by the gloves on the hand of the wearer were carried out. Next, a study was also conducted to investigate the responses of people with hand arthritis towards pressure and thermal stimuli. The experimental works piloted in this stage were critical for the maintenance of the four elements of comfort. The results from the experimental works were translated into regional hand mapping design concept.

5. Establish design criteria

The preference attributes of wearer from the survey and the findings from literature was used to establish the design criteria. The expressive and aesthetic needs from Lamb and Kallal's (1992), model were also adapted for establishment of the design criteria. The FEA model was adapted in design criteria because prior studies had shown that people are more satisfied with their apparel when these elements are incorporated into designs (Gordon & Guttman, 2013; Stokes, 2010). The Identified design criteria were used for establishment of evidence-based framework for design and engineering of therapeutic gloves.

Chapter 5 Arthritis Patients' Experience and Perception of Therapeutic Gloves

Introduction

This chapter presents results of the survey which was piloted in the exploratory phase of this research. Exploratory research is useful to investigate a relatively unexplored topics and a good method to discover new ideas (Denscombe, 2014). The aim of the survey was to gain insight into arthritis patients' experience of wearing therapeutic glove, their perception of benefit from wearing therapeutic gloves and their preferred attributes in terms of glove design. Commercial therapeutic gloves brands commonly used or preferred by participants were identified and used for further experimental investigations in later chapters.

This chapter is adopted from **Nasir, S H**, Troynikov, O and Massy-Westropp, N. Arthritis patients' experience and perception of therapeutic gloves. Submitted for publication to the *International Journal of Fashion Design, Technology and Education* (currently under peer review).

5.1 Methods

The research was based on an online survey of arthritis sufferers who used therapeutic gloves as part of their rehabilitation treatment.

5.1.1 Questionnaire design and development

The questionnaire included multiple choice and open-ended questions designed to collect data about existing therapeutic gloves, users' experience and perceptions of the gloves, and their preferences for the attributes of a new therapeutic glove. The questions were based on previous studies (Ho, 2008; Massy-Westropp et al., 2003;

Williams et al., 1998) and the opinions of a reference group of hand therapists located in Melbourne, Australia and textile experts. Feedback from these experts on drafts was incorporated into the final questionnaire. Qualtrics version 58039 (Qualtrics Labs Inc, Provo, UT) was used to design the online questionnaire and manage its distribution and collection.

5.1.2 Recruitment

Invitations to participate in the survey and survey links were posted on social networking sites (hosted by Facebook and Twitter) dedicated to arthritis between February and June 2014. Eligibility requirements for participation were that participants were diagnosed with hand arthritis and used therapeutic gloves as part of their rehabilitation treatment. Each potential participant was presented with brief information about the study, their role and rights, and asked to confirm their understanding and give consent before starting the questionnaire. The survey ended in July 2014 when additional participants failed to provide new information (Massy-Westropp et al., 2003; Sargeant, 2012), and the minimum target of 30 respondents for analysis was achieved (Denscombe, 2014).

5.1.3 Data collection

The questionnaire was divided into four main sections (Appendix I). In the first section, participants provided demographic data, and information about their arthritis, and descriptions of their therapeutic gloves. The second section measured user experience and perceptions of their gloves, and these were explored using open-ended questions. Five-point Likert scales were used to quantify participants' perceptions towards the key attributes of their therapeutic gloves (1 = maximum positive score, 5 =

maximum negative score). In the third section, participants were asked about aspects of the utility of their gloves: fit; the quality of the zipper, velcro and seams; and the elastic performance of the gloves. In the last section, participants were asked for design suggestions regarding colour, materials and trims. They were also requested to rank nine criteria for using or buying a therapeutic glove (1 = first priority, nine = last). This section aimed to facilitate the design and engineering of a functional and comfortable therapeutic glove.

5.1.4 Data analysis

Statistical Package for the Social Sciences (SPSS) version 22 (IBM, Armonk, NY) was used to analyse the data. Descriptive statistics including frequencies and means were used to analyse the closed-ended questions (multiple-choice). Coding was used to analyse the answers for open-ended questions which involved seeking recurring themes in the data. The answers were grouped into different categories. Items in the Likert scale were coded during data analysis so that '1' was the highest positive value and '5' was the lowest negative value. Spearman correlation analysis was employed to determine the strength of the relationships between selected variables. Responses in ranking were calculated using average ranking with the largest average ranking was the most preferred criteria. The average ranking was calculated as follows,

$$\frac{x_1w_1 + x_2w_2 + x_3w_3 + x_nw_n}{\text{Total number of participants}}$$

Where x-number of participants who chose that particular ranking and w-weight of ranked position with rank 1 has a weight of 9, rank 2 has a weight of 8 and rank 3 has a weight of 7 and so forth.

5.1.5 Ethics

The Design and Social Context College Human Ethics Advisory Network, sub-committee of the RMIT University Human Research Ethics Committee, approved the study under project number CHEAN B 0000016269-01/14.

5.2 Results

5.2.1 Demographics and arthritis stages

Responses were received from 30 participants (23 women and seven men), of whom 10 were aged 41–50 years, 12 were 51–60 years and eight were 61–70 years.

Duration of arthritis disease ranged from one to 50 years. Two participants reported stage one arthritis (swelling of the joint lining, causing pain, stiffness and inflammation), 11 stage two (thickening of the joint lining), 13 stage three (restricted movement, partial dislocations, muscle wasting, joint pain, cartilage loss), and four stage four (cartilage destruction, immobility). Spearman correlation analysis indicated strong, positive correlations between duration and stage of arthritis, as expected ($r_s=0.640$, $p<0.05$).

5.2.2 Therapeutic gloves

Participants had used therapeutic gloves for two months to 15 years (mean four years). Twenty-six participants purchased ready-made gloves; the top four brands reported were Isotoner® therapeutic compression gloves, IMAK® compression gloves, Thermoskin® thermal support gloves and Futuro® energising support gloves.

5.2.3 Experience and perception of gloves

Participants gave one or more reasons for wearing therapeutic gloves; reducing swelling was the most common. Other reasons were to improve hand function,

protection, mobility, psychological affirmation and provision of warmth (Table 5.1).

Table 5.1 shows that participants mainly wore gloves to reduce hand symptoms.

Twenty-four participants (80%) reported improvement after using therapeutic gloves in regards to reducing swelling and pain, provision of warmth and joint protection. Participants commented:

“I was able to perform a task longer with less pain.”

“Less swelling and pain.”

“Stops hands getting cold at night and reduces swelling.”

“Grip is better, warmer, less strain on joints, alignment of fingers.”

Six participants (20%) felt no improvement after using therapeutic gloves; some related comments were:

“Maybe my rheumatoid arthritis is too severe.”

“No improvement in arthritis but provided comfort.”

“There was a decrease in swelling but not in pain.”

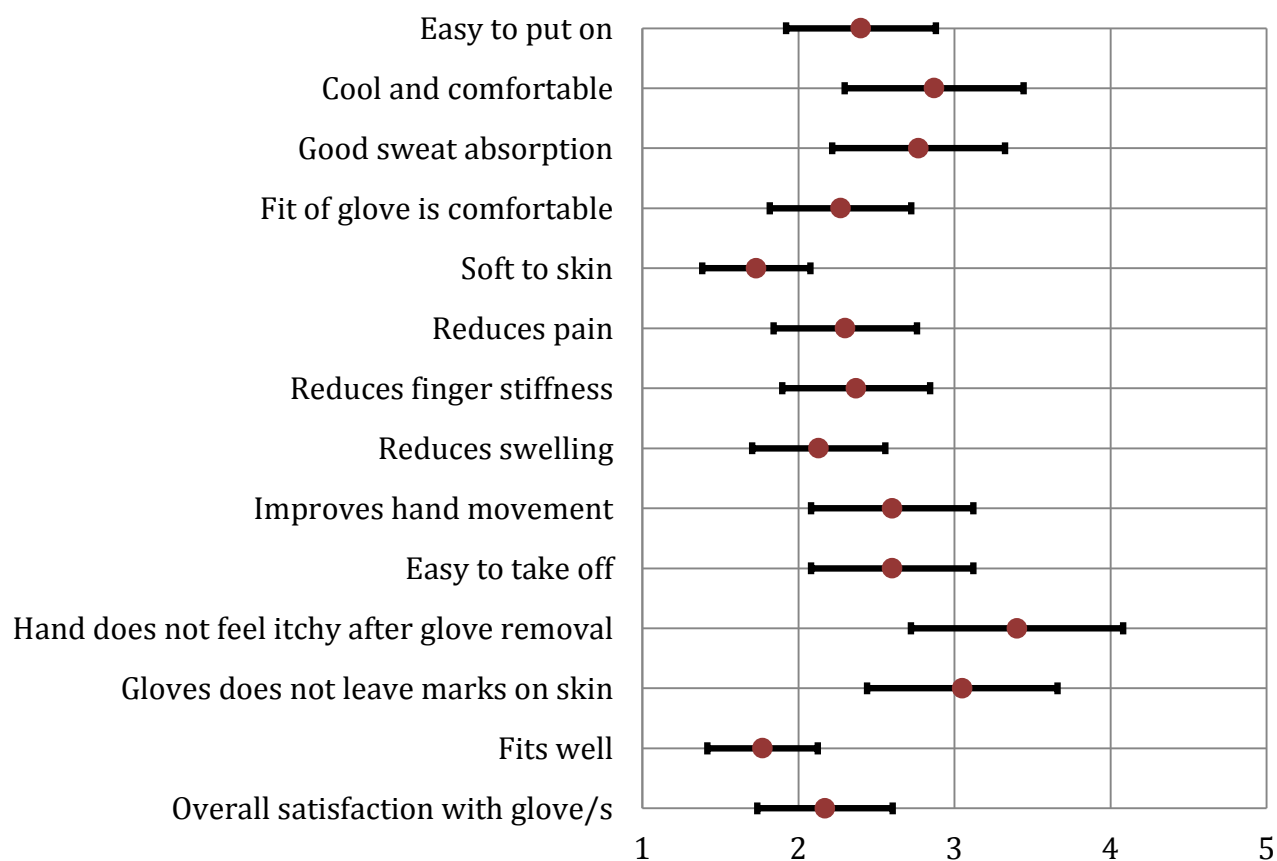
Wearing adherence was high, with 24 participants (80%) reporting wearing their gloves up to eight hours a day as recommended by the majority of hand therapists (Nasir et al., 2014). Four of the participants reported wearing their gloves for 9–16 hours/day, and one participant claimed to wear theirs 24 hours/day. Three participants admitted they did not adhere to the recommended wear duration, due to discomfort.

Table 5.1: Participants' reasons for wearing therapeutic gloves

Categories	Reasons	Number of participants
Symptoms	Reduce pain	7
	Maintain function and prevent pain	4
	Reduce swelling	10
	Stop hand from hurting the joints	1
	Reduce stiffness in the morning	3
Function	Extra support for hand	4
	Support hands against cane and other things	1
	Mobility of fingers	2
	Joint mobility	2
	Feel less vulnerable when using hands	3
Comfort	Keeps hand warm	3
	Provide support and warmth to flaring joint	2
	Compression of the glove is soothing	1
	Relieve stress on joints	1
Appearance	People sometimes notice there is something wrong with my hand	1

Note: Total number of participants does not necessarily add up to 30. This is due to that each participant could give more than one reason for wearing therapeutic gloves.

Figure 5.1 shows that participants found the therapeutic gloves soft to the skin and fit well. Positive to neutral opinions were obtained about the ease of putting gloves on, and whether gloves reduce pain, stiffness and swelling. Neutral to negative attitudes were expressed about gloves leaving marks on the skin and hands feeling itchy after glove removal. No other definite problems were reported, possibly due to participants' tendency to choose the neutral option (scale point 3) based on their taste and preference (Edwards & Smith, 2014; Nowlis et al., 2002).



Note: 1 is the maximum positive score and 5 is the maximum negative score

Figure 5.1: Participants' perception towards 14 key attributes of their therapeutic gloves

Spearman correlation analysis was carried out to determine the strength of the relationship between the feeling of improvement after using therapeutic gloves and the improvement attributes shown in Figure 5.1. Moderate positive correlations exist between participants' feeling of improvement after using therapeutic gloves and the reduction of pain ($r_s=0.449$, $p<0.05$), reduction in finger stiffness ($r_s=0.445$, $p<0.05$) and improvement in hand movement ($r_s=0.425$, $p<0.05$). The correlations were not statistically significant for reduction of hand swelling and overall satisfaction with therapeutic gloves.

5.2.4 Utility

Twenty-one participants (70%) indicated that the fit of gloves was adequate; however, 16 (53.3%) reported that after prolonged wear, the gloves become loose. Seventy per cent of participants agreed that the quality of their therapeutic gloves was good, but only 50% agreed that the zippers, velcro fastenings or seams were of good quality. One participant thought the quality of the seam was poor because it had loose threads. Some commented that the inside seam rubbed the hand and caused discomfort. Thirty per cent of the participants reported washing their gloves every three to four days, and 13% of the participants stated using the gloves for more than a week before washing. The overall stretchability of the gloves was good, with only three participants indicating reduction in stretch after washing the gloves. Lastly, 21 participants (70%) stated that the gloves lasted six months before losing their therapeutic effect.

5.2.5 Preference attributes

Preferences for therapeutic glove colour are varied. Most participants preferred skin colour or other light colours. One participant favoured skin colour because it is not very noticeable. Three participants preferred multicolour gloves with patterns, and the comments were:

“I would like to have different colour and design on the glove. If you have to wear them, they could be a bit more stylish.”

“I would like a choice of colours and designs to go with my outfits!”

Sixty percent of the participants preferred a velcro closure because they are easier to fasten than zippers. However, one participant remarked that velcro loses strength eventually.

Seventeen participants (56.7%) preferred cotton gloves because they believed it has good water absorbency and heat transfer properties, especially in summer. Three participants (10%) preferred a combination of cotton and elastane to make gloves stretchy and easy to put on. Five participants (16.7%) expressed concern that their gloves got sweaty and smelled quickly.

At the end of the questionnaire, participants were asked to rank criteria being considered when using or buying a therapeutic glove. Table 5.2 demonstrates that 23.3% of participants ranked “reducing pain, stiffness and swelling” as their first priority with the highest average ranking of 6.70. The second highest average ranking was attributed to “comfort” with an average ranking of 6.27. The top five important attributes on the basis of average ranking were (1) reducing pain, stiffness and swelling, (2) comfort, (3) good fitting, (4) improve hand function and (5) freedom of movement. The findings of this survey suggested that aesthetic aspects – colour, design, and materials – were seen less significant than the functional and comfort aspects.

Table 5.2: Ranked criteria when using or buying a therapeutic glove

Selection criteria	Ranking									Average ranking
	1	2	3	4	5	6	7	8	9	
	Number of participants									
Ease to put on and off	5	4	2	1	1	9	3	3	2	5.17
Materials	4	1	2	0	1	2	4	14	2	3.77
Durability	0	3	1	3	3	3	9	7	1	3.93
Comfort	4	6	6	4	4	0	6	0	0	6.27
Good fitting	3	6	6	4	6	2	1	2	0	6.20
Freedom of movement	3	0	5	5	5	11	0	1	0	5.43
Improve hand function	2	4	1	9	9	0	3	0	2	5.57
Reducing pain, stiffness and swelling	7	6	7	4	1	1	2	0	2	6.70
Color or design	2	0	0	0	0	2	2	3	21	1.97

5.3 Discussion

Demographic data obtained from this survey seems to be in agreement with previous reports and studies indicating arthritis being more dominant among women than men, and that its occurrence increases with age (Access Economics, 2007; Arthritis and Osteoporosis Victoria, 2013; Schofield et al., 2014; Wong et al., 2010).

A notable finding from this survey is that only two of the most used gloves were studied for their effectiveness (McKnight & Kwoh, 1992; Oosterveld & Rasker, 1990); further research especially covering the attributes of comprising materials and the glove design is needed.

The vast majority of participants of this study felt improvement after using therapeutic gloves especially in arthritic symptoms which are in agreement with the review in Chapter 3. Choosing the right fabric is important to maintain the wear comfort of the user as well as their durability (Ng-Yip, 1993). Therefore, the detailed

instructions on glove aftercare should be provided by the manufacturers as part of the product packaging, which is currently often, is not the case.

Twenty-five participants gave differing views on the aesthetics of gloves. It is plausible that participants who prefer a skin-coloured glove desire for it to be unobtrusive and not identify them as having a disability. However, some participants preferred the gloves to be embellished with colour design and pattern. This may be partly explained by the negative attitudes towards the use of skin colour in pressure garments which shown to have adverse associations with illness and disability (Macintyre & Baird, 2006; Thompson et al., 1992). Thus, the availability of colours and aesthetic designs will also be of importance.

Consistent with previous research, the therapeutic function of the glove was identified as one of the primary factors influencing glove use or purchase (Ho et al., 2009b). The next most important attributes were good fit and comfort, both of which influence the satisfaction and compliance of the user. Similarly, McKnight and Kwoh (1992) concluded that patient preference in choosing which glove is superior is related to fit and comfort.

5.4 Conclusions

Despite improvements in the treatment of arthritis, this disease can severely decrease a person's ability to carry out daily activities, work, and leisure. This study identified arthritis sufferers' experience and perceptions of therapeutic gloves used as part of their rehabilitation treatment. The participants reported symptom improvement during glove wear, and their adherence was high. Healthcare professionals should play a role in guiding the patients in choosing a suitable glove based on their general and specific needs. In addition, manufacturers need to be aware of the needs of users to

promote adherence with the treatment and achieve better healing outcomes through more comfortable and effective glove design.

Chapter 6 Physical Parameters, Tensile Attributes and Properties

Relevant to Physiological Comfort of Commercial Therapeutic

Gloves Fabrics

Introduction

The objective of the research described in this chapter was to evaluate and compare the physical parameters, tensile attributes and properties relevant to the physiological comfort of fabrics used in commercial therapeutic gloves.

Some sections presented in this chapter appear in the following publications: **Nasir, S H**, Troynikov, O. Elastic attributes of fabrics suitable for therapeutic compression gloves. *Advanced Materials Research*. 2014; Vol. 1048: pp. 21-25; and **Nasir, S H**, Troynikov, O. The effect of elastic strain on tribological characteristics of fabrics suitable for therapeutic gloves. *The 13th Asian Textile Conference*. 3 - 6 November; Geelong, Australia 2015. pp. 924-927.

6.1 Materials

Six fabrics used in commercial therapeutic gloves were selected and tested in this study as benchmark gloves. Four samples were of fabrics commonly used for commercial therapeutic gloves, and the other two samples were fabrics cut directly from commercial therapeutic gloves. These samples were selected based on market analysis on the current trend in commercial therapeutic gloves and also on the survey study reported in Chapter 4. Details of the fabric samples' construction and composition are shown in Table 6.1. The fibre content information was sourced direct from the manufacturers and/or from the product packaging. Figure 6.1 shows microscopic images of the next-to-skin sides and outer layer sides of the fabric samples.

Table 6.1: Construction and composition of commercial fabric samples

Fabric code	Source type	Fabric construction	Fibre content (%)
F1	Fabric	Warp-knitted, powernet	63% polyamide, 37% elastane
F2	Fabric	Warp-knitted, powernet, next-to-skin side brushed	75% polyamide, 25% elastane
F3	Fabric	Warp-knitted, sharkskin	68% polyamide, 32% elastane
F4	Fabric	Three-layer composite	Next-to-skin: 34% polyester Middle layer: 57% neoprene Outer layer: 9% polyamide
GF1	Glove	Warp-knitted, sharkskin	80% polyamide, 20% elastane
GF2	Glove	Weft-knitted, single-jersey	95% cotton, 5% elastane

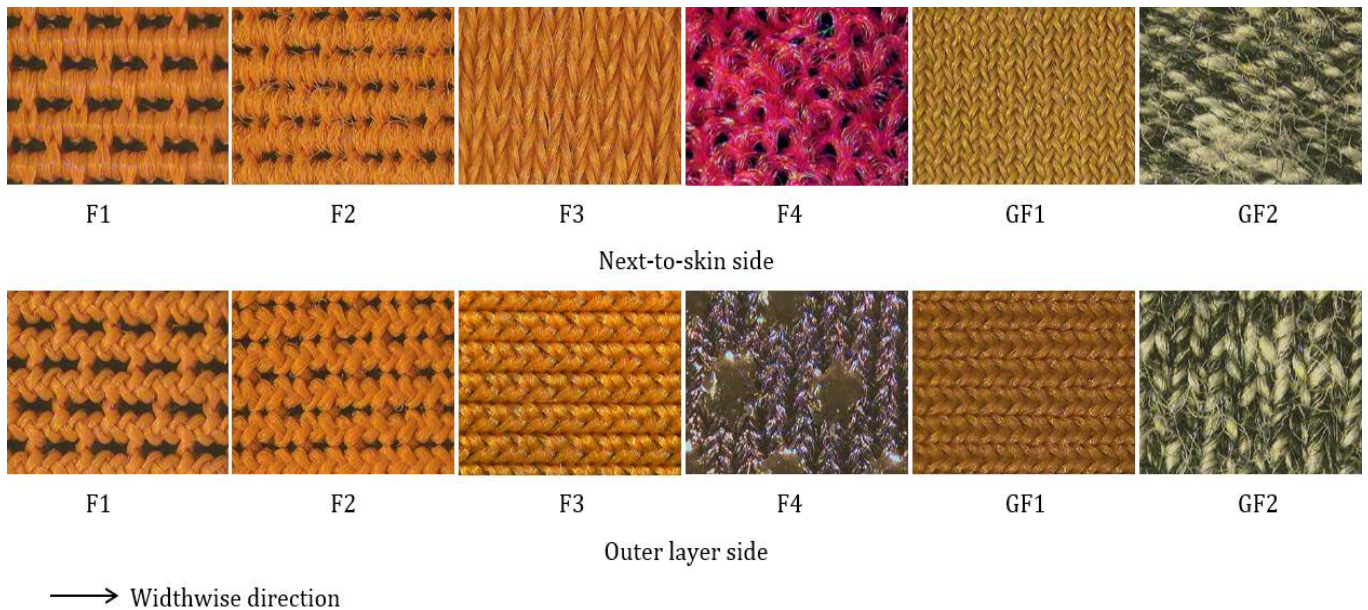


Figure 6.1: Microscopic images of experimental fabrics in relaxed state

6.2 Methods

Before each test commenced, the samples were conditioned to eliminate the influence of atmospheric moisture content, which can affect the physical properties of

fibres. In general, the fibres that absorb the greatest amount of moisture experience the greatest change in properties. Dimensional, mechanical and electrical properties are the three main types of properties affected (Saville, 1999).

All the tests in this study were performed under standard testing conditions of $20\pm 2^{\circ}\text{C}$ and $65\pm 3\%$ relative humidity (AS 2001.1-1995), using standard equipment and testing procedure.

6.2.1 Determination of selected physical properties

The physical properties of fabrics influence their tensile attributes and characteristics related to physiological comfort. The physical properties tested were stitch density, mass per unit area, and thickness. Five specimens from each fabric sample were tested and the average value was reported for each test.

Number of wales and courses per unit length were measured as per AS 2001.2.6-2001 (2001) and mass per unit area was measured according to AS 2001.2.13-1987 (1987). Thickness was measured as the distance between the reference plate and parallel presser foot of the thickness tester as per AS 2001.2.15-1989 (1989).

6.2.2 Determination of tensile properties

Modified test methods based on British Standard BS 4952: 1992 were used to measure the tensile properties of the four experimental fabrics. Due to the small amount of fabric able to be cut from the commercial gloves, the sample size for these fabrics was reduced to $50\text{ mm} \times 50\text{ mm}$. Three samples were cut from each fabric. Tests were carried out using an Instron Tensile Strength Tester (model 5565A). The gauge length was set at 40 mm and the rate of traverse at 500 mm/min.

In most therapeutic gloves, the fabric is oriented so that the warp or wale is aligned with the widthwise direction of the glove. However, in some products the fabric is oriented so that the warp or wale is aligned with the lengthwise direction of the glove. To standardise the testing direction, all the therapeutic glove fabrics were tested according to direction it was manufactured (Figure 6.2).

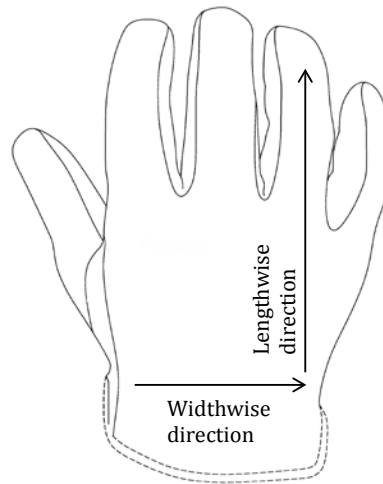


Figure 6.2: Testing directions of therapeutic gloves

6.2.2.1 Determination of force at a specified extension

The stress–strain behaviour of the glove in the lengthwise direction affects the freedom of the bending motion of the hand and fingers when the glove is worn. In contrast, the stress–strain behaviour in the widthwise direction of the glove affects the magnitude of glove–skin interfacial pressure (Yu et al., 2015a), since the reduction factors are applied to the circumferential dimensions of the hand. Fabric testing can help to understand the relationship between these properties.

For determination of instantaneous force at a specified extension, each sample was tensed up to 35% strain at the rate of extension and retraction of 500 mm/min in

accordance with BS 4952: 1992. The instantaneous force at a specified extension was obtained from the stress–strain graphs at the end of each experiment.

6.2.2.2 Determination of tension decay and residual extension after repeated use

The ability of the fabrics to maintain elastic properties after repeated use was determined by fatiguing the samples for 60 cycles of extension and retraction. This testing was based on the assumption that the gloves are worn throughout the day, and the wearer will make repeated hand movements while performing daily activities. Each sample was strained at 10% and 20% strains in lengthwise and widthwise directions at a rate of extension and retraction of 500 mm/min. Earlier research determined the range of practical extension for therapeutic gloves to be 10–20%, guiding the selection of strains for these experimental fabrics (Anand et al., 2013; Macintyre, 2007). Fabric tension decay was determined by calculating the percentage difference between the forces required to extend the sample in the 1st cycle and the 60th cycle (Eq.1).

$$Tension\ decay = ((F_1 - F_{60}) / F_1) \times 100 \quad (1)$$

Where F_1 is the initial force value and F_{60} is the force value after 60 cycles of extension and retraction.

For determination of residual extension, the sample was laid flat on a smooth surface after the test. The gauge length (L) was re-measured after 30 minutes and 1440 minutes (24 hours) of relaxation, and the residual extension was calculated according to Eq.2 and Eq.3:

$$Re_{30} = ((L_{30} - L_0) / L_0) \times 100 \quad (2)$$

$$Re_{1440} = ((L_{1440} - L_0) / L_0) \times 100 \quad (3)$$

Where Re is residual extension (%), L_0 is fabric initial length (mm), L_{30} is fabric length (mm) after 30 minutes relaxation, and L_{1440} is fabric length (mm) after 1440 minutes relaxation.

6.2.3 Determination of physiological comfort properties

The air permeability, thermal and water vapour resistance, and sensorial comfort properties of the fabric samples were tested in turn, as described in the following sections.

6.2.3.1 Air permeability

An air permeability tester (model M021S, manufactured by SDL Atlas) was used to measure the resistance of fabric to the passage of air at pressure of 10 Pa (note that ISO standard 9237-1995 requires a 100 Pa pressure difference, but the instrument could not generate that pressure for some fabrics, therefore using lower pressure is acceptable for comparative purposes). Five samples from each fabric were tested according to ISO 9237:1995, and the air permeability of each was calculated as:

$$R = \frac{\overline{qv}}{A} \times 167 \quad (4)$$

Where R is the air permeability (mm/s), \overline{qv} is the arithmetic mean flow rate of air (l/min), A is the area of specimen under test (cm²) and 167 is the conversion factor from cubic decimetres.

Fabric optical porosity was measured to determine the impact of porosity on fabric air permeability. Optical porosity is expressed as transmittance (%) of visible light through fabric (Wardiningsih, 2009). A microscopic image of the fabric was presented by Motic stereo microscope with magnification of 2× (objective lens). Motic image software was used to capture and process the image. The light from a microscope

is transmitted through the voids and converted into white pixels, while the yarn that blocks the light is converted into black pixels. Then, Image J software was used to determine the optical porosity of the obtained image. Five measurements of optical porosity were taken for each fabric.

6.2.3.2 Moisture management properties

A moisture management tester (MMT), manufactured by SDL Atlas was used to measure liquid moisture transport behaviours in multiple directions: outward on the top surface of the fabric (next-to-skin side); through the fabric sample from the top to the bottom surface; and outward on the bottom surface (outer layer side) according to AATCC Test Method 195-2009. Five samples of 80 mm × 80 mm each were tested. Each fabric sample was placed flat between the top and bottom sensor rings of the MMT. A standard saline solution of 0.22cc (a conductive medium prepared using a standard method) was dropped on the centre of top surface of the fabric during the first 20 seconds (sec). The electrical conductivity of the fabric due to the test solution and its moisture management properties were measured for 120 sec after pumping began. The top surface of the fabric is considered the surface closest to the skin of the human body (next-to-skin side), and the bottom surface of the fabric is the closest to the neighbouring environment (outer layer side).

Wetting Time, WT_t (top surface) and WT_b (bottom surface), is the time in which top and bottom surfaces of the fabric just start to get wet respectively after the test commences.

Absorption rate, AR_t (top surface) and AR_b (bottom surface), is the average moisture absorption ability of the fabric's top and bottom surface during the rise of water content, respectively.

Maximum wetted radius, MWR_t (top surface) and MWR_b (bottom surface), is defined as maximum wetted ring radius at the top and bottom surfaces.

Spreading speed, SS_t (top surface) and SS_b (bottom surface), is the accumulative spreading speed from the centre of the fabric sample to the maximum wetted radius.

The accumulative one-way transport index (AOTI) represents the difference between the accumulative moisture contents of the two surfaces of the fabric, and signals whether the fabric has good moisture management properties. In terms of comfort, the higher the AOTI, the quicker and more easily liquid sweat can be transferred from the next-to-skin side to the outer layer of the fabric, thus keeping the skin dry.

Overall moisture management capability (OMMC) indicates the overall ability of the fabric to manage the transport of liquid moisture. The larger the OMMC, the higher the overall moisture management capability of the fabric.

Using the above indices, the test samples were evaluated for their liquid moisture management properties. Sometimes, however, the values of the indices were difficult to interpret. To address this, the indices were converted from value to grade based on the following grading (AATCC Test Method 195-2009, 2009; Yao et al., 2006):

- Wetting time (sec) in top and bottom: 1) ≥ 120 no wetting; 2) 20-119 slow; 3) 5-19 medium; 4) 3-5 fast; 5) < 3 very fast
- Absorption rate (%/sec) in top and bottom: 1) 0-10 very slow; 2) 10-30 slow; 3) 30-50 medium; 4) 50-100 fast; 5) > 100 very fast
- Max wetted radius (mm) in top and bottom: 1) 0-7 no wetting; 2) 7-12 small; 3) 12-17 medium; 4) 17-20 fast; 5) > 22 very fast

- Spreading speed (mm/sec) in top and bottom: 1) 0-1 very slow; 2) 1-2 slow; 3) 2-3 medium; 4) 3-4 fast; 5) >4 very fast
- AOTI: 1) <-50 very poor; 2) -5 to 100 poor; 3) 100-200 good; 4) 200-400 very good; 5) >400 excellent.
- OMMC: 1) 0-0.2 very poor; 2) 0.2-0.4 poor; 3) 0.4-0.6 good; 4) 0.6-0.8 very good; >0.8 excellent.

6.2.3.3 Thermal and water vapour resistance

The thermal resistance (R_{ct}) and water vapour resistance (R_{et}) of fabrics F1, F2, F3 and F4 were evaluated using a sweating guarded hot plate according to ISO 11092:2014. Fabrics GF1 and GF2 (cut from commercial gloves) were not tested due to the size limitation. The sample size needed which was 300 mm × 300 mm was not enough to be cut even from the largest size (xl) available from glove GF1 and glove GF2.

The sweating guarded hot plate is able to simulate both heat and moisture transfer from the body surface through fabric layers to the environment. The test apparatus consisted of a guarded hot plate assembly enclosed in a climatic chamber, with the air speed generated by the air flow hood set to 1 ± 0.05 m/s. The test section was in the centre of the plate, surrounded by a guard and lateral heater that prevented heat leakage. The temperature of the guarded hot plate was kept at 35°C (representative of the temperature of human skin).

For the determination of the R_{ct} of the fabrics, standard atmospheric conditions of 65% relative humidity and 20°C temperature were set. Three samples of 300 mm × 300 mm were cut from each fabric (F1–F4). Each sample was placed on a porous metal plate surface and the heat flux from the plate to the environment was measured. After the system reached steady state, the total R_{ct} of the fabric was calculated as:

$$R_{ct} = \frac{A(T_s - T_a)}{H - R_{ct0}} \quad (5)$$

Where R_{ct} is the thermal resistance of the fabric ($\text{m}^2 \text{ }^\circ\text{C/W}$), A is the area of the test section (m^2), T_s is the surface temperature of the plate ($^\circ\text{C}$), T_a is the temperature of ambient air ($^\circ\text{C}$), H is the electrical power (W), and R_{ct0} is the thermal resistance of the boundary air layer ($\text{m}^2 \text{ }^\circ\text{C/W}$).

To measure the R_{et} of the fabric, distilled water was fed to the surface of the hot plate from a dosing device. The water entering the measuring unit was preheated by passing through the guard heater section. A level switch is connected to the measuring unit to maintain a constant rate of evaporation. A piece of smooth, water vapour permeable, liquid water impermeable barrier (a membrane) was fitted over the plate. The air bubbles and wrinkles beneath the membrane were smoothed out from the centre outwards to the guard heater section, and the fabric sample was placed above the membrane. The electrical power needed to maintain the plate at a constant temperature of 35°C gives an indicator of water evaporation rate. Air temperature was set at 35°C and relative humidity controlled at 40%. After a steady state is reached, the total evaporative resistance of the fabric is calculated by:

$$R_{et} = \frac{A(P_s - P_a)}{H - R_{et0}} \quad (6)$$

Where R_{et} is total water vapour resistance provided by the liquid barrier and fabric ($\text{m}^2\text{Pa/W}$), A is the area of test section (m^2), P_s is the water vapour pressure at plate surface (Pa), P_a is the water vapour pressure of the air (Pa), H is the electrical power (W) and R_{et0} is the total R_{et} provided by the boundary air layer ($\text{m}^2\text{Pa/W}$).

6.2.3.4 Sensorial comfort properties

Fabric sensorial comfort properties were measured on both the next-to-skin side and outer layer side, using Kawabata evaluation system KESFB4-A (Kato Tech Co. Ltd). Fabric samples were tested in a relaxed state (0% strain) and elastic strains of 10% and 20%. A plate with smooth edges measuring 50 mm in width, 50 mm in length and 2 mm in thickness was used to apply various elastic strains in lengthwise and widthwise directions. For the testing of samples in the relaxed state, samples were cut to 50 mm × 50 mm (the same size as the plate) and placed on the plate. For the testing of samples at 10% and 20% strains, samples were cut so that straining them over the plate in lengthwise and widthwise directions would generate the required tension (Figure 6.3).

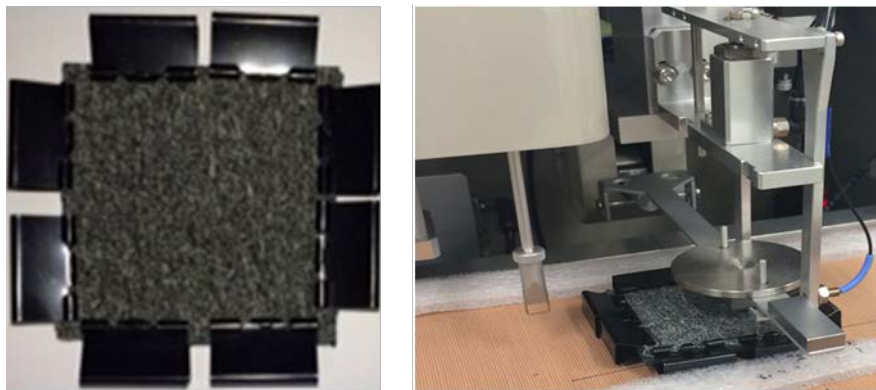


Figure 6.3: Fabric sample stretched over testing plate

The coefficient of friction (MIU) is calculated by averaging the output over the distance between 0 mm and 20 mm, and is defined as

$$MIU = \frac{F}{N} \quad (7)$$

Where F is the frictional force and N is the standard load of sensor pressing the fabric. $0.5N$ is a constant standard set load that mimics the average pressure of garments against the skin.

The geometrical surface roughness mean deviation (SMD) is the value obtained by filtering the measurement data with a high-pass filter to extract the waviness profile of wavelengths greater than 1 mm (frequencies smaller than 1 Hz) and by numerically integrating over the absolute value of the distance moved from the standard position along the path taken by the sensor. It is expressed as

$$SMD = \frac{1}{L_{max}} \int_0^{L_{max}} |Z_0 - Z| dL \quad (8)$$

Where L_{max} is the maximum distance travelled by the sensor over the fabric (cm), Z is the vertical deformation of the sensor from a standard position (cm), and L is the distance the sensor moves across the fabric surface (cm).

The MIU and SMD values were recorded individually and simultaneously for the 'go and return' stroke. Measurements were taken on each fabric sample three times in the lengthwise direction and widthwise direction respectively.

6.3 Statistical analysis

Microsoft Excel 2013 was used to analyse the data. Descriptive statistics such as mean values were presented in tables and bar charts. The standard deviation (SD) values were presented in the tables and graphically presented in bar charts as error bars. One-way analysis of variance (ANOVA) was performed to determine whether the properties of the sample fabrics differed significantly from each other. The significance level was set at $p < 0.05$. Linear regression was also used to analyse the relationship between two variables.

6.4 Results

6.4.1 Physical properties of fabrics

The therapeutic glove fabrics investigated in this research possessed a wide range of physical properties (Table 6.2). Fabric F4 had the highest mass per unit area and it was constructed from a laminated fabric. Fabrics F1 and F2 had almost identical thickness and mass per unit area, with slight differences in the number of wales and courses per cm. The fibres of the yarns in fabric F2 were raised due to the brushing process which slightly increases the thickness of the fabric, although its mass per unit area was lower than fabric F1 (Figure 6.1). Fabrics F3 and GF1 were similarly closely related. Fabrics F3 and GF1 have sharkskin warp-knitted structures, commonly used for producing fabric with high elastic modulus. In this structure, the long floats of yarn made by the back guide bar were exposed on the technical back, providing smooth surfaces and high elastic modulus.

Table 6.2: Fabric physical properties

Fabric code	Wales per cm	Courses per cm	Mean mass per unit area (g/m²) ± SD	Mean thickness (mm) ± SD
F1	15	36	269.3 ± 0.01	0.55 ± 0.01
F2	17	32	266.7 ± 0.01	0.54 ± 0.00
F3	22	39	356.0 ± 0.00	0.84 ± 0.01
F4	24	28	612.0 ± 0.14	2.12 ± 0.05
GF1	31	55	300.0 ± 0.00	0.86 ± 0.00
GF2	16	28	270.7 ± 0.01	0.77 ± 0.01

6.4.2 Tensile properties of fabrics

Figure 6.4 and Figure 6.5 show the tensile properties of the fabrics in the form of stress–strain curves with strain up to 35% in both lengthwise and widthwise directions.

It can be observed from Figure 6.4 that fabric F1 recorded the highest stress in the lengthwise direction and fabric GF2 the lowest. The sequence of stress recorded in the lengthwise direction from the highest to the lowest was $F1 > F4 > F2 > F3 > GF1 > GF2$. Fabrics F2 and F3 had very similar lengthwise stress; the plots were in very close proximity and had very similar form.

Fabrics GF2 demonstrated 'square' stretch (also known as 'balanced' stretch) in terms of their tensile performance in both directions (1.9 N/50 mm lengthwise and 2.3 N/50 mm widthwise). The experimental results showed that Fabric F1 recorded the highest stress in both directions than the other fabrics. It is evident from Figure 6.4 and Figure 6.5 that fabric stress in the lengthwise direction is lower than in the widthwise direction (except for fabric F1).

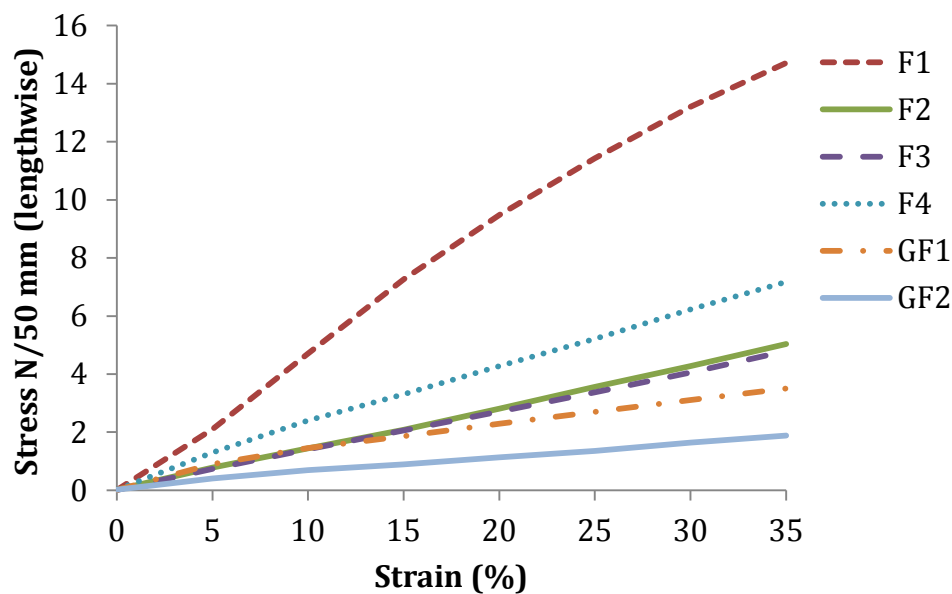


Figure 6.4: Stress-strain behaviours of fabrics in lengthwise direction

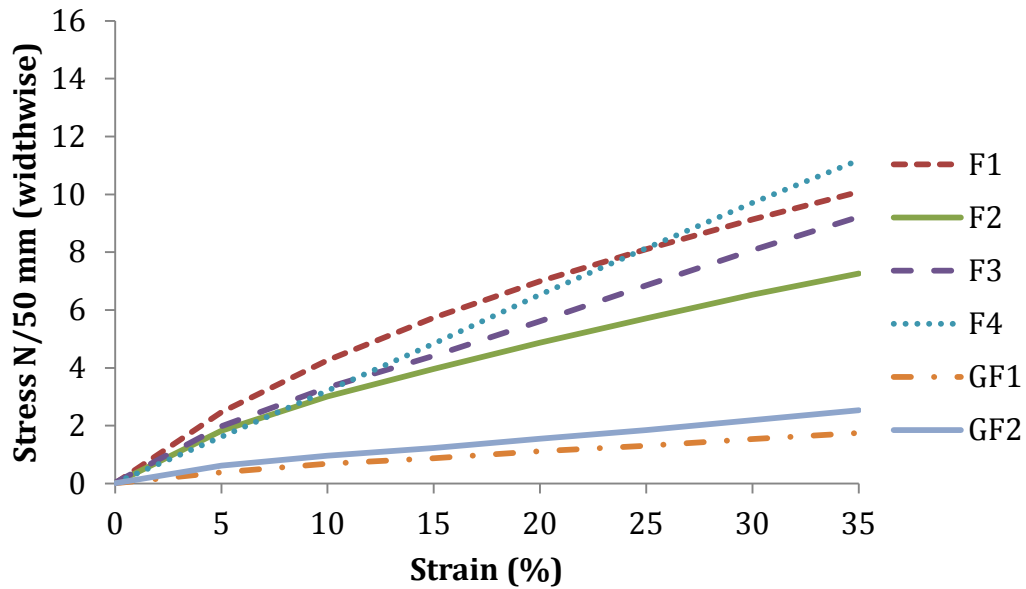


Figure 6.5: Stress–strain behaviours of fabrics in widthwise direction

Table 6.3 shows the fabric tension decay after 60 cycles of extension and retraction in lengthwise and widthwise directions. It is apparent that all fabrics exhibited a certain amount of tension decay after repeated extension and retraction. Fabric F1 recorded the highest percentages of tension decay in the lengthwise direction. In the lengthwise direction, the tension losses at 10% and 20% strains were significantly different ($p < 0.05$) for fabrics GF1 and GF2. Meanwhile, in the widthwise direction, the tension losses at 10% and 20% strains were significantly different ($p < 0.05$) for fabrics F3, F4 and GF1.

Table 6.3: Tension decay of fabrics at 10% and 20% strains

Fabric code	Lengthwise (%)			Widthwise (%)		
	10%	20%	p-value	10%	20%	p-value
F1	24.12	25.98	>0.05	12.42	13.50	>0.05
F2	12.76	12.81	>0.05	6.48	7.08	>0.05
F3	10.90	9.61	>0.05	16.73	12.88	<0.05
F4	10.94	11.70	>0.05	17.40	13.38	<0.05
GF1	15.42	12.80	<0.05	12.38	12.54	>0.05
GF2	10.23	13.65	<0.05	12.78	16.93	<0.05

Normally, when a fabric is continually stretched and then allowed to recover, it does not immediately return to its original shape. Its elastic recovery depends on the force applied, the length of time for which the force is applied, and the length of time that the fabric is allowed to recover (Wang et al., 2011a).

The residual extensions (%) of the fabric samples after 30 minutes and 1440 minutes of relaxation are shown in Table 6.4. After 30 minutes of relaxation, fabrics F3 and GF2 showed 100% recovery in lengthwise direction, whereas fabric GF1 showed 100% recovery in widthwise direction. The experimental results revealed that all fabrics used in this experiment have good recovery performance, greater than 95% after 1440 minutes of relaxation. With 1440 minutes relaxation after 10% strain, all fabric recorded 100% recovery except for fabric F1 in both directions and fabric F3 in the widthwise direction.

Table 6.4: Residual extension (%) of fabrics after 30 minutes and 1440 minutes of relaxation

Fabric code	30 minutes		1440 minutes	
	10% strain	20% strain	10% strain	20% strain
Lengthwise				
F1	1.67	2.50	0.42	0.83
F2	0.42	3.33	0.00	3.33
F3	0.00	0.83	0.00	0.42
F4	1.25	3.33	0.00	1.25
GF1	0.83	1.67	0.00	1.25
GF2	0.00	1.25	0.00	0.42
Widthwise				
F1	0.83	1.25	0.42	0.83
F2	0.83	0.83	0.00	0.83
F3	0.83	0.83	0.83	0.83
F4	1.25	2.92	0.00	1.25
GF1	0.00	2.08	0.00	1.25
GF2	2.50	0.00	0.00	0.00

6.4.3 Physiological comfort properties of fabrics

6.4.3.1 Air permeability

In a hot environment, higher air permeability allows more air to move around the skin, facilitating the removal of humid air and reducing perspiration discomfort (Slater, 1986a; Slater, 1986b).

Table 6.5 shows the air permeability of the experimental samples. It can be observed that all tested fabrics were air permeable, except for fabric F4 (due to the presence of neoprene lining). Fabrics F1 and F2 were substantially more air permeable

than the other fabrics, as their high optical porosity results suggest. Fabric GF2 recorded the lowest air permeability and optical porosity values.

The linear regression in Figure 6.6 shows that there was a strong correlation ($R^2 = 0.9597$) and a linear relationship between optical porosity and air permeability: as optical porosity increased, air permeability increased.

Table 6.5: Air permeability and optical porosity of fabrics

Fabric code	Mean air permeability (mm/s) \pm SD	Mean optical porosity (%) \pm SD
F1	363.3 \pm 10.04	13.5 \pm 0.12
F2	173.5 \pm 22.17	9.5 \pm 0.52
F3	13.5 \pm 4.51	2.2 \pm 0.72
F4	Not applicable	Not applicable
GF1	14.6 \pm 2.14	2.7 \pm 1.30
GF2	5.3 \pm 0.52	1.0 \pm 0.15

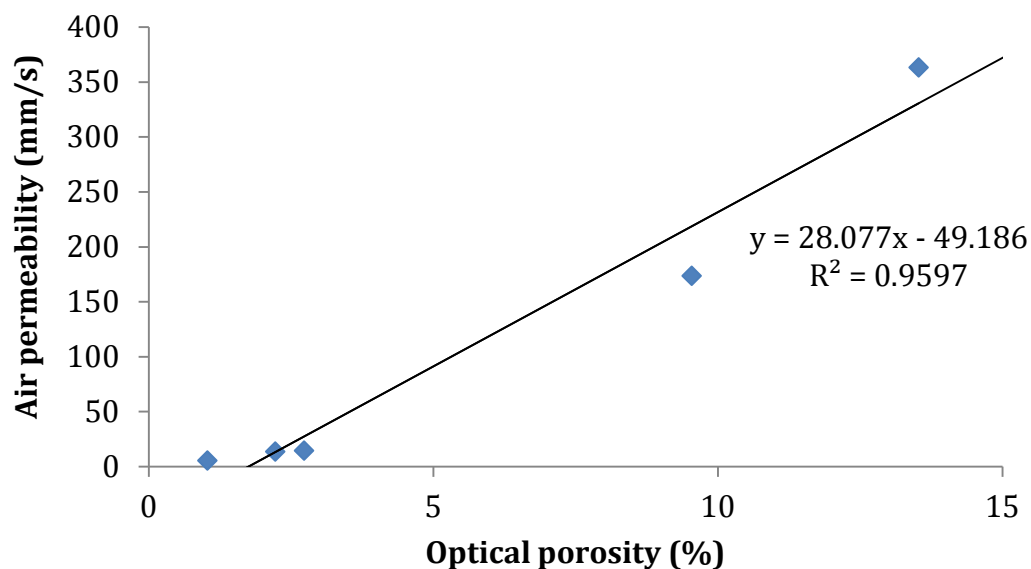


Figure 6.6: Relationship between air permeability and optical porosity

6.4.3.2 Moisture management properties

Table 6.6 shows the moisture management properties of the fabrics, with the results converted into grades in Table 6.7. As shown in Table 6.6, fabrics F1 and F2 had maximum wetting times (no wetting) on the top surfaces and medium wetting times on their bottom surfaces. This indicates that when the saline solution drops onto the top surface (next-to-skin side of the fabric), it quickly transfers to the bottom surface (outer layer side of the fabric). On the other hand, fabrics F3, F4, GF1 and GF2 recorded medium wetting times on the top surfaces and maximum wetting times on the bottom surfaces. This indicates that although the fabrics wet quickly on the next-to-skin side, liquid did not transfer to the other side.

Table 6.6: Moisture management properties of fabrics

Fabric code		WT _T	WT _B	AR _T	AR _B	MWR _T	MWR _B	SS _T	SS _B	AOTI	OMMC
		(sec)		(%/sec)		(mm)		(mm/se)		(%)	
F1	Mean	120.0	7.1	0.0	8.2	0.0	5.0	0.0	0.7	771.7	0.6
	SD	0.0	0.5	0.0	6.2	0.0	0.0	0.0	0.1	62.4	0.0
F2	Mean	120.0	6.5	0.0	1.6	0.0	5.0	0.0	0.8	758.6	0.6
	SD	0.0	12.0	0.0	7.4	0.0	0.0	0.0	0.2	15.6	0.1
F3	Mean	7.0	120.0	68.2	0.0	5.0	0.0	0.7	0.0	-979.4	0.0
	SD	0.8	0.0	6.8	0.0	0.0	0.0	0.1	0.0	68.3	0.0
F4	Mean	6.6	120.0	84.7	0.0	12.5	0.0	2.6	0.0	-1091.1	0.0
	SD	1.6	0.0	8.23	0.0	2.89	0.0	0.7	0.0	82.7	0.0
GF1	Mean	8.8	120.0	74.9	0.0	5.0	0.0	0.6	0.0	-1023.6	0.0
	SD	2.2	0.0	5.7	0.0	0.0	0.0	0.1	0.0	38.9	0.0
GF2	Mean	9.0	120.0	417.7	0.0	5.0	0.0	0.6	0.0	-992.7	0.0
	SD	2.0	0.0	17.4	0.0	0.0	0.0	0.1	0.0	65.3	0.0

Table 6.7: Moisture management properties of fabrics in grades

Fabric code	Grades									
	WT _T	WT _B	AR _T	AR _B	MWR _T	MWR _B	SS _T	SS _B	AOTI	OMMC
F1	1	3	1	3	1	1	1	1	5	4
F2	1	3	1	3	1	1	1	1	5	4
F3	3	1	4	1	1	1	1	1	1	1
F4	3	1	4	1	3	1	2	1	1	1
GF1	3	1	4	1	1	1	1	1	1	1
GF2	3	1	5	1	1	1	1	1	1	1

Similar trends were observed for absorption rate: fabrics F3, F4, GF1 and GF2 recorded high absorption rates on their top surfaces while fabrics F1 and F2 recorded high absorption rates on their bottom surfaces. A higher absorption rate on the bottom surface indicates that moisture is transferred from the top to the bottom surface, thus the top surface remains drier than the bottom surface.

Table 6.7 shows that the maximum wetted radius grades for the top surfaces of F1, F2, F3, GF1 and GF2 were ‘no wetting’, and the grade for fabric F4 was ‘medium’. For fabrics F3, GF1 and GF2, the 5 mm wetted radius measured on the top surface was mainly due to the existence of water droplets (Figure 6.7). However, the wetted radius at the bottom of the fabric did not change, since the water did not reach the bottom surface throughout the testing period of 120 sec. It is desirable that the top wetted radius remains small while the bottom wetted radius is comparatively large, so that perspiration is transferred from the skin to the outer surface. This aid the evaporation of the sweat generated by the body of the wearer to the environment.

Figure 6.8 illustrates the wetted radius and the differences in water transfer between the top and bottom surfaces of the experimental fabrics. Fabrics F1 and F2 had very slow spreading speed and no wetting. The powernet structure of fabrics F1 and F2

mean that when the liquid drops onto the fabric surface from the nozzle, some of the liquid immediately drops onto the plate surface and is not absorbed by the fabric. All fabrics tested in this study had no wetting or minimum wetted radius, and very slow or slow spreading speed on both surfaces.

The AOTI results show that fabrics F1 and F2 had excellent ability to transport moisture from the top surface to the bottom surface of the fabric (illustrated in Figure 6.8). The other four fabrics (F3, F4, GF1 and GF2) recorded very poor AOTI (Table 6.7). This indicates that the liquid could not diffuse from the top surface to the bottom surface of the fabric

Fabrics F1 and F2 had excellent OMMC (Table 6.7). This indicates that liquid sweat can be easily and quickly transferred from next-to- skin side to the outer layer side to keep the skin dry. However, for the other fabrics the OMMC values were close to zero, indicating that liquid (sweat) cannot diffuse easily from the next-to-skin side surface to the outer layer side and will accumulate on the top surface of the fabric.



Figure 6.7: Rolled liquid drops on the top surface of fabrics F3, GF1 and GF2 after 120 sec.

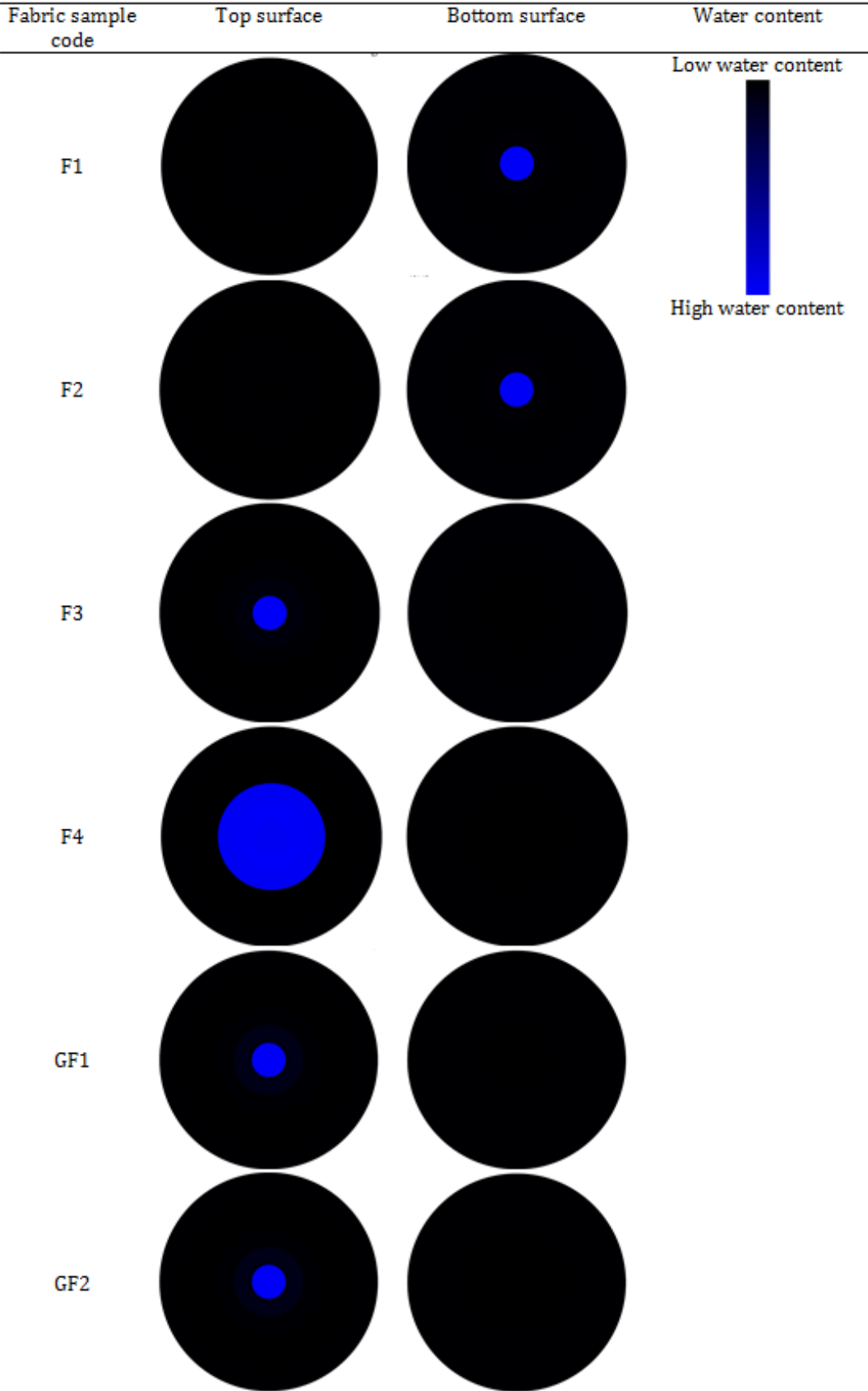


Figure 6.8: Wetted radius and water content of fabrics

6.4.3.3 Thermal and water vapour resistance properties

The R_{ct} of a fabric is a quantitative evaluation of the fabric's ability to provide a thermal barrier to the wearer. Results in Figure 6.9 shows that fabric F4 had the highest value of R_{ct} . The R_{ct} values of fabrics F1, F2 and F3 were very similar, and the differences between them were not significant ($p=0.077$).

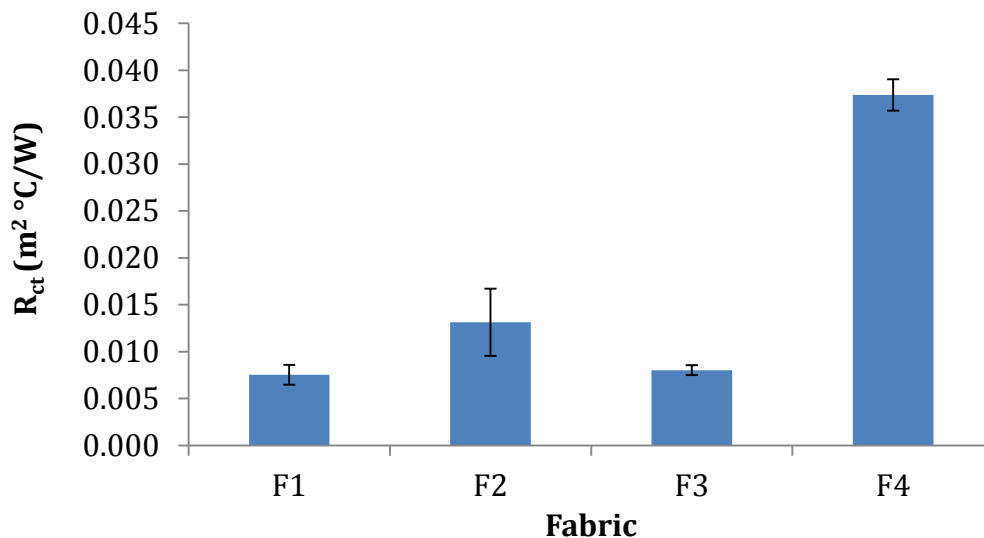


Figure 6.9: Thermal resistance (R_{ct}) of fabrics

The R_{et} values of the fabric samples are portrayed in Figure 6.10. It can be observed that fabrics F1 and F2 had similar R_{et} ; the values were not statistically significantly different ($p=0.069$). Fabric F3 had significantly higher R_{et} than fabrics F1 and F2. The R_{et} value of fabric F4 was impossible to measure due to the presence of a neoprene lining in the fabric, as shown in Figure 6.11.

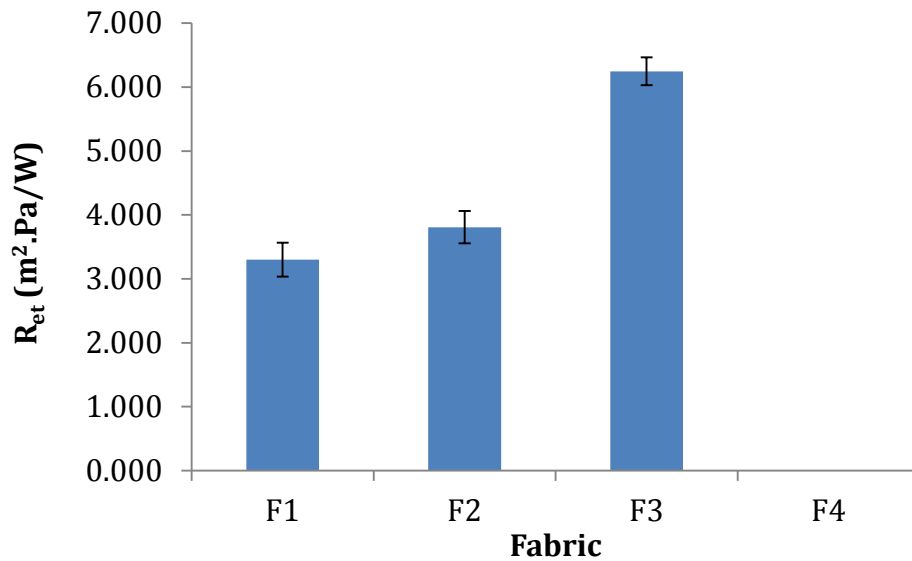


Figure 6.10: Water vapour resistance (R_{et}) of fabrics

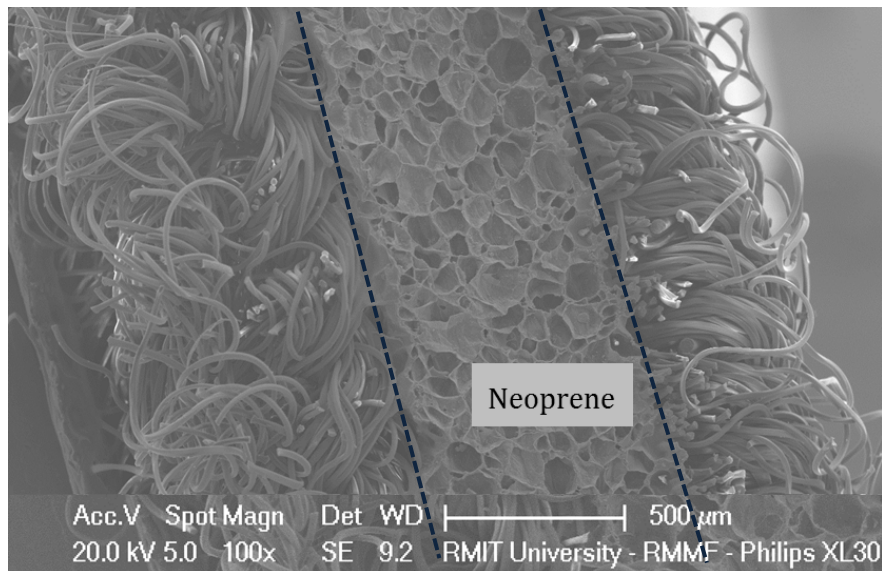


Figure 6.11: Cross-sectional SEM image of neoprene layer in fabric F4

6.4.3.4 Sensorial comfort properties

The MIU values of the next-to-skin side of the fabrics in a relaxed state are plotted in Figure 6.12. All six fabrics had low MIU (below 0.30). The MIU values of the outer layer side of the fabrics in a relaxed state are shown in Figure 6.13. Similar to the next-to-skin side, all six fabrics in this study had low friction (below 0.30) on their outer layer side. Although the texture of fabric F4 was embedded with silicone beads (intended to

enhance the grip support of a user), the MIU values of the fabric were not significantly higher than those of the other fabrics.

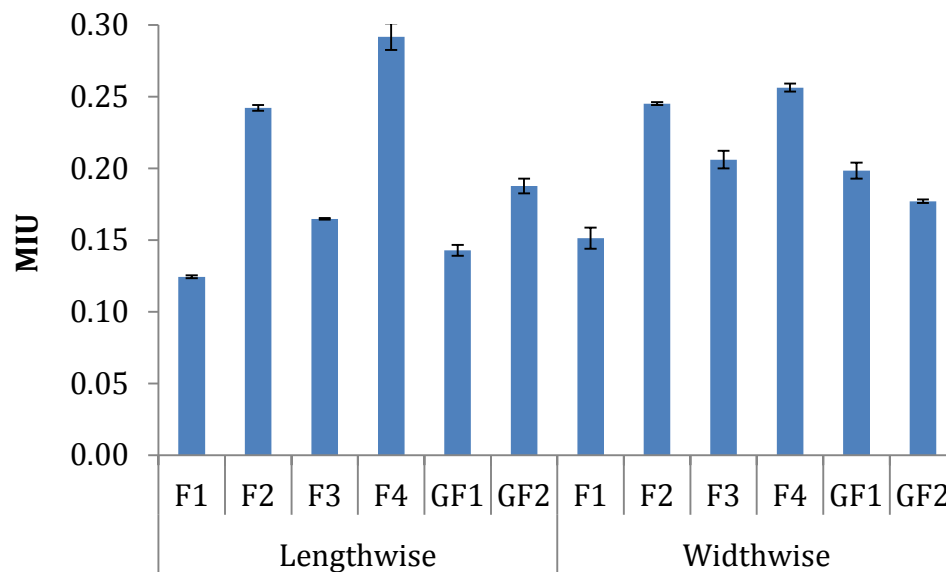


Figure 6.12: Coefficient of friction (MIU) of fabrics in relaxed state – next-to-skin side

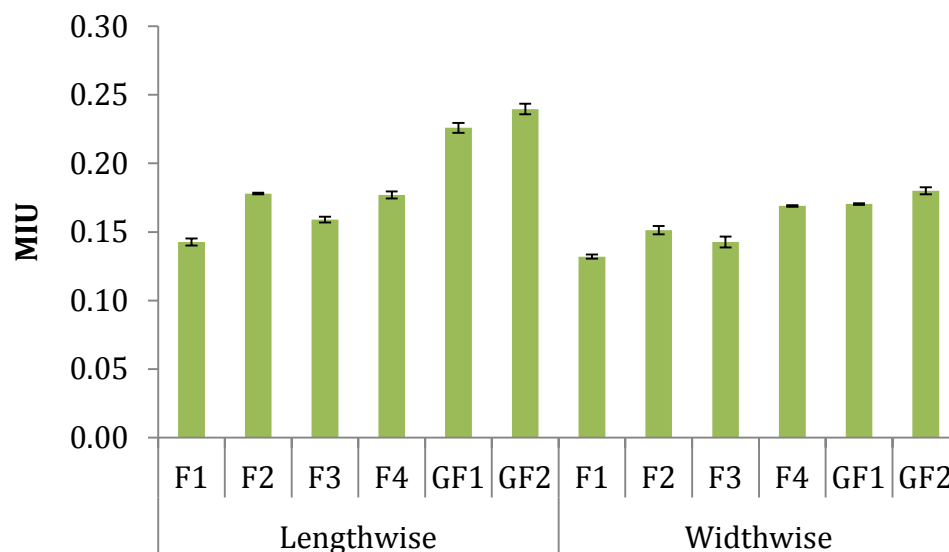


Figure 6.13: Coefficient of friction (MIU) of fabrics in relaxed state – outer layer side

The SMD values of the experimental fabrics on their next-to-skin sides and outer layer sides are shown in Figure 6.14 and Figure 6.15 respectively. Fabrics F1 and F2 recorded the highest SMD values on both side of the fabrics in lengthwise directions.

The mean SMD of the fabrics on the next-to-skin side was slightly lower than on the outer layer side.

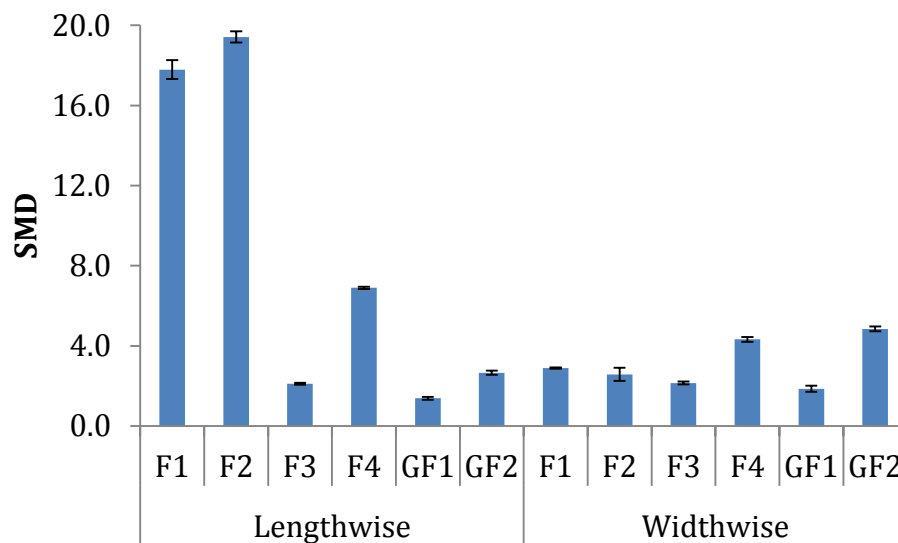


Figure 6.14: Surface roughness mean deviation (SMD) of fabrics in relaxed state – next-to-skin side

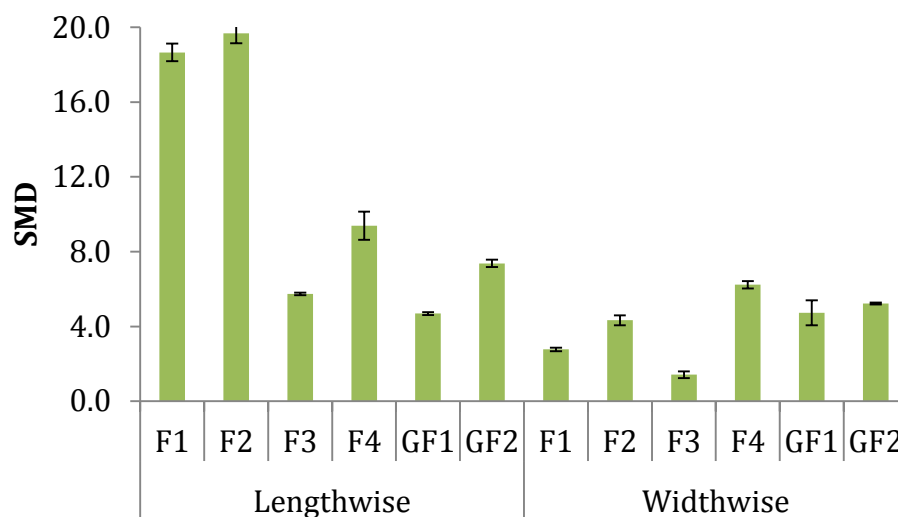


Figure 6.15: Surface roughness mean deviation (SMD) of fabrics in relaxed state – outer layer side

The MIU values of fabrics for various strains on the next-to-skin side and outer layer side are illustrated in Figure 6.16 and Figure 6.17. All fabrics recorded low MIU

(below 0.30) on both sides of the fabric. Significant differences were found between the values of MIU at different elastic strains for almost all fabrics, except for fabric GF1 at lengthwise direction in the next-to-skin side and fabric GF2 at lengthwise direction in the outer layer side. This indicates that elastic strains influence the MIU of the fabrics. In addition, there was a clear difference between the fabric topography under 20% strain and the relaxed state, which can be seen in Figure 6.18.

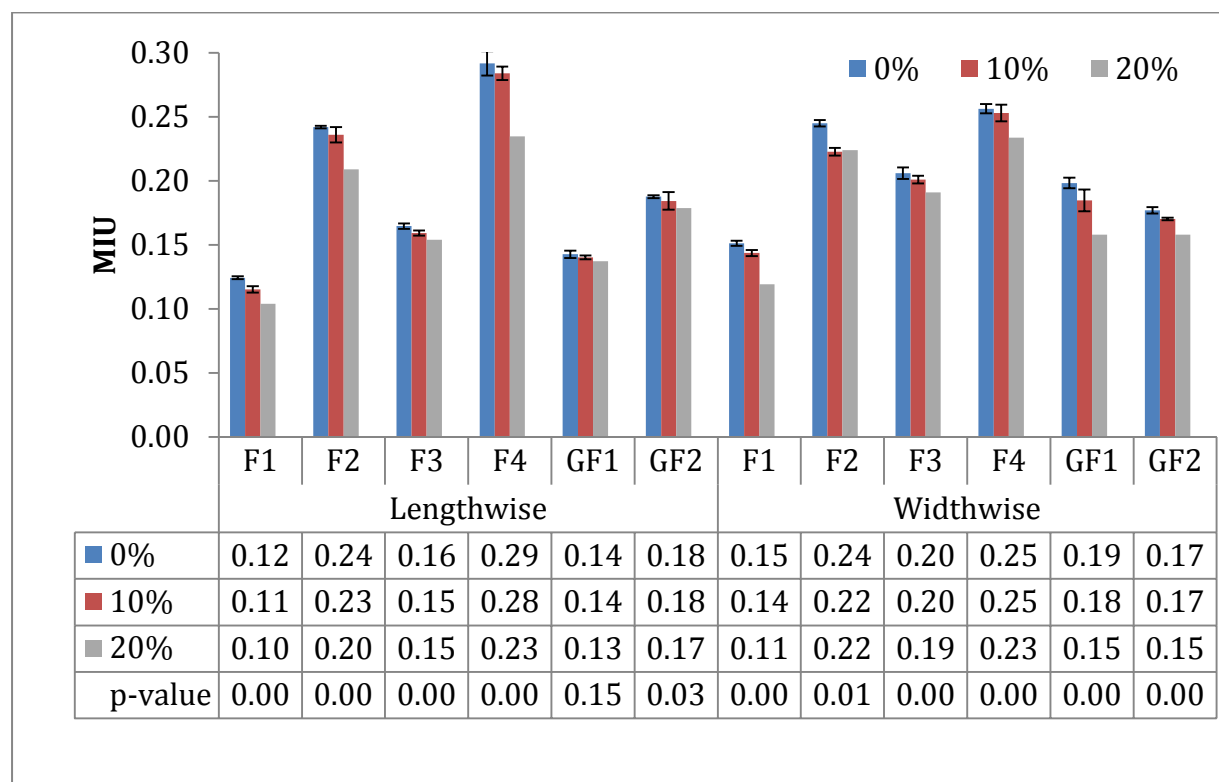


Figure 6.16: Coefficient of friction (MIU) of fabrics at various strains – next-to-skin side

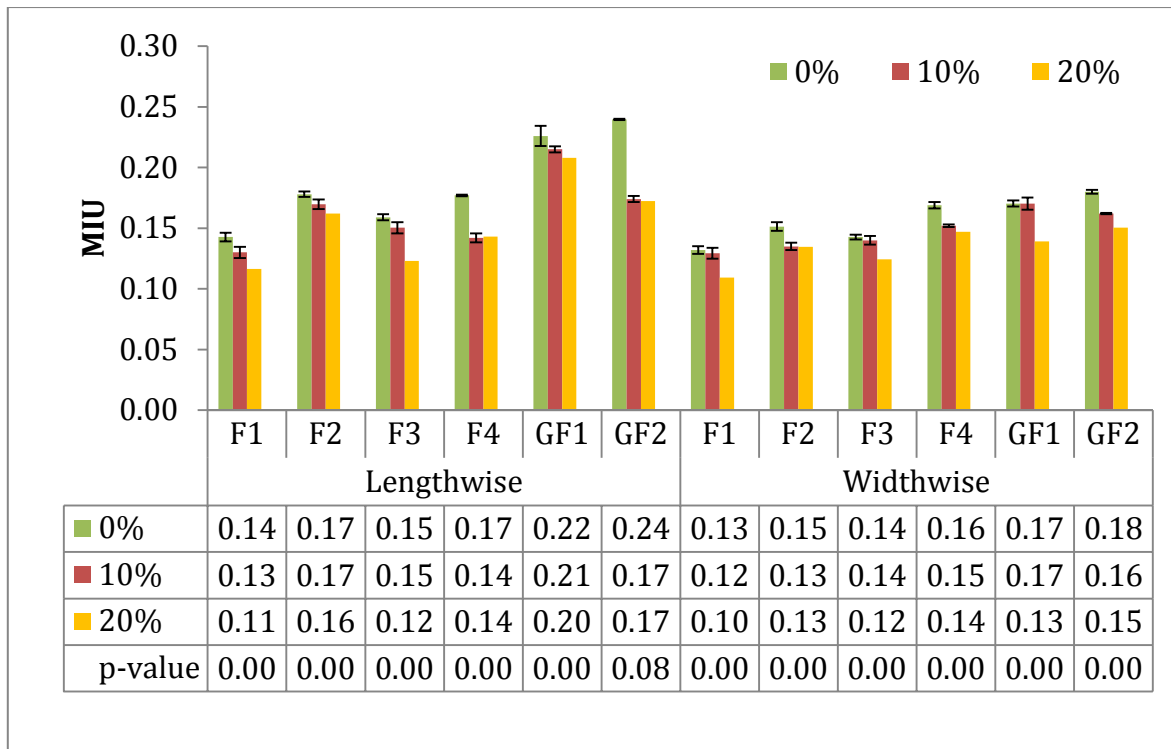


Figure 6.17: Coefficient of friction (MIU) of fabrics at various strains - outer layer side

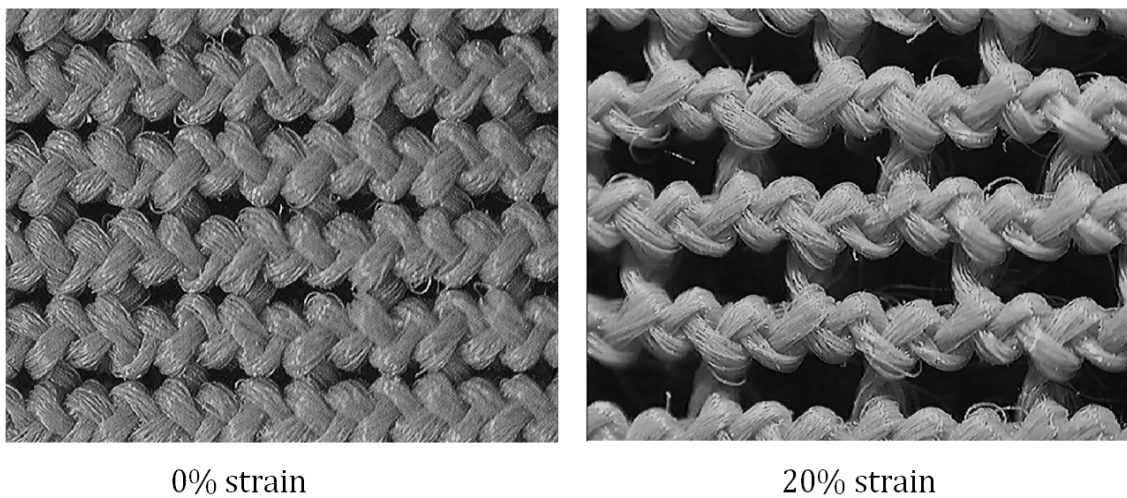


Figure 6.18: Microscopic images of 0% and 20% strain in lengthwise and widthwise direction, Fabric F1

The SMD values of six fabrics on their next-to-skin sides and outer layer sides are presented in Figure 6.19 and Figure 6.20 respectively. Once again, fabrics F1 and F2 recorded higher SMD in the lengthwise direction than the other fabrics. One-way

ANOVA shows that significant differences exist between the values of SMD at different elastic strains for all fabrics.

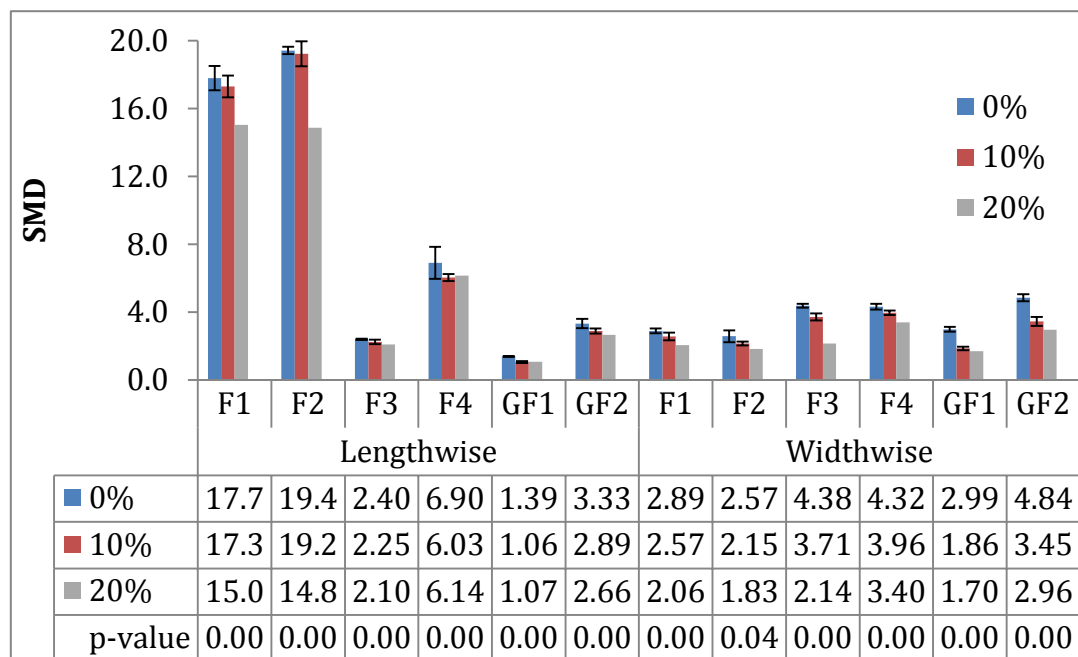


Figure 6.19: Surface roughness mean deviation (SMD) of fabrics at various strains – next-to-skin side

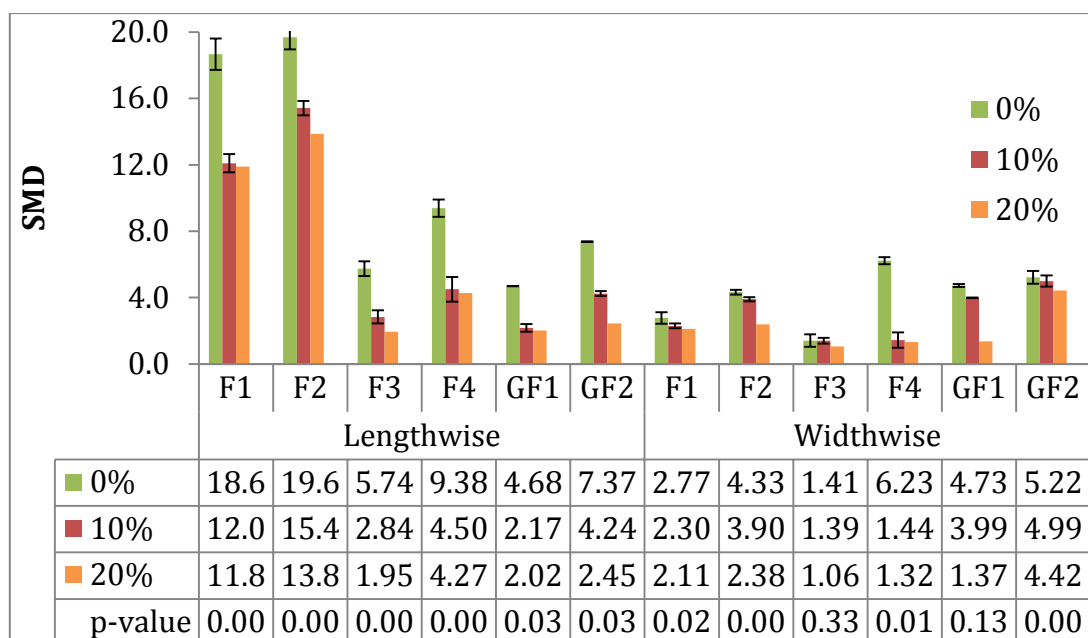


Figure 6.20: Surface roughness mean deviation (SMD) of fabrics at various strains - outer layer side

6.5 Discussion

The main objective of the research presented in this chapter was to investigate the physical parameters, tensile attributes and properties relevant to the physiological comfort of fabrics used in therapeutic gloves. The therapeutic glove fabrics were mainly warp-knitted structures made from polyamide and elastane fibres.

Fabric F1 recorded the highest stress under 35% strain, which indicates that gloves made from this fabric would generate the highest interfacial pressure when worn. The high stress (14.72 N/50 mm) of fabric F1 is explained by its pownet structure and low number of wales per cm, making it difficult to stretch. A lower reduction factor is required for a fabric with a higher stress, as higher tensile force requires the user to exert greater force to move the hands and fingers (Yu et al., 2015a; Yu et al., 2015b). The stress-strain behaviour of fabrics in the lengthwise direction affects the bending motion of the hand and finger when the glove is worn. Thus, it is important to select a suitable reduction factor in order to preserve the ROM of the user. Fabric GF2 demonstrated 'square' stretch, also known as 'balanced' stretch, in terms of their tensile performance. This avoids the skin to be stretched in the direction where the fabric extension is higher. This is important when the fabric is used on bony areas (Anand et al., 2013).

The experimental data showed that all fabrics exhibit a certain amount of tension decay after repeated extension and retraction. Fabric F3 recorded the lowest percentage of tension decay in the lengthwise direction. This can be attributed to the structure of the fabric, which comprises long floats of yarns that restrict yarn movement during extension, making this fabric less deformable over time. The results also reveal that fabrics with high stress tend to have more deformations after repeated extension

and retraction, leading to a large amount of fabric stress loss and changes in generated pressure (Yu et al., 2013a). Experimental fabrics used in this research also exhibited good recovery performance, with mean recovery of greater than 95% after multiple extension and retraction cycles.

Fabric F1 and F2 recorded substantially higher air permeability than the other fabrics due to their open powernet structures. Both fabrics recorded high optical porosity, which facilitates air permeability (Tashkandi, 2014). Several factors affect the air permeability of fabric, such as fibre type, surface characteristics, fabric construction, fabric thickness and surface characteristics (Afzal et al., 2014; Hu et al., 2006; Zhang et al., 2002). In this study, fabric structure and stitch density were shown to have significant effects on air permeability. Fabrics F3 and GF1 recorded lower air permeability and optical porosity than fabrics F1 and F2; this could be due to their higher stitch density. A strong and significant positive correlation ($R^2 = 0.9597$) between optical porosity and air permeability was noted, confirming previous studies that indicated air permeability and optical porosity are strongly related (Mahbub, 2015; Ogulata et al., 2006; Tashkandi, 2014).

Fabrics F1 and F2 had excellent OMMC. This was expected, because both fabrics had powernet structure, thus when saline solution drops onto the fabric on the top surface, some immediately drops onto the plate surface and some is transferred to the bottom surface of the fabric. However, the other four fabrics recorded poor moisture management capability. This could be due to their tight construction, as other researchers have demonstrated (Long, 1999; Onofrei et al., 2011). Three fabrics exhibited hydrophobic characteristics, in that liquid droplets could be clearly seen after the MMT test (Figure 6.7). Since the fabrics studied in this research were sourced

directly from commercial sources, no information about the application of chemical finishes was available.

Fabric F4 had the highest value of R_{ct} , due to a middle layer of neoprene. The function of the neoprene is to provide warmth, which is claimed to increase the blood flow and decrease the arthritic pain (Sluka et al., 1999a).

Fabric F3 had significantly higher R_{et} than fabrics F1 and F2. According to a previous study (Van Amber et al., 2015b), thicker and heavier fabrics are more resistant to water vapour transfer. This could be due to greater volumes of fibres slowing the flow of water vapour. In addition, lower optical porosity directly affects (lowering) the R_{et} value. This observation is in accordance with data from Yanilmaz and Kalaoğlu (2012). The R_{et} value of fabric F4 could not be measured due to the neoprene lining in the fabric. Although neoprene keeps the hand warm, it can be very uncomfortable for the wearer due to its lack of breathability and restriction of the movement of water vapour (Pereira et al., 2007). A low R_{et} value results in drier skin, thereby improving physiological comfort (Fan & Tsang, 2008).

Therapeutic gloves are in full contact with the skin due to their negative fit; this can cause discomfort for patients, particularly in summer. The direct contact permits a minimal microclimate between the skin and fabric materials, suggesting that new fabric structures with advanced comfort properties need to be used for therapeutic gloves. A comfortable material should not create excessive change in skin temperature; efficiently remove moisture and water vapour to the atmosphere, and not irritate or cause allergic reactions on the skin (Oğlakcioğlu et al., 2016)

All the fabrics recorded MIU value below 0.3, which was considered low as mentioned in the study by Troynikov et al. (2011). on their next-to-skin side due to

their fine microstructure; this means they present a smooth sensation. According to Ke et al. (2014), fabric with a low MIU on the next-to-skin side is expected to have higher ease of wearing, which helps the user don the therapeutic glove. Fabrics F1 and F2 recorded higher SMD in the lengthwise direction than the other fabrics, due to lower numbers of wales per cm. When the number of wales per cm is smaller, fewer yarns are available per unit area, and therefore the surface roughness is higher. The MIU and SMD of the experimental fabrics in this study were low, indicating that the fabrics under investigation are soft to the skin and feel smooth. The results correlate with the survey results in Chapter 5, in which the majority of participants said therapeutic gloves were soft to the skin. Moreover, participants stated that therapeutic gloves were easy to don and doff, which shows that therapeutic glove fabric has lower MIU on the next-to-skin side. The MIU and SMD of the samples were also tested in extension conditions similar to those occurring when therapeutic gloves are worn. The results also showed that introduction of strain in lengthwise and widthwise directions reduced the MIU and SMD of the fabric. The reason for this was the reduced number of contact points in the fabric and the relatively homogenous surface geometry when the fabric is strained, as previously mentioned by Ke et al. (2014), and Troynikov et al. (2011).

6.6 Conclusion

Comprehensive investigations of physical, tensile and physiological comfort properties of therapeutic glove fabrics were conducted. It was concluded that:

1. Fabric structure and physical properties influence the fabric tensile and physiological comfort performance, which are important parameters for therapeutic gloves.

2. All fabrics exhibited a certain amount of tension decay after extension and retraction cycles. However the recovery performance was good (greater than 95%) for all fabrics.
3. Only two fabrics recorded excellent OMMC. Fabric with neoprene lining had a high R_{ct} value, but its breathability was compromised.
4. All fabrics recorded low MIU and SMD in relaxed and in various elastic strains on the next-to-skin side. This indicates that the fabrics under investigation were soft to the skin, feels smooth, and have higher ease of wearing.

Therapeutic gloves are strained over the hand when worn; moisture from perspiration or from the environment would be present at the skin. So the fabrics must be tested in similar conditions if possible, as the presence of strain and moisture could potentially influence the comfort properties of gloves. The performance of fabric cannot be directly converted into the performance of a glove due to the changes in the physical parameters of fabrics when the glove is worn (due to the strain), and also the differences between the temperature and humidity in real-life wear and the steady state in which the fabric is tested.

The findings from this study could facilitate the selection of fabrics for design and development of therapeutic gloves that satisfy critical physiological comfort needs.

Chapter 7 Influence of Hand Movement on Skin Deformation and Glove-Skin Interfacial Pressure

Introduction

The literature in Chapter 2 has shown that the fit of a glove directly influences the hand function of the wearer and resultant wear comfort. To optimise the effectiveness of therapeutic gloves and adherence to their wearing, accurate and efficient measurement of wearers' hand dimensions and characteristics is crucial. Restriction of hand movement when wearing a glove will generate high interface pressure between the glove and the hand, which may, apart from discomfort, lead to abrasion and bruising of underlying tissue, especially if the glove fits tightly and its materials are of low elasticity and bending modulus.

This chapter is divided into two parts. The first part discusses the influence of hand movement on skin deformation and the second part discusses the influence of hand movement on glove-skin interfacial pressure.

7.1 Influence of hand movement on skin deformation

This section investigates the skin relaxed-strain ratio at the dorsal side of the hand which could help to characterise the skin deformation behaviour during hand movements. Regional hand mappings based on the skin relaxed-strain ratio have been developed and incorporated into the evidence-based design framework for therapeutic glove in later chapter.

This section is adopted from **Nasir, S H**, Troynikov, O. Influence of hand movement on skin deformation: A therapeutic glove design perspective. *Applied Ergonomics*. 2016; Vol. 60: pp. 154–162; and **Nasir, S H**, Troynikov, O and Watson, C. Skin deformation

behavior during hand movements and their impact on functional sports glove design, *Procedia Engineering*, 2015; Vol. 112: pp. 92–97.

7.1.1 Experimental and instrumentation

7.1.1.1 Subjects

Thirteen healthy female volunteers aged 40–65 years, with medium (M) hand size were recruited to participate in this study. The subjects had no major injury or trauma to their right hands. Experimental procedures were approved by the Design and Social Context, College Human Ethics Advisory Network, a sub-committee of the RMIT University Human Research Ethics Committee (CHEAN B 0000016260-01/14). Each subject was informed of the purpose of the study and the method of maintaining confidentiality. Participants provided written informed consent and received no remuneration for participating in this study.

Two key dimensions, hand length and hand circumference, were selected based on the literature (Williams, 2007) and the fact that many industry glove sizing systems use one or both of these dimensions to define size categories. The range for the length and circumference of the right hand of the subjects was 190–220 mm and 200–225 mm, respectively, both in the range of size M.

7.1.1.2 Experimental procedure

Before the scanning process, each subject was informed of the whole test procedure and the actions they should take during the scanning (Appendix II).

The right hand of each subject was scanned in a relaxed posture and two dynamic postures, grip hand posture and power grip hand posture, as shown in Figure 7.1. For the relaxed hand posture, subjects were asked to relax their hand on the glass plate of

the scanner with fingers abducted. For the grip hand posture, subjects were asked to grip a plastic ball with a diameter of 190 mm without additional effort or force applied to the ball to mimic the hand while holding a cup. For the power grip hand posture, subjects were asked to clench their fist. The study focused on the dorsal side of the hand due to the significant deformation which occurs during various activities of daily living. In most hand movements, the skin of the dorsal side of the hand stretches, whereas the skin of the palmar side of the hand contracts.

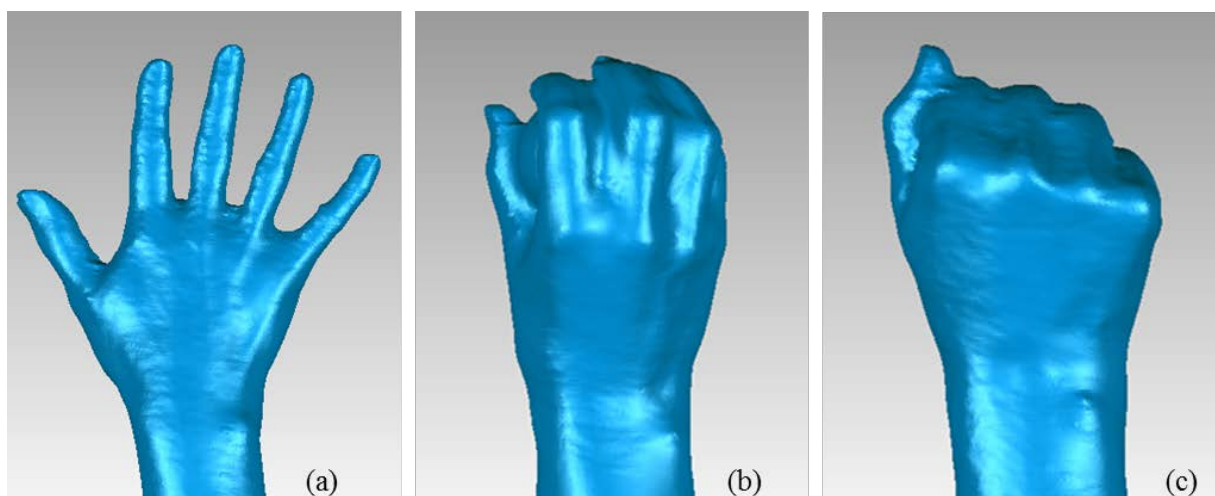


Figure 7.1: Experimental postures used in the study: (a) relaxed, (b) grip and (c) power grip

7.1.1.3 Instrumentation and method

In this study, 3D INFOOT scanner (I-Ware Laboratory Co.) was used to scan the subject's hand and to generate point cloud raw data for each scan (Figure 7.2). The accuracy of the scanner was previously validated using objects other than a foot such as using a steel cylinder (Kouchi & Mochimaru, 2001) and a ball of known dimensions (Kouchi & Mochimaru, 2010; Kouchi et al., 2012); with these studies reported accuracy of the scanner being within 1.0 mm. The INFOOT scanner comprises eight charged-coupled-device cameras and four laser projectors and it is capable of scanning and

constructs an object in 10 sec. The INFOOT scanner resolution was within 0.1 mm. Either cameras or projectors can be used to generate point cloud data for any 3D object. If the object is a foot, the INFOOT scanner post-processing software can be used to process the data. For this study, the scanner was used to only generate the point cloud datasets for a 3D object, which is a hand. The scan speed was 15 mm/sec and the scanned image was saved in a stereolithography format. Raw point cloud data was then imported into and processed by using Geomagic Studio (Raindrop Geomagic, Research Triangle Park, NC, USA) similar to the study conducted by Kouchi et al. (2012).

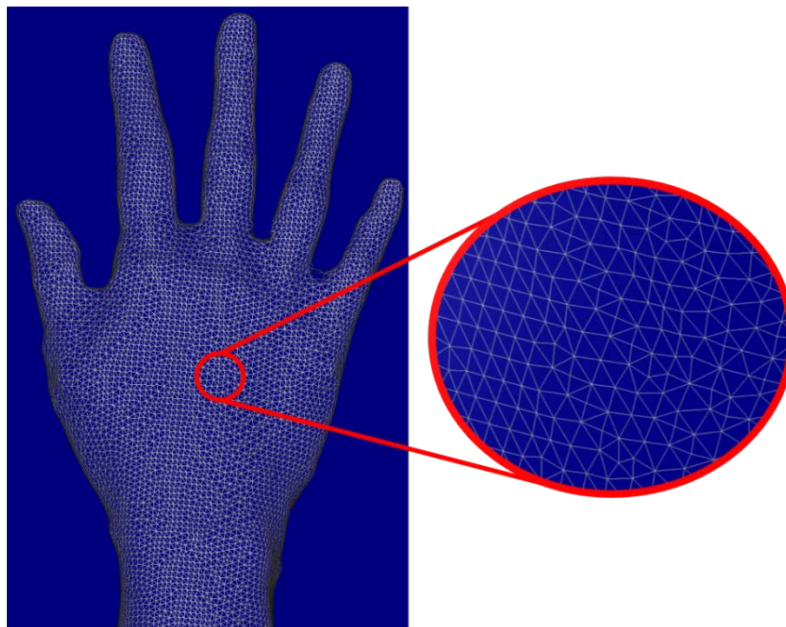


Figure 7.2: 3D-generated raw point cloud data from the hand scanned by 3D INFOOT scanner

Prior to scanning, foam markers with 6 mm diameter and 1.35 mm thickness were placed on each subject's right hand according to the determined positions of landmarks, as shown in Figure 7.3. The physical markers were added to measure the skin deformation between two landmark points, as previously conducted by Wang and Wang (2015). In order to form a guide for measurement of the surface area of the hand in

resultant 3D models, a medical tape (Elastoplast Elastic Fabric) with 5 mm width and 0.61 mm thickness was gently fixed along the peripheral line of the opisthenar area (Figure 7.3 and Figure 7.4). The tape used was of such elasticity and low thickness that it did not restrict hand movement or skin deformation.

Before the tape was applied to subjects' skin, they were first instructed to hold their hands in the power grip posture (which produces greatest skin deformation) (Figure 7.4a and b). The tape was then lightly attached to the skin, and subjects were instructed to relax and grip their hand repeatedly a few times. This was done to ensure that the tape adhered well to the dorsal side of their hand and did not cause any resistance to their hand movements or skin deformation.



Figure 7.3: Placement of landmarks (a) on subject's hand and (b) in Geomagic



Figure 7.4: Placement of tape on subject's hand in the following order; (a) front view in power grip posture, (b) side view in power grip posture, and (c) top view in relaxed posture

It is clear from Figure 7.4a and b, that when the tape and landmarks are first placed on a subject's hand in power grip posture, the tape conforms very well to subject's hand surface with skin not being deformed by it, and follows the surface closely with no gaps between it and the skin. Further, when the subject assumes a relaxed hand posture (Figure 7.4c), it is clear that skin easily moves to its natural state without any interference from the tape or landmarks.

To observe and analyse skin deformation in different directions, the hand was divided into three regions: phalangeal, metacarpal, and metacarpal-carpal, and deformation assessed in horizontal and vertical directions (Table 7.1).

Measurements of skin deformation (skin relaxed-strain ratio) between two landmark points in different directions (Figure 7.5) and in different regions of the hand

(Figure 7.6) were measured using Geomagic Studio software, as described above. Each measurement was repeated three times to reduce measurement error, and mean values calculated.

Table 7.1: Experimental directions, sections and regions used.

Directions /sections	Hand regions	Landmark point				
Vertical	Phalangeal	1-2	3-4	5-6	7-8	9-10
	Metacarpal	2-12	4-13	6-14	8-15	
	Metacarpal- carpal	12-20	13-20	14-20	15-20	22-23
Horizontal	Metacarpal	11-12	12-13	13-14	14-15	15-16
	Metacarpal- carpal	17-18				
Surface area	Metacarpal	Across 11-16				
	Metacarpal- carpal	11-19-21-23-16-11				

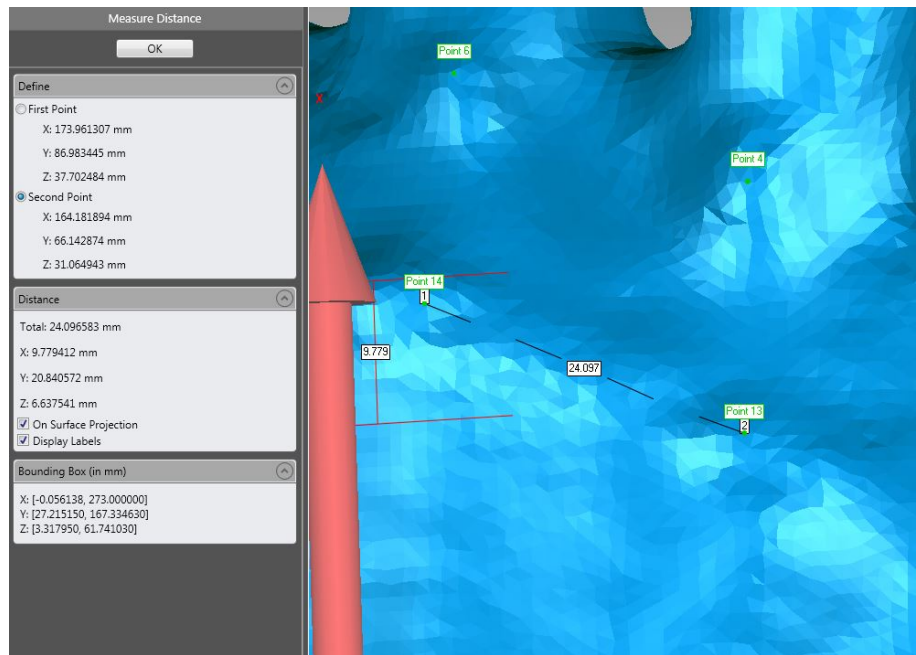


Figure 7.5: Measurement of distance between two landmark points (mm) using Geomagic Studio

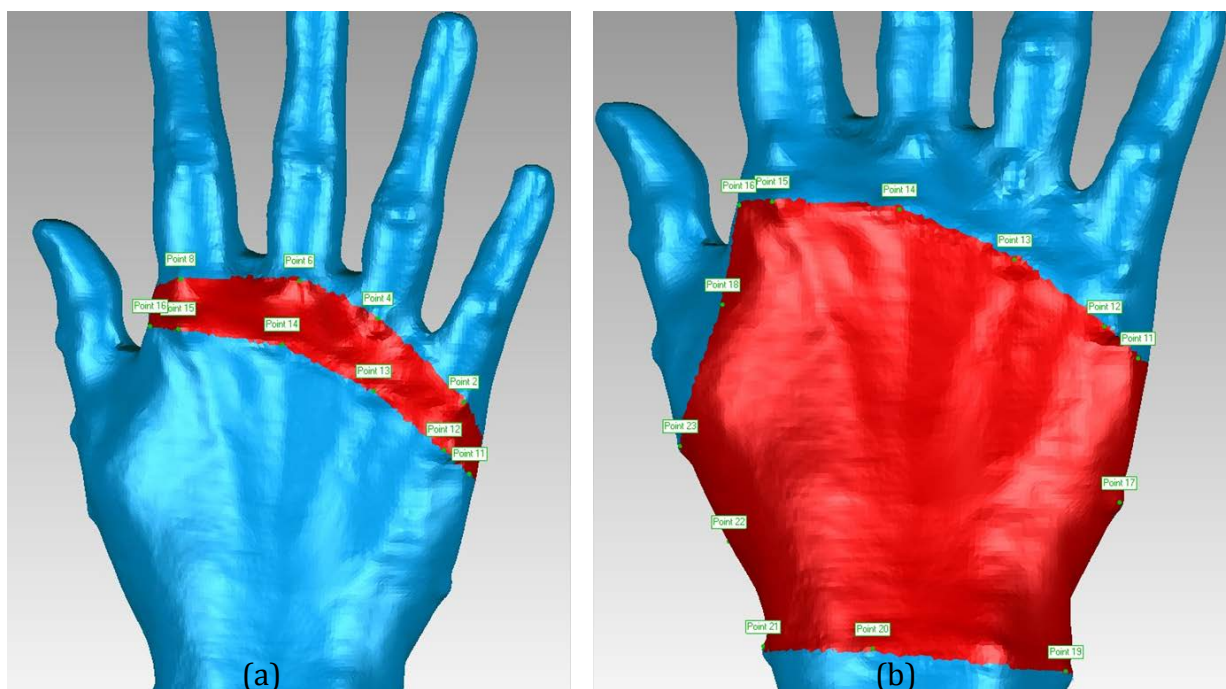


Figure 7.6: Measurement of surface areas in (a) metacarpal region and (b) metacarpal-carpal region using Geomagic Studio

The skin relaxed-strain ratio λ_p (%) between two landmark points was determined as $\lambda_p = [(b-a)/a] \times 100$, where b (mm) represents the distance between the landmarks in one particular dynamic posture; and a (mm) represents the distance between the landmarks in a relaxed posture (Wang & Wang, 2015).

As well as measuring the skin relaxed-strain ratio in between two landmark points in vertical and horizontal directions, the present study measured the skin relaxed-strain ratio of the surface area in metacarpal and metacarpal-carpal regions. The surface area in the phalangeal area was not measured due to suppression of each finger. The skin relaxed-strain ratio of each surface area λ_a (%) was determined as $\lambda_a = [(b-a)/a] \times 100$, where b (mm²) is the surface area in one particular dynamic posture; and a (mm²) is the surface area in a relaxed posture.

7.1.1.4 Data analysis

To analyse the effect of hand movements on skin deformation, 20 different measurements of skin relaxed-strain ratio (λ_p), were obtained between two landmark points in horizontal and vertical directions (Table 7.1). In addition, two measurements for the skin relaxed-strain ratio of surface area (λ_a), were obtained for metacarpal and metacarpal-carpal regions in each posture (Table 7.1).

SPSS was used to analyse the data. First, a Shapiro-Wilk test was performed to determine normality of data distribution. It involves arraying the sample values by size and measuring fit against expected means, variances and covariances. These multiple comparisons against normality give the test more power than other normality tests.

The hypotheses involved in this test were: H_0 – the data are normally distributed, H_1 – the data are not normally distributed. If the p-value is less than 0.05, then the null hypothesis that the data are normally distributed is rejected. If the p-value is greater

than 0.05, then the null hypothesis is not rejected. Since significant non-normality was found, statistical significance was assessed with Kruskal-Wallis H test. The Kruskal-Wallis H test is considered the nonparametric alternative to the one-way ANOVA. In this study, the Kruskal-Wallis H test was used for two purposes. The first was to determine if there are statistically significant differences in hand dimensions between the postures at each point number, and second was to determine if there are statistically significant differences in hand dimensions between the postures in each region. All significance levels were set at $p < 0.05$.

7.1.2 Results

Figure 7.7 demonstrates the mean skin relaxed-strain ratios (%) in the vertical direction for grip and power grip postures. The metacarpal region showed the greatest change in skin relaxed-strain ratios (λ_p), which ranged between 38% and 71% for grip posture, and 55–103% for power grip posture. The corresponding values in the phalangeal region for the grip postures ranged between 16% and 27% and increased slightly to 28–47% in the power grip posture. However, minimal changes in skin relaxed-strain ratios can be seen in the metacarpal-carpal region for both dynamic postures, which ranged between 5% and 9% in the grip posture and 8–13% in the power grip posture. The highest change in skin relaxed-strain ratios was recorded for points 2–12 in the metacarpal region in power grip posture. Analysis of the comparative measurement using Kruskal-Wallis H test revealed that there were significant differences in hand dimensions between the postures at all sets of points except for points 12–20 and 13–20 (Table 7.2).

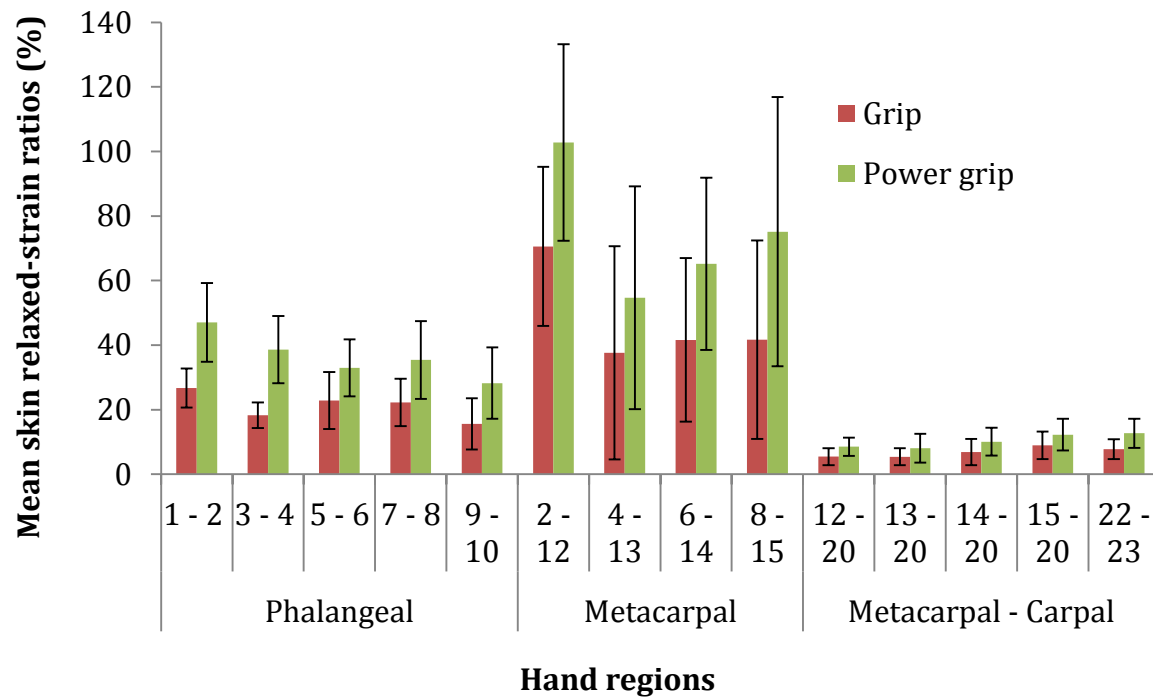


Figure 7.7: Mean skin relaxed-strain ratios (%) for different hand regions in vertical direction for grip and power grip postures. Error bars represent \pm SD

Table 7.2: Multiple comparisons of hand dimensions in different postures (Kruskal-Wallis H test)

Directions	Points	Relaxed	Grip	Power Grip	p-value
Vertical (mm)	1-2	13.5	17.1	19.8	<0.05
	3-4	19.1	22.6	26.4	<0.05
	5-6	22.6	27.8	30.3	<0.05
	7-8	20.3	24.8	27.4	<0.05
	9-10	13.9	15.7	17.7	<0.05
	2-12	5.0	8.2	9.6	<0.05
	4-13	7.5	9.8	11.0	<0.05
	6-14	7.6	10.6	12.5	<0.05
	8-15	6.1	8.1	9.8	<0.05
	12-20	67.9	71.6	73.6	>0.05
	13-20	70.3	74.1	75.9	>0.05
	14-20	73.4	78.3	80.6	<0.05
	15-20	77.3	84.2	86.6	<0.05
	22-23	54.0	58.2	60.7	<0.05
Horizontal (mm)	11-12	22.0	23.7	25.5	<0.05
	12-13	22.4	24.1	25.3	<0.05
	13-14	23.3	25.9	27.2	<0.05
	14-15	26.0	29.2	31.3	<0.05
	15-16	22.4	25.5	27.0	<0.05
	17-18	117.6	122.1	125.6	<0.05

The values of skin relaxed-strain ratios in the horizontal direction exhibited similar distributions to those in the vertical direction in both dynamic postures. Figure 7.8 shows the mean skin relaxed-strain ratios (%) in the horizontal direction for grip and power grip postures. Again, the greatest change in skin relaxed-strain ratios were observed in the metacarpal region, ranging between 8% and 14% in the grip posture

and 13–21% in the power grip posture. Points 15–16 in the metacarpal region recorded the greatest skin relaxed-strain ratios in both dynamic postures. In the grip posture, points 15–16 recorded 14% of skin strain, increasing marginally to 21% in the power grip posture. Analysis demonstrated significant differences in hand dimensions between the postures at all points in the vertical direction ($p<0.05$).

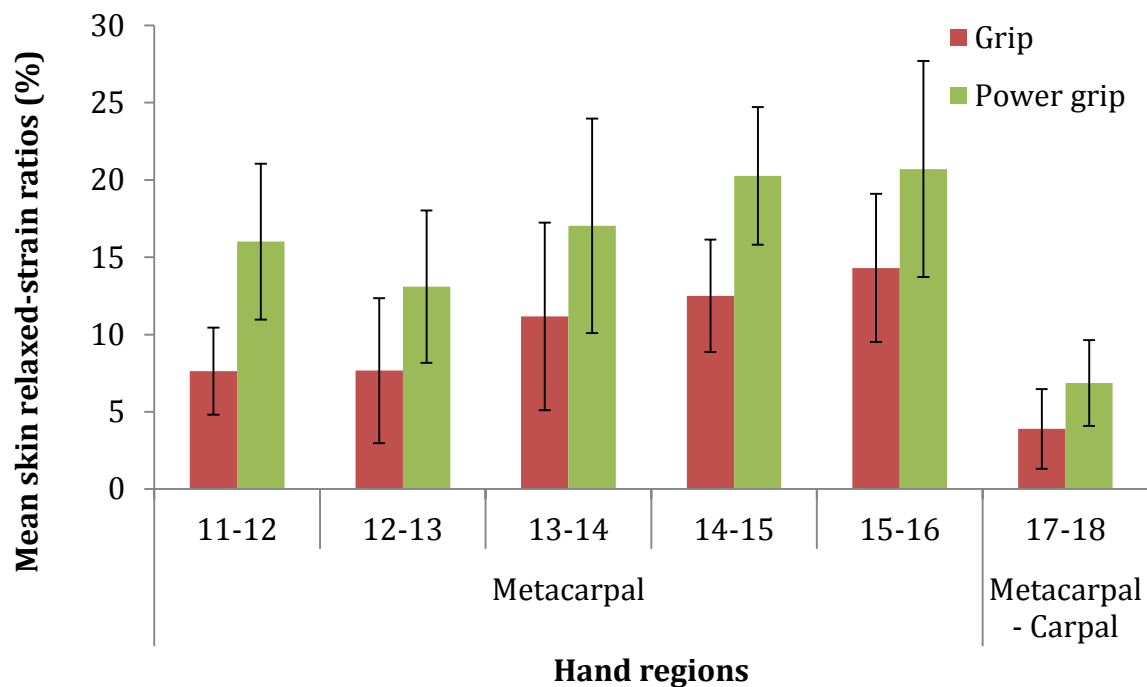


Figure 7.8: Mean skin relaxed-strain ratios (%) for hand regions in the horizontal direction for grip and power grip postures. Error bars represent \pm SD

The surface area skin relaxed-strain ratios (λ_a) in the metacarpal and metacarpal-carpal regions showed the same distribution observed for skin relaxed-strain ratios in vertical and horizontal directions (Figure 7.9). The skin relaxed-strain ratios in the metacarpal regions were 6% for grip posture and 8% for power grip posture. Meanwhile, surface area skin relaxed-strain ratios in the metacarpal region were nearly twice higher than those in the metacarpal-carpal region: 16% for grip posture and 30% for power grip posture.

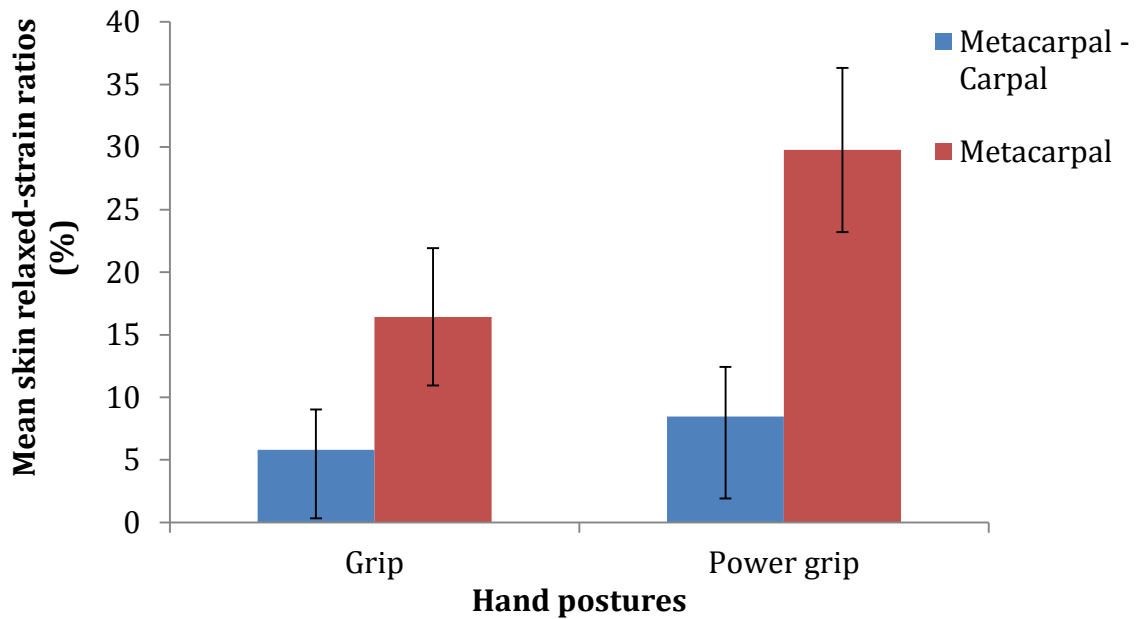


Figure 7.9: Mean skin relaxed-strain ratio (%) of surface area in metacarpal and metacarpal-carpal regions. Error bars represent \pm SD

In addition to evaluation of the statistical differences in hand dimension between the postures at each point, the study also tested for statistically significant differences in hand dimensions between the postures in each region. Table 7.3 illustrates comparisons of hand dimensions in multiple postures and regions. The results indicate statistically significant differences in hand dimensions between the postures at each region of hand, except for surface area in the metacarpal-carpal region.

Table 7.3: Comparisons of hand dimensions in multiple postures and regions (Kruskal-Wallis H test).

Directions	Hand regions	Relaxed	Grip	Power Grip	P-value
Vertical (mm)	Phalangeal	17.9	21.6	24.3	<0.05
	Metacarpal	6.5	9.2	24.3	<0.05
	Metacarpal-carpal	68.6	73.3	75.5	<0.05
Horizontal (mm)	Metacarpal	23.2	25.7	27.2	<0.05
	Metacarpal-carpal	117.6	122.1	125.6	<0.05
Surface area (mm ²)	Metacarpal	1177.8	1370.7	1527.5	<0.05
	Metacarpal-carpal	8571.8	9066.6	9298.8	>0.05

7.1.3 Discussion

The fit of a glove have been shown to have a significant impact on hand function and wear comfort, influencing users' adherence to use of the glove (Batra et al., 1994; Dianat et al., 2012; Tremblay-Lutter & Weihrer, 1996; Yu et al., 2015a). Since therapeutic gloves are recommended by most hand therapists for at least eight hours' wear (Nasir et al., 2014), it is essential that they are comfortable during normal use (Macintyre & Baird, 2006). The impact of hand movements on skin deformation in the vertical and horizontal directions of the hand was not considered in previous studies and is addressed in the present research. The objective of this study was to examine skin relaxed-strain ratios at the dorsal side of the hand to describe skin deformation behaviour during different hand movements. This study will be useful when designing a therapeutic glove with a negative fit, for which glove sizes are 10% to 20% smaller than hand size.

The study found significant differences in hand dimensions between the postures (relaxed, grip and power grip) across most point pairs. The skin relaxed-strain ratios in the vertical direction were much larger than those in the horizontal direction, with the

greatest deformation (103%) in the vertical direction in the metacarpal region. This may be attributed to the higher amount of skin strain in the vertical direction when the grip movement is formed. Moreover, the results of this study show that the metacarpal region had significantly larger skin relaxed-strain ratio than the phalangeal and metacarpal-carpal regions, especially in the power grip posture. When the hand transitions from a relaxed posture to a power grip posture, the curvature of the bones in the metacarpal region becomes more significant, increasing skin deformation. This is consistent with the findings of Giele et al. (1997) and Yu et al. (2013a) showing that the geometry and curvature of the hand produce skin deformation that varies greatly across regions during different hand movements.

The surface area skin relaxed-strain ratios in the metacarpal region was 16% in the grip posture, increasing to 30% in the power grip posture. Our findings supported Williams's (2007) study, which concluded that additional glove material at the dorsal side is required to accommodate the change in skin strain when a power grip is performed. However, Williams's (2007) study did not investigate the skin relaxed-strain ratio in different directions and regions of the hand. Tremblay-Lutter and Weihrer (1996) evaluated the fit of chemical protective gloves, revealing that an average ease value of +17.5 mm in palm circumference is needed for a comfortable fit. Their results are useful for protective glove manufacturers, although the findings were based on subjective trials with different sized gloves (varying in their dimensions) with different subjects.

Data from this research can be used to map the skin deformation of the hand and predict the allowance needed in different regions of the hand for designing and engineering gloves with different applications, taking into consideration the activity

level and environment. This study also demonstrated that 3D scanning technology and analytical software such as Geomagic Studio can be used to characterize skin deformation behaviour during various hand movements.

7.1.4 Conclusion

The metacarpal region showed significantly higher skin relaxed-strain ratios than both the phalangeal region and metacarpal-carpal region, regardless of test directions and postures. Significant differences in hand dimensions were observed between the postures across most point pairs. Kruskal-Wallis H test also revealed that there were significant differences in hand dimensions between the postures for each region, except for surface area in the metacarpal-carpal region. This research will form a base for future studies of the skin deformation behaviour of the hand in dynamic postures. It provides valuable guidelines for the design and engineering of therapeutic gloves with optimal function and comfort.

Regional hand mappings based on the skin relaxed-strain ratios have been developed in each posture and incorporated into the design framework in Chapter 9.

7.2 Influence of hand movement on glove-skin interfacial pressure

This section investigates the glove-skin interfacial pressures in different hand postures using three different kinds of commercial therapeutic gloves. Regional hand mappings based on the glove-skin interfacial pressure have been developed and incorporated into the evidence based design framework for therapeutic glove in later chapter.

The work from this section has been presented and published as part of the proceeding: Troynikov, O, **Nasir, S H** and Bafekrpour, E. Interface pressure generated by

sports gloves to the hand of the wearer and its impact on sports gloves engineering. *21st European College of Sport Science (ECSS) Congress*. 6 – 9 July; Vienna, Austria 2016.

7.2.1 Materials

Three different commercial therapeutic gloves identified from the survey study in Chapter 5 were selected for this study. All three gloves are used to reduce swelling and pain by applying a certain degree of compression as claimed by the manufacturers. Two of the gloves are also used for provision of warmth which claimed to help improving blood circulation and reducing pain (Table 7.4).

Table 7.4: Experimental therapeutic gloves

Code (refer Chapter 5)	Functions (suggested / claimed)
F4	Applying compression to ease pain and provision of warmth
GF1	Ease pain and swelling from arthritis
GF2	Applying mild compression to reduce joint swelling and provision of warmth

To eliminate the influence of the atmospheric moisture content on the fabrics, the samples were conditioned in the standard controlled environment for 24 hours under standard testing conditions $20\pm2^{\circ}\text{C}$, $65\pm3\%$ relative humidity according to ASTM D1776-04.

7.2.2 Experimental and instrumentation

7.2.2.1 Subjects

Five healthy females volunteers aged 45-60 years, with M hand size were recruited to participate in this study. The subjects had no major injury or trauma to

their right hands. Experimental procedures were approved by the Design and Social Context, College Human Ethics Advisory Network, a sub-committee of the RMIT University Human Research Ethics Committee (CHEAN B 0000016260-01/14). Each subject was informed of the purpose of the study and the method of maintaining confidentiality. Subjects provided written informed consent and received no remuneration for participating in this study.

The size categories were selected based on the two key dimensions identified in section 7.1.1.1.

7.2.2.2 Experimental procedure

Before the measuring process, each subject was informed of the whole test procedure and the actions they should take during the interfacial pressure measurement. The experiment was carried out in an environment-controlled chamber under standard testing conditions $20\pm2^{\circ}\text{C}$, $65\pm3\%$ relative humidity. The subjects were required to wear three different kinds of therapeutic gloves, with fitting size M.

The measuring sensors were placed at four different locations on the dorsal side of the hand (Figure 7.10): P1 - first MCP joint, P2 – second MCP joint, P3 – third PIP joint, P4 MCP joint. The locations were chosen based on two factors; the high distribution of skin deformation as demonstrated in section 7.1.2 and the common places where people have arthritic pain. Medical tape (Elastoplast Elastic Fabric) was used to ensure that the sensor adhered well to the skin.

The right hand of each subject was measured in a relaxed posture and two dynamic postures; grip hand posture and power grip hand posture, as shown in Figure 7.11. The experimental postures were kept consistent with the study in section 7.1.1.2.

To eliminate inter-observer variability, the same investigator performed all measurement for all subjects.

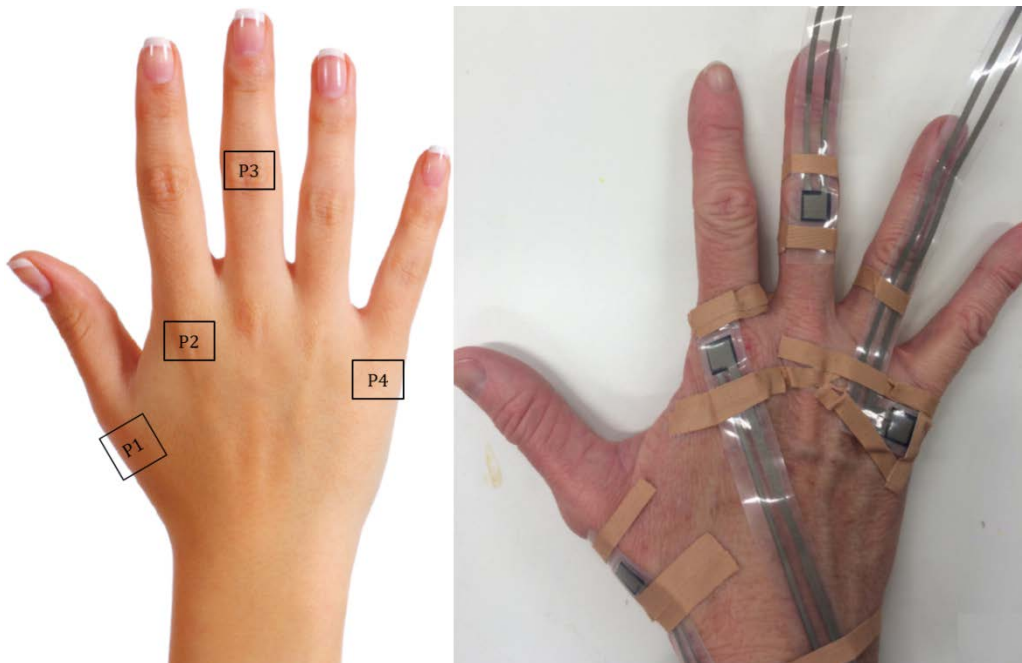


Figure 7.10: Locations and placement of sensor on subject's hand

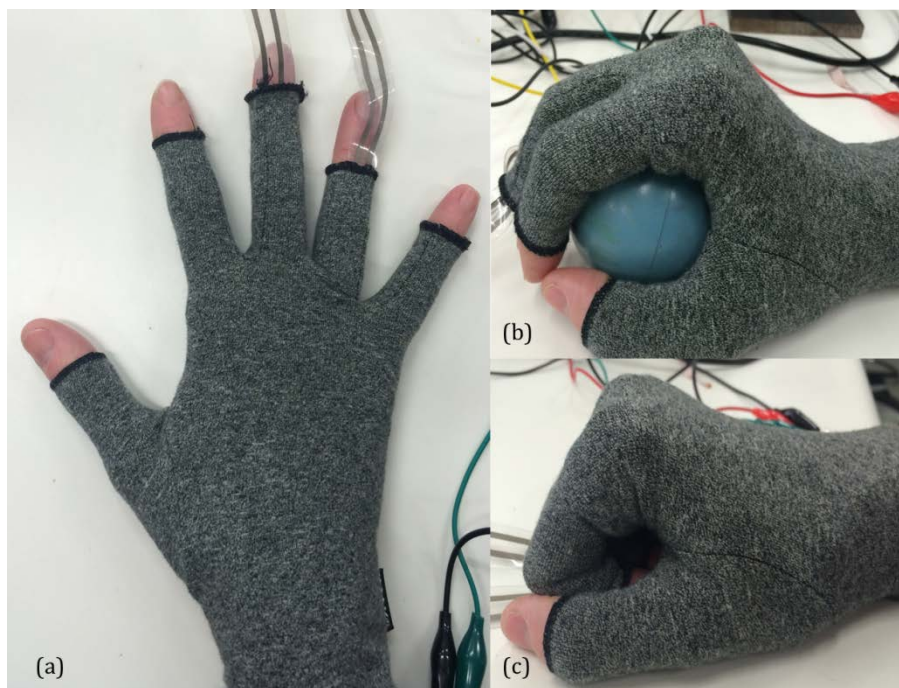


Figure 7.11: Experimental postures used in the study: (a) relaxed, (b) grip and (c) power grip

7.2.2.3 Instrumentation and method

Sensor is a device that receive a stimulus and responds with an electrical signal (Fraden, 2010). A pressure sensor is a device that converts the energy from a pressure stimulus into a quantifiable electrical signal output which can be read by an observer or an instrument (Almassri et al., 2015). Four pressure sensors developed by RMIT University (Parmar et al., 2016) were used to measure the interfacial pressure exerted by a glove onto the skin. Each sensor consisted of a rectangular sensing area of 49 mm² and had a thickness of 0.1 mm.

Before the glove-skin interfacial pressure measurement, the pressure sensor was first calibrated by placing it on a reference load cell and applying a known pressure (Figure 7.12). The reference load cell was supplied by Meltrons and works with an error of less than 0.02% full-scale output (Parmar et al., 2016). The pressure for calibrating the sensor was applied by Instron 5565A, with compression plate traversing at a crosshead speed of 0.1 mm/s. A user-defined program developed on Bluehill 3 software performed the cyclic loading and unloading test. The electrode of each pressure sensor was connected to RMIT's proprietary pressure detection circuit developed on National Instruments - LabVIEW. The change in voltage output during the application of pressure was then measured and plotted on a time (s) versus pressure (kPa) graph. All pressure sensors used in the experiment have been calibrated according to the above procedures. The correlation coefficients were all greater than 0.90.

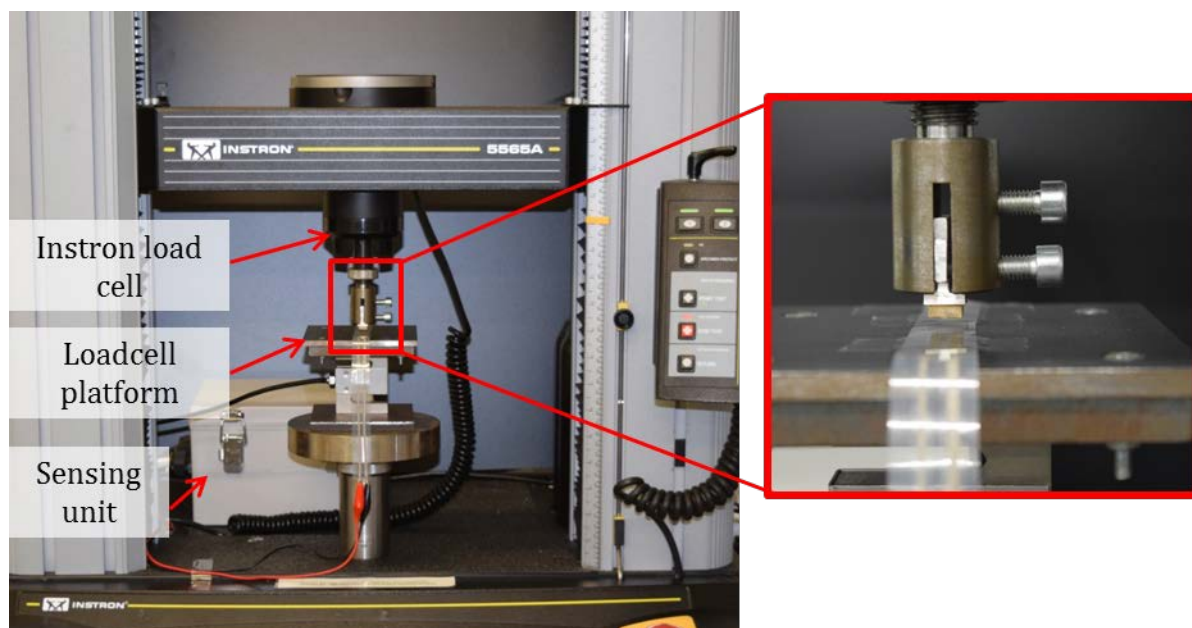


Figure 7.12: Experimental setup for calibration of the sensor

After the calibration, all four calibrated pressure sensors were placed onto the four identified locations on the dorsal side of the hand respectively. The glove-skin interfacial pressure measurement protocol was designed to produce contact pressure that would result in measurable changes at different postures.

At the beginning of the experiment, before the subject donned the therapeutic glove, it was ensured that all sensors were offset and displayed zero pressure reading. The subject was then instructed to relax her hand on the table with fingers abducted and the glove-skin interfacial pressures in this relaxed posture were recorded by the investigator. The measurement software displayed the amount of glove-skin interfacial pressure in kPa. After the relaxed hand posture, the subjects performed the grip hand posture, and the investigator recorded the glove-skin interfacial pressures in this posture. The same procedure was also followed for the power grip posture. For each posture, the investigator waited for 10 sec before taking the glove-skin interfacial

pressure measurement. Each measurement was repeated three times, and the mean values were calculated.

Due to the sensitivity of the pressure sensor, it was ensured that the rectangular probe of each pressure sensor was fully and evenly in contact with the skin to achieve an accurate and reliable pressure measurement.

7.2.2.4 Data analysis

SPSS was used to analyse the data. Shapiro-Wilk test was performed to determine the normality of data distribution as described in section 7.1.1.4. If the data is not normally distributed, a nonparametric approach using Kruskal-Wallis H test can be employed to fulfil the research objectives. Since significant non-normality was found, statistical significant was assessed with Kruskal-Wallis H test.

In this study, the Kruskal-Wallis H test was used for two purposes. The first was to determine if there are statistically significant differences in glove-skin interfacial pressure between the postures at each location, and second was to determine if there are statistically significant differences in glove-skin interfacial pressure between the different types of gloves in each location. All significance levels were set at $p < 0.05$.

7.2.3 Results

Figure 7.13 shows the glove-skin interfacial pressure in three different postures with three different types of therapeutic gloves. The lowest glove-skin interfacial pressure was obtained when the hand is relaxed and resting on the table, with a mean pressure of 2.58 kPa. When the hand is clenched into a fist (power grip posture), the glove is considerably stretched, inducing a higher glove-skin interfacial pressure. In the

power grip posture, the highest glove-skin interfacial pressure of 52.38 kPa was recorded at location P2 for glove GF2.

From Figure 7.13, a clear trend can be seen in which at locations P2, P3 and P4, the glove-skin interfacial pressure increased from a relaxed posture to a grip posture. The interfacial pressure further increased when the hand was clenched in a power grip posture. In the case of location P1, the increase in interfacial pressure with various hand postures is not apparent.

Analysis of variance using Kruskal-Wallis H test demonstrated that there were statistically significant differences in glove-skin interfacial pressures between the postures in each location ($p < 0.05$). However, there were no statistically significant differences found in glove-skin interfacial pressures between the different types of gloves at all locations (Table 7.5).

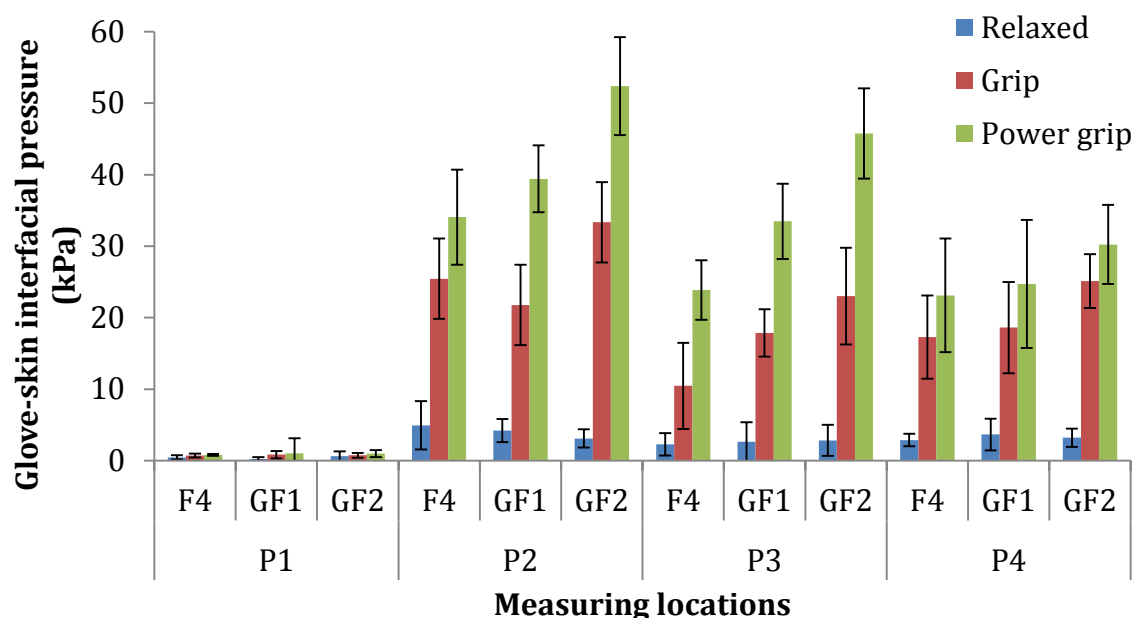


Figure 7.13: Glove-skin interfacial pressures in four different locations using three different types of therapeutic gloves. Error bars represent \pm SD

Table 7.5 Analysis of variance using Kruskal-Wallis H Test

Locations	Responses	p-value
P1	Postures	<0.05
P2	Postures	<0.05
P3	Postures	<0.05
P4	Postures	<0.05
P1	Gloves	>0.05
P2	Gloves	>0.05
P3	Gloves	>0.05
P4	Gloves	>0.05

7.2.4 Discussion

The pressure exerted by therapeutic glove is believed to be critical in maintaining efficiency of therapeutic treatment and user compliance with the treatment; as pointed out in Chapter 2. Prolonged and excessive garment pressures causes not only discomfort, but also lead to abrasion and bruising of underlying tissues (Das & Alagirusamy, 2010a; Dianat et al., 2014; Yu et al., 2015a). The ideal pressure for therapeutic glove has never been scientifically established, and it was found that the amount of pressures exerted in different types of gloves are quite different in previous studies (Culic et al., 1979; Swezey et al., 1979) and can be clearly seen in this study as well although the differences were not statistically significant.

The result of this study revealed that the geometry of the hand in different locations and the radius of the anatomic curvature impacts the glove-skin interfacial pressures; which is consistent with the finding from Yu et al. (2013a) and Giele et al. (1997). The pressures obtained at P2, P3 and P4 are consistently higher than P1 due to the large curvatures and pointy geometry of P2, P3 and P4. The position of P2, P3 and

P4, which is in bony and rigid surface of the MCP and PIP joints resulted in higher glove–skin interfacial pressures.

The magnitudes of glove-skin interfacial pressures also varied with changes in hand postures. This statement is supplemented with the analysis of variance, where significant differences were found in glove-skin interfacial pressures between the postures at all locations. As discussed in section 7.1.3, when the hand transitions from a relaxed posture to a power grip postures, the curvature of the bones become more significant. Due to the skin strain, the strain placed onto the fabric also changes, which directly affects the fabric tension and hence, the converted glove pressure.

In glove pattern design, the reduction factor is applied in the widthwise direction of the hand. Therefore, the stress-strain behaviour in the widthwise direction of the fabric could influence the glove-skin interfacial pressure (Yu et al., 2015a). It is interesting to note that although the stress-strain of fabric F4 was higher than GF2 (section 6.4.2), the interfacial pressure of the glove was lower than GF2 in most locations at different postures. This indicated that a lower reduction factor was applied to glove F4.

7.2.5 Conclusion

This pilot study shows that glove–skin interfacial pressure is greatly influenced by hand postures, especially at the bony and rigid surface. The changes in geometry during different hand movements should be carefully considered in design and engineering of therapeutic gloves in order to maintain the efficiency of the therapeutic glove treatment and user comfort during wear.

Regional hand mapping based on the glove-skin interfacial pressure were developed in each posture and were presented in Chapter 9.

Chapter 8 Pressure and Thermal Discomfort Thresholds of People with Hand Arthritis

8.1 Introduction

This chapter examines the pressure and thermal (cold and heat) discomfort thresholds of arthritis patients. Discomfort threshold is the amount of stimulus at which the sensation changes to discomfort (Koo et al., 2013). The sense of discomfort can rapidly turn into pain sensation which could negatively affect the perception of wear comfort, and adherence to the glove therapy (Ripper et al., 2009).

The manuscript for the study is currently under review in *Applied Ergonomics*.

8.2 Methods

8.2.1 Subjects

Thirteen women with hand OA and/or RA (62 ± 5.6 years old) were recruited through advertisement on websites, and posters and flyers distributed to local libraries, community centres, sports centres, campuses of universities and local clinics.

Experimental procedures were approved by RMIT University Human Research Ethics Committee (project number 19653). Each subject was informed of the purpose of the study and the method of maintaining confidentiality. Subjects provided written informed consent and received no remuneration for participating in this study.

The inclusion criteria for participant were: (1) age of 18 - 70 years; (2) diagnosed with hand OA or RA by a general practitioner or rheumatologist or registered health care practitioner; (3) ability to have an adequate conversation in English.

The exclusion criteria were (1) history of upper extremity or neck pain, fractures, or any neurologic disorder; (2) pregnant or intend to be pregnant; (3) injuries in the area to be tested.

8.2.2 Experimental procedure

All the experiments were carried out in an environmentally-controlled chamber under standard testing conditions $20\pm2^{\circ}\text{C}$, $65\pm3\%$ relative humidity.

Each subject underwent pressure stimulation followed by thermal (cold and heat) stimulation, with a 10-minute break in between. During the break, participants were asked to answer the Cold-Heat pattern questionnaire (Appendix III). Subjects were instructed to not tolerate the discomfort sensation during the testing and to press the cut-off switch as soon as they started to feel discomfort. They were assured that neither cold nor heat stimulation would cause any physical damage to their body and were allowed to withdraw from the experiments at any time. Throughout the experiment, the subjects sat comfortably on a chair with arms rested on the table.

Five test sites on the dorsal side of the hand (Figure 8.1) were of interest: P1 – first DIP joint, P2 - second DIP joint, P3 - third PIP joint, P4 – third MCP joint, P5 – first carpometacarpal (CMC) joint. The locations were chosen based on two factors: the high distribution of skin deformation and glove-skin interfacial pressure as demonstrated in Chapter 7 and the common place where people have hand OA and RA as discussed in Chapter 2. The dominant hand where subjects have more arthritic pain was chosen for testing.

All the discomfort threshold measurements were carried out by the same assessor and the sequence for assessing the five individual locations was randomised.

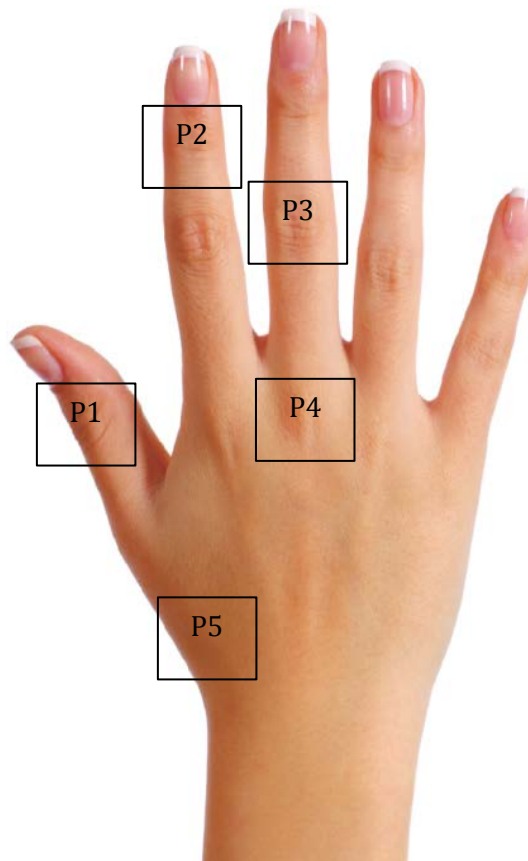


Figure 8.1: Measuring locations on subject's hand

8.2.2.1 Self-reported measures

Subjects were instructed to draw and record the intensity and locations caused by arthritic pain experienced in the past 24 hours prior to the experiment on an anatomic map (Figure 8.2). They were taught to record the pain on a numerical rating scale of 10 where 0 defined 'no pain' and 10 defined 'maximal pain. Pain could occur at any time during the past 24 hours; during rest, movement or during the night.



Figure 8.2: Example of mapping the locations and intensities of arthritic pain

The Cold-Heat pattern questionnaire developed and validated by Ryu et al. (2010) was used in this study. The questionnaire was used to determine whether it could be used as a tool to categorise patients into groups that targeting the right treatment modality to the right people. This questionnaire consists of two sections; Cold questionnaire and Heat questionnaire. Cold-Heat pattern questionnaire score was then calculated by adding up all the relevant item scores and subtracting the Cold questionnaire score from the Heat questionnaire score [23]. Participants with a negative score were classified into cold pattern group (those who are sensitive to cold), whereas those with a positive score were classified into hot pattern group (those are sensitive to heat).

8.2.2.2 Assessment of pressure and thermal discomfort thresholds

A computerised algometer (Algomed, Medoc, Ramat Yishai, Israel) (Figure 8.3) was used to measure the pressure discomfort thresholds. The algometer consisted of a round aluminium foot plate with a padded rubber contact surface of 1cm². The algometer was applied perpendicularly to the sites at a rate of 30 kPa/sec. The subjects were instructed to press the cut-off switch (stop button) when the sensation changed from pressure to discomfort. Pressure discomfort thresholds were tested three times over each point, and the mean data was used for the analysis. Twenty sec interval was allowed between each measure.

A thermode (thermal sensory analyser, TSA-II, Medoc, Ramat Yishai, Israel) (Figure 8.4) consisted of surface area 16x16 mm was used to measure the thermal discomfort thresholds. For each cold and heat measure, the baseline temperature was set at 32°C. The thermode was applied perpendicularly to the sites and the temperature was then decreased or increased gradually at a rate of 3°C/sec until the subjects start to feel discomfort and press the cut-off switch (stop button). Three consecutive stimuli were delivered for each site with 20 sec interval between each measure, and the mean data was used for analysis. The safety cut-off temperatures were set at 0°C and 50°C. For subjects whose threshold was beyond the cut-off temperatures, these temperatures were recorded as their thresholds.

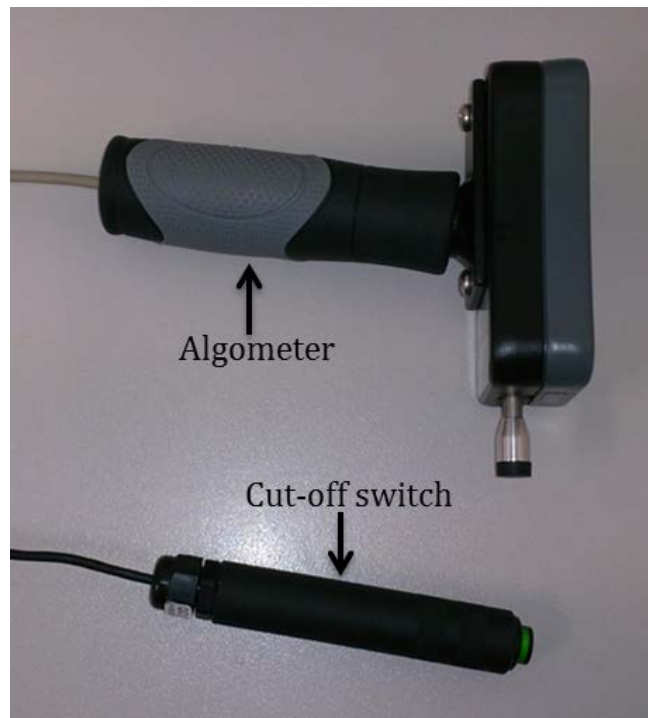


Figure 8.3: Algometer Algomed, Medoc

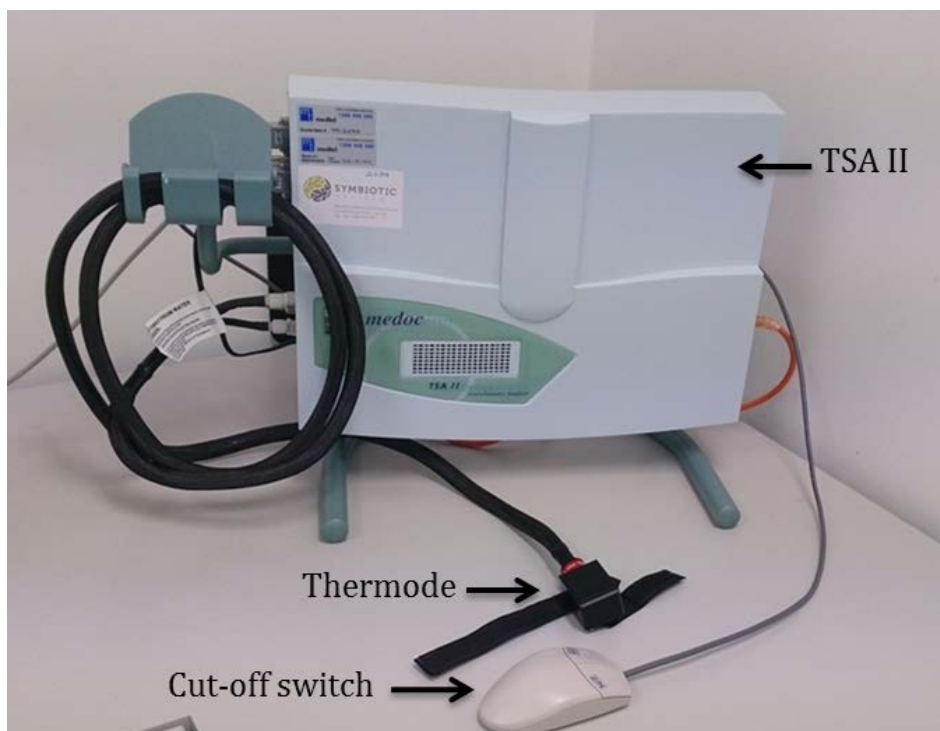


Figure 8.4: Thermal sensory analyser, TSA-II, Medoc

8.2.3 Data analysis

Responses in locations of arthritic pain and the intensities were calculated using a weighted average ranking. The weighted average ranking (W_{AR}) in each location was calculated as follows:

$$W_{AR} = \frac{i_1 + i_2 + i_3 + i_n}{W} \quad (9)$$

Where i - the pain intensity of arthritis chosen by each participant at that particular position and W -the weight based on number of subjects who chose that particular position. If the number of subject who chose the location is one, the weight will be 13, if two subjects, the weight will be 12, and so forth.

The pressure and thermal discomfort thresholds data were analysed with SPSS. Results are expressed as mean, SD and 25th and 75th percentiles. Shapiro-Wilk test was performed to determine the normality of data distribution. The hypotheses involved in this test were: H_0 – the data are normally distributed, H_1 – the data are not normally distributed. If the p-value is less than 0.05, then the null hypothesis that the data are normally distributed is rejected. If the p-value is greater than 0.05, then the null hypothesis is not rejected. Since significant non-normality was found, statistical significant was assessed with Kruskal-Wallis H test and Mann-Whitney U test, the nonparametric alternative to the one-way ANOVA and independent t-test. The Kruskal-Wallis H test was used to determine if there were statistically significant differences in pressure/ cold/ heat discomfort thresholds values between the tested locations for each participant, and between the participants in each location. The Mann-Whitney U test was used to determine if there were statistically significant differences between the cold pattern and heat pattern groups. Spearman correlation analysis was employed to determine the strength of the relationships between the duration of arthritis and the

discomfort thresholds for pressure, cold and heat. All significance levels were set at $p < 0.05$.

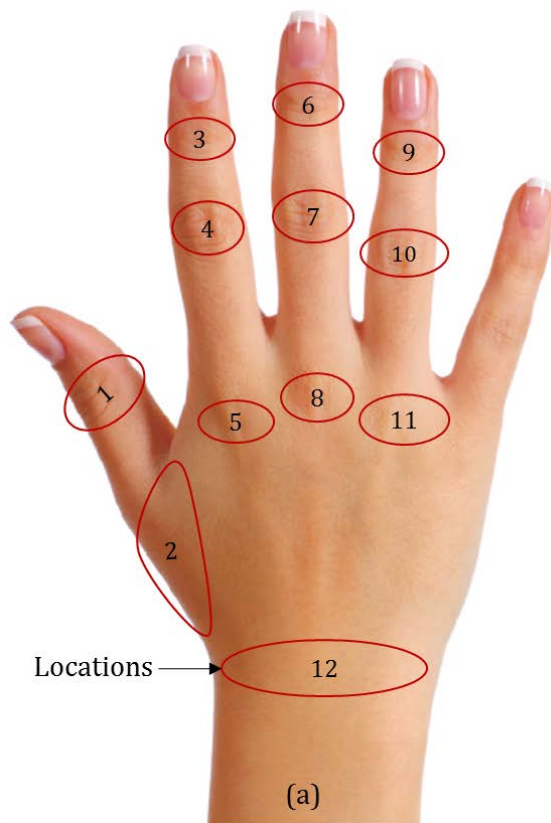
8.3 Results

8.3.1 Demographic and clinical data of subjects

Between January 2016 and August 2016, a total of 13 women with hand arthritis agreed to participate in this study. The range of age was 48 – 70 years (mean 62.2, SD 5.6 years). Duration of arthritis disease ranged from one to 40 years (mean 8.3, SD 10.7 years).

8.3.2 Locations and intensities of arthritic pain

A total of 12 different locations were identified by the subjects as the locations where they had arthritic pain (Figure 8.5). Locations 2 and 7 were the two locations with the highest average ranking, with nine and seven subjects in each location.



Average ranking	Locations
10.00	2
4.86	7
3.44	1
3.38	4
1.55	3
1.55	6
1.18	10
1.08	5
0.83	12
0.75	8
0.54	11
0.38	9

Figure 8.5: (a) locations of arthritic pain identified by the subjects and (b) weighted average ranking in each location

8.3.3 Pressure discomfort thresholds

The mean pressure discomfort thresholds for all locations ranged from 53.0 ± 22.6 kPa to 383.8 ± 53.9 kPa. Analysis of the Kruskal-Wallis H test demonstrated that seven of the subjects have significantly different pressure discomfort thresholds at different locations of the hand as shown in Table 8.1. Furthermore, the analysis also revealed that pressure discomfort thresholds were significantly different between subjects at all tested locations ($p < 0.05$). Three subjects recorded substantially lower values of pressure thresholds (< 100 kPa) in comparison to the other subjects; which indicate that these subjects were very sensitive to pressure stimuli. Subject number 10 recorded the lowest pressure discomfort thresholds of 29.42 kPa at location P3.

Spearman correlation analysis indicated strong negative correlation between duration of arthritis and pressure discomfort thresholds ($r_s = -0.67$, $P < 0.05$); the longer the duration of arthritis, the more sensitive the subjects will be towards pressure sensation.

Table 8.1: Pressure discomfort thresholds (in kPa) at different sites

Patients	Locations						p-value
	P1	P2	P3	P4	P5	Average±SD	
1	159.85	176.52	185.35	161.81	226.54	182.01±27.03	>0.05
2	375.60	428.56	298.13	408.94	318.72	365.99±56.33	>0.05
3	196.14	235.36	225.56	225.56	323.62	241.25±48.34	<0.05
4	215.75	254.98	147.10	166.72	254.98	207.90±49.72	<0.05
5	402.08	460.92	362.85	379.52	313.82	383.84±53.94	>0.05
6	166.72	294.20	199.08	235.36	333.43	245.76±68.13	<0.05
7	441.31	313.82	186.33	245.17	264.78	290.28±95.99	<0.05
8	372.66	333.43	264.78	372.66	176.52	304.01±83.79	>0.05
9	235.36	176.52	117.68	156.91	254.98	188.29±56.51	<0.05
10	78.45	58.84	29.42	29.43	68.65	52.96±22.58	<0.05
11	98.07	98.07	58.84	68.65	58.84	76.49±20.10	>0.05
12	173.58	45.11	55.90	51.98	57.86	76.89±54.27	>0.05
13	156.91	107.87	88.26	117.68	117.68	117.68±25.00	<0.05
Average	236.34± 120.59	229.55± 134.40	170.71± 100.87	201.57± 125.52	213.11± 105.50	210.26± 25.98	
P value	<0.05	<0.05	<0.05	<0.05	<0.05		

8.3.4 Thermal discomfort thresholds

Table 8.2 shows the values for cold discomfort thresholds for each subject. Subject number 13 recorded the highest average of cold discomfort thresholds (21.79°C) and location P5 recorded the lowest average cold discomfort thresholds.

Analysis of the Kruskal-Wallis H test in Table 8.2 demonstrated that more than half of the subjects have significantly different cold discomfort thresholds at different locations of the hand. Moreover, the analysis also revealed that the sensitivity towards cold was different between subjects at each location ($p < 0.05$). There was strong positive correlation between the cold discomfort thresholds and duration of arthritis ($r_s = 0.56$, $p < 0.05$), which demonstrate that the longer the years in OA or RA, the person being more sensitive to cold.

Table 8.2: Cold discomfort thresholds at different sites of hand

Subjects	Locations					Average±SD	p-value
	P1	P2	P3	P4	P5		
1	3.82	4.46	2.40	3.06	1.50	3.05±1.16	<0.05
2	0.00	0.00	4.00	3.12	3.17	2.06±1.91	<0.05
3	28.82	24.34	5.18	27.80	15.10	20.25±10.01	<0.05
4	0.50	0.21	7.22	0.90	5.04	2.77±3.17	<0.05
5	0.00	0.00	1.27	0.00	0.00	0.25±0.57	>0.05
6	5.10	6.27	9.53	0.00	0.00	4.18±4.15	<0.05
7	0.00	0.00	19.10	5.77	15.30	8.03±8.80	<0.05
8	0.00	0.00	0.00	0.00	0.00	0.00±0.00	>0.05
9	0.00	0.00	0.00	0.00	0.00	0.00±0.00	>0.05
10	19.39	17.90	23.13	19.95	0.00	16.07±9.19	<0.05
11	19.52	16.73	18.22	16.90	17.80	17.83±1.13	<0.05
12	22.90	9.90	22.30	17.80	17.20	18.02±5.22	<0.05
13	25.10	23.78	22.69	24.40	13.00	21.79±5.00	>0.05
Average	9.63± 11.47	7.97± 9.53	10.39± 9.28	9.21± 10.49	6.78± 7.55	8.79± 1.43	
p-value	<0.05	<0.05	<0.05	<0.05	<0.05		

The values for heat discomfort thresholds are shown in Table 8.3. The average heat discomfort thresholds were highest at location P4 (48.23°C) and lowest at location P5 (46.90°C). At location P2, two subjects recorded substantially lower heat discomfort thresholds compared to the other subjects (38.31°C and 39.92°C respectively) (Figure 8.6). Subject number 11 was very sensitive towards the heat stimuli with the average heat discomfort thresholds of 40.97°C.

Analysis of the Kruskal-Wallis H test in Table 8.3 demonstrated that there were significant differences in the recorded heat discomfort thresholds between the tested

locations for subjects number 3 and 10. In addition, the analysis also revealed that heat sensitivity was significantly different between subjects at all tested locations ($p < 0.05$).

There was medium negative correlation between the heat discomfort thresholds and duration of arthritis ($r_s = -0.34$, $p > 0.05$), which demonstrate that the longer the years in OA or RA, the lower the heat discomfort threshold was or the person being more sensitive to heat.

Table 8.3: Heat discomfort thresholds at different sites of hand

Subjects	Locations						p-value
	P1	P2	P3	P4	P5	Average \pm SD	
1	49.11	50.00	50.26	47.74	51.27	49.68 \pm 1.33	>0.05
2	50.00	50.00	48.60	48.56	47.00	48.83 \pm 1.25	>0.05
3	36.89	38.31	48.75	47.44	39.00	42.08 \pm 5.56	<0.05
4	49.25	47.52	48.56	50.00	50.85	49.24 \pm 1.28	>0.05
5	50.00	50.00	50.00	50.00	50.00	50.00 \pm 0.00	>0.05
6	48.50	49.40	46.60	50.00	49.17	48.73 \pm 1.31	>0.05
7	50.00	50.00	48.00	48.50	44.27	48.15 \pm 2.35	>0.05
8	50.00	50.00	50.00	50.00	50.00	50.00 \pm 0.00	>0.05
9	50.00	49.20	49.20	50.00	50.00	49.68 \pm 0.44	>0.05
10	42.35	49.50	43.69	48.57	50.00	46.82 \pm 3.54	<0.05
11	44.95	39.92	39.63	40.57	39.77	40.97 \pm 2.25	>0.05
12	48.76	46.12	48.47	50.00	45.50	47.77 \pm 1.89	>0.05
13	49.00	49.80	48.30	45.60	42.90	47.12 \pm 2.84	>0.05
Average	47.60 \pm 3.95	47.67 \pm 3.98	47.70 \pm 2.96	48.23 \pm 2.67	46.90 \pm 4.25	47.62 \pm 0.47	
p-value	<0.05	<0.05	<0.05	<0.05	<0.05		

Figure 8.6 shows the ranges of 5th to 95th percentiles for both cold and heat discomfort thresholds. The ranges were larger for the cold discomfort thresholds compared to the heat discomfort thresholds (Figure 8.6).

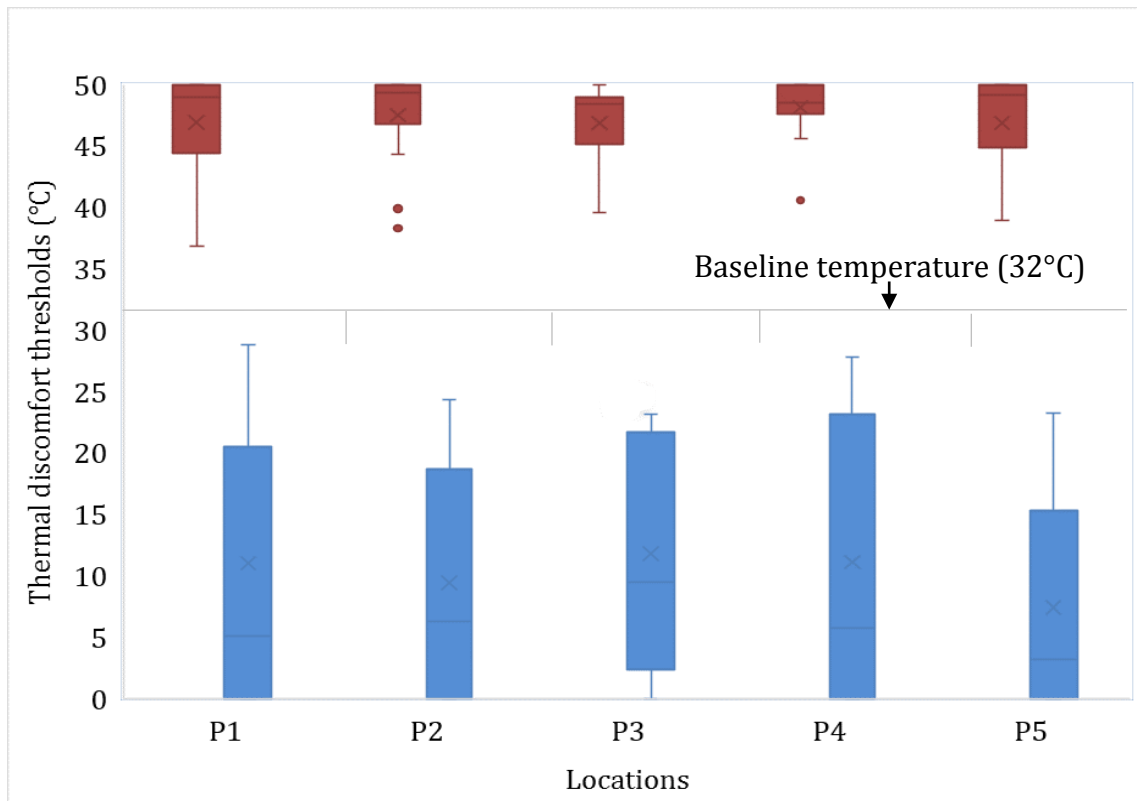


Figure 8.6: Cold (blue) and heat (red) discomfort thresholds at different sites of hand

8.3.5 Classification of participants into cold pattern and heat pattern groups

According to Cold-Heat pattern questionnaire, eight subjects were classified into cold pattern group –sensitive to cold, and five were diagnosed into heat pattern group–sensitive to heat (Table 8.4). As seen in Table 8.5, subjects who are in heat pattern group recorded slightly higher mean pressure discomfort thresholds than subjects in cold pattern group, however, there was no statistically significant difference found in the mean pressure discomfort thresholds between the two groups (Table 8.5)

Subjects who are in cold pattern group recorded higher mean of cold discomfort thresholds (10.3°C) in comparison to participants in heat pattern group; which mean that they are more sensitive towards cold stimuli. However, no statistically significant difference was found between the two groups. For the heat discomfort threshold, both groups recorded mean of 47.6°C.

Table 8.4: The cold pattern and heat pattern score and grouping for each subject

Subjects	Cold pattern score	Heat pattern score	Cold-Heat Pattern Score	Groups
1	2/10	5/10	3	heat
2	5/10	3/10	-2	cold
3	6/10	4/10	-2	cold
4	6/10	7/10	1	heat
5	6/10	8/10	2	heat
6	6/10	5/10	-1	cold
7	1/10	6/10	5	heat
8	6/10	0/10	-6	cold
9	3/10	1/10	-2	cold
10	6/10	1/10	-5	cold
11	0/10	1/10	1	heat
12	6/10	1/10	-5	cold
13	8/10	4/10	-4	cold

Table 8.5: Pressure, cold and heat discomfort thresholds of subjects in different groups (mean \pm SD)

Groups	Pressure discomfort thresholds (kPa)	Cold discomfort thresholds (°C)	Heat discomfort thresholds (°C)
Cold pattern	199.1 \pm 110.7	10.3 \pm 9.6	47.6 \pm 2.5
Heat pattern	228.1 \pm 115.82	6.4 \pm 7.0	47.6 \pm 3.8
p-value	>0.05	>0.05	>0.05

8.4 Discussion

There are two physical agent modalities that are used in therapeutic glove designs. The first type is glove designed to apply pressure to underlying hand tissue and skin (pressure therapy), and the second type is glove made to provide warmth to the wearer (heat therapy). To select an effective modality and design a glove that is functional and comfortable, it is important to identify the sensitivity of individuals towards the thermal and pressure stimuli. The main objectives of this study were to identify the intensity and locations caused by arthritic pain at different parts of the hand of an arthritis patient, determine the pressure and thermal discomfort thresholds at different parts of the hand and to determine whether the Cold-Heat pattern questionnaire could be used as a tool to categorise subjects into groups that targeting the right treatment modality to the right people.

The current study recruited a total of 13 subjects: nine OA subjects and four RA subjects. The locations identified by the subjects as the locations where they had arthritic pain agrees with those in previous studies (Arden & Nevitt, 2006; Manno, 2012). OA commonly involves the DIP, PIP and first CMC joints of the hand while RA commonly involves the PIP and MCP joints of the hand. Identifying the locations of arthritic pain can help designers and manufacturers of therapeutic gloves develop gloves with targeted treatment locations.

Several subjects exhibited very low thresholds towards pressure stimuli. This could be due to continuously increased nociceptive impulse activity in arthritis giving rise to peripheral sensitization (Chiarotto et al., 2013; Dhondt et al., 1999; Sofat & Kuttapitiya, 2014). Spearman correlation indicated strong negative correlation between duration of arthritis and pressure discomfort thresholds ($r_s = -0.67$, $P < 0.05$); the longer

the duration of arthritis, the more sensitive the subjects becomes towards pressure sensation, as can be seen in Table 8.1. Subject number 10 had RA for 40 years and the result demonstrated that the subject was very sensitive to pressure stimuli with lowest average pressure discomfort thresholds of 52.96 ± 22.58 kPa. Additionally, threshold levels of subject number 10 at locations P3 and P4 (29.42 kPa and 29.43 kPa respectively) were lower than the recorded glove-skin interfacial pressure at a number of locations (Figure 7.13). Therefore, it is safe to assume that if the subject wears the therapeutic gloves there is a high possibility that she will feel strong discomfort.

It was observed that most of the recorded pressure discomfort thresholds are higher in comparison to the glove-skin interfacial pressures (Figure 7.13). However, further investigation can be carried out by recording threshold levels at various locations of the hand with longer application of pressure; for example 15 to 45 minutes. This could be helpful in designing an optimum level of glove-skin interfacial pressure without compromising the wear comfort of the user.

The pressure sensitivity is not uniformly distributed over the hand for more than half of the subjects. The pressure discomfort thresholds were noticeably lower at P3 (third PIP joint) and highest at PI (first DIP joint). Since the pressure sensitivity is not uniformly distributed over the hand, regional variation in the responses of the pressure stimuli should be taken into consideration in the design and engineering of therapeutic gloves with pressure to underlying hand tissue and skin (pressure therapy).

In Chinese medicine practice, patients are commonly divided into two groups which are “Cold” and “Hot”. Patients with hot pattern generally have symptoms of thirst, hot feeling in the joints and dry stools, whereas patients with cold pattern generally have symptoms of cold feeling in the whole body, cold feeling in the limbs, and cold

feeling in the joints. Based on the classifications, patients will be treated differently according to their groups. (Lu et al., 2009; Ryu et al., 2010; van Wietmarschen et al., 2012). Personalized medicine provides information that allows targeting the right treatment option to the right patient. This study found no statistically significant difference in the mean pressure, cold and heat discomfort thresholds between the cold pattern and heat pattern groups. Small sample size could be the reason of no statistically significant found in the study. A clearer questionnaire will be beneficial to get consistent results since some subjects found some of the questions were difficult to understand.

Considerable variation between subjects was found for the cold discomfort thresholds in contrast to very little variation for heat discomfort thresholds. Cold sensation is known to be more subject to variation and difficult to evaluate (Hagander et al., 2000; Navarro & Kennedy, 1991; Wakolbinger et al., 2014). This study found that some subjects were very sensitive to heat, with one subject recorded average heat discomfort thresholds of 40.97°C in five locations; the average heat discomfort thresholds for subjects was 47.62°C. Two subjects reached 50°C at each location without reporting discomfort; which exhibited high thresholds towards heat.

Analysis of the Kruskal-Wallis H test demonstrated that thermal discomfort thresholds of subjects were significantly different at all tested locations. Also, this study found that some subjects have a different level of sensitivity towards cold and heat at different areas of the hand. Since there was a significant different of sensitivities in cold and heat stimuli at different areas of hand, it is important to evaluate the distributions of sensitivity at hand and translated into hand mapping for glove design and engineering. Therapeutic gloves which are designed to provide warmth (heat therapy)

to the hand are more suitable for people who are sensitive to cold. This type of glove is not recommended to an individual who has low heat discomfort threshold because it will cause discomfort to the wearer. Therapeutic glove designed to provide pressure therapy might be more suitable for this group of people.

8.5 Conclusion

In conclusion, this study found significant variations in terms of pressure, cold and heat discomfort thresholds between subjects. Participants with longer disease duration are more sensitive to pressure, cold and heat stimulation. Since there were differences in the level of sensitivities toward pressure, cold and heat stimuli at different areas of hand, designers are recommended to use an ergonomic approach to design the gloves based on the thresholds distribution of the hand. Such design approach will improve the wear comfort and therapy effectiveness. The role of the Cold-Heat pattern questionnaire in assisting the design of therapeutic gloves for particular groups of people requires further research.

Regional hand mappings of two subjects (number 8 and 11) were developed and presented in Chapter 9.

Chapter 9 An Evidence-Based Framework for the Design and Engineering of Therapeutic Gloves

Introduction

The findings from the literature review, survey, objective material testing, and physical testing served as the basis for the development of a framework for the design and engineering of functional and comfortable therapeutic gloves. In this chapter, the design factors for therapeutic gloves are outlined. Then, a theoretical framework for the design and engineering of therapeutic gloves is proposed. Finally, the regional hand mappings established from the physical testing in Chapters 7 and 8 are presented.

9.1 Design factors of therapeutic gloves

Before developing a framework, it is important to identify the design factors of therapeutic gloves. Table 9.1 shows the design factors and criteria of therapeutic gloves. Design factors and criteria identified in this research can be used as guidelines to develop glove designs that consumers will accept easily.

At the beginning of this research, a literature review was conducted to explore the current state of knowledge about the types and designs of therapeutic gloves for people with hand arthritis that are commercially available and/or patented. No design factors for therapeutic gloves have been established to date, although such classification is essential to enable medical practitioners and product engineers to focus clearly on the design of gloves and select appropriate materials for specific functions.

Therapeutic gloves have the usual functional requirements of other kinds of gloves and particular requirements arising from the needs of people with hand arthritis. Following identification and assessment of existing glove designs in the literature, the

functional requirements of therapeutic gloves were classified in Chapter 2 based on improvement of hand function and reduction of hand symptoms (Figure 2.6).

The survey of arthritis sufferers in Chapter 5 revealed five important attributes participants consider when using or buying a therapeutic glove: (1) reduction of pain, stiffness and swelling, (2) comfort, (3) fit, (4) improvement of hand function and (5) freedom of movement. The findings from the survey suggested that the functional and comfort aspects of therapeutic gloves are the most important. From the literature, it was established that comfort consists of four components: thermo-physiological, ergonomic, sensorial and psychological comfort. These elements are vital to maintain the wear comfort of the patients and their compliance with the treatment.

Although the findings from the survey suggested that aesthetic aspects (psychological) in terms of colour, design, and materials were seen as less significant than the functional and comfort aspects, expressive and aesthetic aspects adapted from the FEA consumer needs model (Lamb & Kallal, 1992) were incorporated into the design factors. This is because prior studies had shown that people are more satisfied with their apparel when these elements were incorporated into the design (Gordon & Guttman, 2013; Stokes, 2010). The expressive need is related to the ways the glove influences self-esteem or makes the patient feel. Poor appearance or construction of therapeutic gloves makes patients feel self-conscious. Previous studies reported that the standard beige colour of pressure garments had negative connotations of illness or disability, potentially lowering self-esteem and leading to psychological problems (Macintyre & Baird, 2006). The aesthetics need is the appearance of the glove in terms of colour, style, shape, material, fitting and finishing.

Table 9.1: Design criteria for each factor of therapeutic gloves

Design factors	Design criteria
1. Functional needs	
i. Improvement of hand function	<ul style="list-style-type: none"> • Inclusion of strap/flap, padding and non-slip material at selected areas or regions for grip support • Segmentation of the glove with different material stiffness for greater dexterity
ii. Reduction in hand symptoms	<ul style="list-style-type: none"> • Compression at selected locations for pain relief and reduction of swelling • High thermal resistance fabric for provision of warmth for pain relief and reduction of swelling
2. Comfort needs	
i. Thermo-physiological requirements	<ul style="list-style-type: none"> • Low thermal resistance fabric for people sensitive to warmth • High thermal resistance fabric for glove design for provision of warmth • Lower water vapour resistance fabric (0-13m².Pa/W) (Ho, 2008) for breathability • Good moisture management properties (\geq grade 3) (Ho, 2008) • Fabric with higher air permeability • Fabric that is breathable and has good moisture management properties for high-sweat zones (e.g. the palm)
ii. Ergonomic requirements	<ul style="list-style-type: none"> • Segmentation of the glove with stretchable fabric for ease of hand movement • Fabric with minimal tension under stretch to prevent excessive pressure
iii. Sensorial requirements	<ul style="list-style-type: none"> • Soft and smooth fabric • Flat and smooth stitch types

	<ul style="list-style-type: none"> • Minimal seams
iv. Psychological requirements	<ul style="list-style-type: none"> • Aesthetically pleasing – simple, pretty, fun colours, sporty, feminine or masculine • Invisible on the skin: white, skin or pale colours • Resembles a ‘normal’ glove and flattering to the wearer • Closure mechanisms that permit easy donning and doffing

9.2 An evidence-based framework

To date, no publish systematic research has been conducted on the design and engineering of therapeutic gloves. Therefore, it is necessary to develop a theoretical framework to guide the design and engineering of therapeutic gloves. The development of apparel products is a creative problem-solving process, in which the design factors can range from the time and resources of a company to the specific needs of the user (Gordon & Guttmann, 2013). Figure 9.1 shows a conceptual overview of the design and engineering of therapeutic gloves based on the work presented in this thesis. The concepts established in this research could be applied to the design of any apparel, especially for special needs garments that are not routinely developed in the market.

Since the user is the focus of functional apparel design, the design process should start with identifying the user’s needs (Black & Cloud, 2008; Bye & Hakala, 2005). After analysing the user’s needs, the design factors for the product can be developed. Design factors can also be established through a literature review, product evaluation, and/or consultation with an expert in the specific area.

Defining the design requirements is the next step in providing solutions to the needs of the user. A successful design requires the designer’s understanding of the end

user's needs and the capability to translate it into garment attributes (Bye & Hakala, 2005).

The design realisation stage involves two key processes: design and fundamental architecture, and materials selection. In this stage, materials are selected, patterns developed, construction methods explored and finishing techniques chosen and applied. Sketches of the proposed product will be made to explore possible design solutions. The final prototype is evaluated according to design factors and can involve user satisfaction and garment performance evaluation. If the prototype does not meet the requirements of the design criteria, the design process will be re-initiated.

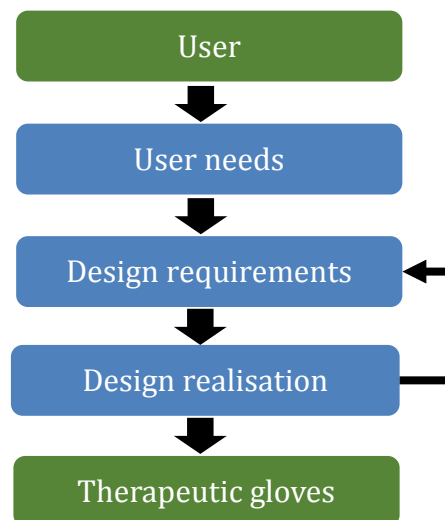


Figure 9.1: Proposed conceptual overview of the design and engineering process for therapeutic gloves

Figure 9.2 outlines the proposed framework for design and engineering of therapeutic gloves, derived from the conceptual overview in Figure 9.1.

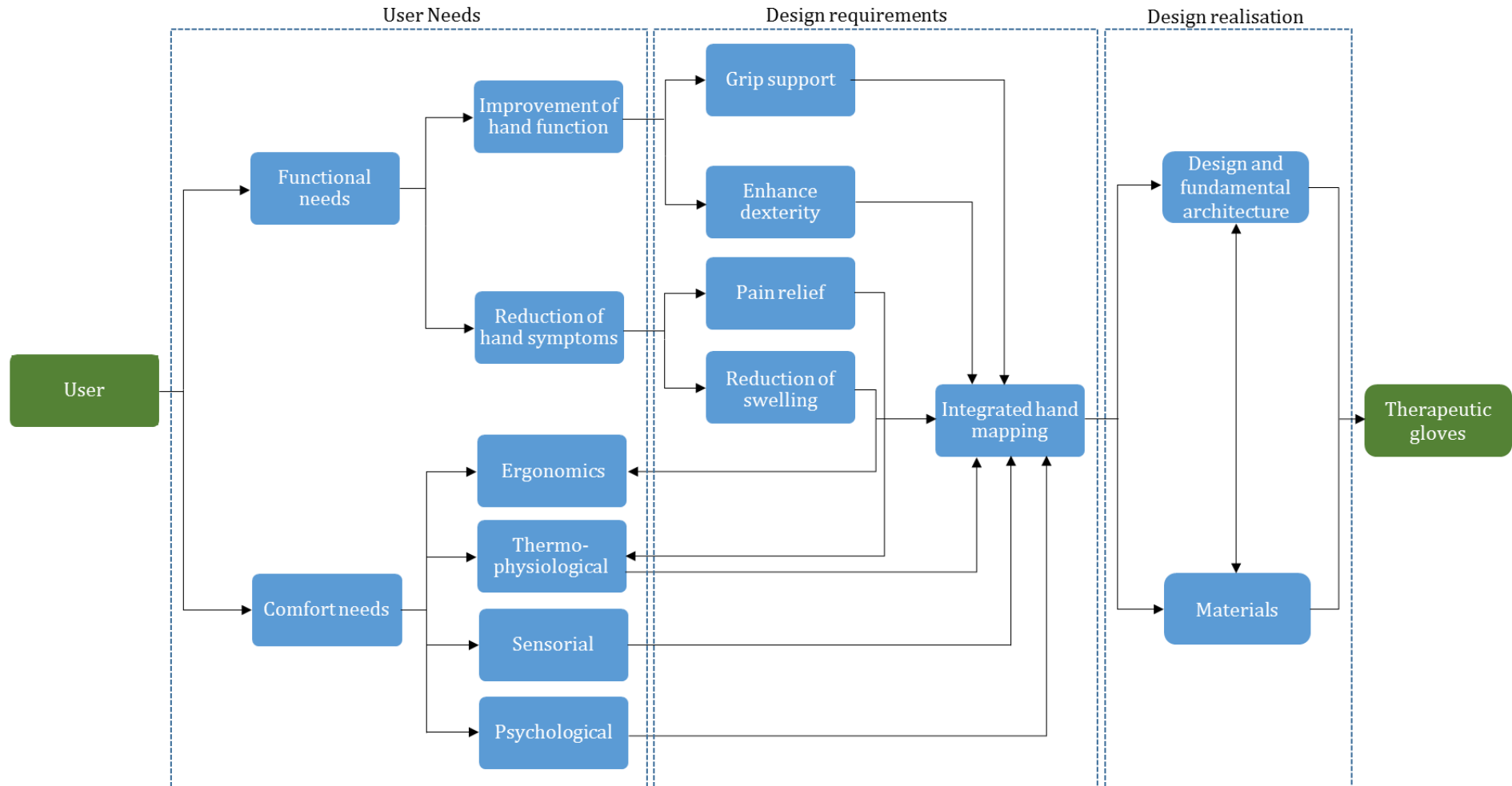


Figure 9.2: Proposed framework for the design and engineering of therapeutic gloves

As illustrated in the framework in Figure 9.2, the overall process of design and engineering of therapeutic gloves consists of three principal stages: identification of the user's needs, development of design requirements, and design realisation. As noted above, attention to user needs is critical in defining the problems a product must solve (Bye & Hakala, 2005). Identifying user needs provides a means for establishing design factors (Lamb & Kallal, 1992). In this framework, which is specific to therapeutic gloves, the needs of the user are classified as functional and comfort needs.

Functional needs consist of the ability to relieve arthritis-related symptoms and the ability to improve the hand function of arthritis patients. Comfort needs consist of four aspects: thermo-physiological, ergonomic, sensorial and psychological needs. These cross-comfort requirements lead to the design of therapeutic gloves with desirable thermo-physiological, ergonomic, sensorial and psychological comfort attributes. As described by Bartels (2011) and Li and Dai (2006), wear comfort is crucial in today's textile market and a key parameter in all clothing.

The second stage in the design and engineering process is the development of design requirements. Design requirements are the design solution for the established design factors. As previously discussed in Chapter 2, designs for improvement of hand function currently consist of straps, padding, elastic materials and silicone beads, which act as grip support and enhance dexterity. For reduction of arthritic symptoms, the gloves are designed to apply pressure to underlying hand tissue and skin, and use high thermal resistance materials with the aim of reducing swelling and providing pain relief. Based on the identified needs and design requirements, the hand could be mapped according to the functional and comfort requirements.

The design realisation stage includes design and fundamental architecture and materials selection. Hand mapping design, material properties, fabric structures and fibre combinations can be used strategically to meet the requirements of the therapeutic gloves in terms of function and comfort. Different designs for different applications in terms of functional needs can be created as well.

9.3 Regional hand mapping concept

In recent years, a new trend in sport and performance garment design and engineering has been proposed that employs the body mapping concept (Jinyun, 2013; Lee et al., 2013; McCann, 2015; Smith & Havenith, 2011; Troynikov & Watson, 2015). For example, sportswear can be designed based on mapping of local sweating and heat production patterns, as illustrated in Smith and Havenith (2011) and Troynikov and Watson (2015). These authors claimed that designs based on the body mapping concept were able to improve the wear comfort of athletes in hot and warm climates. Material with varying properties, fabric structures and fibre combinations are placed strategically around the body to address the different functional and physiological demands of different body zones. Quick-drying fabrics with high moisture absorbency are used at high-output zones of the body (e.g., back, chest) to prompt sweat evaporation during intense activities. Unlike traditional sportswear made of one piece of fabric with the same material and fabric construction, body-mapped sportswear is engineered by sewing together two or more pieces of fabrics with different physical properties to accommodate the physiological demands of the body.

In this research, the concept of regional hand mapping was used to consider three aspects that could influence the physiological comfort of the wearer: skin deformation during hand movements, glove–skin interfacial pressure during hand movements, and

different levels of sensitivity towards pressure and thermal stimuli. Data collected from the experiments described in Chapters 7 and 8 were mapped with a spectrum of colours. By recognising the colour differences in different regions and areas of the hand, it is easier to distinguish the physiological requirements of therapeutic gloves and integrate such information into the design.

9.3.1 Regional hand mappings based on skin deformation

The mean skin relaxed-strain ratios in the vertical direction of the hand were quantified in Chapter 7 to enable skin deformation mapping of the hand. Quantification of skin deformation with appropriate wearing ease in garment construction permits unrestricted movement of the wearer's body, thus improving comfort (Choi & Hong, 2015; Wang, 2011). Ease of movement in a glove is critical, because restriction of hand movement will generate high interface pressure between the glove and the hand tissue and skin, which may, apart from discomfort, lead to abrasion and bruising of underlying tissue (Das & Alagirusamy, 2010a; Dianat et al., 2014).

The regional mapping visualisation of the skin deformation of the hand is shown in Figure 9.3 with a spectrum of colours representing a range of skin relaxed-strain ratios. The metacarpal region recorded the greatest change in the skin relaxed-strain ratios in both postures, and this can be clearly observed from the colour representation in the region. Based on the colour mapping, therapeutic gloves could be developed with regional segmentation that accommodates the skin relaxed-strain ratios of the hand.

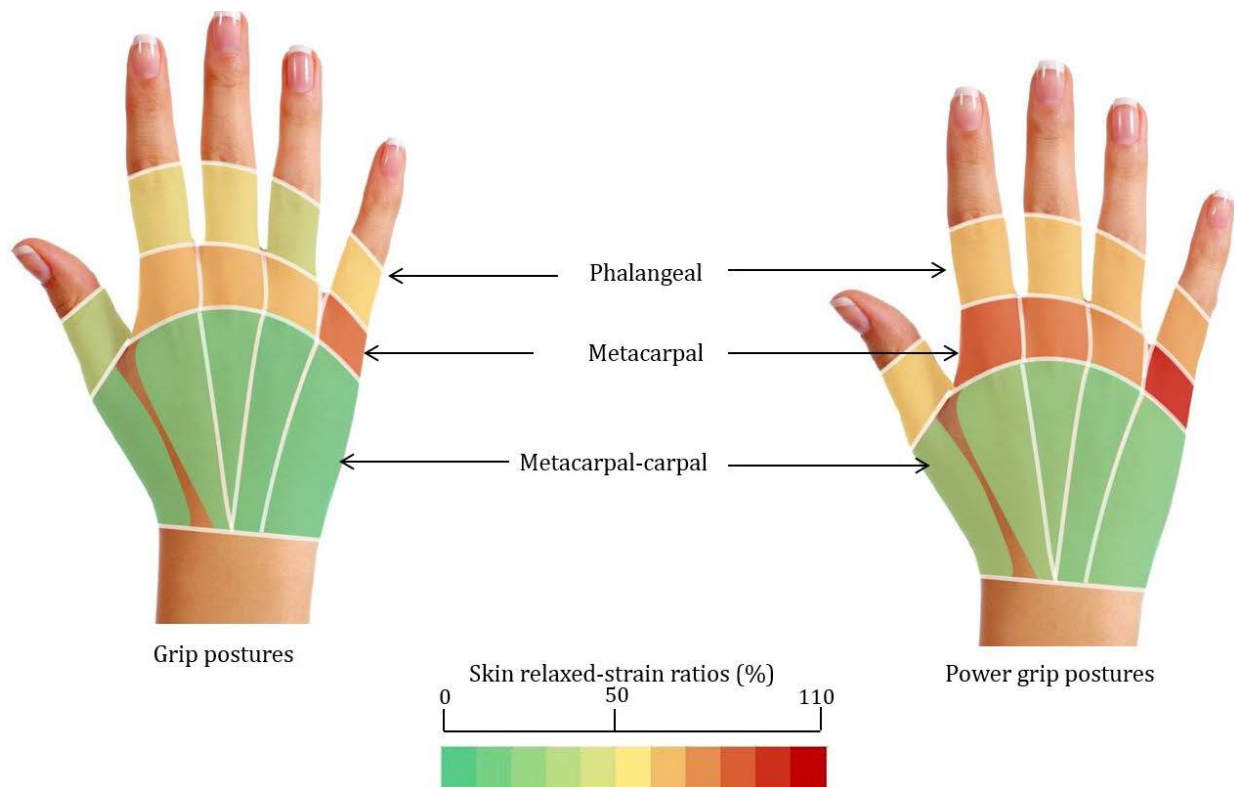


Figure 9.3: Regional mapping of skin relaxed-strain ratios in different postures

9.3.2 Regional hand mappings based on glove-skin interfacial pressures

Glove-skin interfacial pressures were measured at four different locations based on two factors: the regions of highest skin deformation and the places where people commonly have arthritic pain. The magnitudes and distributions induced by poorly designed therapeutic gloves could adversely affect wearers' comfort and compliance during the treatment. Mapping of the glove-skin interfacial pressure in the critical areas provides valuable data to be incorporated into therapeutic glove design to improve comfort, which ultimately will lead to better adherence to the glove therapy.

The glove-skin interfacial pressures from three different kinds of commercial therapeutic gloves were averaged; the mapping visualisation of the glove-skin interfacial pressure is shown in Figure 9.4 In the illustration, the colour in the metacarpal and phalangeal areas changes from light yellow in relaxed posture to red in

power grip posture. This shows that the glove–skin interfacial pressures are greatly influenced by hand postures, especially at bony and rigid surfaces. The trend in the colour visualisation in Figure 9.4 is very similar to that in Figure 9.3. This work revealed that the changes in the geometry of the hand during different hand movements should be carefully considered in the development of therapeutic gloves, as this aspect is crucial in maintaining user comfort during wear.

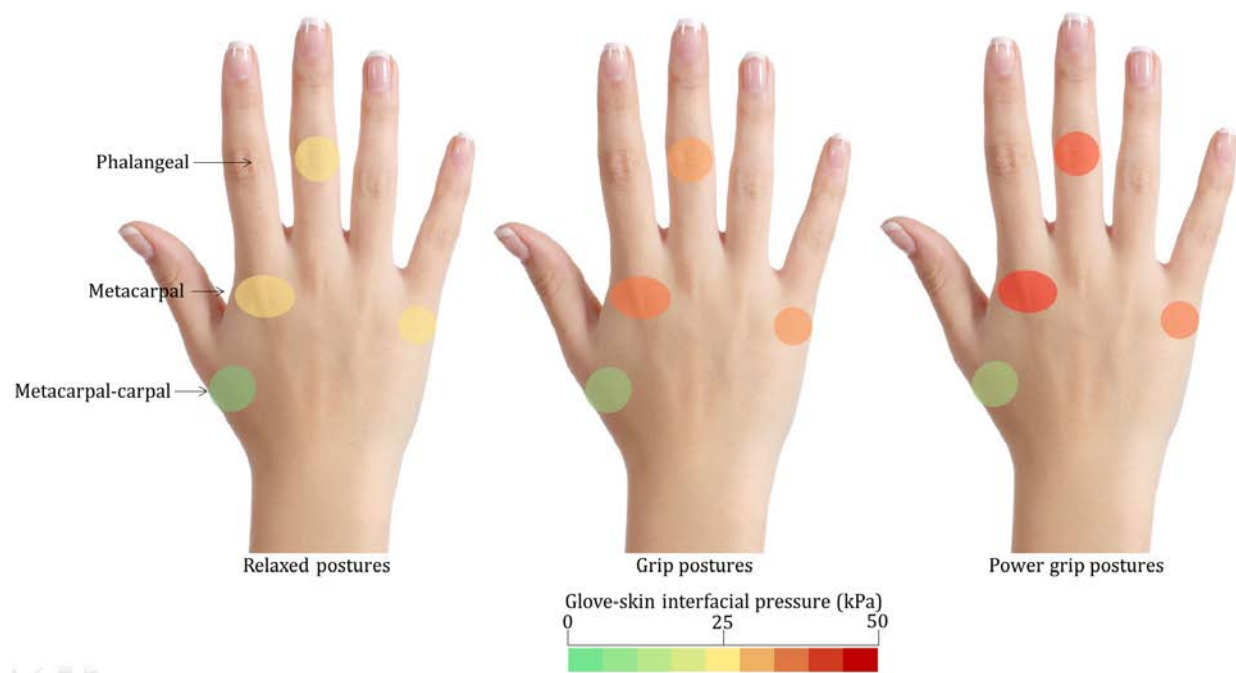


Figure 9.4: Regional mappings of glove–skin interfacial pressure

9.3.3 Regional hand mappings based on pressure and thermal discomfort thresholds

The experimental results detailed in Chapter 8 show that pressure and thermal sensitivity vary between individuals. This shows the importance of choosing a glove that is comfortable for an individual and has optimal therapeutic effectiveness. Choosing an appropriate glove requires patients and clinicians to work together to explore the variety of gloves available and select the most appropriate product to meet both clinical and lifestyle needs (Krimmel, 2009). The type of glove chosen depends on

many factors, such as the patient's mobility, ability to apply and remove the glove, severity of arthritis, tolerance of pressure generated to the underlying hand tissue and skin, and sensitivity to type of therapies (e.g. thermal). These factors, together with the patient's preference for the design and materials of the glove, should be considered in order to encourage patient adherence and optimal therapy effectiveness.

The widely differing pressure and thermal discomfort thresholds of two participating arthritis patients are shown Figure 9.5, Figure 9.6, and Figure 9.7. For pressure discomfort thresholds, Subject P8 recorded an average of 304.01 kPa in five locations, while subject P11 recorded a substantially lower average of 76.49 kPa. As discussed in Chapter 8, the pressure discomfort thresholds are not uniformly distributed over the hand, and this can be seen as well in the pressure discomfort mappings of the patients. Therefore, regional variation in the responses to pressure stimuli should be translated into glove design using strategic design placement of knitting structures with different tension properties.

Subject P8 reached the maximum thresholds for both cold (0°C) and heat (50°C) stimuli without reporting discomfort, indicating that this subject has high tolerance towards cold and heat stimuli (Figure 9.6 and Figure 9.7). In contrast, subject P11 was very sensitive to both cold and heat stimuli, reporting the lowest average heat discomfort threshold and fourth-highest cold discomfort thresholds of all research participants. Since this subject is highly sensitive to thermal stimuli, use of a thermal glove would necessitate careful selection of materials to maintain wear comfort.



Figure 9.5: Pressure discomfort thresholds of two arthritis patients

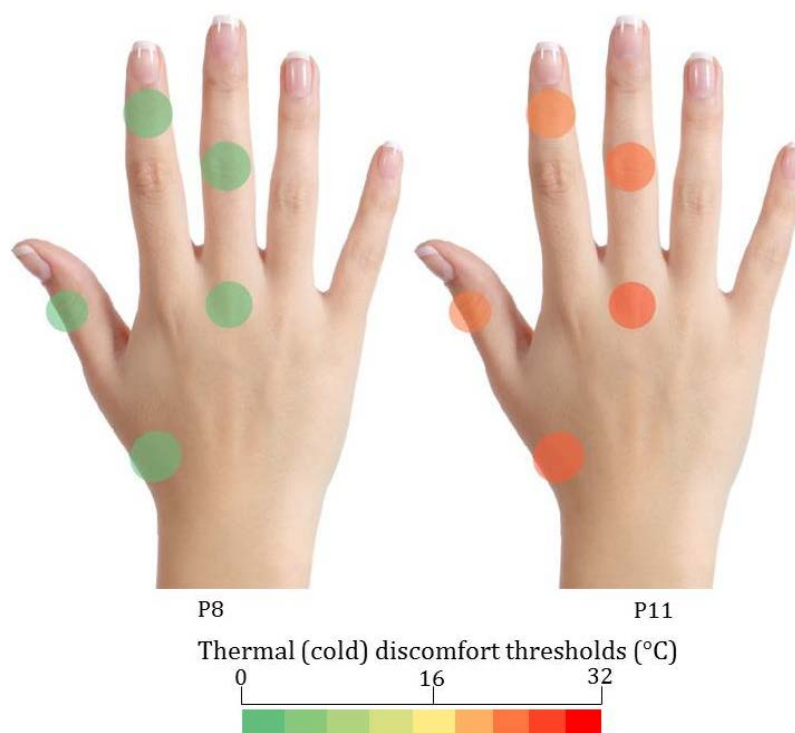


Figure 9.6: Thermal (cold) discomfort thresholds of two arthritis patients



Figure 9.7: Thermal (heat) discomfort thresholds of two arthritis patients

9.4 Conclusion

In summary, this chapter describes the development of a framework for the design and engineering of therapeutic gloves. The design factors of therapeutic gloves were first identified by analysing the designs of therapeutic gloves already available in the market and/or patented. A framework for design and engineering of therapeutic gloves was then proposed, illustrating how the functional and comfort needs of the wearer must be considered and integrated. Therapeutic gloves can be designed based on the concept of integrated hand mapping. Regional hand mappings based on skin deformation, glove-skin interfacial pressure and levels of sensitivity towards pressure and thermal stimuli were presented. The regional hand mapping established in this research represents a valuable and practical method for the design and engineering of therapeutic gloves with improved comfort and functionality, which ultimately will lead to better adherence to glove therapy.

Chapter 10 Conclusion and Recommendations for Future Work

10.1 Conclusion

In this research, an evidence-based framework for the design and engineering of therapeutic gloves for individuals suffering from hand arthritis was developed. The method integrates knowledge from multiple disciplines, including surveying patients' needs and preferences, an investigation of textile material properties, 3D scanning of the hand in different postures to evaluate skin deformation, investigation of glove–skin interfacial pressure in different hand postures, and evaluation of the pressure and thermal discomfort thresholds of arthritis patients in different parts of the hand.

Therapeutic gloves are widely used in mainstream treatment of arthritis patients. However, little previous research (seven clinical trials and one case study) has been conducted on optimising their design, and there is no systematic classification of therapeutic gloves. Thus, it is hard for the practitioner, as well as patient and product engineers, to acquire a comprehensive understanding of glove features and their proposed benefits to the wearer. In addition, since therapeutic gloves are worn during the day and/or at night to relieve symptoms of arthritis and improve hand function, it is important for the gloves to provide excellent thermo-physiological, ergonomic, sensorial and psychological comfort. The purpose of this research was to fill these knowledge gaps and develop an evidence-based framework for the design and engineering of therapeutic gloves. By conducting theoretical and experimental investigations, the objectives of this PhD research were achieved. The objectives and the process of their achievement can be summarised as follows.

1. To identify and characterise the effectiveness of existing therapeutic gloves in terms of hand function and hand symptoms

This objective was achieved by reviewing the evidence for whether therapeutic gloves improve hand function and reduce hand symptoms in people with hand OA and RA (Chapter 3). Seven clinical trials and one case study satisfied the selection criteria and were included in the review. The review identified that therapeutic gloves for management of hand RA can lead to substantial improvements in hand symptoms (pain, stiffness and swelling), although the exact mechanisms of their action remain unclear. In terms of improvement of hand function, the results were inconclusive, except for the grip strength, with some studies reporting significant improvement and others reporting slight improvement. Although patients with hand OA were often recommended to wear therapeutic gloves, only few of the reviewed studies considered patients with hand OA.

2. To investigate users' perceptions of effectiveness, comfort and preference when utilising therapeutic gloves

The survey described in Chapter 5 elicited the experiences and perceptions of 30 arthritis patients who used therapeutic gloves as part of their rehabilitation treatment. Most patients had worn therapeutic gloves to reduce hand swelling. Twenty-four participants reported improvement: reduced swelling and pain, provision of warmth, and greater joint protection during glove wear. Five attributes – reducing pain, stiffness and swelling, comfort, good fit, improved hand function and freedom of movement – were identified as key glove needs. These needs were grouped into two key needs, function and comfort, in the evidence-based framework.

3. To evaluate the commercial benchmark therapeutic gloves in terms of physical parameters, tensile attributes and properties relevant to physiological comfort of the wearer

This objective was achieved by well-planned experimental work (Chapter 7). Material properties, including physical parameters, tensile attributes and properties relevant to the physiological comfort of the wearer were tested in a systematic comparison of six commercial therapeutic glove fabrics. It was found that all the benchmark fabrics had a certain amount of tension decay after multiple extension and retraction cycles; however, the recovery performance was greater than 95% for all fabrics. In terms of moisture management properties, only two fabrics recorded good moisture management capability. Fabric embedded with neoprene recorded a high R_{ct} value, which is desirable for glove design to provide warmth. However, the breathability of the fabric was compromised due to the neoprene lining. Fabric with poor breathability can lead to an uncomfortable sensation due to accumulation of moisture on the skin within the glove which could impact the wear comfort. Lastly, all fabrics recorded low MIU and SMD in relaxed and under various elastic strains on the next-to-skin side, which indicates that the gloves are soft to the skin, feel smooth, and have high ease of wearing. The ease of wearing aids the user don and doff the therapeutic glove.

4. To evaluate the effect of hand movement on skin deformation as well as on the interface pressure the gloves impart to the hand of the wearer

The achievement of this objective was described in Chapter 7. The chapter is divided into two parts: the first outlines the development of a method of measuring the skin relaxed-strain ratios at the dorsal side of the hand during three different hand movements. The research demonstrated significant differences in hand dimensions in

each posture (relaxed, grip and power grip). The metacarpal region showed significantly higher skin relaxed-strain ratios than other regions. This is because when the hand transitions from a relaxed posture to a power grip posture, the curvature of the bones in the metacarpal region becomes more significant, increasing skin deformation.

The second part describes the development of a method of measuring the glove-skin interfacial pressure at the dorsal side of the hand in three different hand postures. Consistent with the findings in part one, the research revealed that the geometry of the hand in different locations and the radius of the anatomic curvature impacts the glove-skin interfacial pressures. The glove-skin interfacial pressures also varied with changes in hand posture; significant differences were found in glove-skin interfacial pressures between the postures at all measured locations. Regional hand mappings based on the skin deformation and glove-skin interfacial pressure were developed and presented in Chapter 9.

5. To evaluate the pressure and thermal discomfort thresholds on the hands of arthritis patients

The achievement of this objective was described in Chapter 8. The pressure and thermal (cold and heat) discomfort thresholds of 13 women with hand OA and/or RA were examined. Significant variations in pressure, cold and heat discomfort thresholds were found between subjects. Some participants also recorded significantly different level of sensitivity towards pressure, cold and heat at different locations of the hand. Since sensitivity is not uniformly distributed over the hand, regional variation in the responses of the pressure and thermal stimuli should be taken into consideration in the design and engineering of therapeutic gloves. This study also showed that it is crucial to

identify the locations of arthritic pain to help designers and manufacturers develop therapeutic gloves with targeted treatment locations. Regional hand mappings based on the pressure and thermal discomfort thresholds were developed and presented in Chapter 9.

6. To propose an evidence-based framework for design and engineering of therapeutic gloves with improved functional attributes as well as improved wear comfort

Based on the literature review in Chapters 2 and 3, and research findings obtained in Chapters 5–8, an evidence-based framework for the design and engineering of therapeutic gloves was established. Each phase in the framework was described in detail. Design factors for therapeutic gloves were based on two key needs (functional and comfort) identified in Chapter 5. Regional hand mappings based on data about skin deformation, glove–skin interfacial pressure and the levels of sensitivity towards pressure and thermal stimuli were presented. The regional hand mapping established in this research provides a valuable guideline for design and engineering of therapeutic gloves with improved functionality and comfort, which ultimately will lead to better adherence to glove therapy.

10.2 Limitations of the study and recommendations for future works

The major objectives of this research project were achieved. However, this study had some limitations that restrict the generalisation of the results. Future research can overcome these limitations and expand upon the results obtained in this work, as outlined below.

1. The number of individuals surveyed in Chapter 5 was small; higher numbers of subjects will increase confidence in the findings. Future investigation could include more participants from different countries and geographical locations, with different physical characteristics.
2. Future research could investigate a larger number of therapeutic glove fabrics (potentially with different material properties). Due to material constraints, the sample size was reduced in the tensile testing, and the R_{ct} and R_{et} of two fabrics were not evaluated.
3. The subjects chosen in Chapter 7 and Chapter 8 focuses on female subjects above the age of 40 only, as previous studies reported arthritis being more dominant among women than men, and that its occurrence increases with age (Access Economics, 2007; Arthritis and Osteoporosis Victoria, 2013; Schofield et al., 2014; Wong et al., 2010). Future studies could investigate if a gender difference exists in the studies conducted in this research
4. The subjects in the physical tests described in Chapter 7 were not suffering from hand arthritis. It is reasonable to deduce that presence of hand arthritis influences the impact of hand movement on skin deformation and glove–skin interfacial pressure. Due to time limitations, the study only focused on a small sample of women aged 40–65 years. Further investigation should include a bigger sample size with a wider age group, and involve male subjects.
5. Classifications of patients into different groups based on Cold-Heat pattern questionnaire and their sensitivity towards cold and heat stimuli have potential for personalised treatment (targeting the right therapeutic product to the right patient). However, further studies with a larger sample size are needed to

substantiate these findings. A clear and easy to understand questionnaire will be beneficial to get consistent results since some subjects found some of the questions were difficult to understand.

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Appendices

Appendix I: Questionnaire



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- Associate Professor Dr Olga Troynikov, School of Fashion and Textiles, RMIT University, olga.troynikov@rmit.edu.au, 03 9925 9108)
- Dr Nicola Massy-Westropp, School of Health Sciences, University of South Australia, nicola.massy-westropp@unisa.edu.au, 08 8302 2486)

Dear Participant,

You are invited to participate in a research project conducted by RMIT University. Please read this sheet carefully and be confident that you understand its contents before deciding whether to participate. If you have any questions about the project, please ask one of the investigators.

Who is involved in this research project? Why is it being conducted?

The primary investigator is Siti Hana Nasir, a PhD candidate at School of Fashion and Textiles and this project is part of her PhD research. This research is being conducted under the supervision of Assoc. Prof. Dr. Olga Troynikov and Dr. Nicola

Massy-Westropp. The research is being conducted to develop an improved therapeutic glove with aim to reduce the arthritic symptoms and improve the hand function of rheumatoid arthritis sufferers through the use of therapeutic glove.

Why have you been approached?

As a person who suffers from arthritis, you are invited to take part in this research to understand your experience and perception towards the use of therapeutic glove.

What is the project about? What are the questions being addressed?

The research aims to reduce the arthritic symptoms and improve the hand function of arthritis sufferers using therapeutic glove. It is hoped that this study will help to find solutions to common problems associated with existing therapeutic gloves. It will also provide manufacturers of therapeutic gloves, medical practitioners, and therapists with important information about the needs of the patients who wear therapeutic gloves. The questionnaire will include four sections which are:

1. Information regarding user's therapeutic gloves.
2. User's perception of their gloves.
3. Gloves durability.
4. Suggestions for new product.

If I agree to participate, what will I be required to do?

If you agree to participate, you will need to answer a questionnaire consisting of four parts. Most of the questions are answered by selecting from the choices; also there are questions that will need a short detailed answer (long answers are not required).

What are the risks or disadvantages associated with participation?

There will be no discomfort or risk involved in your participation in this study.

What are the benefits associated with participation?

While we intend that this research may improve the performance of therapeutic glove, we cannot and do not guarantee or promise that you will receive any personal direct benefits from this study.

What will happen to the information I provide?

To preserve participant anonymity, PLEASE DO NOT place your name or any identifiable information anywhere in the questionnaire. The personal information that will be collected will be your gender and age only, by which you are not identifiable. If you give us your permission by signing this document, we plan to publish aggregated results in relevant scientific conferences and journals where individual answers will not be identifiable. Results from the study will be available to you on request. Data of this project will be stored in a locked office, in locked filing cabinets and will be retained by RMIT University for a minimum of 5 years. Paper materials will be disposed of through secure waste systems at RMIT University. Electronic data will be erased utilizing the recommended protocols at that time.

What are my rights as a participant?

Your decision whether or not to participate will not prejudice your future relations with RMIT University or your therapist. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

Whom should I contact if I have any questions?

If you have any questions, please feel free to ask us. If you have any additional questions later, the investigators will be happy to answer them.

What other issues should I be aware of before deciding whether to participate?

Nothing further.

You will be given a copy of this form to keep.

If you have any concerns about your participation in this project, which you do not wish to discuss with the researchers, then you can contact the Ethics Officer, Research Integrity, Governance and Systems, RMIT University, GPO Box 2476V VIC 3001. Tel: (03) 9925 2251 or email human.ethics@rmit.edu.au

Questionnaire

Please answer all questions pertaining to your current therapeutic glove unless otherwise indicated. Place a check (✓) in the box next to your answer.

1. Information about therapeutic gloves

i. How long have you had hand arthritis?	<input type="checkbox"/> Month _____ <input type="checkbox"/> Years _____
ii. What stage is your arthritis?	Stage I <input type="checkbox"/> Stage II <input type="checkbox"/> Stage III <input type="checkbox"/> Stage IV <input type="checkbox"/>
iii. How long have you been wearing therapeutic glove/s?	<input type="checkbox"/> Month _____ <input type="checkbox"/> Years _____
iv. Is your therapeutic glove/s ready-made or custom-made?	<input type="checkbox"/> Ready-made <input type="checkbox"/> custom-made
v. If ready-made, what brand/s of therapeutic glove/s do you currently wear?	_____
vi. What are you hoping to change by wearing the therapeutic glove?	_____ _____
vii. Could you feel any improvement after wearing the therapeutic glove?	If yes, what is the improvement? _____ If no, why do you think? _____ _____
viii. Indicate the number of hours per day you were asked to wear the glove/s?	<input type="checkbox"/> 1-8 hours <input type="checkbox"/> 9-16 hours <input type="checkbox"/> 17-24 hours
ix. Indicate the number of hours per day you wear the glove/s? If not the same amount of time as recommended - why?	<input type="checkbox"/> 1-8 hours <input type="checkbox"/> 9-16 hours <input type="checkbox"/> 17-24 hours _____

2. Please rate your reaction to each item as it might be used to describe your therapeutic glove/s. The scale is from 1-5; 1 is the maximum positive score, 5 is maximum negative score.

best 1 2 3 4 5 worst

Easy to put on	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Hard to put on
Cool and comfortable	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Hot
Good sweat absorption	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Poor sweat absorption
Fitting of the glove is comfortable (not too restrictive)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Very tight to wear (too restrictive)
Soft to skin	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Harsh to skin
Reduces pain	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Increases pain
Reduces finger stiffness	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Increases finger stiffness
Reduces swelling	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Increases swelling
Improves hand movement	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Restricts hand movement
Easy to take off	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Hard to take off
Hand does not feel itchy after taking glove/s off	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Hand feel itchy after taking glove/s off
Gloves does not leave marks on the skin after taking off	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Gloves leave marks on the skin after taking off
Fits well	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Does not fit well
Overall very satisfied with the glove/s	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Overall dissatisfied with the glove/s

3. Durability of therapeutic gloves

i. What do you think of the glove fitting after prolonged wear?	Initial fit: <input type="checkbox"/> Adequate <input type="checkbox"/> Loose <input type="checkbox"/> Tight After prolonged wear: <input type="checkbox"/> Adequate <input type="checkbox"/> Loose <input type="checkbox"/> Tight
ii. What do you think of the glove quality?	<input type="checkbox"/> Good <input type="checkbox"/> Fair <input type="checkbox"/> Poor
iii. What do you think of the quality of the trims (zipper, velcro, thread/seams)?	<input type="checkbox"/> Good <input type="checkbox"/> Fair <input type="checkbox"/> Poor
iv. How often do you wash your gloves?	<input type="checkbox"/> Every day <input type="checkbox"/> 3-4 days <input type="checkbox"/> Once a week <input type="checkbox"/> > than 1 week
v. Stretchability after washing	<input type="checkbox"/> Good <input type="checkbox"/> Fair <input type="checkbox"/> Poor
iv. How long does your glove last before it loses its therapeutic effect?	<input type="checkbox"/> 6 months <input type="checkbox"/> 1 year <input type="checkbox"/> >1 years

4. Suggestions for new product

i. What colour do you prefer your glove would be? Any specific design on it?	
ii. What kind of materials do you prefer (example: cotton, nylon, spandex, etc.) or doesn't matter?	
iii. What kind of trim do you prefer (zipper, velcro, thread/seams)? Or doesn't matter.	

<p>iv. Column to the right shows some of the important factors for the design of new therapeutic gloves: Please rank them in the order of importance, most important (1) to least important (9) Please place your numbers in the box.</p>	<table> <tr><td><input type="text"/></td><td>Easy to put on and put off</td></tr> <tr><td><input type="text"/></td><td>Materials</td></tr> <tr><td><input type="text"/></td><td>Durability</td></tr> <tr><td><input type="text"/></td><td>Comfort</td></tr> <tr><td><input type="text"/></td><td>Good fitting</td></tr> <tr><td><input type="text"/></td><td>Freedom of movement</td></tr> <tr><td><input type="text"/></td><td>Improve hand function</td></tr> <tr><td><input type="text"/></td><td>Reducing pain, stiffness and swelling</td></tr> <tr><td><input type="text"/></td><td>Colour or design</td></tr> </table>	<input type="text"/>	Easy to put on and put off	<input type="text"/>	Materials	<input type="text"/>	Durability	<input type="text"/>	Comfort	<input type="text"/>	Good fitting	<input type="text"/>	Freedom of movement	<input type="text"/>	Improve hand function	<input type="text"/>	Reducing pain, stiffness and swelling	<input type="text"/>	Colour or design
<input type="text"/>	Easy to put on and put off																		
<input type="text"/>	Materials																		
<input type="text"/>	Durability																		
<input type="text"/>	Comfort																		
<input type="text"/>	Good fitting																		
<input type="text"/>	Freedom of movement																		
<input type="text"/>	Improve hand function																		
<input type="text"/>	Reducing pain, stiffness and swelling																		
<input type="text"/>	Colour or design																		

Please indicate your gender and age.

Gender Male ☐ Female ☐

Age < 30 ☐31-40 ☐ 41-50 ☐51-60 ☐61-70 ☐ >70

Thank you for your time and answering the questions.

Appendix II: Influence of hand movement on skin strain distribution and glove-skin interfacial pressure



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- Associate Professor Dr Olga Troynikov, School of Fashion and Textiles, RMIT University, olga.troynikov@rmit.edu.au, 03 9925 9108)

Dear Participant,

You are invited to participate in a research project conducted by RMIT University. Please read this sheet carefully and be confident that you understand its contents before deciding whether to participate. If you have any questions about the project, please ask one of the investigators.

Who is involved in this research project? Why is it being conducted?

The primary investigator is Siti Hana Nasir, a PhD candidate at School of Fashion and Textiles and this project is part of her PhD research. This research is being conducted under the supervision of Assoc. Prof. Dr. Olga Troynikov. The research is being conducted to develop an improved therapeutic glove with aim to reduce the arthritic symptoms and improve the hand function of rheumatoid arthritis sufferers through the use of therapeutic glove.

Why have you been approached?

You are invited to participate in the study to help the researchers establish a framework of pattern engineering for development of therapeutic gloves. This study is important because fit and comfort are the main characteristic required in developing therapeutic gloves

What is the project about? What are the questions being addressed?

This study will look deeply on the effect of hand structure and hand movement on skin deformation and its effect on skin interfacial pressure. It is hoped that this study will help to find solutions to common problems associated with existing therapeutic gloves which is the fit and comfort of the gloves.

If I agree to participate, what will I be required to do?

There are two parts to your participation: the first part is scanning of your hand and the second part is measurements of your hand while the glove is worn

If you agree to participate, for the first part the investigator will ask you to relax your hand on the glass plate of the scanner with fingers abducted while they scan your hand. You will also need to move your hand in different positions such as clenching fist tightly and holding a plastic ball to mimic the hand while holding a cup.

In the second part of this study, you will be asked to wear three different types of therapeutic gloves and move your hand in different postures as described earlier, while the investigator measures your glove-skin interfacial pressure. Thin plastic pressure sensors the size of 10 cents coin will be placed between glove and your hand to measure glove-skin interfacial pressure in three different postures mentioned above.

What are the risks or disadvantages associated with participation?

We do not anticipate that you will experience any discomfort due to your participation in this research, nor do we foresee any abnormal risks related to your involvement in the study. If at any stage you experience any discomfort, the experiment will be terminated. The 3D scanner we possess is safe to use with humans as it only projects white light in the area to be scanned.

What are the benefits associated with participation?

While we intend that this research may improve the performance of therapeutic glove, we cannot and do not guarantee or promise that you will receive any personal direct benefits from this study.

What will happen to the information I provide?

In order to make arrangement with you for the hand scanning, personal information that will be collected initially including name and contact details. Information that will be collected from you will be de-identified with code number and may include: gender, age, weight, height, and hand dimensions. Only the code numbers data that have been de-identified will be used for analysis and presented in publications.

The information that is obtained in connection with this study and that can be identified with you will remain strictly confidential and will be disclosed only with your permission or except as required by law. If you give us your permission by signing this document, we plan to publish aggregated results in relevant scientific conferences and journals where individual answers will not be identifiable. Results from the study will be available to you on request. Data of this project will be stored in a locked office, in locked filing cabinets and will be retained by RMIT University for a minimum of 5 years.

Paper materials will be disposed of through secure waste systems at RMIT University.

Electronic data will be erased utilizing the recommended protocols at that time.

What are my rights as a participant?

Your decision whether or not to participate will not prejudice your future relations with RMIT University or your therapist. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

Whom should I contact if I have any questions?

If you have any questions, please feel free to ask us. If you have any additional questions later, the investigators will be happy to answer them.

What other issues should I be aware of before deciding whether to participate?

Nothing further.

You will be given a copy of this form to keep.

If you have any concerns about your participation in this project, which you do not wish to discuss with the researchers, then you can contact the Ethics Officer, Research Integrity, Governance and Systems, RMIT University, GPO Box 2476V VIC 3001. Tel: (03) 9925 2251 or email human.ethics@rmit.edu.au

Appendix III: Pressure and thermal discomfort thresholds in patients with arthritis



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- Dr Zhen Zhang, School of Health Sciences, RMIT University, zhen.zheng@rmit.edu.au, 03 9925 7167

Dear Participant,

You are invited to participate in a research project conducted by RMIT University. Please read this information carefully and be confident that you understand its contents before deciding whether to participate. If you have any questions about the project, please ask one of the investigators.

Who is involved in this research project? Why is it being conducted?

The primary investigator is Ms Siti Hana Nasir, a PhD candidate at School of Fashion and Textiles and this project is part of her PhD research. This research is being conducted under the supervision of A. Prof. Dr. Olga Troynikov, Dr Zhen Zhang. The research is being conducted to develop an improved therapeutic glove. Therapeutic

gloves are commonly used by arthritis sufferers to improve their hand functions and hand symptoms.

Why have you been approached?

You have been invited to participate in this project based on the following criteria:

1. you are aged between 18 – 65 years 2. You have been diagnosed with Stage I or Stage II hand rheumatoid arthritis or Stage I hand osteoarthritis 3. You have no history of pain at the hand (as a control subject).

What is the project about? What are the questions being addressed?

Arthritis is a form of joint disorder that involves inflammation of one or more joints. Pain and impaired hand function are the clinical representations of arthritis. Therapeutic glove is one of the therapeutic treatments available for arthritis patients; especially for those in early stage of the disease. There is a variety of commercial therapeutic gloves with different therapeutic functions such as compression and thermal. Selecting the most appropriate glove could improve user's compliance and optimal therapy effectiveness.

Since people respond to therapies differently, some therapies are more effective for a group of people and might not be so for another group. It is important to identify who responds to which therapeutic treatment. This project aims to identify the pressure and thermal (cold and heat) discomfort thresholds of people with hand arthritis. Discomfort threshold is the point along a curve of increasing perception of a stimulus at which discomfort begins to be felt. Sense of discomfort can rapidly turn into pain. It is important for a glove to be comfortable in order to encourage user's compliance and therapy effectiveness. At the end of this project, a framework for development of improved therapeutic gloves for people with hand arthritis will be developed. It is

hoped that this project will help find solutions to common problems associated with existing therapeutic gloves such as comfort of the gloves and adherence of wearing them.

If I agree to participate, what will I be required to do?

The project consists of two stages. The first stage is for people with hand arthritis only. If you are in this group, you will be asked to record the intensity and locations of your arthritic pain during the past 24 hours prior to the visit to RMIT. The pain will be rated on a numerical rating scale of 10 where 0 defined 'no pain' and 10 defined 'maximal pain'. The primary investigator will explained in details how to record the pain intensity. Pain could occur at any time during the 24 hours prior to the visit; during rest, movement or during the night. You will also ask to indicate the locations of your pain on a hand map which will be sent to you by email or post.

In the second stage, you will be invited to the Pain Analysis Laboratory at RMIT University, Bundoora to measure your discomfort thresholds. At the start of the session, you will be asked to answer on Cold-Heat pattern questionnaire. Next, your pressure discomfort thresholds at different locations of the hand will be measured and recorded. A computerised algometer (Algomed, Medoc, Ramat Yishai, Isreal) (Figure 8.3) with a circular probe of surface area 1cm^2 will be applied to the testing sites on the surface of your hand. The algometer will be applied perpendicularly on the sites at a rate of 30kPa/s until the pressure becomes uncomfortable and you press the cut-off switch (stop button) by yourself.

The same procedure will be followed for the thermal discomfort thresholds. A thermode (thermal sensory analyser, TSA-II, Medoc, Ramat Yishai, Israel) (Figure 8.4) with area of $16\times 16\text{mm}^2$ will be used on the surface of the skin of you hand. The

thermode is controlled by a computer and has safety cut-off temperatures set at 0°C and 50°C. The temperature will be decreased or increased gradually at a rate of 3°C/s until you start to feel uncomfortable and press the cut-off switch (stop button) by yourself. For the heat stimuli, the safety cut-off temperatures will be set at 50°C. For participants whose threshold is beyond this range, these temperatures will be recorded as their threshold.

Your discomfort threshold is the point when you start to feel discomfort. You do not need to tolerate the discomfort during the testing. We want you to let us know as soon as you feel discomfort. The whole session in stage two will last for a maximum of one hour.

What are the risks or disadvantages associated with participation?

There will be minimal risk involved in your participation in this project. The feeling of discomfort from the pressure and thermal stimuli are temporary and will disappear once the stimulus is removed. If you find that the pressure or thermal stimulation too uncomfortable, you are free to discontinue participation at any time.

What are the benefits associated with participation?

While we intend that this research may improve the performance of therapeutic glove for many patients, we do not guarantee or promise that you will receive any personal direct benefits from this project.

What will happen to the information I provide?

In order to make arrangement with you for measurement of discomfort thresholds, personal information of your name and contact details will be collected initially. Further information that will be collected from you will be de-identified with a code number and may include: gender, age, stage and duration of arthritis. Only the

code numbers data that have been de-identified will be used for data analysis and presented in academic publications. The information that is obtained in connection with this project and that can be identified with you will remain strictly confidential. If you give us your permission by signing this document, we plan to publish aggregated results in relevant scientific conferences and journals where individual answers will not be identifiable. Results from the project will be available to you on request. Data of this project will be stored in a locked office, in locked filing cabinets and will be retained by RMIT University for a minimum of 5 years. Paper materials will be disposed of through secure waste systems at RMIT University. Electronic data will be erased utilizing the recommended protocols at that time.

What are my rights as a participant?

Your decision whether or not to participate will not prejudice your future relations with RMIT University. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

If you find that you cannot tolerate the thermal stimulus, an ice pack will be given to you to cool your hand. If you find that you cannot tolerate the pressure and thermal stimuli, you are free to discontinue participation at any time without prejudice.

Will I be paid for my involvement in this research project?

You will not be paid for your participation in this research. However, we will reimburse your public transport fees or parking permit for the visit to the Pain Analysis Laboratory at RMIT University, Bundoora.

Whom should I contact if I have any questions?

If you have any questions, please feel free to ask us. If you have any additional questions later, the investigators will be happy to answer them.

What other issues should I be aware of before deciding whether to participate?

Nothing further.

You will be given a copy of this form to keep.

If you have any concerns about your participation in this project, which you do not wish to discuss with the researchers, then you can contact the Ethics Officer, Research Integrity, Governance and Systems, RMIT University, GPO Box 2476V VIC 3001. Tel: (03) 9925 2251 or email human.ethics@rmit.edu.au

Cold-Heat Pattern Questionnaire

Below are conditions regarding the “Cold-Heat” pattern. Please answer either “Yes” or “No” based on health status during the preceding week.

Symptoms	Conditions	Answer
Cold pattern Aversion to cold Preference for heat Abdominal coldness Coldness of the limbs Cold pain Pale face Absence of thirst Long voiding of colourless urine Loose stools Thin clear sputum and nasal mucus	I've had aversion to cold. I've preferred warmth. I've experienced coldness in the abdomen. I've felt coldness in the hand or foot. I've had painful sensations of cold that were relieved by warmth. My face has been pale. I've not been thirsty. I've produced large volumes of colourless urine. I've delivered loose stools. I've produced thin and clear sputum or nasal mucus	
Heat pattern Preference for cold Body heat Heat of the limbs Feverish pain Flushed face and eye Thirst Scanty voiding of dark-coloured urine Dry stool Thick yellow sputum and nasal mucus Hot breath	I've preferred sensations of cold. I've felt excessively warm. My palms or soles have felt hot. I've experienced feverish pain. My face or eyes have been flushed. I've been thirsty or my mouth has felt dry. I've produced minimal volumes of urine that were dark-coloured. My stools have been dry. I've produced thick yellow sputum or nasal mucus. My breath has been hot.	

Adapted from Ryu et al. (2010).