Improving fit through the integration of anthropometric data into a computer aided design and manufacture based design process

FACULTY OF SOCIAL SCIENCE AND HUMANITIES
DEPARTMENT OF DESIGN AND TECHNOLOGY

IMPROVING FIT THROUGH THE INTEGRATION OF ANTHROPOMETRIC DATA INTO A COMPUTER AIDED DESIGN AND MANUFACTURE BASED DESIGN PROCESS

by
GAVIN LESLIE WILLIAMS

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Abbreviations and acronyms

2D – Two dimensional

3D – Three dimensional

ADL – Activities of Daily Living

BSL – Bennett's Safetywear Limited

CAD – Computer Aided Design

CAESAR – Civilian American and European Surface Anthropometry Resource Project

CAM – Computer Aided Manufacture

CAI – Computer Aided Inspection

DERA – Defence Evaluation and Research Agency

DIP – Distal interphalangeal

DLO – Defence Logistics Agency

HDDP – Hand Data Deployment Project

MCP – Metacarpophalangeal

MIMAS – Manchester Information & Associated Services

MoD – Ministry of Defence

NURBS – Non-uniform Rational B-Splines

OPAC – Online Public Access Catalogue

PIP – Proximal Interphalangeal

PPE – Personal Protective Equipment

R – Coefficient of Reliability

RP – Rapid Prototyping

TEM – Technical Error of Measurement

LOUGHBOROUGH UNIVERSITY

ABSTRACT

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Ph.D.

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Gavin Leslie Williams

For all types of clothing and body worn technologies it is important to consider how they integrate and interact with the complex shapes that form the unique profile of the human body. This interaction determines the fit of these products and it is often difficult to generate a fit that can simultaneously accommodate these complex shapes. Achieving the correct fit is determined by a number of different factors that must be combined appropriately to create the fit associated with a particular product. This is particularly applicable to Personal Protective Equipment (PPE) to ensure it provides protection while maintaining comfort, mobility and good interaction with the surrounding environment. Integrating suitable anthropometric data into the design and manufacture of this type of clothing plays a critical role in achieving a good fit. By using various processes of Computer Aided Design (CAD) and Computer Aided Manufacture (CAM), the detail contained within these data can be quickly and accurately transferred into physical tools.

The aim of this study was to demonstrate and validate a method of enhancing the fit of PPE handwear. This has been achieved through an action research strategy using descriptive and practical research methods. The research tools primarily used are case studies, used to demonstrate how manually collected 2D anthropometric data can be used to generate computer models that represent these data in a 3D form. The products of the case studies are tools that have been introduced into the design and manufacture processes of commercial handwear manufacturing environments. The tools have successfully been used to produce gloves using two different manufacturing methods and been assessed to analyse their fit. An improvement in fit for the gloves has been quantified through user trials to determine the level of increased performance afforded to the wearer.

The conclusions drawn from the case studies demonstrate that the integration of anthropometric data and CAD/CAM can greatly influence the fit of handwear and improve the iterative processes of its design. However, the data alone does not achieve this as the added integration of tacit knowledge related to glove design is needed to ensure the correct properties are included to the meet the needs of the target population. The methods developed in the case studies have the potential to be applied to other products where fit and interaction with the human body are important design considerations.

Keywords: Anthropometry; CAD; CAM; RP; handwear design and evaluation; Fit; PPE; Design decision making.

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Chapter One:
Introduction

1.1 Background

For all types of clothing and body worn products it is important to consider how they interact with the complex shapes that form the unique profile of the human body. This interaction constitutes the fit of these products and it is often difficult to generate a fit that can simultaneously accommodate these complex shapes. This is because the process for determining fit relies on a variety of different factors. It must consider the materials and manufacturing processes used, the size and shape of the target user, the environment in which the product is to be used and, most significantly, the performance of the wearer associated with the product and task. The combination of these factors that constitutes the correct fit for one type of clothing or body worn product may not be required or may be inappropriate for other types. For example, the appropriate fit for a child’s bicycle helmet will be different to the fit required for a helmet worn by an infantry soldier. Therefore, achieving the correct fit is determined by what fit is appropriate for that particular product.

Achieving an appropriate fit is particularly applicable for high performance clothing. This type of clothing aims to protect the wearer while simultaneously maintaining good mobility and interaction with the surrounding environment. Such clothing and body worn products are categorised as Personal Protective Equipment (PPE). They provide protection for specific areas of the body and come in various forms including body armour, handwear, footwear, helmets, face masks and eye protection. Each type is designed to protect that area of the body to enable the wearer to perform a task or series of tasks safely. The main difficulty concerning PPE is that it must offer the same level of protection to various populations that need to carry out a diverse range of tasks.

Attempting to accommodate the wide range of different users simultaneously can lead to significant problems when wearing PPE. Its primary function is to ensure that the wearer can operate with materials or in environments that would otherwise be harmful. However, adverse effects experienced by users, such as impaired performance; discomfort; distress; and restricted range of motion, often results in these products not being worn or worn incorrectly (Akbar-Khanzadeh, 1995 and Reuter, 1998). This exposes the wearer to the harmful elements against which they are intended to be protected. There is a requirement, therefore, to ensure that PPE can provide the necessary protection whilst enabling the wearer to complete their tasks satisfactory and efficiently. The fit of PPE plays a central role in fulfilling this requirement, as incorrect fit is the main cause of the adverse effects experienced (Akbar-Khanzadeh, 1995).

The type of PPE where fit is particularly significant is in protective handwear, as it is primarily through our hands that we interact with our environment. Creating a good fit for a glove means ensuring a secure interaction between the hand, the glove and the object being handled. An inaccurate fit is caused by an excess of material around the hand which leads to a failure of this interaction. This allows the glove to move independently from the hand, impeding the wearer by not enabling them to use the appropriate grip pattern for the task they wish to perform.

The types of environments where protection of the hands is needed ranges considerably. Protection against conditions of extreme heat and extreme cold, chemical and biological agents, abrasive materials and electrical discharge, is required to enable necessary tasks to be carried out. This is reflected in the range of protective handwear that is available, as each environment dictates specific requirements to provide the necessary level of protection. For example, surgical latex gloves (figure 1.1) are very thin and made from a single material (Sempermed, 2004). In contrast, the gloves a firefighter may wear (figure 1.2) are assembled from several layers to increase the level of protection and manufactured from a composite of materials (Bennett Safetywear, 2006).

Figure 1.1 – Surgical latex gloves (Sempermed, 2004).

Figure 1.2 – Fire-fighting gloves (Bennett Safetywear, 2006).

The fit for the different types of protective handwear will vary due to the different materials and environments. For all types, however, the appropriate fit will allow the wearer to perform the necessary tasks as efficiently as possible. This is achieved by ensuring the hand is sufficiently protected without excessively impairing the performance of the wearer. A loss in performance can be determined by comparing the ability to complete the tasks bare handed, as this is the benchmark condition that the wearer is accustomed to. In almost all situations where protective handwear is worn, the wearer would complete the necessary tasks most efficiently with their bare hands, but the environment does not allow this due to extreme conditions or hazardous materials. Therefore, the aim for protective handwear must be to achieve a fit that provides adequate protection while enabling the wearer to perform as close as possible to their bare handed capabilities, especially for dexterous tasks such as keyboard typing and component assembly.

This aim, however, is rarely achieved as the protection element of PPE handwear is often more dominant than the characteristics for good fit. This results in a glove that will provide the appropriate protection but does not afford the wearer optimum task performance. Previous research into protective handwear for military applications has revealed how task performance is impaired by incorrect fit, (McDonagh-Philp and Torrens 2000; Torrens and Newman 2000; Weihrer and Tremblay-Lutter, 2000; Torrens *et al,* 2001; and Scanlan *et al,* 2004). These studies have illustrated that not achieving the correct fit means protective handwear can considerably affect the natural capabilities of the wearer to complete dexterous tasks, increasing the amount of time needed and reducing hand strength. They also highlight the frustration felt by users concerning the gloves they must wear to protect their hands. Numerous other studies have been conducted to investigate the effect of protective handwear on different aspects of task performance, (e.g. Batra, 1994; Bishu and Klute, 1995, Buhman, 2000; and Rock, 2001). Various types of gloves are assessed in these studies, determining how properties of material type, material thickness, fit, manufacturing processes and the environment affect the ability of the wearer. The number of different studies conducted to investigate this effect indicates that it is a problem for all forms of protective handwear and for all users. These users are able to clearly define their needs. However, the current design and manufacturing processes used for protective handwear do not integrate sufficient characteristics to meet these requirements. This issue is a continuing problem, and to some extent it has been accepted that wearing protective handwear will inevitably mean a significant loss in task performance. However, methods of enhancing fit during the design of this type of PPE will contribute towards improving the capabilities of the wearer, reducing the problems and frustrations that currently exist.

1.2 The need for a new approach to handwear design

The basis for investigating methods of improving fit for protective handwear originates from past experiences of conducting handwear assessments and collaborations with handwear manufacturers. The assessments highlighted the difficulties that occur when performing basic tasks while wearing protective gloves, (Torrens and Newman, 2000; McDonagh-Philp and Torrens, 2000; Torrens *et al,* 2001). While the main objective of these assessments was evaluating gloves for military personnel, the problems and issues arising from them are related to all forms of PPE handwear. The fit of the gloves caused a significant reduction in task performance, greatly increasing the time needed to complete tests that were comparably simple when completed with bare hands. Therefore, one of the main outcomes of these studies was to recommend a higher degree of fit for protective handwear to afford the wearer an improved level of performance. This was reinforced by the comments and feedback of the participants in these assessments, who had a desire and a need for the equipment issued to them to be as effective as possible.

The involvement with these assessments enabled the opportunity to observe the methods and technologies employed by manufacturers of protective handwear. This gave an insight into how the fit of a glove is determined and the many different factors that influence its accuracy. Many of the methods used were predominately reliant on traditional skills based on tacit knowledge gained through trial and error over many years of experience. This means that the core methods of handwear manufacture have not changed significantly since those developed in the 19^{th} Century which saw the establishment of glove sizes and more precise cutting techniques (British Glove Association, n.d.[a]). This is especially true for ‘cut and sew’ manufactured gloves that use 2D patterns to create the constituent parts of the glove which are manually machine stitched together. This remains the most popular process for manufacturing gloves with a composite of materials, necessary for some types of protective handwear. While these methods form an established industry, capable of producing gloves to a high quality standard on a mass manufacturing scale, they fail to take advantage of current technological advances. The lack of major change in this design process provides scope to introduce new methods which can enhance the skills and knowledge in this industry. Methods that involve time compression technologies such as computer aided design (CAD), computer aided manufacture (CAM), rapid prototyping (RP) and rapid manufacture (RM) would enable greater accuracy to be achieved and give more control over quality assurance. Some glove manufacturing methods such as dip moulding and automated machine knitted gloves have introduced computerised and automated processes. However, many of the critical design decisions remain empirically driven, using existing templates as a basis for new designs. Integrating new methods into existing design processes would allow more detail to be incorporated into the size and shape of the glove to improve fit. Integrations into the current manufacturing methods would enhance the accuracy of these traditional skills, ensuring that this detail is sufficiently represented in the glove and the benefits passed on to the wearer.

Incorporating more detail into the design of protective handwear is a significant step in improving fit. A major component of this detail is the size and shape of the target user, as this is a critical part in ensuring the correct fit is attained. Using dimensions and proportions of the hand will create a glove that can better accommodate the different areas and their range of motion. This type of data is known as anthropometric data and is widespread in the design of products that interact with the human body. It is a key component for the design of seating, furniture, power tools, and other utilitarian objects. The collection of anthropometric data is a common procedure to understand the size and shape of a particular population. Surveys designed to collect anthropometric data often have a number of different goals, one of which is to aid the design of clothing by providing an enhanced fit. The use of anthropometric data in current design methods of protective handwear is very limited, which is a factor in many of the problems that cause poor fit and impaired performance. In addition there is no prescribed system of inspection or quality control to determine if the anthropometric data that is included in the design process is accurately integrated into the final glove.

Methods and tools of CAD assist designers to generate designs that incorporate the detail and characteristics necessary that meet the intended specifications. By using CAM, RP and RM these designs can be realised with speed and precision to adequately represent the detail and characteristics within a physical prototype or product. Other areas of the apparel industry have introduced these methods to improve and develop their design and manufacture processes, (Gray, 1992; Istook, 2001; Volino and Magnenat-Thalmann, 2005). It has increased the speed and accuracy of creating new products, enabling more complex designs to be created using different types of materials. Protective handwear, however, has yet to adopt such methods to the same degree into its design and manufacturing environment. It has, therefore, been unable to discover the potential benefits that may result from the inclusion of these novel technologies.

1.3 Research aim and objectives

The experiences gained from assessing protective handwear and the observations made of its design and manufacture, have highlighted the importance of fit and integrating properties of good fit into the design process. Enhancing fit will afford an increase in task performance for the wearer, reducing many of the problems that currently exist. The aim of this research study was to demonstrate and validate a method of enhancing appropriate fit for protective handwear.

Based on this aim, it was hypothesised that using anthropometry resources with methods of CAD/CAM, a tool or tools could be produced that would aid the design and manufacture of protective handwear.

The tool(s) would contain appropriate anthropometric data and fit characteristics to provide a greater level of detail for the designer than is currently available. This detail would enable a more accurate fit to be incorporated into the gloves produced, thereby improving the fit for the wearer. The tool(s) would also provide a feedback system to evaluate the fit of a glove, verifying that the anthropometric data and fit characteristics were correctly transferred.

The potential improvements made by the tool(s) would be measured in terms of reducing cost and enhancing performance, both for the manufacturing processes and the gloves. Improvements in the manufacturing processes would be evident if a decrease in the time taken and an increase in the accuracy for manufacturing a new glove could be demonstrated when using the tool(s). Improvements in the fit of the gloves produced would be measured by comparing them against equivalent gloves that are currently available using a series of tasks to assess the performance of the wearer.

Along with the research aim the following research objectives were set;

- To identify and explore the key issues surrounding the design and manufacturing of apparel using anthropometric data and CAD/CAM; identifying gaps in current knowledge and methodology relating specifically to handwear.

- To develop and validate suitable design methods to improve the fit of handwear.

- To implement the proposed method(s) and consider its effectiveness.

- To determine how the proposed method can be further developed and refined so that it may be applied to other products in the field of body worn PPE.

1.4 Thesis structure

The main part of this study is presented in the form of two case studies which used action research to achieve the research objectives and fulfil the research questions. Case studies were used to investigate and demonstrate a proposed design method of integrating anthropometric data and CAD/CAM to design and manufacture handwear. The first case study focuses on the design of 3D computer models generated from 2D anthropometric data of a large scale anthropometry study. Collaboration with a handwear manufacturer enabled these models to be developed into a gauge that could assist in the design of 2D patterns of manually machined stitched gloves.

The second case study is a continuation from the first, using the methods and techniques developed in the generation of the computer models to design a mould tool for the manufacture of handwear using a dip moulding process. This manufacturing procedure uses a tool shaped to the internal dimensions of the required part, in this case a glove. To be able to use the computer models from the first case study as dip moulding tools, they required development to incorporate the necessary properties that are contained within current tools. The inclusion of this detail results in a model that is a combination of current design knowledge in glove manufacture and hand anthropometric data, enabling gloves to be produced with enhanced fit for the wearer.

These two examples of using anthropometric data and CAD/CAM show how the two disciplines can be successfully used together in the design and manufacture of handwear. They demonstrate processes for integrating anthropometric data into a CAD model and CAM/RP methods to accurately reproduce those models into a physical 3D form.

Figure 1.3 illustrates the structure of the thesis, describing what is discussed within each of the eight chapters. The details of the case study material are given in two chapters within the thesis. This first chapter outlines the research aim and objectives of the study, providing a background to the research and explaining the need for the PPE to have enhanced fit for the wearer. A review of the current literature associated with the research area was carried out and is presented in the second chapter. The review examined the areas of anthropometry, glove design and evaluation, dexterity and coordination evaluation, the use of CAD/CAM in clothing design and quality control methods. Using the review, gaps in the current knowledge were identified enabling a clear direction for the research and highlighted where contribution to new knowledge may be achieved.

Chapter 3 outlines the approach used to design an appropriate research methodology to fulfil the research objectives. There were several factors influencing the design of the methodology, including the form of research used, the research purpose, strategy, method and the research tools selected. The chapter gives a description of these factors and explains how they formed the chosen methodology, providing justification for the selections made.

Chapter 4 discusses the anthropometric data that have been used to generate the 3D computer models in the case studies. The data plays an important role within both case studies. The chapter describes how the anthropometric data were taken, the processing procedures used, the generation of size ranges and the decisions made when introducing elements of glove design.

Chapter 5 and 6 discuss the two case studies. Chapter 5 illustrates the first case study, the design of size gauges for the evaluation of handwear during its manufacture; and Chapter 6 gives details of the second case study, the design of a mould tool for the manufacture of handwear. Chapter 7 examines the accuracy of the two outcomes that have emerged from these case studies. It discusses the methods used to validate the accuracy of both the size gauge and the glove dip moulding tool, determining if the methods of CAM used were appropriate and sufficiently accurate.

The final chapter presents the conclusions and future implications of the research. The conclusions reflect on the how the research has fulfilled the original objectives. Following on from this, further implications of the research were discussed to address how the outcomes of the case studies may be used in the future and how they may be developed for other similar applications.

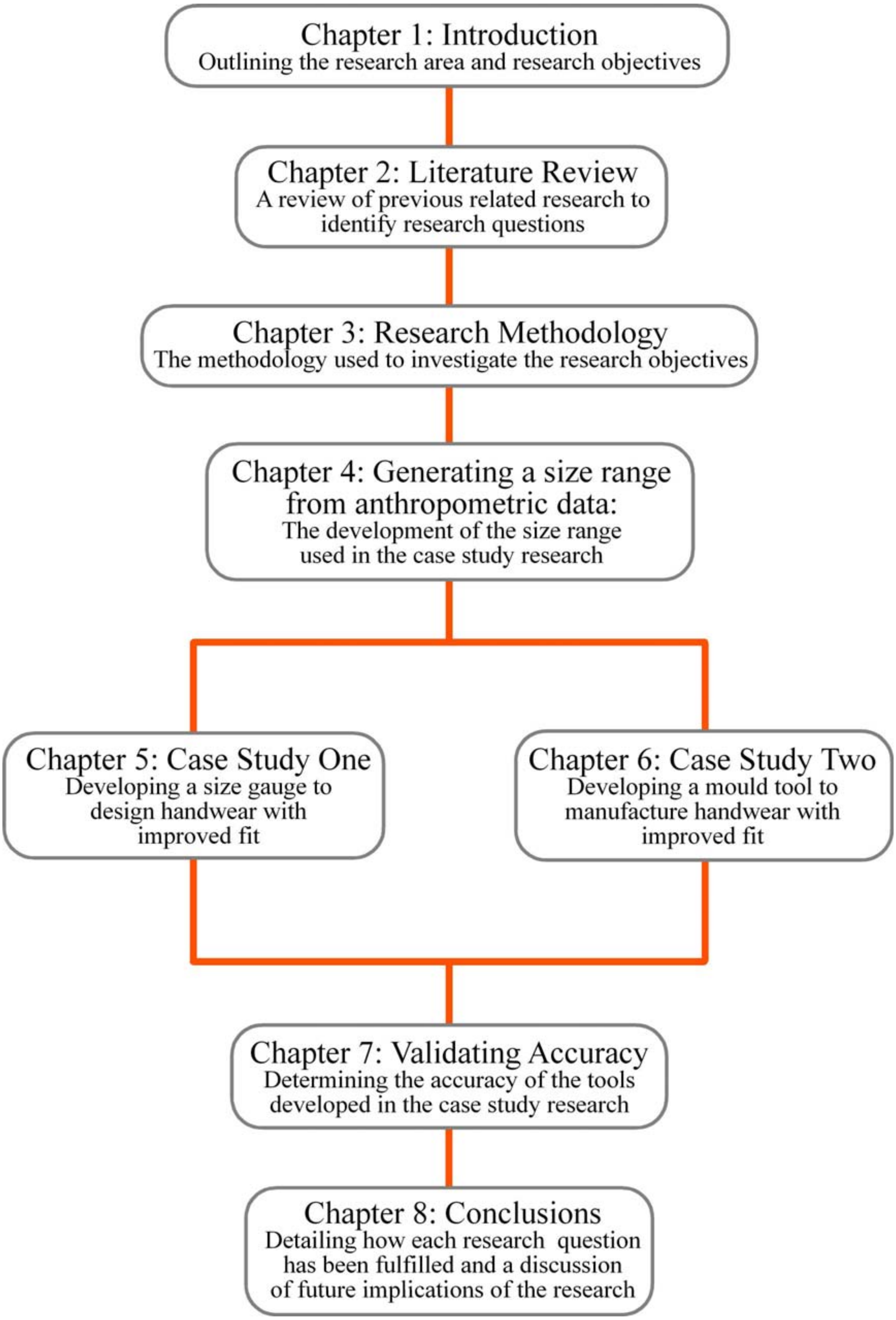


Figure 1.3 – Thesis structure

Chapter Two:
Literature Review

2.1 Aim

One of the research objectives, outlined in Chapter 1.3, was to identify and explore the key issues surrounding the design and manufacturing of clothing using anthropometric data. To achieve this, a review of present and past literature on these issues was undertaken. A literature review forms an important section of a research study, the aim is to provide the background and justification for the research undertaken, (Bruce, 1994). Bourner (1996) lists several reasons why a review must be completed before embarking on a research project. The main reasons are listed below.

- To identify gaps in the literature.
- To avoid carrying out research that has already been conducted.
- To identify other groups working in the same/similar research fields.
- To identify influential works in the research field.
- To identify opposing views.
- To put the research into perspective.
- To identify information and ideas that may be relevant to the research study.
- To identify methods that could be relevant to the research study.

From the list given by Bourner (1996), perhaps the most important reason to conduct a literature review is to highlight and identify the gaps in knowledge that currently exist with in the research area. Finding these gaps serves two main purposes; it firstly supports the need for the PhD as the present research and literature does not contain the research topics that aim to be investigated. Secondly, it facilitates the investigation to fill these gaps, ensuring that the work is original and contributing to new knowledge within the research field.

2.2 Literature review strategy

To source the relevant literature for the review the following strategy was employed. This involved four main stages,

- Defining the topics
- Identifying key words and phrases
- Identifying resources and literature searching
- Generating a literature database

2.2.1 Defining the topics

To ensure the literature review covered all the necessary aspects of the research study, the subject area was divided into a series of topics that could be reviewed individually. The following outlines these different topics, with a description and reasons why it was reviewed.

Collecting and applying anthropometric data

This topic reviewed how anthropometric data is collected and used within a design process. This was reviewed to understand the different applications of anthropometry and how it is currently integrated into various disciplines.

Clothing design and manufacture

This topic provides a review of the methods and issues associated with the design and manufacture of clothing, specifically reviewing the processes and skills used when creating new clothing patterns.

Anthropometry in the design and evaluation of clothing

This topic expands on the first and specifically examines the use of anthropometry for designing and evaluating clothing and body-worn products. This area was reviewed to gain an understanding of the technologies and methods that have been developed and issues that are arise from integrating this type of data into a design process.

Computer aided design and manufacture in the clothing industry

CAD/CAM is used in a variety of applications within design and manufacture. This topic explores the different methods and applications of CAD/CAM in the clothing and textiles industry, determining the areas where its use has had the greatest impact and where improvements can still be made.

The use of gauges in production engineering

The research aim was to improve the fit of protective handwear and uses case studies to explore methods to accurately design and manufacture these types of gloves. This topic reviews the ways in which gauges are used in production engineering to ensure products are made to the correct size and within acceptable tolerances.

2.2.2 Key words and phrases

From the topics listed above a series of key words and phrases were generated to search for useful and relevant information. A list of key words and phrases used is given below.

Anthropometric data	CAD in clothing design	Glove performance
Anthropometry in design	CAD in glove design	Handwear evaluation
Using anthropometry	CAM in clothing design	Glove evaluation
Computer aided design	CAM in glove design	Handwear fit
Computer aided manufacture	CAD in pattern design	Glove fit
Rapid Prototyping	CAM in pattern design	Clothing fit
3D body scanning	Customised/Customized gloves	PPE fit
Applying anthropometry	Customised/Customized handwear	PPE performance
Anthropometry in clothing design	Handwear design	Human fit
Anthropometry in handwear design	Glove design	Customised/Customized clothing

Anthropometry in CAD	Glove manufacture	Tolerance/Tolerances/ Tolerancing
Anthropometry in CAM	Clothing manufacture	Virtual try-on
Anthropometry in rapid prototyping	Handwear performance	Made to measure clothing

The words and phrases that are chosen to define a research topic can greatly influence how much information is retrieved (Neville *et al,* 2002). This list, therefore, was a detailed summary of the topics, to focus the search on the key concepts and locate the necessary information.

When combining search terms a simplified version of the Boolean search method was used, as not all search engines accept Boolean commands and the meanings can differ between different search engines, especially within Internet search engines. This simplified method used +, - , and " " instead of the AND, NOT, ANDNOT, OR commands used in Boolean searches. Table 2.1 describes the meanings of the symbols used. These symbols were used to narrow and expand the results obtained from the key words and phrases.

Symbol	Command
+	Must include term
-	Must exclude term
" "	Must include phrase

Table 2.1 – Definition of symbols used in conjunction with key words and phrases

2.2.3 Identifying sources and literature searching

The information relevant to the literature review was available in a number of different formats. The sources which were used in this literature review are listed below.

- Books
- Reference Materials
- Journals
- Conference Papers
- Internet
- British Standards
- Electronic Databases
- Government Publications
- Dissertations
- Theses
- Indexes/Abstracts Printed

Using these resources, the key words and phrases were used to search for the necessary literature. The primary source for finding information was through the Pilkington library at Loughborough University. Each keyword and phrase was entered into the library search engine OPAC (Online Public Access Catalogue). The OPAC search engines at local East Midlands Universities were also searched, with inter-library loans used for references unavailable in the Pilkington library. Outside the University libraries, Internet article search engines (e.g. Article 1st and Web of Science) were used, again, entering the same key words and phrases to find relevant references. Staff and academic librarians at the Pilkington library were consulted to ensure these resources were used efficiently and effectively.

A substantial quantity of references that were collected have been used for MoD sponsored research projects within the Department of Design and Technology. Many of these references are relevant as this research was concerned with human body extremities protection and evaluation, as well as anthropometry and applied ergonomics. These references are collated within an Excel spreadsheet, and this additional resource was searched using the key words and phrases to find the significant references.

Internet searches have been conducted by entering the key words and phrases into search engines and using the simplified search method described in 2.2.2. This is the most up-to-date and current resource and was used to find researchers and research groups that are investigating the same or similar research topics that may not have formally published any recent investigations. These searches identified key authors and researchers and further Internet searches were performed with these names and research groups using search engines such as Google Scholar (Google Scholar, 2007) and the Web Citation Index (ISI Web of Knowledge, 2007) to find published material and where they have been cited.

The Internet enabled a comprehensive search of journals and conference proceedings as many of these publications are available online. The key words and phrases were used within associated search engines of the publication websites, such as Science Direct, Sage and the Taylor & Francis Group, to find and download journal and conference papers. To keep updated with recently published journals that are published online, the table of contents of relevant journals was delivered via e-mail subscriptions. This gave quick and easy access to these journals, ensuring any new publications could be integrated into the literature review. A list of the journals that were subscribed to is given below.

- Applied Ergonomics
- CAD User
- Computer Aided Design
- Computer Aided Geometric Design
- Computers & Graphics
- Computers & Industrial Engineering
- Design Studies
- Ergonomics
- International Journal of Clothing Science and Technology
- International Journal of Industrial Ergonomics
- Journal of Biomechanics
- Journal of Engineering Manufacture
- Journal of Quality Management
- Measurement
- Rapid Prototyping Journal

In addition to subscribing to e-mail alerts from these specific journals, the key words and phrases were used to remain informed of other papers that were pertinent to the identified topics. The MIMAS (Manchester Information & Associated Services) Zetoc resource provides access to the British Library's Electronic Table of Contents database which covers journals and conference proceedings from 1993 to date. By using the MIMAS Zetoc Alert Service, e-mail alerts were received when a journal or conference paper was published which contained a key word or phrase in the title.

After the initial searches using the key words and phrases were complete, the references collected were reviewed to gather relevant information within them and categorise them into the relevant topic. These references were then used to gather more key words and phrases that were used in the same search engines as previous searches. By reviewing the reference list and bibliographies within these references it was possible to collect more relevant information and identify researchers and research groups working in the same or similar field. This cycle of collecting references and using them to gather more reference material and key words, phrases and areas of interest continued to ensure the review topic had been sufficiently explored.

2.2.4 Literature database

After collecting the references it was necessary to organise them into their relevant topics. This was done by compiling a database using EndNote®. This piece of software enables the creation of an unlimited number of databases by entering bibliographic data into a record which displays all the necessary fields for a given type of reference. The references can be exported to Microsoft Word in a number of different bibliographical or user defined styles, which means constructing reference lists and bibliographies is very simple. Each reference has its topic area defined within EndNote® that corresponded to a filing system where a hard copy was kept, enabling easy access to all references when necessary.

2.3 Collecting and applying anthropometric data

Anthropometry, as described by Pheasant (2005), is the term given to the branch of the human sciences that deals with body measurements, particularly with measurements of body size, shape, strength, mobility and flexibility, and working capacity. When designing products that interact with the human body, the size and shape of that body must be taken into account. This approach is a method used within ergonomic design which focuses on the physical and mental characteristics of the user on which to base the design of an object, system or environment. This user-centred design method aims to achieve the best possible match between the product being designed and the users, in the context of the task being performed (Pheasant, 2005). Anthropometric data are the physical characteristics of the user and, therefore, are a major aspect in matching the physical form and dimensions of the products or workplace to those of its user.

The variety of different products and environments that interact with the human body means the use of anthropometry as a resource in the design process is widespread. One of the first industrial designers to see the importance and benefits of anthropometric data was Henry Dreyfuss. Since opening his practicing office in New York in 1929, Dreyfuss focussed on design problems relating to the human figure, believing that machines which were adapted to people would be the most efficient, (Dreyfuss, 1967). Dreyfuss is perhaps best known for the anthropological charts he produced to represent the consumers for whom he and his associates designed. The charts were compiled from detailed measurements and capabilities of the human body to fill the gaps between human behaviour and machine design. Figure 2.1 shows the level of detail that was contained in the charts for various percentiles of an adult male from data collected by Dreyfuss and his colleagues. The two initial charts were of a man and a woman, named by Dreyfuss as Joe and Josephine, and used as a reference to determine the size, shape or position of a product or activity. The charts served as a reminder to Dreyfuss and his colleagues that everything his office designed 'is used by people, and that people come in many sizes and have varying physical attributes' (Dreyfuss, 1967, p24).

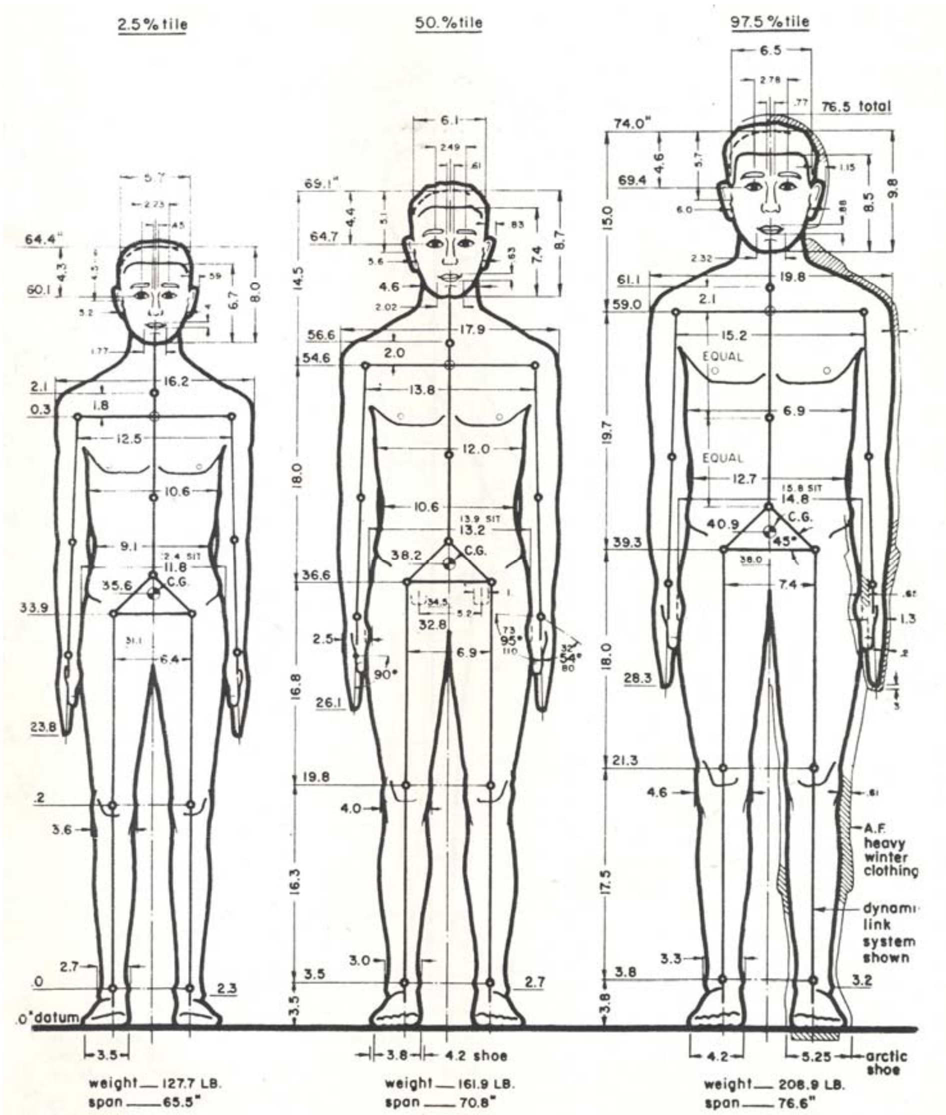


Figure 2.1 – Anthropological charts developed by Henry Dreyfuss, (Dreyfuss, 1978).

This approach towards design that Dreyfuss adopted now sees anthropometric data involved in determining how the human form interacts with a product or environment. The apparel industry is heavily reliant on the use of anthropometric data to control the fit of protective and fashion clothing. Work and living space design uses anthropometry to specify issues of clearance, reach, and posture in determining how people interact with the surroundings in which they live and work. Seating design uses anthropometry to ensure a sitting posture is comfortable over a period of time and appropriate for the relevant task or activity. Handles can be defined as any point of an object that interacts with the hand, (Pheasant, 2005) therefore; anthropometric data of the hand is an integral part of handle design to form the correct shape necessary for the task it is required to do. Finally, anthropometric data plays a part in the health and safety characteristics of a product or environment, ensuring the design is fully detailed to prevent injury or fatality.

Due to this significant role that anthropometry plays, it is necessary for the data to be accurate, as any errors or inaccuracies within the measurements will be reflected in the final product or environment designed using it. Collecting anthropometric data has traditionally meant an operator using callipers, tape measures and scales to record a person's physical geometry, such as weight, stature, sitting height, arm circumference or wrist breadth. The operator must be a trained individual having knowledge of anatomy, especially locations, names and shapes of bones and muscles, as these are the landmarks from which measurements are taken, (Roebuck, 1995). These traditional methods are where inaccuracies can occur.

The human body has very few definitive edges and consists of rounded contours. This makes identifying the landmarks needed for each measurement and controlling the posture of the participant difficult. Consequently, achieving accurate data better than 5mm in most measurements is considered virtually impossible (Pheasant, 2005). Human error is a factor with even the most experienced of operators and although measures to minimize it can be introduced, it cannot be avoided (Kouchi *et al*, 1999). There is always some variation between repetitions of measurements of any object, (BS ISO 5725- Parts 2 and 6:1994). Pheasant (2005) lists four components of measurement error within anthropometric data; error from the measuring equipment, error from locating the landmark, error from standardising the posture of the subject and error from the subject's understanding of or response to instructions for adopting the required posture.

Standard anthropometry methods (Lohman and Roche *et al,* 1988; BS EN ISO 7250:1998) have been developed in an attempt to overcome or minimize the problems of inaccurate measuring tools, differences in technique used by operators, and variations in body stance terminology. Another issue with the collection of anthropometric data is the variability through natural biological fluctuations. This is far less easy for the operator to control, for example, a body is never still and the body mass can shift when measurements are being taken. The measurement procedure is intrusive, often causing subjects to stand unnaturally or change stance as fatigue affects posture. Wampen (1864) observed that touching the shoulder with measurement instruments could cause alternative contractions and relaxations in adjoining muscles. Time of day is also an influencing factor (Ulijaszek, 1994); Montagu (1960) suggests that the subject should be measured in the morning because of a decrease in stature towards the evening, which can typically vary this measurement by approximately 15 mm (Pheasant, 2005). While Rutan (1977) noted that waist circumference may vary by 51mm over a 24 hour period.

Being aware of these inaccuracies and errors allows for them to be accounted for after an anthropometric survey has been conducted. Kouchi *et al* (1999) describes two aspects to measurement error: the closeness of the measured value to the true value (accuracy) and the closeness of two repeated measurements (precision). To determine whether a series of anthropometric measurements can be considered accurate and precise there are two estimates that can give information on the reliability and error of the data, (Ulijaszek, 1994). These two estimates, the technical error of measurement (TEM) and the coefficient of reliability (R), are in the form of equations which use details from the anthropometric study. The values from these equations give information on the magnitude of measurement error and precision of the observers used. The TEM is obtained by carrying out a series of repeated measurements taken independently of one another on the same subject, either by the same observer (intra-observer) or by two or more observers (inter-observer) (Pederson and Gore, 1996; Ulijaszek, 1994) with the units given in the same units as the variable measured. The differences found are then entered into an appropriate equation. According to Frisancho (1990) (see Ulijaszek, 1994, p.33), if the TEM for intra-observer and inter-observer is close to a reference value in a series of repeated measurements then the measurements can be considered accurate.

Although the TEM can be used to determine the accuracy of the measurements within a specific anthropometric study, the values obtained using it may not apply outside the age range of the population used to obtain them, (Ulijaszek, 1994). The coefficient of reliability illustrates what proportion of the between-subject variance in a measured population is free from measurement error (Ulijaszek, 1994). For example a measurement with an R value of 0.9, indicates that 90% of the variance is due to factors other than measurement error. Meuller and Martorell (1988) suggest measures of R can be used to compare the relative reliability of different anthropometric measurements and to estimate sample size requirements. Furthermore it can also be used to determine the number of replicated measurements needed to obtain a reliable measure (Himes, 1989). Many studies to assess the errors attributed to intra-observer and inter-observer error (e.g. Gavan, 1950; Jamison and Zegura, 1974; Bennett and Osborne, 1986; Gordon and Bradtmiller, 1992) have commented that while it is not possible to completely eliminate these errors, they can be minimised by controlling the variables which cause them.

It is common practice to carry out accuracy and precision studies of anthropometric surveys in order to investigate the error magnitude and precision of the operators (Marks *et al,* 1989; Forest *et al*, 1999; Smith and Norris, 2001; Robinette and Daanen, 2006). This enables the data published from such surveys to be used within comparative studies as the measurements are analysed using consistent, universally recognised methods of analysis. However, as Bennett and Osborne (1986) conclude from their study, raw anthropometric data used in this way should be done with considerable caution and investigators using it should be aware of the measurements that are least reliable.

The errors and inaccuracies that result from using traditional methods of collecting anthropometric data suggest that a more accurate alternative would be to remove the operator as much as possible. These methods are primarily based around the use of digital photographs and three-dimensional (3D) body scanning. Gazzuolo and DeLong *et al* (1992) have developed a means of collecting anthropometric data by taking a series of photographs to generate two-dimensional garment patterns. The authors anticipated that by removing the need for a traditional operator, the measurement procedure would become less intrusive and more efficient in terms of time, effort and cost. However, while this technique eliminates some of the problems that arise with manual techniques, it brings in new problems and issues. For instance the accuracy of the data obtained is dependant on the resolution of the photographs taken and the accuracy of the measurements continues to rely on the skill of the observer to locate the appropriate landmarks on the photographs. Gazzuolo and DeLong *et al* (1992) conclude that using photographic methods cannot be used alone to collect anthropometry as not all the necessary measurements can be taken. More recent studies however (Hung *et al,* 2004; Meunier and Yin, 2000[b]) have shown that using 2D images can produce comparable results to traditional measurement methods, mainly due to the development of computer software to automatically extract the required dimensions from the photographs. These systems offer a low cost, quick method of measuring human size and are often used in the apparel industry for determining appropriate garment fit. However, although these technologies have gone some way to eliminate some of the accuracy issues with manually collected anthropometry, others have arisen in terms of identifying landmarks, shape quantifications and calibration issues.

A development of this approach is dual digital-photographic anthropometry (DDPA) which has been developed primarily for the assessment of human total body volume, body composition and circumference measurements (Mikat, 2002). While previous studies (Mikat, 2000 and Mikat *et al*, 2000) have shown this technique to be reliable and valid in estimating body shape and size, it is unable to provide an accurate method for extracting linear anthropometric data and therefore, at present is not an improved system over current manual collection techniques.

The most recent advances in collecting anthropometric data by non-intrusive means are in 3D body scanning. This commonly involves the surfaces of the body being scanned and generating a computer surface model. The necessary landmarks can be identified and anthropometric measurements extracted automatically, see figure 2.2. This technique is capable of extracting an infinite number of data points from the surface model and can therefore collect vast amounts of measurements from a single scan, (Simmons, 2003).

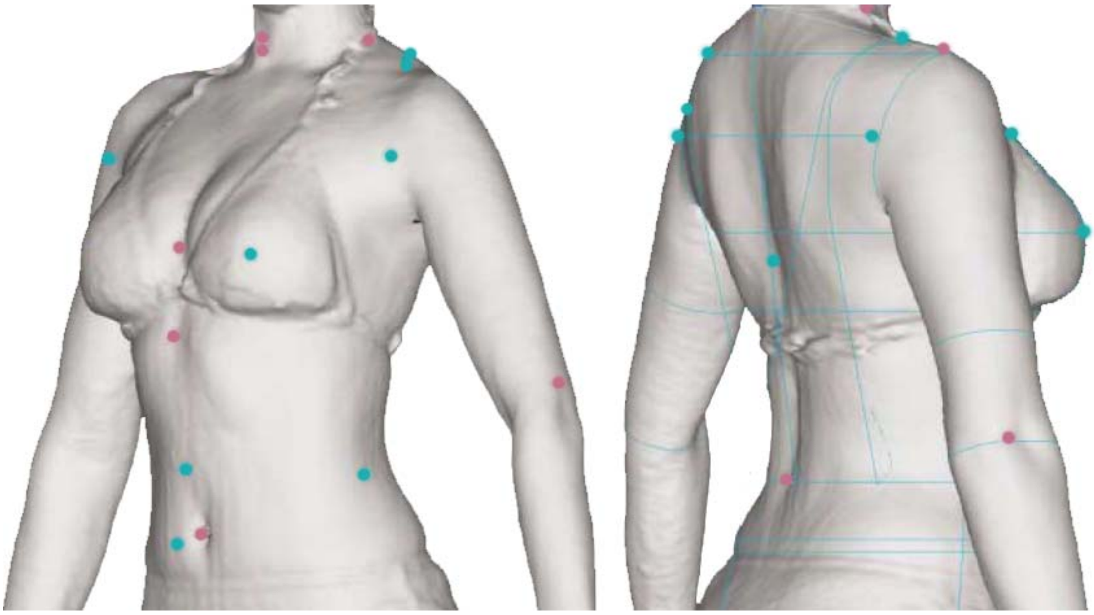


Figure 2.2 – Landmarks identified on a body scan for automatic measurement extraction, (Hamamatsu, 2003).

In terms of technology, commercial body scanners fall into three main categories; light stripe, laser and linear array. Treleaven, (2003) provides a description of the three different types and the commercial companies that are using the technology. Light stripe scanners use light patterns projected on the body. The projected light stripes are created via projectors, the subject's body distorts the projected pattern and these distortions are captured by cameras. The way the stripes curve over the subject measures the three-dimensional shape. Systems that use this technology are The USA Textile/Clothing Technology Corporation $[TC]^2$ (Textile clothing and technology corporation, 2003), Telmat (Telmat Industries, 2000), 3Q (3Q, 2003)), Wicks & Wilson (Wicks & Wilson, 2003) and The Loughborough Anthropometric Shadow Scanner (LASS), (West, 1993).

Laser scanners use harmless, invisible laser beams to measure the body. The laser is used as a light source and charged-couple device (CCD) technology, scans the field of view detecting the displacement of the light by a body or surface. Commercial scanners using this technology include Hamamatsu Photonics Bodylines (Hamamatsu, 2003), Cyberware (Cyberware Inc., 1999) and Tecmath (Techmath, 2001). Linear array scanners are an emerging technology, largely still in the development stage. They use millimetre wave camera technology that is able to scan through clothing.

Pacific Northwest National Laboratory (Pacific Northwest National Laboratory, 2003), and QinetiQ (BBC News, 2001) are developing these types of scanners.

The use of 3D body scanning systems has been actively adopted by the apparel industry, (Istook and Hwang, 2000; Simmons, 2003 and D'Apuzzo, 2007). The technology is being utilised and researched in the development of;

- Automated custom fit (Xu *et al,* 2002; Wang *et al*, 2005)
- Scan measurement extraction and use (Pargas *et al,* 1997; Certain and Stuetzle, 1999; Zhong and Xu, 2006)
- Fit prediction and analysis (Ashdown *et al*, 2004 and Loker *et al,* 2005)
- Virtual try-on simulations (Protopsaltou *et al,* 2002; Cordier *et al,* 2005; and Yan and Rui., 2006)
- Custom pattern development (Fuhrmann, *et al,* 2003; Voellinger-Griffey and Ashdown, 2006; Istook, 2006).

Each of these applications increases the involvement of consumers with clothing design both for purchasing via the Internet and in a traditional retail store (Loker *et al*, 2004). Large-scale anthropometric surveys now use 3D body scanners to increase the efficiency of anthropometry collection in terms of time, effort and cost with an aim to provide more accurate and standardised size charts for clothing manufacturers. The UK National Sizing Survey, (Size UK, 2003) was a survey of 11,000 subjects using a three-dimensional whole body scanner to extract 130 body measurements. The scanner used was from the USA Textile/Clothing Technology Corporation, who also developed the software that was able to extract the large number of measurements. The aim of the survey was to capture the size and shape of the UK population. By offering this information to clothing retailers it enabled them to update and amend their size charts and garment specifications. This would ensure their size charts accommodate the size and shape of their target consumers, (Size UK, 2003). A similar survey in the USA, Size USA, using the same scanner and scanner software, has also been completed and surveyed over 10,000 subjects, (Size USA, 2003). The Civilian American and European Surface Anthropometry Resource (CAESAR) project is an anthropometric survey of the civilian adult population of NATO (Robinette *et al*, 2002), collecting data on 2,400 U.S. & Canadian and 2,000 European civilians. This survey used was the first to use 3D body scanning to measure all subjects and also used the whole body scanner from Cyberware.

3D body scanning has been integrated into the development of performance clothing where fit is an important part of its function. The U.S. military routinely use 3D body scanning to issue uniforms and use anthropometric data to design and prototype better fitting clothing and equipment. The U.S. Army Soldier and Biological Chemical Command, Natick, Massachusetts, have a program of three-dimensional anthropometric data acquisition and analysis, (U.S. Army Soldier and Biological Chemical Command, 2001). This entails the scanning of a soldier's body surface with a laser-based digitizing system (Cyberware Inc., 1999), using the data collected to derive models of the human form. The 3D models can then be used with commercial CAD software to design and quickly prototype new clothing concepts. In addition, The U.S. Army is developing computer-aided fit testing (CAFT) software that helps evaluate how well clothing and equipment fits the human body before prototyping and manufacture begins. It is doubtful, however, that this process can be applied to the extremities. Whole body scanning only gathers data from 95% of the body, with areas such as the feet and hands difficult to scan and capture the necessary detail for anthropometric measurement. Figure 2.3 shows a processed scan of a female figure using a Cyberware whole body 3D scanner. This illustrates the level of detail that 3D body scanning can achieve; however, the detail captured of the hands and feet is very limited. This consequently means that designing, prototyping and manufacturing clothing and body-worn equipment for the extremities would not be currently possible using these methods.

Figure 2.3 – A sample scan of a female figure using Cyberware whole body 3D scanner. (Sample model available from www.cyberware.com)

The scanning equipment that captures the shape of the body is the hardware component of the data collection process. It is the software associated with the scanners that generates the surface model of the human body and extrapolates the anthropometric measurements. Therefore processing the captured data remains the fundamental stage of gathering anthropometry and great care must be taken to ensure that this is carried out as accurately and precisely as possible. A problem also exists with the consistency between the various scanners currently available, (Simmons, 2003). The variations in methods used to capture the specific body measurements means no standardised criteria can be communicated between the different scanning technologies, limiting its full potential.

The accuracy of 3D body scanning compared to manual measuring techniques has been subject to considerable debate (Daanen and Brunsman, 1998); nevertheless, the advantages it has in terms of speed and efficiency means it will become increasingly popular and introduced into a greater variety of applications. The technology, however, has limitations which affect all types of scanners and restricts the amount of anthropometric measurements that can be collected. These limitations are primarily caused by the inability to capture the entire surface of the body, which means some areas cannot be used to collect data. The optimum position for scanning is a modified anthropometric position, with the feet positioned 30 cm apart and arms abducted from the body (Ashdown *et al*, 2004). This position maximises the amount of detail that can be captured, however, some areas of the body remain shaded and, therefore, obscured; e.g. the armpits, the crotch area and in between the fingers (Daanen and Brunsman, 1998). Other areas are difficult to fully capture due to direction in which the light/laser is projected onto the body. Almost all scanners project the light/laser horizontally onto the surface; therefore areas that are parallel to this cannot be accurately captured, i.e. under the chin, the top of the shoulders and the top of the head, (Daanen and van de Water, 1998; Ashdown *et al*, 2004). The Cyberware and Hamamatsu laser scanners overcome this problem by using cameras or mirrors mounted above the projection system to capture these areas (Cyberware Inc., 1999 and Hamamatsu, 2003), however for other scanners this limitation persists.

In addition to the difficulties of capturing the whole body, other issues can affect the quality of the detail captured during the body scanning process. The digitisation of large surfaces necessary when using laser body scanners means it can take up to 30 seconds to scan the whole body (Istook and Hwang, 2001). It is difficult for the body to stay completely immobile for this amount of time, due to uncontrolled movements such as breathing or muscle contraction. This can lead to errors when capturing the shape of the body and subsequently in the data extracted from it, (Jones and Rioux, 1997; D'Apuzzo, 2007). Hair, clothing and skin tone can cause similar problems by absorbing and scattering the light/laser when projected onto the body. This prevents the cameras from capturing a complete set of data points, eroding the quality of the scanned object, (Jones and Rioux, 1997; Ashdown *et al*, 2004).

These limitations of body scanners mean that this technique is unable to extract all forms of anthropometric data. The UK National Sizing Survey, for instance, needed to take between eight and ten measurements manually (Treleaven, 2003), due to difficulties the scanning process had with hair and limitations of the scanner size extraction software. Many of these measurements would be critical for the design of clothing or body-worn equipment (e.g. height, weight, hand girth and hand length). Although the hardware and software technology is advancing, it is difficult to see how some of these measurements may be taken accurately using this process. As outlined in the limitations above, issues due to shading and line of sight mean that current body scanning technology cannot take detailed measurements of the extremities. This means that it is difficult to design products that interact with the hands and feet using 3D computer models, as the detail needed cannot be captured using 3D body scanning.

Attempts to scan the hand independently using a hand-held 3D scanner have been able to capture the hand shape by scanning the dorsal and palmar areas separately (Chang *et al,* 2007). This method uses a glass panel to support the subject's hand and reduce involuntary movement during the scanning process. Although errors due to the refraction of the laser through the glass have been controlled, issues of deformation of the palmar surface mean the natural form of the hand would not be captured correctly. The glass support is needed because the average measuring time for each subject is 20 minutes, significantly longer than 3D body scanners. These issues mean that, at present, this novel technique is unable to provide the same level of accuracy and repeatability as 3D body scanners. However, it highlights some of the difficulties that must be overcome to capture the complex shape of the hand surface.

Foot scanning techniques, that scan the foot individually, has lead to the development of systems which allow the foot to be sized accurately for the manufacture of customised footwear. The scanners vary in their design; some simply scan the plantar (sole) area of the foot, using the data for sizing and to design customised inserts for footwear such as orthotic supports. Scanners such as the one developed by Amfit, digitise the plantar surface of the foot, which enables a 3D surface model to be generated, (Amfit, 2003). This can then be manufactured using a CAD/CAM milling fabrication system to produce the customised inserts for footwear. Other, more complex foot scanners can scan the dorsal (upper) and plantar (sole) areas of the foot simultaneously. This is done by placing the foot directly onto a scanner/camera to capture the detail of the plantar surface and using a series of scanners/cameras placed above or perpendicular to the foot to collect data from various points around the dorsal area, see figure 2.4. Manufactures such as Shoemaster (Shoemaster, 2003), Digitoe (Digitoe, 1988) and those involved with the EUROShoE project (EuroShoe, 2003) use foot scanning to generate surface models of the foot that are used to accurately size the foot and design custom made footwear. Studies have demonstrated that these methods have the capabilities to manufacture shoe lasts for customised (Leng and Du, 2005) and mass customised (Barnett *et al,* 2004) footwear. This can be done by designing the two-dimensional patterns around the three-dimensional surface model or by manufacturing a last through CAM and rapid prototyping.

Figure 2.4 – A foot being scanned using the INFOOT 3D foot scanner from Shoemaster (Shoemaster, 2003).

Using scanned data of the foot in this way is successful because the scanner can capture all the detail required. Detail such as the shape and size of each toe and the gaps between them are not required, as it does not need to be accommodated in the footwear. If more detailed, complex surface models were necessary, then data must be collected from all areas of the foot, the ankle and lower leg. It is for these reasons why scanning the hand for the manufacture of handwear is very difficult and currently not possible. Although of similar anatomical form to the foot, the hand is much more difficult to accommodate; as areas such as the fingers, thumb and finger crotches are complex in their configuration and interaction with one another. Capturing the necessary anthropometric data from these areas is therefore fundamental for generating a CAD model to manufacture handwear. The current body scanning systems are not able to record this kind of precise detail and so other means may be necessary to achieve the detailed CAD models required. The U.S Army Natick Soldier Center in their program of three-dimensional anthropometric data acquisition and analysis has attempted to scan hands but as yet have been unsuccessful in generating a useable high definition surface.

An alternative approach to 3D body scanning is to use photographs to create 3D computer models of objects for use in CAD environments. D-sculptor is a piece of subtractive silhouette software which allows the generation of 3D computer models from 2D digital photographs, (D Vision Works, n.d.). This software uses a number of photographs from varying angles of the object to create a fully textured computer model that can be exported for use in a variety of different CAD packages. This technology is a quick and simple method of capturing the shape of an object to be used and analysed within CAD software. It has been used to generate 3D models of the human body parts (e.g. heads, hands and feet) and has the potential to be an alternative to expensive 3D body scanners. At present, however, there are several limitations which would need to be overcome for this to be a plausible application. The main disadvantage is accuracy, as the models generated can have +/- 5mm tolerance from the original object. It is very labour intensive, as each photograph must be manually processed which leads to large human error potential, it cannot accommodate for undercuts or detect subtle surface detail. Other applications such as Strata Foto 3D and iModeller use the same principle as D-Sculptor, but share the same drawbacks. Due to the constraints of these types of software, they are unsuitable for collecting anthropometric data, although this is not a function they were designed to do. However, they do provide a useful tool for creating 3D representations of objects within a CAD environment.

2.4 Clothing design and manufacture

Clothing manufacture is an assembly-orientated industry utilising a range of raw materials, product types, production volumes, supply chains, retail markets and associated technologies (Tyler, 2000). Companies associated with this industry can range from small family run businesses to large multinational corporations, manufacturing an enormous variety of garment types (Cooklin, 2006). Clothing design and manufacture is part of a much larger textiles industry. Jones (2002) categorises this industry into four different sectors or levels. Figure 2.5 summarises the four levels.

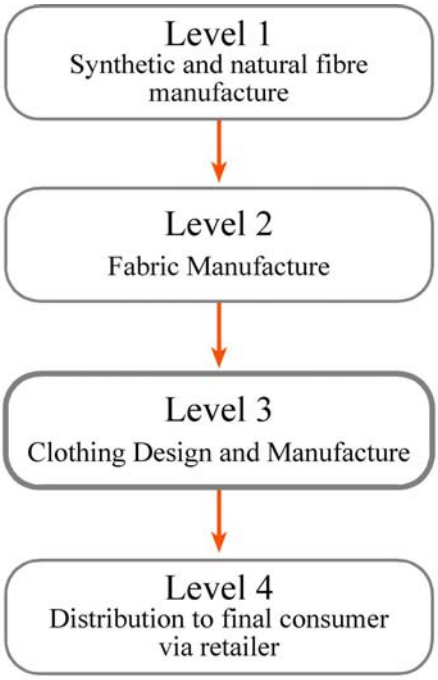


Figure 2.5 – The different levels of the textiles industry, as described by Jones (2002).

Level 1 involves the production of raw materials to manufacture and distribute both synthetic and natural fibres. This becomes the input into level 2, which uses these fibres to produce various types of fabric. Clothing design and manufacture is the third level within the textile industry, importing the fabric to create the various forms of clothing and apparel. Finally, level 4 concerns the distribution of the completed product to the consumer via a retailer.

In the UK, clothing and textiles has historically been an important and dominant industry, establishing large scale domestic manufacturing operations, with peak levels of employment of over 796 000 (Godley, 1996). However, the production of clothing and associated levels of employment have been in decline for many years, (Jones and Hayes, 2004) and since the mid-1990s there has been a dramatic collapse in both employment and manufacturing output within this sector (Jones, 2002). It is now a much smaller manufacturing sector within the UK, employing 95 000 people (Jones, 2002) and accounting for only 3.3% of the total manufacturing output, (Office for National Statistics, 2008).

Despite this decline in employment, clothing design and manufacture remains a very labour intensive industry (Jones, 2002; Tyler, 2000). It has been relatively unaffected by the automation and computer technology that has influenced the development of many other manufacturing processes, such as in the automotive and construction industries (Jones, 2002). Tyler (2000) describes several reasons why it continues to be necessary for this human interaction within clothing production. It is predominantly due to the nature of the raw materials that are available. There are a large variety of different synthetic and natural fabrics and textiles used for clothing; each type varying in thickness, surface finish, density and strength. Fabrics are limp and, in particular, blend in all directions which means it is complicated and expensive to develop jigs and automated equipment to perform assembly operations that can accommodate all of these properties. They also vary in extensibility. This variation not only occurs between different types of fabric, but also exists within the same fabric due to natural grain and weave direction. This means that the join used to assembly the various pieces of a garment must be able to withstand the various degrees of extensibility associated with the different fabrics. This can be difficult, especially for extremely curved joins such as those used to attach a sleeve onto a round armhole, as it necessary to choose the correct type of join to ensure the garment is assembled correctly and securely.

In addition to the characteristics of fabric, Tyler (2000) also describes the significance of human interaction in garment assembly. The method of sewing pieces of fabric together is the central process in clothing manufacture, dominating the output of a clothing factory (Tyler, 2000). A stitch forms a flexible, universal joint that is compatible with the flexibility, drape and handle of the associated fabrics. This remains the only type of joint whose properties are equivalent to those of the fabric and no satisfactory alternative to sewing has yet been developed. Sewing machines provide a semi-automated method of accurately performing a series of stitches quickly, however the operator plays a vital role in assembling the garment; controlling the size of the stitch, the tension of the sewing threads and the rate of stitch formation. This determines the shape of the sewing line and subsequently the shape of the finished garment. The skills of the operator are often learnt and developed through the experiences and empirical knowledge of working with the different fabrics and machinery. The heuristic nature of these methods means they are difficult to teach or automate, and many operators develop their own individual techniques to produce the correct size and shape for the garment. Some automation of the sewing process has been achieved for simple garment assembly; however the difficulties with developing machinery capable of dealing with the various properties of fabric means that manually machine stitching clothing remains the most cost effective process to use (Tyler, 2000).

The issues that Tyler (2000) describes relate specifically to the manufacture of clothing, however, the design and development of clothing also requires a high degree of human input. Clothing design traditionally involves creating 2D patterns compiled from a number of different pieces that represent the different parts of a garment. Different types of garments require different patterns, varying in complexity and construction depending on the required specification. A pattern is a detailed technical drawing, containing all the information necessary for assembling the garment to ensure it is made to the correct size and shape, (Shoben and Ward, 1980). Figure 2.6 shows the two main pieces for a pair of ladies jeans. The solid outer line indicates the size and shape of the pattern pieces and the dashed lines indicate where stitching is required to join it to other pattern pieces during the assembly of the garment (Campbell, 1980).

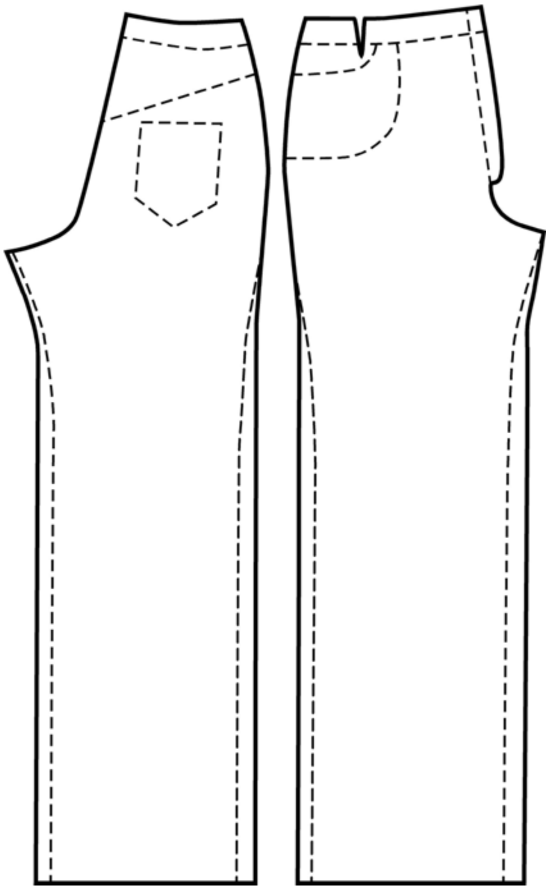


Figure 2.6 – Front and back pattern pieces for a pair of ladies jeans (Campbell, 1980).

The job of a pattern designer involves transforming 3D designs or ideas into their 2D constituent pieces which form the pattern (Fan *et al*, 2004). The design process entails creating each piece individually; deciding how to accommodate the properties of the fabric, the type and position of each join, the location of additional pieces (e.g. pockets, collars, zips or buttons) and how all the pieces are connected to each other (Shoben and Ward, 1980). It is also necessary for a pattern designer to be aware of the developments in fashion and transformations of body size and shape to ensure these changes are represented in the design of the pattern and the associated garment, (Campbell, 1980).

Conventional pattern generation requires the pattern designer to collect the linear (length and circumference) measurements of the body surface with a tape measure, and then apply these measurements to draft the pattern based on a mathematical foundation and approximation (Fan *et al*, 2004). This is a complex process, as the shape of the human form consists of both convex and concave surfaces, and no two human bodies are identical. This means that it is not possible to fully determine the shape of the human body from these types of dimensions and consequently, as described by Whife (1965), (see Fan *et al* 2004, p196) using only these measurements to generate a pattern will not create the perfect fit for a garment. Therefore, the skill of a pattern designer is to use their observation and judgment of the shapes and contours of the human body to create the correct size for a pattern, (Fan *et al*, 2004). This approach is essentially an intuitive visual analysis of the body, using experience and tacit knowledge to determine how the shape of the pattern will achieve a good fit (Gazzuolo and Delong *et al,* 1992).

This preliminary process of 'flattening out' a 3D concept design into a series of 2D pieces forms the basis of a new pattern. It is then necessary to determine that it will produce a garment that will resemble the initial design. To achieve this, a sample garment is made from the pattern and fitted to a model or stand to assess shape and fit, making adjustments and alterations where necessary (Shoben and Ward, 1980). The changes made to the sample garment are then incorporated into to the 2D pattern by the pattern designer. This process can occur several times until the desired size and shape of the garment has been achieved. Once a final shape to the pattern has been decided it is known as the master pattern and usually represents a standard size (Aldrich, 2004). This process means the pattern designer must work closely with a sewing machine operator to ensure the sample garment is an accurate representation of the initial pattern. It is essential therefore, that the pattern designer has extensive knowledge of the techniques used by the sewing machinist to ensure the patterns that are produced can be assembled efficiently and accurately. Equally, the sewing machinist must understand the methods used by the pattern design to ensure the alterations made to the sample garment can be transferred correctly to the 2D pattern (Shoben and Ward, 1980). The iterative process of modifying the sample garment and incorporating the changes into the pattern is again reliant on the experience and tacit knowledge of the pattern designer. As Gazzuolo and Delong *et al* (1992) explain, because the 3D garment plane differs from the 2D pattern plane, changes made to the sample garment do not correspond directly to the shape of the pattern. Therefore, the pattern designer must translate the changes made to the garment in order for them to be represented in the pieces of the pattern. This can be an imprecise process, as indicated by the need for repeated trials and fittings of the garment by the pattern designer and sewing machinist.

The final stage in creating a new pattern is to modify the initial pattern from the standard size to produce a range of sizes; a process known as pattern grading (Aldrich, 2004). The technique of pattern grading entails using a table of body measurements to determine how much to change the dimensions of the pattern to represent different sizes. This is one of the primary roles of the pattern designer as it is the process of developing the initial master pattern into a series of patterns that share the same style, proportions and fit as the sample garment (Bye *et al,* 2008). The goal is to choose size groups in such a way that a limited number of sizes will provide ready-to-wear clothing which fits most individuals in the target population (Fan *et al,* 2004). There are two main methods of pattern grading; the proportional method and the traditional method. Proportional grading produces patterns that change proportionally in circumference and length (Cooklin, 1990). However, problems with fit can occur using this method, as people that have larger circumference measurements are not necessarily taller (Cooklin, 1990). Traditional grading uses a standardised set of relationships to determine the shape of the lines that form the patterns (Bye and DeLong, 1994). Both of these methods use standard and variable grade rules. Standard grades are the same for all sizes, while variable grades change according to the difference in circumference between sizes (Bye *et al,* 2008).

Once all the sizes have been generated the pattern is laid onto the appropriate fabric to cut the required number of pieces for each size. This process, known as lay planning, attempts to layout the patterns on the fabric as economically as possible to ensure the amount of material wasted is kept to a minimum. The fabric is then cut using the pattern as a template. This can be done a layer at a time (single-ply), but to increase the efficiency of the process, the fabric is often laid in layers (or plies) and cut simultaneously (muti-ply) (Aldrich, 2004).

To generate the different sizes, the pattern designer will use a sizing system to specify the proportions and intervals between each size. Sizing systems are based on a selection of body dimensions from an anthropometric survey of the population for which the garment is designed (Ashdown, 1998). Many systems use traditional specifications which have been established by a manufacturer over many years, updated using modern anthropometric data. An example of this is in the sizing method commonly used for gloves, which uses the circumference around the hand as the main criterion. This method originated in the 19th Century when Xavier Jouvin developed a system which used a specially designed measuring tape to measure the hand and specify the glove size required (British Glove Association n.d.[a]). The system created by Jouvin remains an acknowledged approach for glove sizing (BSEN 420:2003), principally because it has been unaffected by metrication.

To standardise the generation of sizes between clothing manufacturers, many countries adopt a series of standards to regulate the size designation of clothing and the type of body measurements used to create sizing systems (Fan *et al,* 2004). In the U.K. the British Standards Institution has published a set of standards to define body dimensions for different types of garments and provide procedures for measuring the body applicable to garment design (British Standards Institution, 2001, 2002, 2004). They also provide standardise terminology, definitions, dimensions and tolerances, and selection of sizes for mass-produced clothes. Sizing standards are based on national sizing surveys, such as those conducted in the U.K. (Size U.K., 2003) and the U.S.A. (Size U.S.A, 2003). As discussed in the previous section of this chapter, these types of survey aim to collect accurate data of body size, shape and volume and relay it back to clothing industry in a format that can be directly applied to garment design, (Fan *et al,* 2004). As body shape changes over time, it is necessary to continually update sizing systems and standards to reflect these changes and avoid problems of poor fit, (Fan *et al,* 2004). Since sizing practises can vary between countries, the International Organisation for Standardisation (ISO) formed an international standard, ISO 8559: 1989, to standardise garment construction and anthropometric surveys throughout the world. This is now the international standard used for all types of size surveys and garment construction (ISO, 1989). In addition, a similar standard, ISO/TR 10652: 1991, was introduced to standardise sizing systems for all garments made for infants, girls, boys, men and women (ISO, 1991).

The recommendations specified within sizing standards recognise that body shapes can differ significantly, not only from country to country but also within countries. It would not be feasible to construct a set of sizing standards that can be universally applied. The standards are therefore, in a format that is open and flexible, to cater for this variability and enable them to be internationally applicable (Fan *et al,* 2004). However, the standardisation of sizing systems has been debated for some time and the acceptance of such standards is not prevalent among all clothing manufacturers (Fan *et al,* 2004). This is because some manufacturers prefer to change measurements quickly to suit consumer needs without the having to reference to rigid standards. Manufacturers often prefer to define their own sizing systems and conduct consumer anthropometric surveys so they can meet the needs of their specific target population (Fan *et al,* 2004). This means sizes can differ between manufacturers, causing some confusion and dissatisfaction for consumers when trying to find clothes that fit properly (Ashdown, 1998; Cotton Incorporated, 1998; Locker *et al,* 2004; Fan *et al,* 2004).

Throughout the pattern design process it is clear that the pattern designer frequently relies upon experience and tacit knowledge to successfully create the correct size and shape of the 2D pattern pieces. The designer must have thorough knowledge of fabric properties, assembly methods and body shape to ensure the pattern accommodates these variables appropriately and can manufacture the garment to the correct specification (Shoben and Ward, 1980; Aldrich, 2004). Many of the decisions made by the pattern designer are based on rule of thumb principles about how the shape and proportions of the human body relate to the 2D surface of a garment pattern. By definition, 'rule-of-thumb' is a rough or practical approach, based on experience rather than theory (Collins English Dictionary and Thesaurus, 2001), this means it is difficult to externalise the many skills and methods used, as some are often unique to an individual designer. This heuristic methodology creates problems when trying to introduce automation and computerisation into this process; similar to those which affect the attempts at automating the sewing processes for clothing manufacture. However, advances in CAD software have seen an increase in specific tools to design, modify and grade patterns, aiming to make the process more accessible to less skilled, inexperienced pattern designers. More complex tools allow the visualisation and simulation of garments in a 3D virtual environment to analyse different types of fabric and evaluate fit using different body shapes and sizes. The various systems being developed and promoted for pattern design and clothing evaluation are described and assessed in the following sections of this chapter.

2.5 Anthropometry in the design and evaluation of clothing

The use of anthropometry in the design and evaluation of clothing and body-worn products allows these types to be produced to meet the needs of a specific population. How the anthropometry is gathered and applied will directly influence the end product and so the techniques and systems used must be as accurate as possible.

A system has been developed by Defence Research and Development Canada, (Meunier and Yin, 2001), which enables the sizing of military personnel to be computerised. The Intelligent Clothing and Equipment Sizing System (ICESS) aims to be a low-cost automated system that has the capability of accurately measuring and sizing individuals, enabling the distribution of clothing and equipment for the Canadian Forces to be more cost effective. Using two digital cameras to take photographs from the front and profile of the subject, 27 landmarks are identified on the body, listed below.

1. Top of head – 2 landmarks (front and side);
2. Neck – 4 landmarks;
3. Acromion – 2 landmarks;
4. Chest – 4 landmarks;
5. Waist – 4 landmarks;
6. Hip – 4 landmarks;
7. Crotch – 1 landmark;
8. Thighs – 4 landmarks;
9. Wrists – 2 landmarks.

These landmarks are then used to extract 36 dimensions, taking two types of measurements, direct and indirect. Direct measurements are linear dimensions, (lengths breadths depths etc.) and are taken from a single view. Indirect measurements are circumferences and are derived or extrapolated from direct measurements. A full list of the dimensions extracted is given in table 2.2. The hands and feet of the subject are measured separately using a flatbed scanner, as the required detail to be measured cannot be seen using the digital cameras. The ICESS software calculates the clothing size of the subject immediately after all the anthropometric measurements are made. This can then be used to issue the subject with the correct uniform and body equipment. This approach has been adopted in the USA and is routinely used for issuing military uniforms (Treleaven, 2003).

Dimension	Dimension
1. Stature	19. Waist breadth, natural
2. Neck breadth, natural	20. Waist depth, natural
3. Neck depth, natural	21. Waist circumference, natural
4. Neck height, natural	22. Waist breadth, trousers
5. Neck circumference, natural	23. Waist breadth, trousers
6. Neck breadth at base	24. Waist circumference, trousers
7. Neck depth at base	25. Waist height, back
8. Neck height at base from back	26. Waist height, front
9. Neck circumference at base	27. Waist angle
10. Acromial height, left	28. Hip breadth
11. Acromial height, right	29. Hip depth
12. Biacromial breadth	30. Hip circumference
13. Sleeve length, left	31. Crotch height
14. Sleeve length, right	32. Thigh breadth
15. Chest breadth	33. Thigh depth
16. Chest depth	34. Thigh circumference
17. Chest circumference	35. Strap length (for backpack)
18. Chest circumference below breast	36. Back length (for backpack)

Table 2.2 – List of measurements taken by the ICESS, (Meunier and Yin, 2001).

Testing the system (Meunier, 2000[a]) entailed using 186 military participants who were measured using the ICESS and issued with the uniform it suggested. The uniforms were then analysed by clothing experts assessing fit and recommending changes where required. The results showed a success rate between 70% and 100% depending on the particular clothing item and sizing rules that accompany it. The accuracy and precision of the system (Meunier and Yin, 1999) was determined by using a database of 349 subjects (95 females and 254 males) who were also measured using manual techniques and through repeated measurements of a plastic mannequin and a human.

This system is used as a tool for correctly issuing clothing and equipment to military personnel, it could however be used as a design tool to manufacture customised clothing and equipment. There is a large amount of anthropometric data gathered and it is possible to use this data to generate pattern designs. This may not be possible for the extremities. The data collected is only used to determine the size needed for a glove or boot, it is insufficient to design and manufacture a customised piece of handwear or footwear. It would be difficult to collect the necessary anthropometric data using the current method that the ICESS describes as the hands and feet are recorded in a two-dimensional format only measuring lengths and breadths. In order to manufacture a piece of handwear or footwear the hands and feet must be recorded in three dimensions to include all surfaces and measure circumferences, depths and datum points. This is especially true of the foot, where the design of a shoe or boot must take into account the ankle and lower leg as accommodating these areas is crucial for comfort and support.

To design a piece of handwear or footwear, it is therefore necessary to obtain detailed measurements of the hand or foot that can represent it three dimensionally. Earlier work at Defence Research and Development Canada (Hidson, 1991[b]) describes a procedure for generating a CAD model of the hand using anthropometric data. This procedure is an example of generating a three-dimensional form of anthropometric data for the design of gloves and addresses many of the issues that arise when integrating anthropometry into a CAD model. A total of fifty dimensions were used to generate the CAD model and it is noted that while a small number of dimensions are suitable for fitting gloves, a much larger number are required to adequately design them. It is not only the number of dimensions that is important; the type of measurement is critical also. A consideration of the requirements of the CAD program must be made prior to collecting the measurements. This is to ensure that the operator can input the data accurately and easily in the correct format that the CAD package recognises. For example establishing a datum point, in this case the lower right corner of the model (figure 2.7), where all dimensions can be referenced.

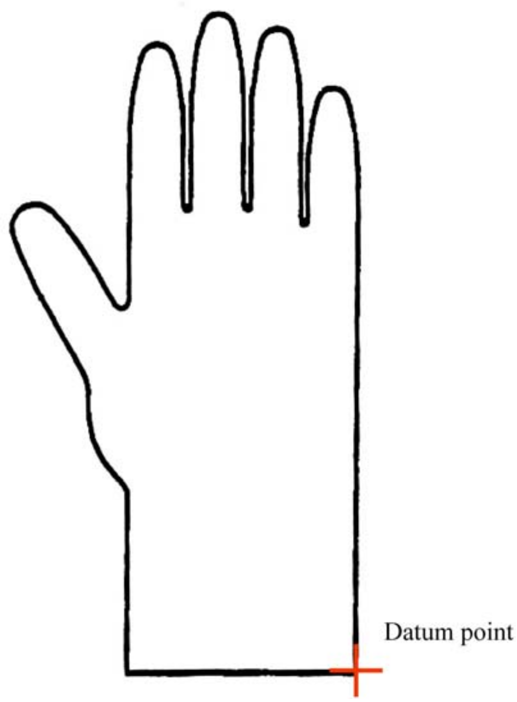


Figure 2.7 – The datum point used by Hidson (1991[b]) to reference all dimensions

The generation of the CAD model used dimensions taken from one subject and not from processed data of an anthropometric data survey. The construction process entailed two main stages. Firstly, the anthropometric dimensions were used to specify the extremities of the model in all directions from the datum point in the lower right hand corner, creating a 2D outline of the hand shape, figure 2.7. This outline was then was used to create 3D geometry which formed the CAD model. This was completed in two stages; initially the fingers and thumb were created (figure 2.8) followed by the palm (figure 2.9).

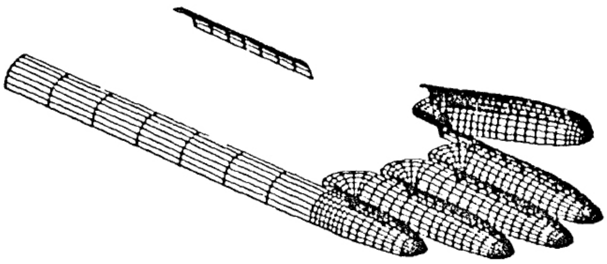


Figure 2.8 – The 3D surfaces representing the fingers and thumb generated by Hidson (1991[b])

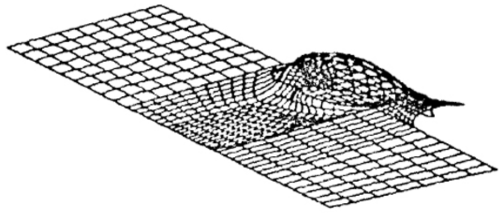


Figure 2.9 – The surfaces representing the palm generated by Hidson (1991[b])

The surfaces for the fingers were then joined to the surfaces for the palm to create the complete hand model (figure 2.10).

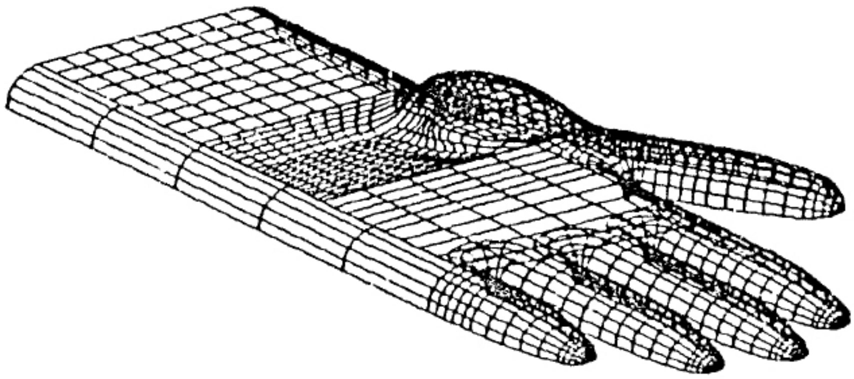


Figure 2.10 – The completed hand model generated by Hidson (1991[b]).

The exact generation of the CAD model is unclear, as a detailed description of how the surfaces were created is not specified. The intended use of the CAD model was as a basis for creating a mould tool which could be used to manufacture gloves. Using computer numerical controlled (CNC) machining, the shape of the model was recreated into a 3D form. This was then introduced into a manufacturing process to produce gloves which could be tested for manual dexterity and comfort.

This research was conducted in 1991 and advances in CAD packages and rapid prototyping technologies would overcome many of the problems that existed at that time. However, some of the issues still remain. For example, how the anthropometric data is collected and what CAD package is to be used to generate the CAD model must still be considered prior to collecting the data. This enables the generation of the CAD model to be accurate and precise. Various types of research into using anthropometry to design body-worn equipment have been published by Defence Research and Development Canada. Hidson alone has published several reports involving CAD/CAM and anthropometry, (Hidson, 1982; Hidson, 1984; Hidson, 1991[a]; Hidson 1991[b]; Hidson, 1992), however much of this research is dated and it has been difficult to obtain recent publications in this area due to its commercial and military confidentiality.

The generation of a CAD or surface model of a body or body part is only an initial stage of the design process of a body-worn product. The model must be used in some way. In most cases a physical representation of the model is produced in order to manufacture a product. Hidson (1991[b]) used his CAD model of the hand to design a glove by CNC machining the model; however other methods are being developed. Wang *et al* (2002) have devised a method of virtual human modelling from photographs. The process involves taking two photographs of the subject (a front view and a profile view) and generating a surface model using the outline of the body shape. One of the proposed applications for this is the rapid prototyping of mannequins of the surface model which can be used to produce custom made mannequin models for the garment industry. Manufacturing physical models of the CAD/surface model could have significant advantages when designing clothing or body-worn products. They can be used to manufacture such products by being in the form of a mould tool or three-dimensional pattern. Because the mannequin would be an exact replica (within a known tolerance) of the CAD/surface model the product should fit the individual to a high degree. In addition to being a manufacturing aid, a mannequin could be used as an evaluation tool. Many items of clothing and body-worn products are manufactured on a large scale and accuracy can sometimes vary from batch to batch. Having a physical mannequin of what the product should fit into/onto can act as a quality assurance tool within an industrial context. Similarly if more than one manufacturer is producing the same item, discrepancies may occur between them. Introducing a physical shape that all manufacturers are working to will eliminate this inconsistency, therefore producing a more accurate product.

Clothing and body-worn products may also be designed virtually within the CAD system. Wang *et al* (2002) describe this as a possible application of the virtual human modelling from photographs. The ability to 'fit' the clothing or body-worn product to the individual within a virtual model has its obvious advantages. Patterns could be designed directly onto the CAD/surface model. Kim and Kang (2002) have also investigated this process determining that a two-dimensional pattern can be generated from a three-dimensional scanned surface. McCartney and Hinds (1992) take a slightly different approach and create garment patterns by offsetting surfaces from a three-dimensional digitised surface.

One commercial company using this approach for garment generation and assessing fit of clothing and body-worn products is My Virtual Model Inc. Their website, www.mvm.com, allows the user to build a virtual model of themselves by answering a series of questions about height, weight and body shape. Figure 2.11 shows the interface used to generate a male virtual model.

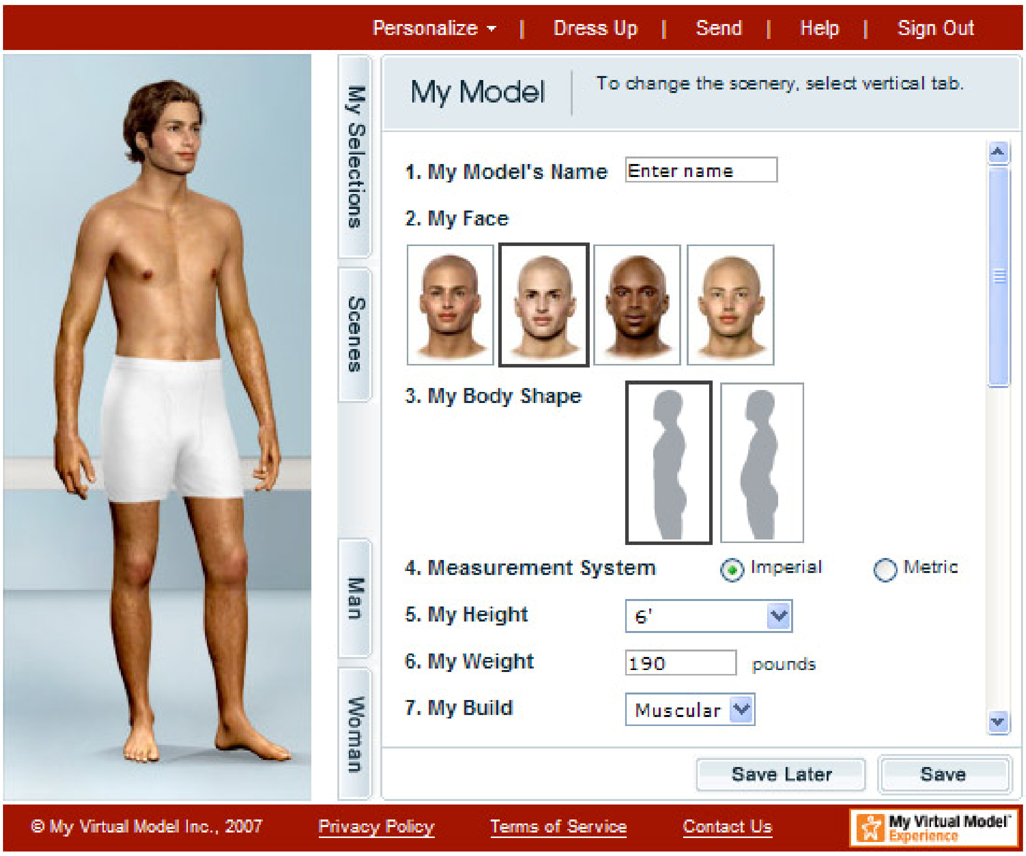


Figure 2.11 – The My Virtual Model interface used to generate a virtual model of the user, (My virtual model inc., 2001).

This model can then be used to try on clothes in a virtual changing room to give a computer generated impression of what they may look like to take ‘the guesswork out of buying clothes’ on the Internet (My Virtual Model Inc., 2001). Although the generation of the model is simplistic, and therefore the fitting procedure is likely to be imprecise, the technology it is based on is similar to that of the Intelligent Clothing and Equipment Sizing System. This could possibly be a commercial outcome of this system as both originate from Canada.

The main drawback with both the use of mannequins and virtual 3D models is that the products designed using them are only as accurate as the CAD model, which is usually generated by either 3D scanned data or anthropometric measurements. This then reinforces the need for the information and the procedures used to build the CAD model must be as accurate as possible, or at least to a standard that is necessary for the end product.

2.6 Computer aided design and manufacture in the clothing industry

As with most manufacturing industries, the clothing and textile industry has benefited greatly from the introduction of CAD/CAM. The use of computers within the textiles industry has developed since the early 1980s (Price *et al*, 1999). Computers and CAD provide the ability to provide a consistently high quality output in a relatively short time allowing retailers to minimise their stock and maximise their profits, (Gray, 1992). It increases the speed and accuracy of developing new textile designs, reducing the lead times needed to produce new products (Bye and LaBat, 1994). The early CAD systems introduced in to the textile industry were able to condense the design process that once took weeks or months to complete into less than 24 hours, (Price *et al,* 1999).

The area where CAD has perhaps been most beneficial within the design and manufacture of clothing is in pattern design. CAD tools have been developed to aid the designer in all stages of this process, (Gray, 1992). Every pattern a company has designed can be stored electronically, providing an instant reference library. Each pattern can be modified quickly and accurately, making the grading process much easier and efficient. Measurements of patterns can be made more accurately than manual methods, meaning measurements for each size can be checked and any mistakes or inaccuracies rectified or changed. Lay-planning software can then calculate the most efficient layout of the patterns within the confines of the cloth, the limitations placed on the pieces by the type of cut being used (knife, laser or high-powered water jet) and the restrictions imposed by the pattern of the material. The patterns for each size can be cut directly using a computer controlled sample-cutting machine. There are many types of commercial software and hardware available to aid all stages of the design process. FashionCAD provides an innovative approach to designing, grading, detailing and lay-planning patterns, see figure 2.12 (FashionCAD, 1998). This software aims to provide a means of generating customised patterns easily and quickly without the need of an experienced professional pattern designer. It can automatically create complex curves within clothing patterns to facilitate the grading of different sizes. This enables a range of sizes to be accurately generated based on a single customised pattern.

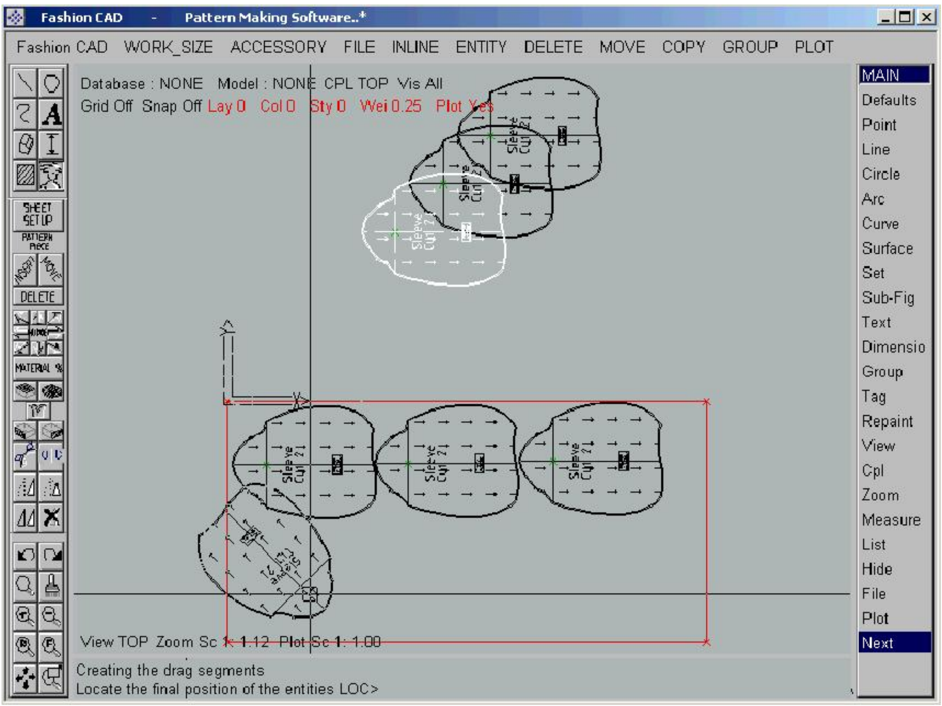


Figure 2.12 – The lay-planning software from FashionCAD to efficiently layout patterns on a cloth, (Fashion CAD, 1998).

Similar systems have been developed by Lectra to provide the software and hardware for designing and grading patterns, and equipment to cut patterns in single and multi-ply formats, (Lectra, 2000). PAD System is another commercial company that offer these tools. It has developed software for three specific areas; master pattern design, efficient nesting of pattern components and batch plotting of patterns over a computer network, (PAD System, 2004). All these systems aim to give the manufacturer the means for efficient pattern design, improved productivity, a reduction in production costs, and to promote creativity across a wide spectrum of apparel applications.

The use of CAD/CAM has seen a phase of digital change in the textile and clothing industry, embracing the increase in research of 3D simulation technology, (Taylor *et al*, 2003). As has previously been discussed, it is possible to design clothing around a 3D CAD model that has been generated from body-scanned data. The ability to design clothing around the end user in a completely virtual environment will inevitably shorten lead times and be more efficient than traditional methods. It enables the garment to be evaluated and modified to achieve the correct fit before any material is cut so the iterative cycle of fitting sample garments to a model or mannequin can be greatly reduced or eliminated. The consumer end of this technology is seen on the My Virtual Model website which gives the opportunity for customers to view the clothes on a similar body as their own. Consumer evaluation of this technology has shown that the ability to use virtual try on tools and buy customised clothing is a popular development in the clothing retail market, (Fralix 2001 and Loker *et al,* 2004). The consumer increasingly demands more direct input into the options that are available to them, and wants retailers to cater for their needs. The use of 3D body scanning and 3D clothing simulation will significantly affect the way clothing is bought, particularly via the Internet, with a predicted 20-30% of all products sold to have some element of customisation within them, (Fralix, 2001).

When used in a commercial environment, 3D modelling and clothing simulation has enabled design tools such as Modaris 3D fit software from Lectra to be developed. This enables apparel companies to reduce development costs and accelerate production cycles by reducing the number of physical prototypes required. The Modaris 3D fit software combines 2D patterns, fabric information and 3D virtual models to enable simulation and validation of styles, fabrics motifs and colour ranges (Lectra, 2000). These types of commercially available tools exist in a number of different packages from various software developers such as OptiTex, (OptiTex,

2004) see figure 2.13, Gerber Technologies (Gerber Technology, 2004) and Assyst-Bullmer, (Assyst-Bullmer, 2004), however, they all use similar methods of 3D visualisation and cloth simulation. The MiraLab research group (MiraLab, 2006) at the University of Geneva has conducted extensive research in this area. It is continuing to develop methods that enable the design of clothing to be improved by allowing the designer to quickly assess issues of fitting and draping without the need to produce physical prototypes. Previous work has addressed the needs for accurate garment prototyping (Volino and Magnenat-Thalmann, 2005), garment simulation for the apparel industry (Volino *et al,* 2005); and online applications that facilitate garment design, pattern derivation and sizing (Cordier *et al,* 2005).

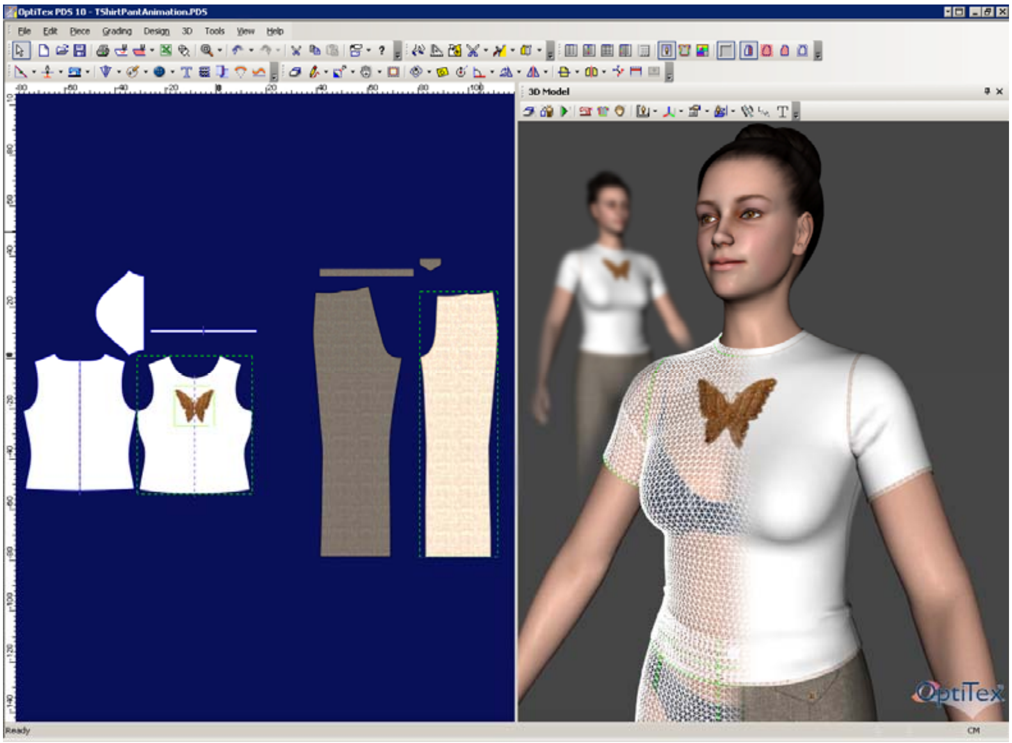


Figure 2.13 – OptiTex software to generate 3D simulations of clothing from 2D patterns, (OptiTex, 2004).

These virtual environments provide an opportunity for a design to be assessed on-screen quickly without the need to produce the garment to evaluate how it will look and react to movement. However, the accuracy and realism of the fabric model is paramount (Hardaker and Fozzard, 1998). These simulation methods have been adapted from tools initially developed for modelling, rendering and animating in the gaming and animation industry, (Taylor *et al,* 2003). This means the emphasis of these systems is on the communication of completed clothing designs and not necessarily the design process of these products. McCartney and Hinds *et al,* (2000) highlighted the areas where CAD packages for apparel design are yet to be fully developed and currently limit companies to truly adopt a computer integrated approach to design and manufacture. The main areas are as follows;

- The inability to provide the designer with a 3D specification of a fully rendered, realistic complete garment.
- The inability to utilise the 3D model to extract all necessary information for the creation of accurate 2D patterns.
- The limited capability to accurately simulate garment characteristics, incorporating all seams and textile mechanical properties during wear.
- The lack of compatibility with current CAD/CAM systems.

The use of CAD/CAM for apparel design is an emerging technology and many of these areas for development identified by McCartney and Hinds *et al* (2000) are being addressed and overcome (Anderson, 2005). For example, 2D pattern generation from 3D computer models is a dominant focus for the apparel industry with many companies integrating this feature into their 3D visualisation software. Also, as these software tools develop and hardware capabilities increase, the ability to generate more complex 3D models with greater detail will enable more accurate representations of clothing and its characteristics to be created (Choi and Ko, 2005).

At present, however, problems with these techniques of clothing design and manufacture centre on the accuracy of the information put into the 3D CAD model. If the product is designed using inaccurate data and there are significant tolerances during manufacture, the garments produced using it will not fit the individual that they are designed for. If the designer is aware of these inaccuracies and tolerances then it is possible to take them into account during the design and manufacturing process. Therefore, in practice the clothing/pattern designer uses CAD/CAM as a tool to assist their work, rather than it being used to completely automate the process. This means that design decisions and the 'rule-of-thumb' aspect in the design process must have a major influence on the outcome of the product. Therefore incorporating these types of factors into a CAD model or an automated manufacturing process would be extremely difficult as they are typically specific to an individual designer. However, any system that is used to design, evaluate or manufacture clothing or body worn products must allow for specific design decision making to be integrated at relevant stages.

2.7 The use of gauges in production engineering

The degree of accuracy necessary for a part will vary according to its function, (Parsons, 1970). Products or parts manufactured for use within an aircraft engine are required to be made to a higher degree of accuracy than those for agriculture machinery. However, whatever the function of the product, it must be made to the correct dimensions specified during its design. The variability in any manufacturing process means that the same product or part is never made to the exact same size. A manufacturing tolerance is applied which ensures they are dimensionally correct even though the size may vary, (Parsons, 1970). Monitoring and controlling tolerances allows products and parts to be produced accurately which is important when they are required to fit within another product or larger assembly. It is therefore necessary to check and verify that the part is to the desired size and shape. This can be done by measuring the dimensions of each part in an assembled product; however, this process would waste a considerable amount of time in the manufacturing process, (Parsons, 1970). It is not always necessary to know the dimensions of a part; simply that it is the correct size and shape. To establish this, gauges are used which determine whether the part is within the accepted tolerance specified during its design. Gauging, therefore, differs from measurement, since it merely determines the dimensional accuracy of a part, without reference to its actual size.

There are a number of different types of gauges and strategies for using them. Since they are used to check the dimensional accuracy of a part they have a necessity to be accurate and reliable themselves. The simplest type of gauge, as described by Meadows (1998), are GO, NO-GO gauges. These gauges are an integral part of a quality control process, used as a measuring tool to test the size and shape of a product (Meadows, 1998; BS EN 3650:1999). A conventional test would inspect the product using predetermined, acceptable tolerances, giving a pass (Go) or fail (NoGo) result. There is, however, often more to a part being functional than just its size. Functional gauges check geometric characteristics, such as perpendicularity, position of features and patterns of features, such as holes, slots and shafts.

The limitations of this type of gauge is that they only provide information on whether the part fits into an assembly or not and gives little or no indication about the accuracy of a part or where any inaccuracies are located. This information is often considered vital to improve a manufacturing procedure by monitoring the deviations from the dimensions specified in the design. It is therefore necessary to introduce methods of inspection that augment the information provided by the gauge. These methods include dial indicators and electronic probes that check the part at various stages to monitor its size and shape ensuring it remains within the acceptable tolerance.

The use of gauges and the monitoring of tolerances and part size are used extensively in precise engineering for the manufacture of precision parts that fit into complex assemblies that require a high degree of accuracy. It may not, therefore, seem applicable when designing and manufacturing clothing and body worn products as these items do not require such a degree of accuracy. For most types of clothing this may be true; however, for PPE and items that are worn in environments which require specific needs, fit and the interaction with the body is crucial. One of the objectives of this study was to develop and validate a method to improve the fit of handwear. A method or tool introduced into the manufacturing process would be a type of gauge used to monitor and control any deviations of the product from the original design. In addition, it would also be used as a tool for quality control; accepting or rejecting parts that were or were not manufactured to the necessary standard. The format of these gauges would greatly depend on the type of clothing or body worn product that is being manufactured and the required accuracy it must adhere to. The accuracy of the gauges themselves must be monitored so that they do not incorrectly accept or reject products.

The accuracy of the gauges, and the subsequent product(s) produced, is dependant on how accurate the end product must be. If the design of the product does not require it to be to a high degree of accuracy then there is no requirement for the manufacturing process to be either. The manufacturing process, therefore, only needs to be as accurate as the end product dictates. This then determines the efficiency and cost effectiveness of the product by ensuring that the amount of time, effort and capital is kept at the optimum amount. This issue of efficacy means a compromise must be reached between the accuracy of the end product and the cost effectiveness of its manufacturing process in order for an efficient product to be produced.

2.8 Conclusions

From the literature reviewed it is clear that anthropometry is increasingly being used in the design and manufacture of clothing. The desire to provide the best possible fit for the consumer means new and innovative body measurement techniques and clothing simulation tools are being developed. The integration of CAD/CAM into clothing design and manufacture attempts to improve these processes by making them more flexible, more accurate and more efficient. The main input of anthropometry is through 3D body scanning. This process provides an easy and efficient means of collecting data and is preferred to more traditional methods because it removes the operator from the measuring process and therefore reduces the influence of human error. The data are collected by generating a computer surface model of the body which the necessary dimensions can be extrapolated from. By generating this model the 3D body scanning process also accurately captures the shape of the body as well as its size. Capturing the shape and size allows the design and manufacture of customised clothing and body-worn products which aim to fit the person precisely as it has been constructed from their individual body shape. In practice however, this process not simple and straightforward. A piece of clothing does not merely need to fit to the contours of the body; other factors must also be incorporated. This means that the product must still be designed and, therefore, design decision-making has an important influence on the whole process.

The inclusion of CAD/CAM into the design and manufacture of clothing has seen an increase in the development of software tools to aid and enhance this process. These tools aim to offer an improved ability to generate, grade and detail clothing patterns with greater accuracy and efficiency by eliminating errors incurred when using conventional methods. In addition, they aim to reduce the time needed to produce a piece of clothing by speeding up the pattern design process and automating many of the methods used in a manual process. Ultimately, these types of software claim to provide the ability to create customised patterns without the need for the expertise and experience of a professional pattern designer (FashionCAD, 1998; Lectra, 2000, PAD System, 2004). However, while such software products clearly provide new and innovative ways of generating patterns, it is a very ambitious claim to be able to replace the role the professional pattern designer plays in clothing design. Creating the appropriate fit is determined by the type of materials used an understanding of how they are correctly assembled, especially for clothing that requires a high degree of fit such as PPE. The skills required to accurately generate the correct size and shape of a pattern that accommodates the necessary material and manufacturing properties cannot easily be incorporated into a software program. These skills rely on rule of thumb principles and empirical knowledge gained through the experience of working with the various types of materials and manufacturing techniques. Computer systems do not have the experience or background knowledge to accomplish the processes of pattern design and alteration. In practice, therefore, these software programs are an addition to the many tools a pattern designer must use to create a pattern, rather than the creation of a completely new automated process.

Another area where CAD has influenced the design and evaluation of clothing is in the development of virtual try-on technology and clothing simulation systems. These products provide a visual aid to the appearance of clothing within a 3D computer environment. Products like Modaris 3D Fit developed by Lectra (Lectra, 2000) and AccuMark V-Stitcher from Gerber Technology (Gerber technology, 2004) enable clothing designers and consumers to view a piece of clothing in simulated environment on a 3D human form. They attempt to replicate the fit and behaviour of clothes allowing the assessment of different styles and variations prior to manufacturing physical samples. However, the limitations currently affecting these products mean they are unable to be fully adopted as practical tools for clothing designers and manufacturers, (McCartney and Hinds *et al*, 2000). This is due to much of this technology being adapted from the computer graphics and gaming industry, which considers efficiency, stability and visual realism of clothing more important than accurately recreating realistic properties (Choi and Ko, 2005). This means that these tools cannot be relied on to determine an accurate fit or used to make critical design decisions on clothing assembly. At present, the primary role they have in clothing design is in the presentation of concept ideas, providing improved static and animated visualisations of clothing in 3D, without the need to produce physical prototypes.

3D body scanning has a major role to play in the development of clothing design and evaluation. It has ability to accurately capture the size and shape of the human body. However, this technology has limited capabilities in capturing detailed representations of the extremities. It is effective at collecting anthropometric data and body shape of the head, torso, arms and legs, as these are relatively simple shapes compared with the hands and feet. This means that the design of products worn on the extremities cannot be done using the techniques used for the rest of the body. Other means of generating accurate CAD and surface models of the extremities must be found in order for accurate products to be manufactured for them. Foot scanning has begun to be developed and introduce customised footwear and footwear inserts, but detailed model generation which includes details of the toes and ankle does not exist. Similarly CAD models of the hand that have the necessary detail and accuracy to manufacture handwear are not available. It is in the extremities, however, where the increase in accuracy will be most beneficial as it is with these areas that the human body most commonly interacts with the environment surrounding it. It appears that the clothing and products worn around the body can be manufactured to a greater accuracy than those on the extremities, where an accurate fit is more beneficial.

The most accurate method of collecting anthropometric data of the extremities remains the manual techniques that are used in the majority of anthropometry surveys. The 3D body scanning and clothing simulation methods that are currently adopted for improving the fit of apparel do not utilise the vast amount of anthropometric data that currently exists from these surveys. It is apparent therefore, that a method of using CAD/CAM to design and manufacture apparel can be developed to exploit this resource, working in parallel with other similar methods to produce clothing with enhanced fit for all areas of the body. The ability to utilise data from a variety of different anthropometric surveys will enable customised fit to be available for a range of different populations. However, it is important to ensure the data contained within a survey can provide enough measurements to create a product with the correct size and shape that meets the needs of the specified population.

Consideration must also be given to the optimum amount of data, as this would contribute towards the efficacy of the design and manufacturing process. The more information that is used to generate a CAD model the more accurate it should be and so increase the accuracy of the products designed using it. The accuracy of the CAD model only needs to be as accurate as the end product dictates. Deciding how much data to use is crucial to the efficacy of the manufacturing process. Using extensive amounts of data that generates a highly detailed and accurate CAD model will be inefficient in terms of time and cost if the end product does not require or will not benefit from this accuracy. Compromising between cost effectiveness, functional effectiveness and accuracy will aim to produce an optimised design and manufacturing process that generates an effective product.

2.9 Summary

In summary, the literature review fulfilled the research objective of identifying and exploring the key issues surrounding the design and manufacturing of apparel using anthropometric data and CAD/CAM. It identified the gaps in current knowledge and methodology relating specifically to handwear.

The review found that anthropometry is a common resource in the design and manufacture of apparel. It is used to achieve the correct fit for various types of clothing and a range of different users. This is largely due to the development in the hardware and software capabilities of 3D scanning and 3D computer modelling that can accurately measure and represent the human body. The use of CAD, CAM and RP methods ensure that the fit generated using anthropometric data can be appropriately recreated in the end product and therefore, afforded to the wearer.

These methods are not used to the same extent in handwear design. This consequently means that these products do not currently benefit from the same developments in creating a more accurate fit for the wearer. This is mainly because of the inability of

3D body scanning to capture sufficient detail of the extremities which has limited the capabilities of CAD modelling to generate and simulate new designs. The use of CAD modelling to design and manufacture handwear would need to integrate manually collected 2D anthropometric data to sufficiently represent the hand as a 3D model.

The outcomes of the literature review raised the following research questions.

a) The literature review identified gaps in current knowledge and methodology of designing and manufacturing handwear. What are the appropriate research methodologies to fill these gaps and achieve the research aim?

b) Is it feasible to modify current methods of apparel design and manufacture to create a novel design tool for the design and manufacture of handwear that improves the quality of fit?

c) If so, what would be the efficacy of the tool in terms of cost effectiveness and functional effectiveness?

d) What improvement can be achieved in the quality of handwear fit and subsequent task performance?

e) Is the method for generating the tool appropriate for designing and manufacturing other products that interact with the human body?

The following chapters discuss the points raised in these questions to determine if what was proposed could be achieved.

Chapter Three:
Research Methodology

To fulfil the research objectives outlined in Chapter 1.3 and answer the research questions identified from the literature review, it was necessary to design a suitable research methodology. There were different elements influencing the structure of the methodology, these included;

- The form of research being carried out
- The research purpose
- The research strategy
- The research method
- The research tools selected

The following chapter gives a description and review of these elements to ensure the chosen methodology was appropriate and able to achieve the research aim. It goes on to explain how each element formed this methodology and provides justification for the selections made.

3.1 Forms of research

There are different ways in which behaviour or events can be viewed and understood. Research can be classed in two forms to reflect these various standpoints (Allison *et al,* 1996). The two forms of research are positivism and phenomenalism, and defining the research type influences the strategies and methodologies chosen within a research study.

Positivistic research is principally based on positive facts and observable phenomena, (Allison *et al,* 1996). This style of research attempts to produce descriptive laws from consistencies or patterns in properties or behaviour. These laws can then be applied on a sample set of data to predict events or effects on much larger sets. This is achieved by relying on certain assumptions, or postulates, of the uniformity of the collected data, table 3.1. Positivistic research frequently uses measurable evidence and therefore, can be described as quantitative.

The postulate of natural kinds. This assumes that all instances in classes and categories of phenomena exhibit the same properties
The postulate of consistency. This assumes that phenomena remain the same or change very little or slowly over time.
The postulate of determinism. This assumes that there is an orderliness and regularity in nature and, therefore, there is a consistency in terms of cause and effect.

Table 3.1 – The three postulates on which positivism is based (Allison et al, 1996)

Phenomenological research does not accept these postulates, relying instead on the view that every phenomenon is unique and this is its most important quality. It is principally concerned with the description and classification of phenomena using observation as a means to examine a situation to reveal the nature of the problems (Allison *et al,* 1996). The outcomes of these observations result in descriptions which are expressed as narrative, mainly in qualitative terms.

3.2 Research purpose

There are many reasons why one may decide to carry out a piece of research, (Birley and Moreland, 1998); however, the objective is to increase knowledge or contribute new knowledge to a particular research field. Robson (1993) classifies the reasons into three categories, illustrating that a research strategy has the purpose to explore, describe or explain a particular event or situation. These three purposes are detailed in table 3.2. It is possible for a particular study to be related to more than one purpose and this may change as the study progresses, however, one purpose will often remain dominant throughout, (Robson, 1993).

Exploratory	▪ To find out what is happening. ▪ To seek new insights. ▪ To ask questions. ▪ To assess phenomena in a new light. ▪ Usually, but not necessarily, qualitative.
Descriptive	▪ To portray an accurate profile of persons, events or situations. ▪ Requires extensive previous knowledge of the situation etc. to be researched or described, so that you know appropriate aspects on which to gather information. ▪ May be qualitative and/or quantitative.
Explanatory	▪ Seeks an explanation of a situation or problem, usually in the form of casual relationships. ▪ May be qualitative and/or quantitative.

Table 3.2 – Classification of the purposes for an enquiry (Robson, 1993)

3.3 Research strategy and method

Establishing the reason or purpose for research is the initial step in the design of the study, a strategy and methodology must be applied to collect and analyse the appropriate data. Research, as described by Allison *et al* (1996), is a 'systematic enquiry which is reported in a form which allows the research methods and the outcomes to be accessible to others (Allison *et al*., 1996, p4). Therefore, the strategy and methodologies chosen are an important and essential issue regarding the planning and perceived route for which the research must take. In a broader meaning, a strategy can be described as a particular long term plan to achieve a goal or success; and a method as a way of proceeding or doing something. Therefore, in terms of a research study, the strategy is the aim or goal that is required and the method is the chosen route or objective to which this goal is achieved.

Identifying the correct purpose of the research enables an appropriate research strategy and method to be selected, as certain types are more appropriate than others. Archer (2004) recommends three approaches for a research strategy; the humanities tradition of research, the science tradition of research and action research. Within each of these strategies there are a number of different methods that can be adopted to collect the appropriate data. Allison *et al* (1996) list seven different types of research methods;

- Scientific Research
- Philosophical research
- Historical Research
- Descriptive Research
- Experimental Research
- Phenomenological Research
- Practical Research

Some of these research methods are more suited to certain strategies than others, while some can be applied to two or all three. Table 3.3 illustrates which of the different research methods described by Allison *et al* (1996) are associated with the three strategic approaches proposed by Archer (2004). The association of research methodology and strategy is determined by the tools and outcomes that each method uses to collect data and analyse the results. Table 3.4 is a comparison the seven research methods, listing a description of each method, the tools associated with it, the outcomes generated and the validation techniques.

It is common for most research studies to adopt one method as a main form of the strategy. However, it is invariably necessary to draw upon other methods as essential parts of the study, as it is unlikely that only a single method can be used to fulfil the requirements of the research goals, (Allison e*t al,* 1996). A research study which has multiple methods as its strategy is commonly termed triangulation and enables data from different sources to be used to corroborate, elaborate or illuminate the research study, (Rossman and Wilson, 1985). When only using a single method, an unknown part or aspect of the results is attributable to the method used in obtaining them, (Robson, 1993). Using triangulation and employing a variety of methods the problem being investigated can be explored from different perspectives to verify the results obtained or explain any discrepancies found.

Strategy	**Research Method**
Humanities Approach	Philosophical Research
	Historical Research
	Practical Research
	Phenomenological Research
Scientific Approach	Scientific Research
	Descriptive Research
	Practical Research
	Experimental Research
Action Research Approach	Practical Research
	Descriptive Research
	Scientific Research
	Experimental Research

Table 3.3 – Research strategies and research methods

Research Method	Description	Tools	Outcomes	Validation
Scientific Research	The progression from an initial identification of a problem through to a conclusion.	Observations, deductive reasoning, experiments, evaluation	Experimental and theoretical results, predictions	Descriptive stats, coding
Philosophical Research	The focus on language, its interpretation, structure and meanings.	Linguistics, metaphysics, epistemology, logic	Consideration of implications and applications in practice	Non-parametric testing (Mann-Witney U, binomial test)
Historical Research	An enquiry which questions an event, development or experience.	Documents, oral evidence, archival records, interviews	Transcripts, description of events/experiences, observations	Non-parametric testing (Mann-Witney U, binomial test)
Descriptive Research	To pursue accurate and adequate descriptions of activities, objects, processes and persons.	Surveys, case studies, correlation, questionnaires	Transcripts, observations,	Coding, descriptive stats, parametric/non-parametric tests.
Experimental Research	To introduce a new element into a situation to observe the effects it produces.	Controlled /natural experiments, observational studies	Narratives, detailed descriptions, reports, experimental results	Non-parametric/ parametric testing, descriptive stats,
Phenomenological Research	The study of events as they appear to the experiencing observer.	Observations, interviews, critical ethnography	Transcripts, narratives, detailed descriptions, measures of behaviour	Non-parametric testing (Mann-Witney test, binomial test)
Practical Research	Research which results in a product(s) to constitute the main evidence of the research process.	Observations, focus groups, diaries, interviews, evaluation	Transcripts, physical artefacts, video, photographs, reports	Descriptive stats, coding, non-parametric tests

Table 3.4 – Comparison of research methods

3.4 Chosen research methodology

The aim of this research study was to develop, demonstrate and validate a method of enhancing appropriate fit for protective handwear. The purpose of the research was to describe this process and portray an accurate profile of what is occurring by the collection of evidence and empirical data, see table 3.2. The type of research questions asked in a study can have a strong influence on selecting the research strategy, (Robson, 1993). The questions formed after conducting the literature review primarily queried the feasibility of producing a design tool to improve the quality of fit in protective handwear. An appropriate way to investigate this query was to create a product or artefact that could be tested to generate communicable knowledge (Archer, 2004). Therefore, an action research approach to the research strategy was adopted. Table 3.3 identifies four research methods that are associated with an action research strategy; practical research, descriptive research, scientific research and experimental research. As the purpose of this study was descriptive in nature, a descriptive research method was chosen. This was to accurately describe the process of designing and validating a design tool that could be used to design and manufacture protective handwear with improved fit. Consequently, a practical research method was also employed as the design tool would need to be physically constructed and constitute the main evidence of the research process.

There are many research tools associated with the two research methods chosen, table 3.4. The main research tool selected for this study was case studies. Case studies would be able to provide a primary source of information to analyse the methods of integrating anthropometry and CAD/CAM used to design the tools for improving the fit of protective handwear. This research was positivistic in nature as it aimed to create a design process for these tools and demonstrate a theory based on empirical investigations of glove manufacture and assessment. By assuming the three postulates, shown in table 3.1, the results provided by the case studies maybe considered indicative of a larger population and not solely of the participants tested in the user trials.

A summary of the chosen research methodology is given in table 3.5.

Research Form Positivistic
Research Purpose Descriptive
Research Strategy Action Research Approach
Research Method Descriptive Research / Practical Research
Research Tool Case Study

Table 3.5 – Summary of the chosen research methodology

The use of case studies as the primary research tool was considered a reliable and relevant research tool. Case studies are a useful tool for the exploration of new or emerging processes or behaviours, and play an important role in generating hypotheses and building theory (Cassell and Symon, 2004). As the purpose of the research was descriptive, case studies offered an in-depth analysis of particular events or activities that can identify and predict relationships in and between variables, (Allison, *et al*., 1996). Gomm *et al* (2000, p6) argue that the use of case studies can “investigate processes in the ‘real world’ rather than in artificially created settings and therefore have advantages over other research methods such as experiments or surveys.”. Birley and Moreland have a similar opinion.

> “The aim of any case study is to describe and understand the phenomenon ‘in depth’ and ‘in the round’ (completeness). In this function case studies do serve a useful purpose, since many important issues can be overlooked in a more superficial study such as a survey.” (1998, p36).

Two case studies were designed to investigate and validate methods of improving the fit for protective handwear. Both case studies used anthropometric resources and CAD/CAM methods to design tools that aimed to assist and improve conventional handwear manufacturing processes. It was necessary to introduce these tools into a current manufacturing environment which required them to be as close to a fully developed product as possible. This meant that a complete design process was used within each case study; from conceptual design development to prototype production and evaluation. This enabled analysis to be made of all the relevant methods involved, as well as the issues pertaining to their interaction and influences over one another. By using case studies it was possible to compare a number of different approaches to the problem in sufficient detail to be able to draw out conclusions that could be applied to lessons which have general applicability (Moore, 1983).

Within each case study there was a range of different data collection methods used. Yin (1994) describes six sources of information, or evidence.

- Documentation
- Archival Records
- Interviews
- Direct observations
- Participant Observations
- Physical Artefacts

Many other sources are available including films, photographs and videotapes; projective techniques and psychological testing; proxemics; kinesics; and life histories (Marshall and Rossman, 1995). Yin (1994) emphasises that none of these single sources of evidence have complete advantage over the others and that a good case study will utilise as many sources as possible. Therefore, both case studies use a combination of all of these sources identified by Yin (1994) as well as dexterity testing, photographs and videotapes. Other research tools applicable to descriptive and practical research methods were also used to complement the data provided by the case studies. Interviews with, and observations of, professionals in the field of handwear manufacture and design were utilised to gain an understanding of existing expert knowledge. To assess each case study, user trials and practical assessments were used to collect quantitative data on the effectiveness of the design tools created. These data were then examined using statistical analysis to compare the different variables involved and determine if results were significant and not occurring by chance.

The use of multiple methods and research tools collected both quantitative and qualitative data. This can be used in a complementary way to enhance the interpretability of the data, (Robson, 1993). Primarily, the data collected were quantitative, in the form of the results from the user trials. The qualitative data (interviews, consultation and videotape etc.) were used to verify and support the findings from the analysis of the user trials, as well as understand any discrepancies that could not be determined from the user trial data alone.

Within both case studies there were two main issues that, if not appropriately managed, could have had significant influences on the validity and quality of the outcomes. Firstly, the close collaboration with handwear manufacturers meant that the outcomes were heavily reliant on their participation. As this study was a research project and not for commercial gain, it could not dictate when and how the manufacturers participated. The organisation of interviews; evaluation processes; and glove production was crucial. It meant that each of these elements needed to be coordinated carefully to coincide, as close as possible, with the availability of the necessary resource the manufacturers were offering. This ensured the case study could progress without loss of momentum.

The second area of concern regarded the need to be aware of the researcher influencing the events and processes within the case study. As Moore (1983, p47) points out, some thought to 'the degree of neutrality' must be given during a case study to give a fair and balanced outcome. This was pertinent to both case studies, especially during the information gathering and evaluation phases. Some affect is unavoidable as the research process itself can distort events, i.e. the Hawthorne effect, (Roethlisberger 1939; Mayo 1933). Care was taken to be impartial during interviews and testing procedures with handwear manufacturers and to ensure user trials were conducted fairly, without bias. This gave balanced results that were an accurate evaluation of the processes that the case studies were designed to analyse.

3.5 Summary

In summary, the research methodology was designed to fulfil the research objectives and answer the research questions. The methodology was influenced by five different elements; the form of research, the research purpose, the strategy, the method and the tools selected.

- The form of research was positivistic in nature as it aimed to create a design process for a tool to improve the fit of protective handwear. This process was used to demonstrate a theory based on empirical investigations of glove manufacture and assessment. By assuming the three postulates of positivistic research, table 3.1, the data collected could be considered indicative of a larger population and not solely of the participants tested.
- The purpose of the study was to describe the process of designing a tool(s) for improving the fit of protective handwear.
- The research strategy used an action research approach. This was influenced by the research questions that emerged from the literature review which examined the possibility of a novel design tool for improving the fit of protective handwear. To investigate this query, physical products were produced for evaluation and assessment.
- Descriptive and practical research methods were used to create the products required to achieve the aim of the study and describe the processes used to produce them.
- The primary research tool used was case studies. The case studies were able to demonstrate how to fully design and prototype tools that could design and manufacture handwear. Other tools were used in conjunction with the case studies to assess the effectiveness of the tools and determine if the handwear had an improved fit for the wearer.

Using this research method, the following chapters discuss how the research aim was achieved by creating and validating two different design tools that were able to produce handwear with an improved fit. The methodology used enabled the tools to be fully developed and evaluated, as well as demonstrate how the gloves produced afforded an improved fit for the wearer.

Chapter Four:
Generating a size range from anthropometric data

4.1 Introduction

The introductory chapter highlighted the need for a new approach to the design of protective handwear and how anthropometric data was an important resource in achieving the correct fit. The case studies demonstrate how methods of integrating anthropometric data and CAD/CAM can create tools for the design and manufacture of handwear with an improved fit. This chapter gives a background to the anthropometric data used in the case studies, explaining the processes used to create a size range which enabled the 3D computer models to be generated. It discusses the necessary developments and modifications made to the original data, required to successfully build these models to the correct specification. The anthropometric data is a fundamental part of these models and chiefly influences their size, shape and construction. The size range that represents the data is a series of six sizes which contain various dimensions of the hand.

The anthropometric data collection and processing detailed in this chapter was part of a separate research project, the Hand Data Deployment Project (HDDP), involving the Department of Design and Technology at Loughborough University and The Defence Logistics Organisation (DLO). The main objective of this project was to use the size range as a basis for designing the shape of a new standard issue protective glove for the British Armed Forces. This study uses the size range in a different approach, integrating it into a design process to generate a tool for the design and manufacture of handwear with improved fit. This approach uses the data as a generic resource meaning that the tools created can be developed to represent anthropometric data from other populations as well as the original military population.

4.2 Data collection and processing

The anthropometric data were collected during a survey of military personnel completed by QinetiQ (formerly the Defence Evaluation and research Agency, DERA) on behalf of the DLO. The survey collected data from 1500 personnel, 275 female and 1225 male, from several different areas of the body. The data collected for the hand was passed onto the Department of Design and Technology at Loughborough University for analysis and processing as part of the HDDP (Torrens, 2001 and Torrens *et al*, 2001). Part of the processing stage entailed dividing the data set into a series of groups to define different sizes for the sample population. This size range was used as a basis for designing the size and shape of a new standard issue glove for the British Armed Forces. This process was carried out by Mrs. Jane Robertson, a consultant ergonomist from Open Ergonomics Limited and Mr George Torrens, lecturer in the Department of Design and Technology. This enabled the data to determine how the new glove would accommodate the intended population.

Before being able to generate the size range, the anthropometric data required reviewing and validating to remove erroneous and irregular data points that would skew the boundaries of each size. The data were separated according to gender and Microsoft Excel was used to create a database and rank each dimension, as well as calculate descriptive statistics such as means and standard deviations (SD). Correlation tables were generated to clarify the relationship between the different dimensions. Data points that were four standard deviations from the mean were inspected and accepted or deleted. This decision was based on the likelihood of the data point being appropriate to the associated data set. For example, a subject with a long palm length and long middle finger length would also be expected to have a long hand length. This is because the hand length dimension is the also a combination of middle finger length and palm length. Similarly, a small hand breadth is associated with a small hand circumference, as these two measurements are taken from the same area of the hand, the metacarpophalangeal (MCP) joints. Figure 4.1 illustrates these two examples.

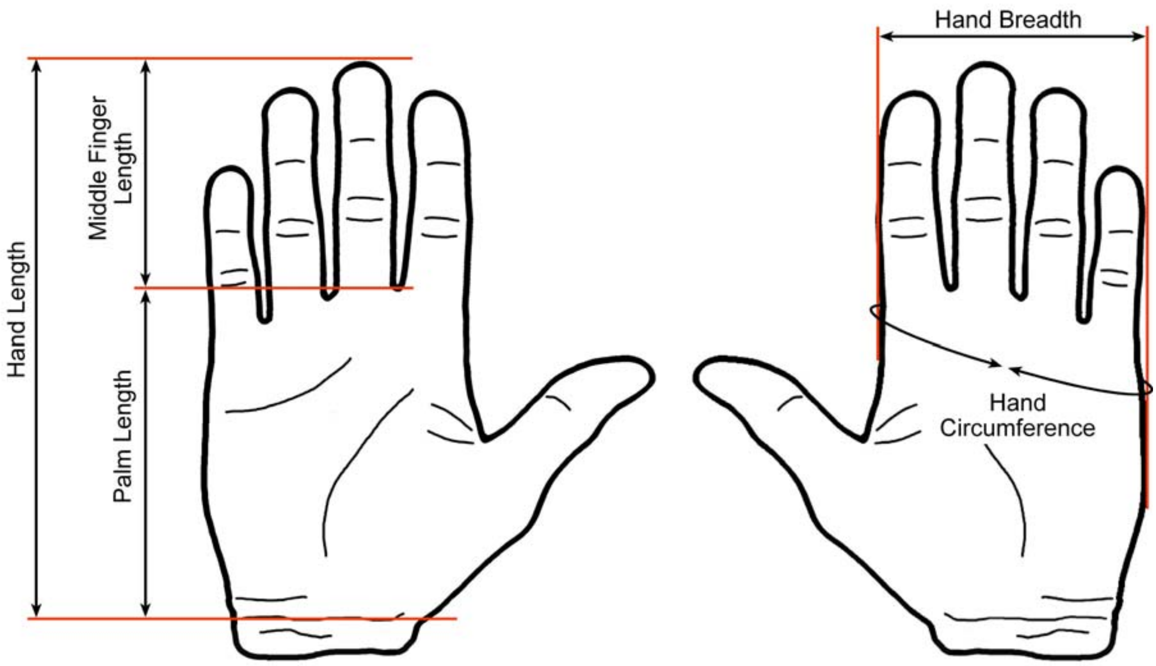


Figure 4.1 – Examples of how some dimensions are associated with one another

If the data points inspected did not conform to these conventional criteria they were removed from the database and attributed to measurement error or a deformity of the hand. Figure 4.2 identifies the digits and digit crotches of the hand. This classification is used throughout the thesis to identify the fingers and thumb instead of using the common descriptive terms, i.e. thumb, index finger, middle finger, ring finger and little finger.

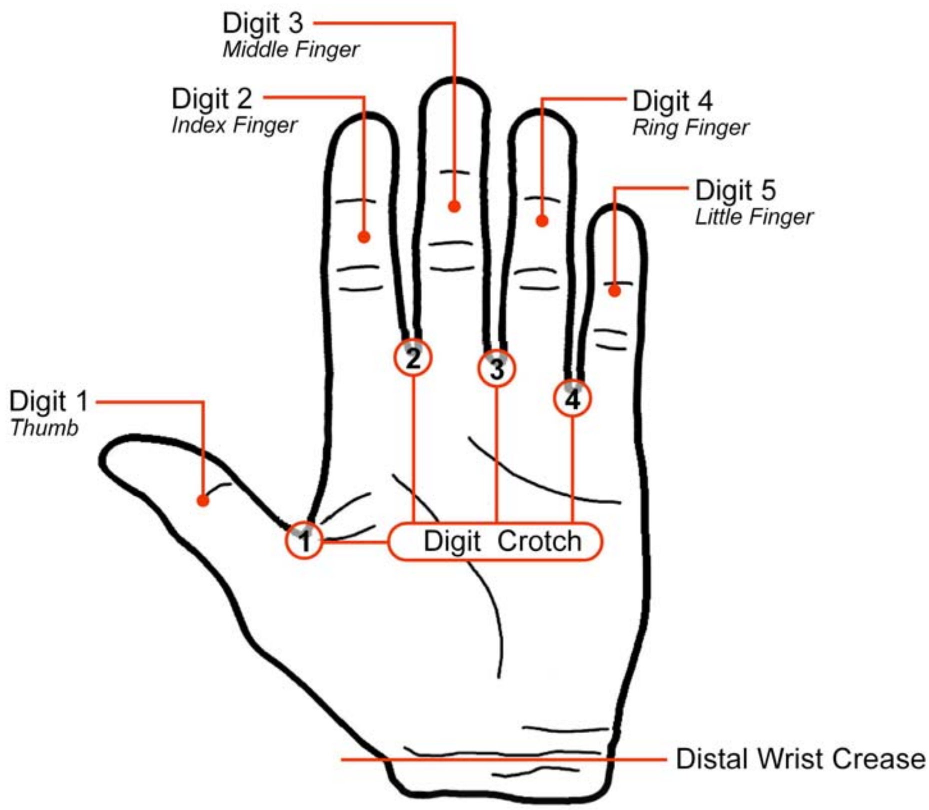


Figure 4.2 – Digits and digit crotches of the hand

The inspection process allowed the creation of percentiles from which the size range was based. The data for male 2nd and 98th percentiles were used to create the main sizes within the range. The data were evenly split into five sections to create five sizes. The 2nd percentile female data were used to create the smallest size, generating six sizes in total. The data were then checked to ensure that larger female hands would be accommodated within the male size range. The transformation from percentiles to glove sizes was not a basic conversion of the percentiles into a specific size; characteristics of glove design were also integrated. By means of a user panel, consisting of experienced experts in each relevant discipline and discussions with military personnel, individual dimensions were identified to be more critical than others in improving the fit of a glove (Noro and Imanda, 1991; Krueger and Casey, 2000, McDonagh-Philp and Torrens, 2000; Torrens and Newman, 2000). These dimensions were hand length, digit 2 length and digit 3 length. Clearly there are more dimensions necessary to create the fit of a glove, however, these three dimensions were found to be crucial (Bradley 1969[b]; Bishu and Klute, 1995; Torrens and Williams, *et al.*, 2001).

The use of these dimensions for glove sizing differs from typical glove sizing methods that use the hand circumference (figure 4.3 and table 4.2), measured around the MCP joints, as the primary criterion to determine the size of a glove. While this provides a straightforward and effective sizing method, length and width dimensions play a more important role in maintaining finger dexterity. Any inaccuracies within circumference dimensions are less influential in providing an accurate fit and will not result in the same impairment of dexterity. Therefore, prioritising the three dimensions identified and creating an accurate glove fit in these areas ensures complex tasks such as using keyboards, manipulating small objects and donning/doffing of clothing, have the least performance reduction due to wearing a glove (Torrens and Williams *et al*, 2001).

The correlations of the identified critical dimensions are given in table 4.1 and show strong correlations ranging from 0.89 to 0.73 indicating close relationships between them. Also listed in the table are the correlations between these dimensions and hand circumference. These correlations are not as strong, particularly between digit 2 length and digit 3 length (0.64 and 0.66 respectively) but indicate there are relationships between these lengths and the circumference of the hand and therefore with the common standard method of glove sizing.

Correlation	**Hand Length**	**Digit 2 Length**	**Digit 3 Length**	**Hand Circumference**
Hand Length	1.00			
Digit 2 Length	0.79	1.00		
Digit 3 Length	0.83	0.89	1.00	
Hand Circumference	0.71	0.64	0.66	1.00

Table 4.1 – Correlations of critical dimensions

A key objective when generating the size data was to ensure the handwear created from it contained accurate fit at the tips of the digits. Accurate fit in this area is achieved by ensuring there is no excess material, i.e. the fabric of the glove, around the fingers and thumb. An excess of material occurs when the glove reaches the crotch of the digit before the tip, creating a gap between the end of the digit and the glove. Previous user trials (Bishu and Klute, 1995; Torrens and Newman, 2000; Torrens and Williams *et al,* 2001) have demonstrated that excess material in this area of a glove can significantly affect the performance of the wearer. To overcome this, the size data was manipulated to shorten digit length and extending digit crotch heights. In the DERA anthropometric survey, digit crotch height was measured from the distal wrist crease to the nearest point on the skinfold of the relevant crotch, see figure 4.2 and Appendix I. Therefore, by using larger percentiles of digit crotch height and smaller percentiles for digit length within each size the desired effect was achieved.

The outcome of this modification to the size data increased the probability that gloves made to this specification would come into contact with the tips of the digits prior to reaching the digit crotch, thus eliminating the occurrence of excess material in this area. A subsequent consequence of this modification was that any gap occurring at the tips of the digits was transferred to the crotches causing potential restrictions when attempting to span the hand. However, through user trials and practical assessments (McDonagh-Philp and Torrens, 2000; Torrens and Newman, 2000) it was found that this was less important than enhancing finger dexterity and so a restricted hand span was compromised to ensure good dexterity at the digit tips.

Using these design considerations and the large amount of anthropometric data, (2^{nd} percentile female to 98^{th} percentile male) the size data aimed to accommodate a wide range of the population measured in the original survey. Each size was made up of a series of dimensions that determine the size, shape and positions of anatomical reference points on the hand. A full list of the dimensions contained within the size data is listed below in table 4.2. Figure 4.3 gives a key to the dimensions and Appendix I lists a full description of how each measurements was taken and the relevant location points used.

Key	Description
1	Hand Breadth
2 (4off)	DIP Joint Breadth - Digit 2, 3, 4, 5
3 (4off)	PIP Joint Breadth - Digit 2, 3, 4, 5
4	Hand Circumference
5	Wrist Breadth
6	Hand Length
7	Palm Length
8 (4off)	Digit Length - Digit 2, 3, 4, 5
9 (4off)	Digit Crotch Height - Crotch 1, 2, 3, 4
10 (4off)	PIP Joint Circumference - Digit 2, 3, 4, 5
11 (4off)	DIP Joint Circumference - Digit 2, 3, 4, 5
12	Tip of Digit 2 to Thumb Crotch
13	Digit 1 Length
14	Wrist Circumference
15	Wrist Depth
16	Hand Depth at MCP Joints
17	Hand Depth at Thenar Pad
18	Digit 1 Joint Breadth
19	Digit 1 Joint Circumference

Table 4.2 – Hand anthropometric dimensions used to generate CAD models

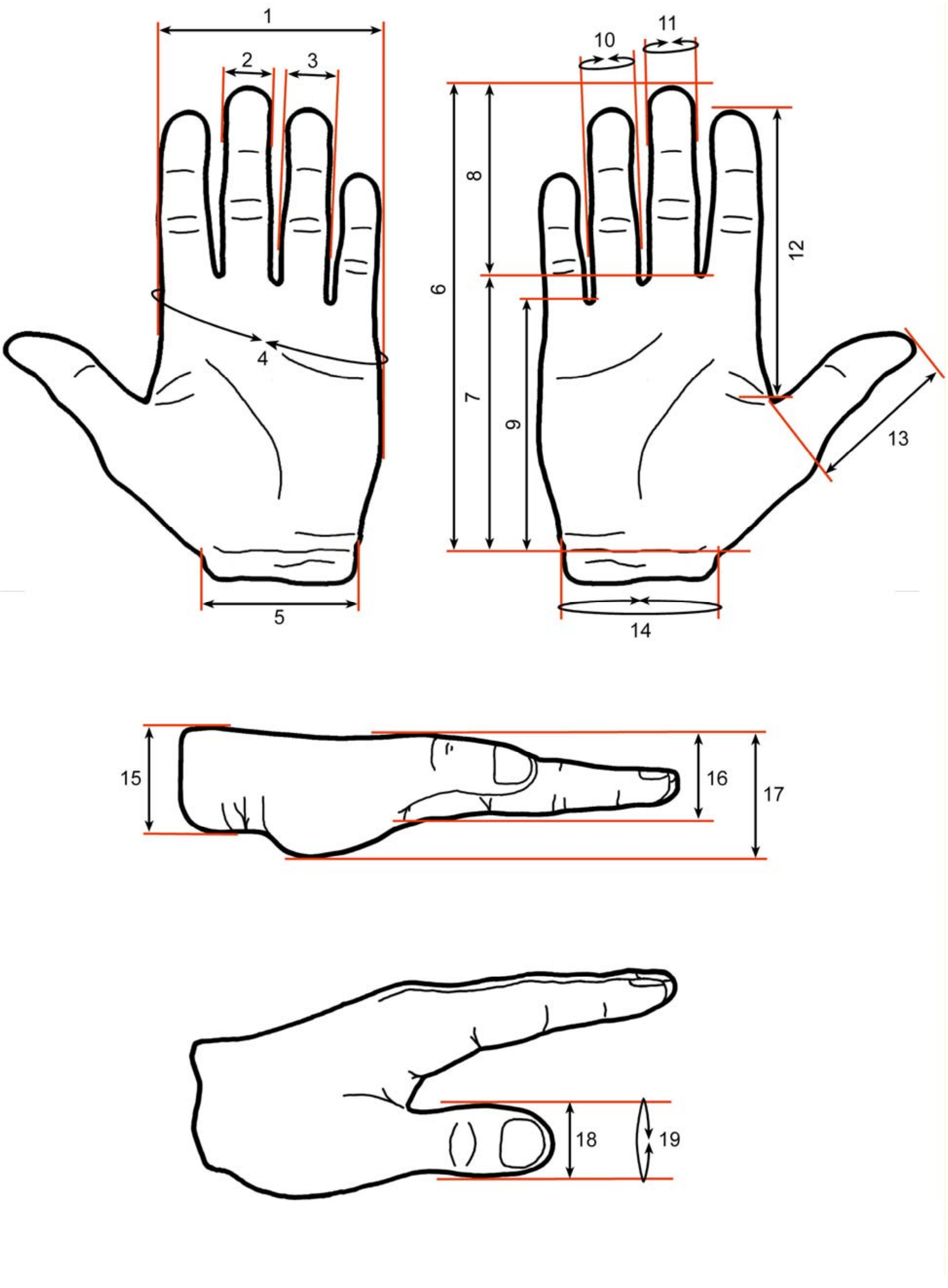


Figure 4.3 – Key to anthropometric hand dimensions used in size data

4.3 Modification of the size data

Table 4.2 and figure 4.3 show the full range of dimensions used to compile the size data. This was modified from the initial size generation process to include extra dimensions that would better define specific areas of the hand and facilitate the design of handwear. Within the same discussions used to determine the critical dimensions of the size data, it was also concluded that the dimensions taken in the initial survey did not fully represent the hand. Additional dimensions were needed to improve the level of detail in some areas of the hand and produce a more precise size range. An additional objective of the Hand Data Deployment Project was to create a computer model using the size data, similar to that developed for the first case study, Chapter 4. The deficit of specific dimensions was also highlighted during the development of this initial 3D model and it became apparent throughout the early stages that there were insufficient data to create a suitably accurate representation of the hand. The main area of the hand requiring additional detail was the depth of the palm. The original anthropometric survey only used hand circumference to represent the depth of the hand. The palm is a significant area of the hand and there are many dimensions that form the complex curvature and shape; it was not feasible to collect all the data to fully detail this region, however, more dimensions were necessary to adequately represent the various features that comprise the structure of the palm.

The problems identified with the original data meant that new dimensions needed to be added to the size range. These dimensions were the depth at the knuckles and the depth at the thenar pad (the fleshy area of the palm located at the base of the thumb), dimensions 16 and 17, table 4.2 and figure 4.3. This gave a more accurate representation of the palm, increasing the level of detail present in the size range. Additionally, wrist breadth and wrist depth were also taken (dimensions 5 and 15) as only wrist circumference was measured in the DERA survey. This enhanced the detail of the wrist and also aided the CAD modelling process as using lengths and breadths rather than circumferences enabled a more accurate 3D representation to be generated. The need for these extra dimensions led to a small anthropometric survey being conducted to collect the additional data required. The survey used undergraduate students from the Department of Design and Technology at Loughborough University and military personnel and included some measurements from the original DERA survey as well as the new dimensions. The measurements taken in this additional anthropometric survey are listed in table 4.3.

Key	Description
1	Hand Breadth
5	Wrist Breadth
6	Hand Length
10	Digit 2 PIP Joint Breadth
	Digit 3 PIP Joint Breadth
11	Digit 2 DIP Joint Breadth
	Digit 3 DIP Joint Breadth
14	Wrist Circumference
15	Wrist Depth
16	Hand Depth at MCP Joints (Knuckles)
17	Hand Depth at Thenar Pad

Table 4.3 – Measurements taken in additional anthropometric survey

The survey measured 143 students (34 female, 109 male) and 16 military personnel (all male). Due to this additional survey being part of the HDDP, there was no influence on the number of subjects or the selection methodology. The selection process was based on the number of students and military personnel that were available to the researchers involved in the HDDP. The data from the repeated dimensions collected in the survey (table 4.3) were compared to the original data to determine the correlation between the two different sets of data. The comparisons showed that the student population and military population were similar in size; with nominal differences between the two sets of data. This meant the additional dimensions could be incorporated into the original size range. A limitation of the additional survey was that there were an insufficient number of subjects to specify 2nd and 98th percentiles for both male and female samples. This meant that the depth specifications for the full size range were estimated, not calculated as for the other dimensions. However, this enabled a revised size range to be generated which included the new depth dimensions of the palm and the length and breadth dimensions of the wrist. The new dimensions for the wrist did not replace the circumference measurement and this remained in the size range as it was an important dimension that defined the wrist shape. Including the additional dimensions gave a more complete representation of the hand, detailing the contours and depths of the palm to a greater extent than was initially carried out in the DERA survey. This provided greater accuracy for designing the size range with an aim to create a shape and size of a new glove to afford an enhanced fit for the wearer. It also allowed the CAD model generated to contain more features of the hand and improve the level of detail within this 3D representation of the size data.

In the following case study research, the data from the size range generated as part of the HDDP are used as the primary resource for the development of the tools aimed at manufacturing, designing and evaluating different types of handwear. The size data, therefore, is a fundamental element of the structure for these tools and the CAD models from which they are derived. The validation of the data is limited due to the main portion being collected and recorded from an independent anthropometric survey, with certain details remaining confidential. The reliability and precision of the data cannot be verified. However, some indication to these properties can be taken from a full validation of the data from the student population conducted by Edwards (2007). As the student population and military population were comparable, this validation was used to indicate the level of precision achieved and highlight any measurements that consistently contained any error. The validation study carried out by Edwards (2007) assessed precision using the technical error of measurement (TEM) and reliability using the coefficient of reliability (R). It found that none of the measurements used in the size data had any significant errors in terms of precision or reliability.

The sources of data, primarily from military personnel, were initially used in the HDDP with intentions for improving handwear for military use. This, however, does not suggest that the design methods developed during the case study research would be exclusively for, or associated with the HDDP, nor that they would be specific to military applications.

Chapter Five:
Case Study One – Development of a size gauge to design handwear with improved fit

5.1 Case study objectives

The following chapter discusses the first case study. This case study was designed to demonstrate how the integration of anthropometric data with methods of CAD/CAM can generate a tool that would improve the fit of handwear. The outcome of this integration is a series of gauges that designers can use to assess the size of a completed glove pattern during the conceptual stage of the design process. This refines the iterative stages of this process by reducing the amount of time and cost needed to complete it; ensuring the final glove is more accurate. To demonstrate this, the gauges were introduced into a commercial manufacturing process to produce a new glove. This addressed the research question;

- **b)** Is it feasible to modify current methods of apparel design and manufacture to create a novel design tool for the design and manufacture of handwear that improves the quality of fit?

By designing suitable assessments to evaluate the gauges and the gloves produced using them, two other research questions were addressed;

- **c)** What would be the efficacy of the tool in terms of cost effectiveness and functional effectiveness?
- **d)** What improvement in the quality of handwear fit and subsequent task performance can be achieved?

To fulfil the points raised in these questions the objectives for this case study were as follows;

- To represent 2D hand anthropometric data in a 3D format by generating 3D computer models.

- To develop these computer models into a tool that assesses size during the design and evaluation of handwear.
- To accurately produce a tool from these computer models using methods of RP and CAM.
- To use the tool in a commercial handwear manufacturing process for the design and evaluation of a new glove.
- To evaluate the gloves manufactured through user trials to assess their fit and determine any improvement.

The methods used in this case study and some preliminary results found in the user trials have been published in an engineering journal (Williams *et al,* 2004[a]) and presented at an international conference, (Torrens and Williams, 2003). This provided feedback and discussion of the issues involved.

5.2 Introduction

This first case study focused on improving the fit of handwear manufactured using 2D patterns, manually machine stitched together to form the 3D glove, see figures 5.35 and 5.42. These types of gloves are commonly used for a wide range of applications, from sportswear to PPE, and remain the most effective technique to manufacture handwear from natural materials, such as leather, and those produced from a composite of materials, such as leather, cotton, rubber and polyester. Important factors that need to be considered during the design of these types of gloves relate to the seam type, size and position; and the properties of the material used. All of these factors influence the design of a pattern and must be considered at an early stage to ensure the glove produced is to the correct size. The tool developed in this case study was an aid in the cut and sew glove manufacturing process, primarily used during the pattern design stage. It gave the pattern designer a 3D reference of the glove size, enabling a quick, accurate assessment to be made during the creation of the 2D patterns.

The case study contained three main stages. The initial stage was to generate computer models using the dimensions within the size range to create a 3D representation of the anthropometric data. Part of the CAD modelling process was to develop a method that enabled the computer models to be modified easily and precisely to allow the different sizes in the size range to be generated accurately. The next stage was to develop a process that would recreate the computer models as physical manikins so they could be integrated into a manufacturing environment and used as a size gauge. It was necessary to select suitable methods of CAM and RP that were capable of producing an accurate replica of the CAD models. The final stage of the case study was the evaluation phase. This was in two parts; the first evaluated the use of a size gauge when integrated into a pattern design process to produce a new glove. The second phase entailed assessing these gloves, using a battery of tests to analyse their fit.

5.3 CAD model generation

The first stage of this case study was to generate 3D computer models using 2D anthropometric data. Using the processed size data generated from the anthropometric survey, discussed in Chapter 4, geometric shapes were created that represented the different elements of the hand. The data also enabled the shapes be assembled together to create the hand form. CAD models were generated for each of the six sizes in the range. An initial model was generated from dimensions of the size three data; this was used as a basis to generate the subsequent models of the other five sizes after the modelling processes and techniques had been proven.

The dimensions within each of the sizes relate to different parts of the hand, see table 4.2 and figure 4.3. These dimensions were used to draw 2D splines and construction lines to generate the 3D solid model. The fingers (digits 2-5) are represented as cylinders with variable cross-sections. The cylinders were formed by firstly drawing four 2D circles to create a skeleton structure, figure 5.1. Each circle is equivalent to each joint within the finger, therefore, the first circle relates to the MCP joint breadth (knuckle joint); the second circle relates to the PIP joint breadth; the third and forth relating to the DIP joint breadth, figure 5.1. The diameter of each circle was determined by the breadth dimension of the respective joint, consequently a DIP joint breadth of 18mm corresponds to a diameter of 18mm for the associated circle. The distance between the first circle and the fourth circle is equivalent to the length of the finger being generated. All the circles are aligned along the same point on a vertical axis on their circumferences and not by their centres. This creates a straight edge to one side (the back) of the cylinder and a taper to the other (the front), which reflects the natural shape of a finger. The circles are then used as a framework to build solid geometry and complete the cylinder, figure 5.2. The final step was to apply a radius at the top of the cylinder which gave it the necessary curvature to represent the shape of the fingertip, figure 5.3

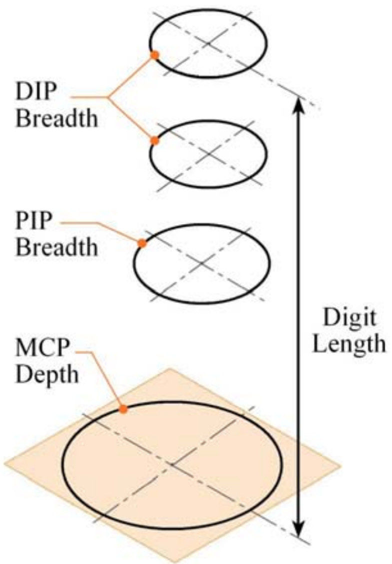


Figure 5.1 – Three circles representing the structure of a finger

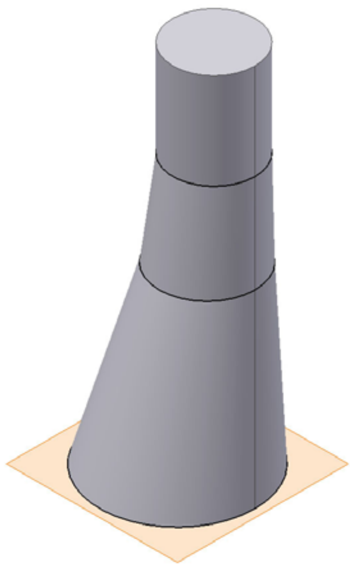


Figure 5.2 – Circles used to generate 3D geometry

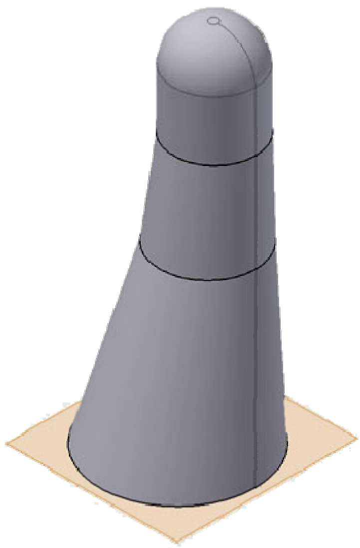


Figure 5.3 – Radius applied to represent curvature of fingertip

The thumb (digit 1) was constructed using a similar method. Again, a series of circles were drawn to represent the joint breadths related to the thumb, figure 5.4. The two dimensions used to draw the series of circles were digit 1 joint breadth and the depth at thenar pad. The joint breadth dimension was used to create the shape of the thumb and the depth at thenar pad dimension was used to construct the joint where the thumb joins the palm. The distance between the circles was determined by the digit 1 length dimension. The circles were use to create 3D geometry with a radius applied to the top of the cylinder to represent the curvature of the thumb tip, figure 5.5.

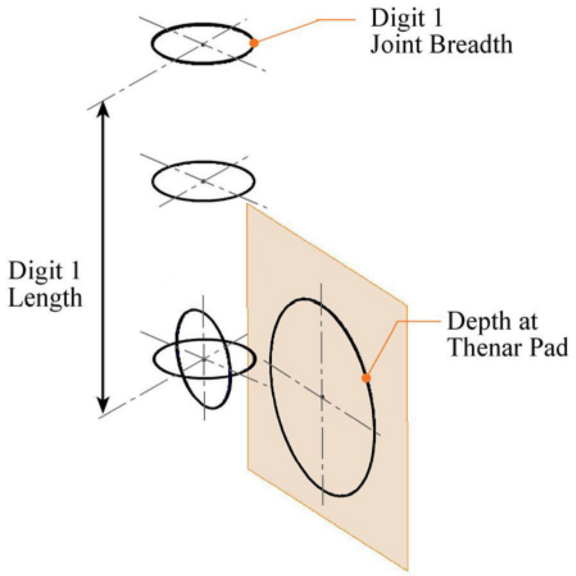


Figure 5.4 – Framework structure for thumb construction.

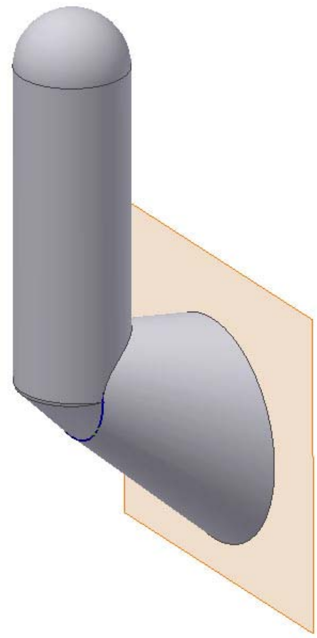


Figure 5.5 – Completed thumb 3D geometry.

The same method was used to create the palm of the hand. The dimensions used to create the palm were as follows:

- Hand breadth
- Palm length
- Depth at MCP joints
- Wrist breadth
- Wrist depth

Figure 5.6 illustrates the framework structure used to build the palm. It consisted of an ellipse to represent the wrist and two rectangles to represent the main section of the palm. The major axis of the ellipse was specified using the wrist breadth dimension and the minor axis using the wrist depth dimension. The size of the rectangles was created using hand breadth and the depth at MCP joints dimensions. Above the ellipse the first of the two rectangles was positioned using the crotch height 1 dimension. The second rectangle was used to create the top of the palm and was positioned using the crotch height 1 dimension, minus the palm length dimension. The ellipse was positioned centrally to the rectangles as there were no dimensions within the size data to specify the location of the wrist relative to the palm.

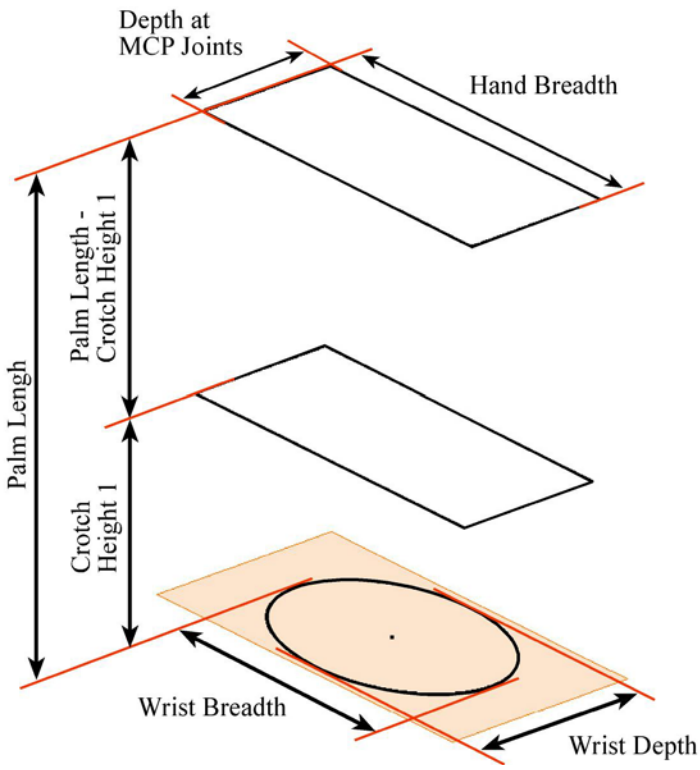


Figure 5.6 – Framework structure used to construct the shape of the palm

The two rectangles were then used to generate the upper section of the palm, with the first rectangle and ellipse used to generate the lower section, figure 5.7.

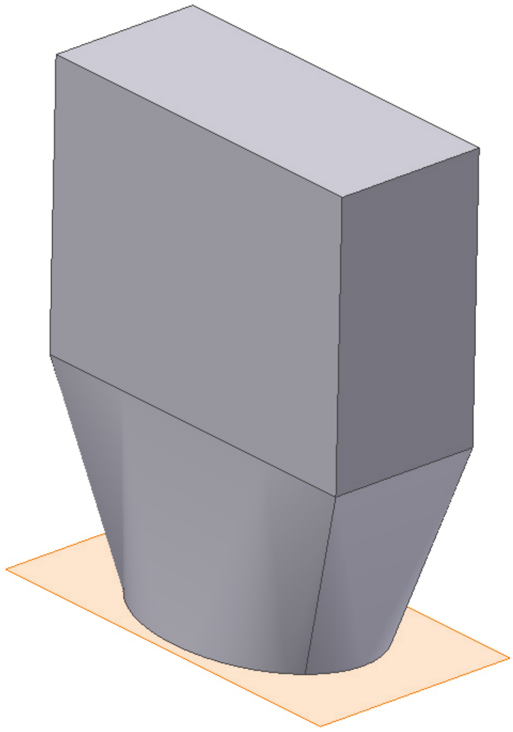


Figure 5.7 – The 3D geometry of the palm created by the framework structure.

To define the shape of the digit crotches, the crotch height dimensions were used to create the required profile along the top edge of the palm, figure 5.8. Sections were removed from top of surface to create the heights needed to represent crotch heights 2, 3 and 4.

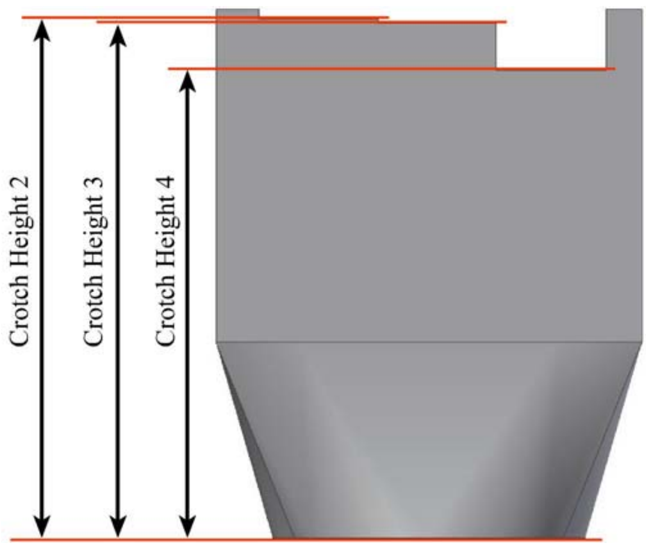


Figure 5.8 – Crotch height dimensions used to define the profile of the digit crotches.

Other dimensions within the size data were then used to determine the position of each element relative to one another and generate the full model. The dimensions for crotch height and hand breadth were used to position all four fingers. Using the wrist as a datum point, each finger was positioned relative to the wrist using the corresponding digit crotch length. Digits 2 and 3 positioned using the dimension crotch height 2, digit 4 positioned using crotch height 3 and digit 5 using crotch height 4. Hand breadth was used to ensure there was an equal distance between each finger, distributing them evenly across the width of the palm, figure 5.8 and 5.9. The thumb was positioned using the crotch height 1 dimension, figure 5.9.

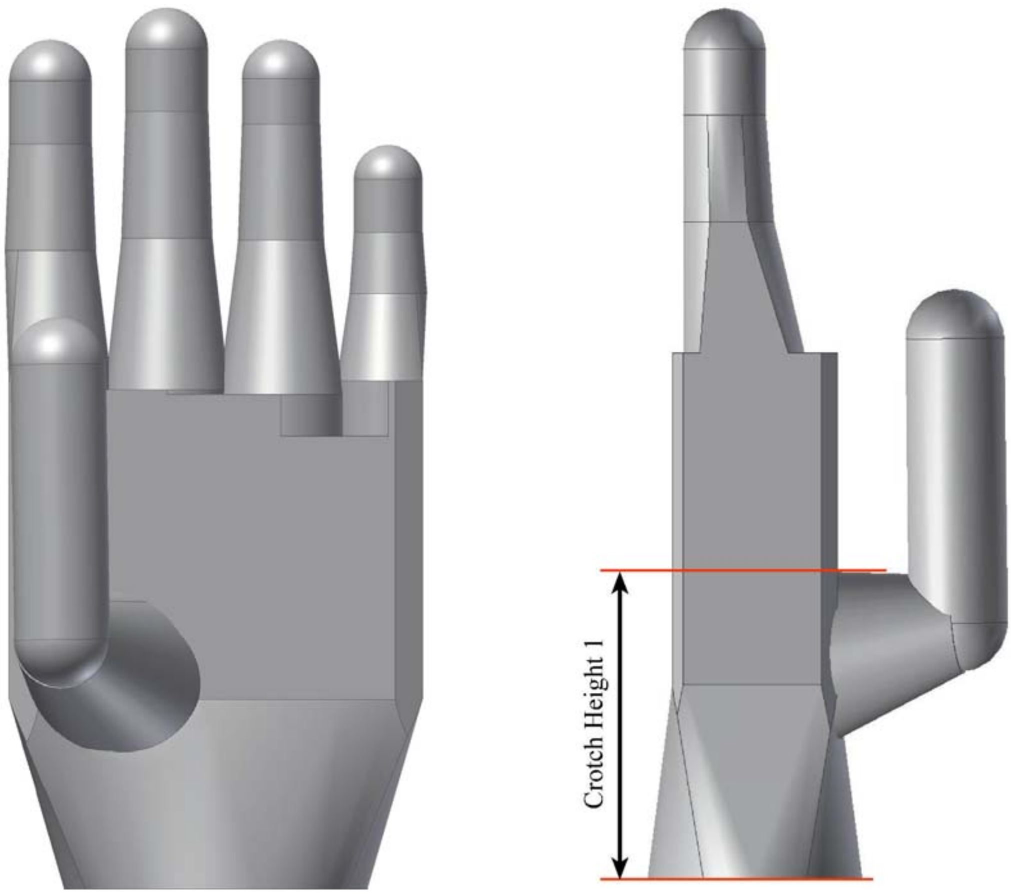


Figure 5.9 – Digit crotch heights and hand length used to locate digits.

Previous attempts of using hand anthropometry to build CAD models have concluded that the collection and processing of the anthropometric data is one of the most important factors when integrating it into the CAD model (Hidson, 1991[b] and Hidson, 1992). The initial CAD model generated during the HDDP, (Torrens, 2001) described in Chapter 4, lacked sufficient accuracy and required additional dimensions which lead to the supplementary anthropometry survey to collect the necessary data. The same conclusion was found when generating this CAD model, as it immediately became apparent during the initial stages of the modelling process that there were insufficient dimensions in the original size data to adequately represent the hand. Considering the previous experiences of Hidson (1991[a], 1991[b]) and the HDDP (Torrens, 2001), the revised size data was used to generate this CAD model to ensure that a sufficient level of detail was achieved and the model could be developed into a conceivable tool for handwear design. As described in Chapter 4.3, the amount of data needed to be collected to fully represent the palm was not possible due to the complex curvature and shape of the palmar surface. In addition integrating this level of detail into the CAD model would over complicate the modelling process, increasing the difficulty and time for modifying and resizing the constituent parts. The extra dimensions added to the size data were sufficient to significantly improve the representation of the palm enabling the features of the knuckles and the thenar pad to be represented and create a smother transition between the palm and the digits.

The size data had a total of 37 dimensions within each size; however, some of these represented the same part of the hand. For example, there were three dimensions to specify the size of the wrist; wrist circumference, wrist breadth and wrist depth, see table 4.2, figure 4.3. When generating the framework structure only length, breadth and depth data were used as the primary source for the size of the relevant feature and in the assembly of all the 3D solid geometry. This benefited the CAD model generation in two ways, by enabling the framework structure to be constructed with greater accuracy and efficiency; and also simplifying the resizing process of the CAD model to create representations of all six sizes. The framework consists of circles, ellipses and rectangles. To draw these shapes accurately within the CAD software diameters, radii, lengths and breadths were needed as the input criteria. Circumferences remained an important part of the modelling process, but were only used to verify the solid geometry created by the framework was to the correct size and shape. Using length and breadth dimensions also facilitated the resizing process for generating the CAD models for the other sizes. By ensuring the dimensions that determine the size and shape of the framework could easily be updated and modified it enabled subsequent CAD models to be generated accurately and efficiently by eliminating the need to continually construct new structures for each model.

The initial construction if the CAD model had two limitations which lead to further modifications being introduced. The intended approach to using the CAD model was to reproduce it as a 3D manikin and integrate this into the design and evaluation processes of handwear. This was not feasible with the initial shape. During a fit assessment it would be necessary to don and doff a glove or other piece of handwear onto the size gauge. Currently, this would not be possible because of two characteristics within the CAD model; the static, opposable position of the thumb and insufficient space between the fingers, figure 5.10.

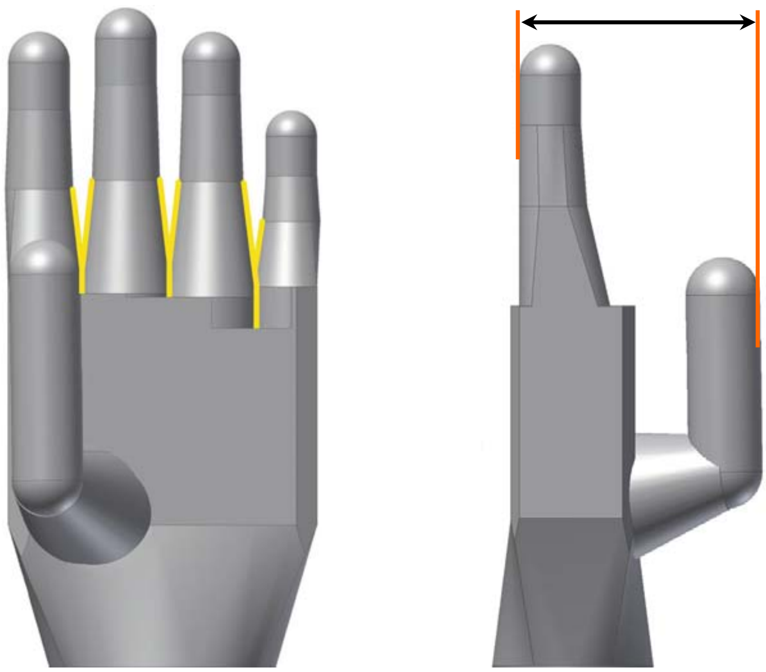


Figure 5.10 – Insufficient space between the fingers and the position of the thumb restricts ability to don a glove.

The distance between the thumb and the digit 2 (determined by the size data) means it would be difficult and cumbersome for even a highly flexible glove to be donned. The thumb cannot be manoeuvred into the glove because of its fixed position, and therefore it would not be possible to don the glove in a conventional fashion. The limited space between the fingers (highlighted in figure 5.10) occurs because the total of the MCP depths is greater than hand breadth. Therefore, because the fingers are assembled parallel to the palm and are constrained to fit within the width of the palm, there is an insufficient gap between each finger to accommodate any material thickness. The base of each finger overlaps one another at the crotch areas, resulting in a lack of space for a glove to fit within the crotch of the manikin.

These two limitations of the CAD model would clearly cause significant problems when integrating it into handwear design and evaluation processes. To resolve these issues, it was necessary to develop the model further, before any 3D reproductions were generated. Firstly, a gap between the fingers was needed at the point where they join the palm. Spreading the fingers or spanning the hand would not resolve the issue as this would cause problems when donning and doffing, similar to those associated with the thumb position. To generate the gap required, the framework structure was re-modelled to reduce the width of each finger, while maintaining the necessary dimensional accuracy. The MCP and PIP joints of the finger were reduced to the size of the relevant DIP joint, figures 5.11 and 5.12. Applying the reduction to only the sides of the fingers ensured the MCP breadths and PIP breadths continued to be represented in the CAD model.

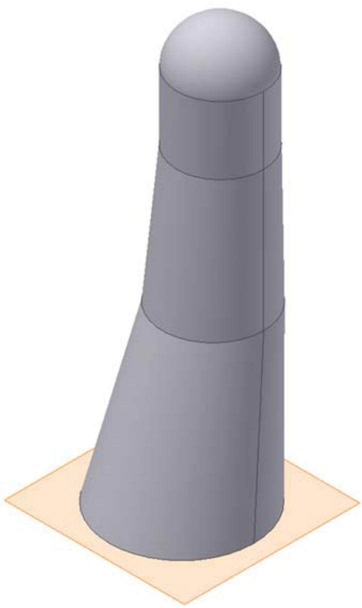


Figure 5.11 – Original finger shape

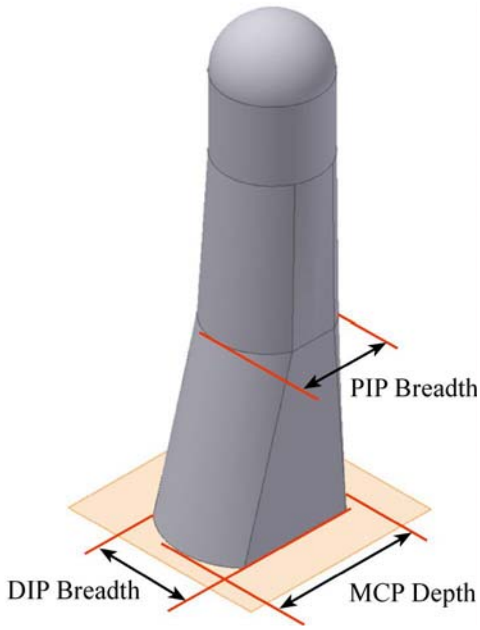


Figure 5.12 – Revised finger shape

When this revised shape was applied to each finger the result increased the distance between the fingers, creating space to accommodate the material thickness of a glove, figure 5.13.

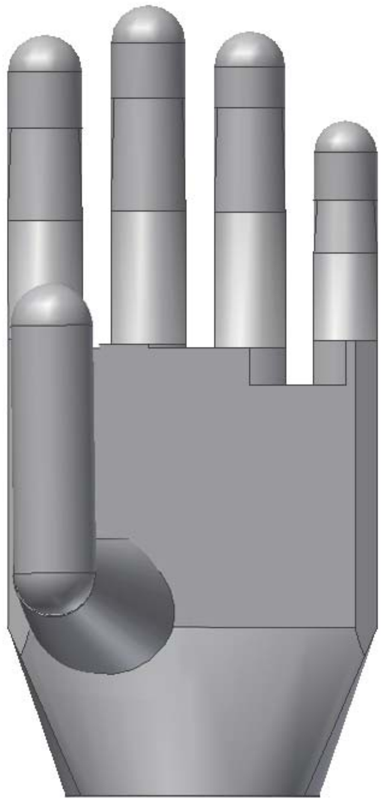


Figure 5.13 – Revised finger shape gives sufficient room at crotches

The second modification required was to resolve the problem caused by the fixed thumb position. A critical property of the manikin created from the CAD model is the ability for it to easily don and doff a glove. Failure to have this property would significantly inhibit the ability for it to be used for the design and evaluation of handwear. Several options were considered. Changing the position of the thumb to the side of the palm would give similar problems and not accurately represent the thumb crotch. Developing a thumb that could be manoeuvred into the glove was a plausible feature of a design tool of this type; however, the components and mechanisms necessary would be difficult to integrate into the CAD model and may be cumbersome to operate. What was required was a simple process to enable a glove to be assessed quickly and accurately.

The solution chosen was to separate the initial CAD model into two models and assess the thumb area of the glove independently from the rest of the hand. This would consequently mean a glove would need to be donned onto two separate manikins to make a full assessment. One of the models had the thumb removed, and could assess the fingers, thenar pad, palm and wrist. The other model had only the thumb, index finger and part of the palm which enabled assessment of the thumb detail. The index finger on this model gave a reference point during an assessment, as without it, the thumb could be located in the glove but would be unable to determine the correct orientation. The separated models can be seen in figure 5.14 and in more detail in Appendix II. Although this solution to the donning and doffing problem required the same glove to be donned and doffed twice to be fully assessed, it enables all areas of the glove to be evaluated easily and accurately.

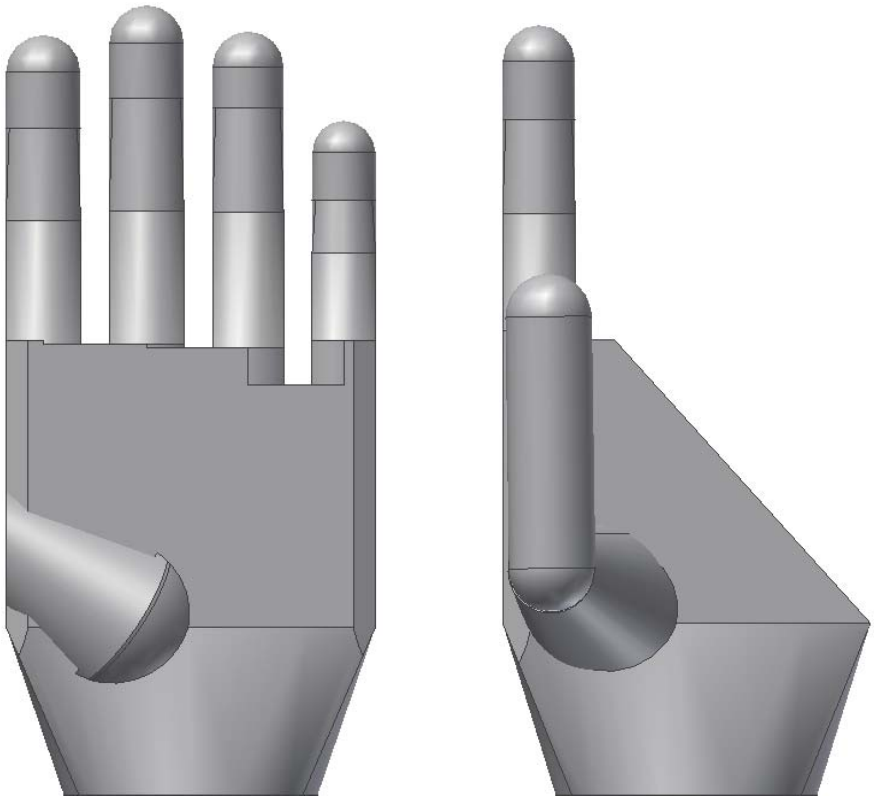


Figure 5.14 – The main CAD model split into two separate models

The final part to be added to the models was the forearm. There were no dimensions within the size data to specify this aspect of the CAD model; therefore, a simple extrusion from the wrist was added to represent this feature. The ellipse which formed the wrist was extruded down to a distance of 150mm and at a draft angle of three degrees to create a tapered elliptical cylinder attached to the bottom of the hand. Figure 5.15 shows the final configuration of the CAD models with the all the parts assembled.

Figure 5.15 – The final configuration of the CAD models.

The unusual shape of the CAD model is a consequence of the composite nature of the size data. The aim of generating the CAD model was not to create a realistic hand shape, but to accurately represent the size data in a 3D form. Each size within the size range incorporates the maximum dimensions required to enable the largest individual within a defined hand size group to fit the handwear, whilst enabling the smallest in the defined size group to be accommodated. Therefore, due to this and the design considerations and modifications made during the generation of the size range, e.g. the shortening digits and extending digit crotch heights shape (Chapter 4.2), the shape size and proportions of the CAD model is unlike an orthodox hand.

Once the correct size and configuration of the CAD model representing size three data had been determined, the next stage in the modelling process was to generate CAD models for the remaining five sizes. Each size within the range was created individually and not proportionally, this meant that each of the CAD models must also be created individually and could not be scaled up or down from the first model. The two models needed for each size were generated independently and not created by splitting one full model into two separate ones, meaning it was necessary to generate two CAD models for each size. Therefore, as there were six sizes, a total of twelve CAD models would be required for all six sizes. To generate ten additional CAD models using the same modelling techniques as used for the first two would have been time consuming and susceptible to the introduction of dimensional errors within the model. A critical property of the CAD models was that they should be generated to the same level of accuracy. This led to a different modelling strategy being applied to ensure that each model could be created accurately and efficiently.

The strategy was derived from the basis that although the human hand varies in size and shape from person to person, the basic arrangement and proportions remain the same. Subsequently, while the sizes of the geometric shapes that constructed the models could not be scaled between sizes, it was possible to standardise their assembly and relevant position to one another. Parameters were derived from the initial model that would be the same for each model in the size range. For example, the distance between each finger was calculated by subtracting the width of the palm from the total width of the fingers, divided by three. This formula could be used for each of the models with four fingers, as there was no data within the size range that governed this gap. It therefore, needed to be determined from other dimensions upon which it was dependant. Furthermore, specific constraints within the model were also the same for each size. For instance, the palm was always joined to the forearm; the fingers were always joined to the palm; and the radius at the top of a digit was always determined by the DIP breadth.

Using these parameters and constraints that were present in all the models, a basic outline of where each component should be assembled and how it is constrained, relative to other components, could be generated. Integrating these constraints and formulae into the initial CAD model allowed the subsequent models for other sizes to be generated by changing the necessary dimensions within the skeleton framework to the relevant dimensions within the size data. This process, however, remained cumbersome and likely to incur errors due to the number of values needing to be changed and confusion over which value generated which part of the model. Therefore, to further facilitate the modelling process and as an alternative to directly changing the values on the CAD model, a database linked to the model was created to enable the values to be entered into a spreadsheet which would automatically create the required geometric shape. The database contained all the dimensions from the size range necessary for generating the model. Changing the value in the database changed the corresponding dimension within the framework structure. For example, changing the value of the hand breadth in the database modified the width of the rectangle that is used to form the palm on the 3D model. By adding the constraints and formulae into the database the configuration and assembly of the parts could also be controlled when modifying the values. For example changing the palm width also changed the gaps between the fingers. This is because of a constraint within the model that specifies digits two and five are constantly attached to the edges of the palm and the formula using the value of the palm width to dictate the size of the gap between the fingers. This ensures that the fingers always remain evenly spread across the width of the palm and the gap between them is equal. A complete list of the parameters and a description of which area of the CAD model it relates to is given in table 5.1.

Parameter Name	**Description**	**Value**
WB	Wrist Breadth	Value from size data
WD	Wrist Depth	Value from size data
FAL	Forearm Length	Value from size data
FADA	Forearm Draft Angle	3 degrees
KD	Knuckle Depth	Value from size data
HB	Hand Breadth	Value from size data
PL	Palm Length	Value from size data
LPSL	Lower Palm Length	CH1
UPSL	Upper Palm Length	PL – CH1
D1B	Digit 1 Joint Breadth	Value from size data
D2PB	Digit 2 PIP Joint Breadth	Value from size data
D2DB	Digit 2 DIP Joint Breadth	Value from size data
D3PB	Digit 3 PIP Joint Breadth	Value from size data
D3DB	Digit 3 DIP Joint Breadth	Value from size data
D4PB	Digit 4 PIP Joint Breadth	Value from size data
D4DB	Digit 4 DIP Joint Breadth	Value from size data
D5B	Digit 5 PIP Joint Breadth	Value from size data
D5DB	Digit 5 DIP Joint Breadth	Value from size data
DG	Gap Between Digits 2-5	(HB – (D2PB+D3PB+D4PB+D5PB)) / 3
CH1	Crotch Height 1	Value from size data
CH2	Crotch Height 2	Value from size data
CH3	Crotch Height 3	Value from size data
CH4	Crotch Height 4	Value from size data
MCP	Depth at MCP	Value from size data
DTP	Depth at Thenar Pad	Value from size data
D1L	Digit 1 Length	Value from size data
D2L	Digit 2 Length	Value from size data
D3L	Digit 3 Length	Value from size data
D4L	Digit 4 Length	Value from size data
D5L	Digit 5 Length	Value from size data
DTC	Digit 2 to Thumb Crotch	Value from size data
D1TR	Digit 1 Tip Radius	D1B
D2TR	Digit 2 Tip Radius	D2DB
D3TR	Digit 3 Tip Radius	D3DB
D4TR	Digit 4 Tip Radius	D4DB
D5TR	Digit 5 Tip Radius	D5DB
DC2	Digit Crotch 2	PL – CH2
D3C	Digit Crotch 3	PL – CH3
D4C	Digit Crotch 4	PL – CH4

Table 5.1 – Parameters within the CAD model database

Figure 5.16 shows the modelling environment when generating the CAD models. The database containing all the relevant data can be viewed together with the 3D model alongside it. Each dimension, constraint and formula is clearly labelled to ensure the correct values are changed when generating or modifying a model. By using this method, the modelling process was significantly simplified. It was no longer necessary to modify the 3D model directly as all the modifications could be made to the database. This produced a process that was considerably quicker and more accurate than creating each model individually. It was not necessary to create both a left and a right model for each size as the size range only contained data of one hand. The CAD models were of the left hand, and the 3D manikins made from them would therefore also be left handed. To produce a right handed manikin, the left hand CAD models could be mirrored in the CAD software. No values required modifying as the same dimensions were used for both left and right handed models.

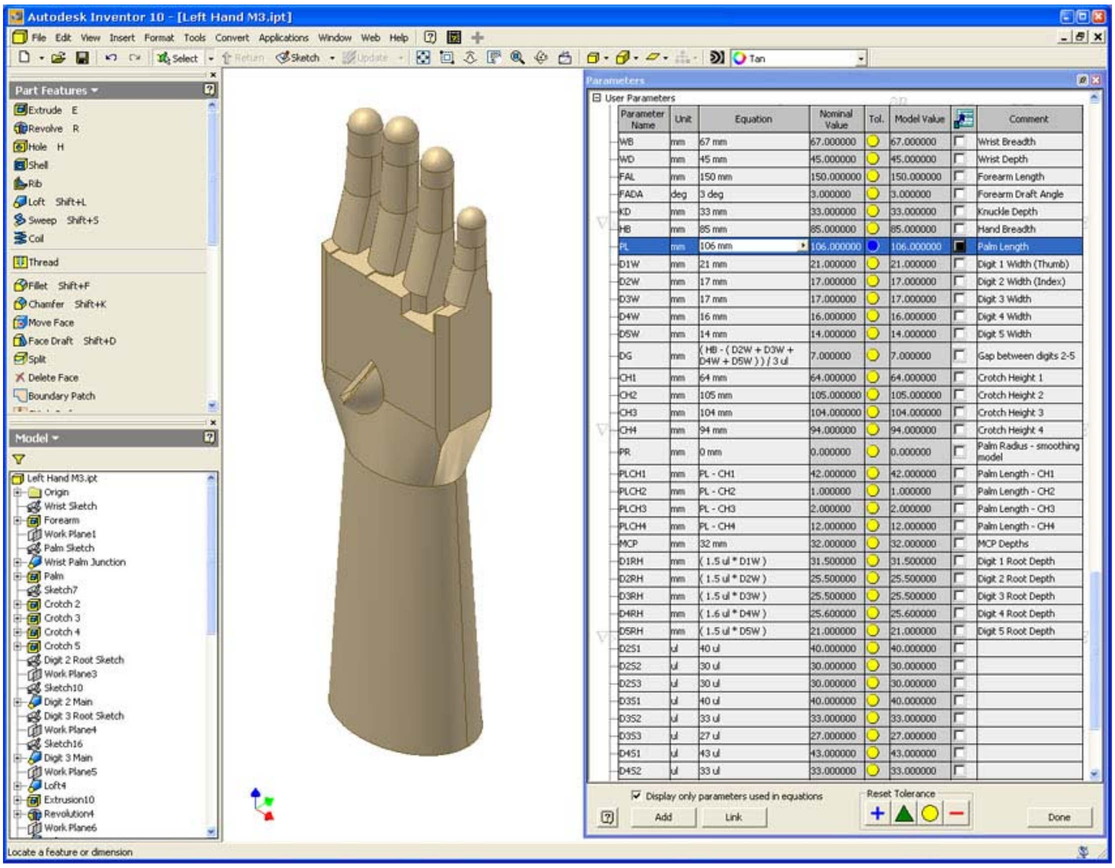


Figure 5.16 – CAD modelling environment showing 3D model with database containing dimensions, constraints and formulae.

With the development of a functional modelling process and technique, the remaining ten models were generated to produce a complete set and represent each size in the range, figure 5.17. Each model set (the hand model and the thumb and finger model) were numbered one to six, corresponding to the size it represented. This completed the first stage of this Case Study and demonstrated the steps necessary to build a 3D computer model from 2D anthropometric data. The next stage was to convert this model from a digital 3D representation of the data to a physical 3D representation so that they can be used within a handwear manufacturing environment.

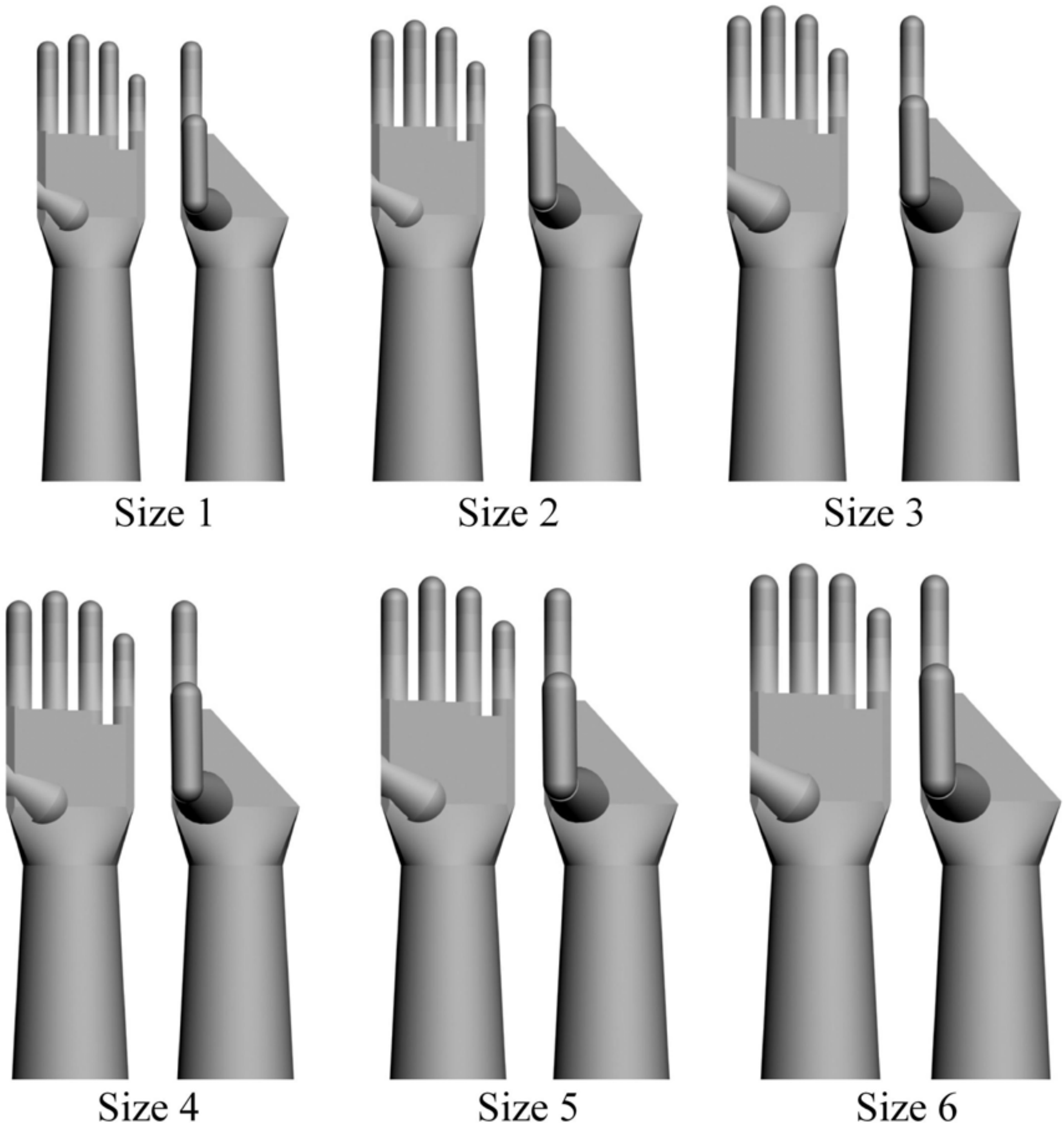


Figure 5.17 – Full set of CAD models

5.4 Reproducing the CAD models as 3D manikins

To integrate the CAD models into the processes of design and evaluation for handwear, it was necessary to reproduce them as 3D manikins. There are a variety of Computer Aided Manufacturing (CAM) and Rapid Prototyping (RP) methods and technologies that can be employed to reproduce a computer model as a physical 3D object. When deciding which combination of these methods and technologies were appropriate for this case study, the most important consideration was to replicate the CAD models as accurately as possible. The development of the modelling process for generating the models focussed on ensuring that the size data were accurately represented. It was necessary, therefore, to choose suitable methods that would sustain this degree of accuracy and ensure the data were correctly reproduced in each model. The choice of which methods to use was limited to what was accessible during the development of the CAD models and manikins. There are many different types of RP technologies capable of recreating CAD models to a very high degree of accuracy. However, not all of these methods were available to the extent that enabled experimentation and investigation to determine which combinations were appropriate to produce the number of parts needed for a full set of manikins.

The approach taken to produce of the manikins was to create moulds of each model into which a resistant material could be cast. The configuration of both the hand model and the finger and thumb model meant there was a simple, consistent split line with only two moulds for each model needing to be produced. Initially, the method to produce the moulds was to generate additional CAD models from the models of the size data. Tools within the CAD software were used to create the parts needed by ‘cutting’ the impression from a solid block representing the mould. This block was then divided into two pieces along the chosen split line to create the top and bottom halves. Figure 5.18 shows the CAD models of the moulds for a hand model generated in this way. The split line divided the moulds along a profile that ensured no undercuts were present. Two location holes were also created in diagonally opposite corners in order to align the two halves correctly.

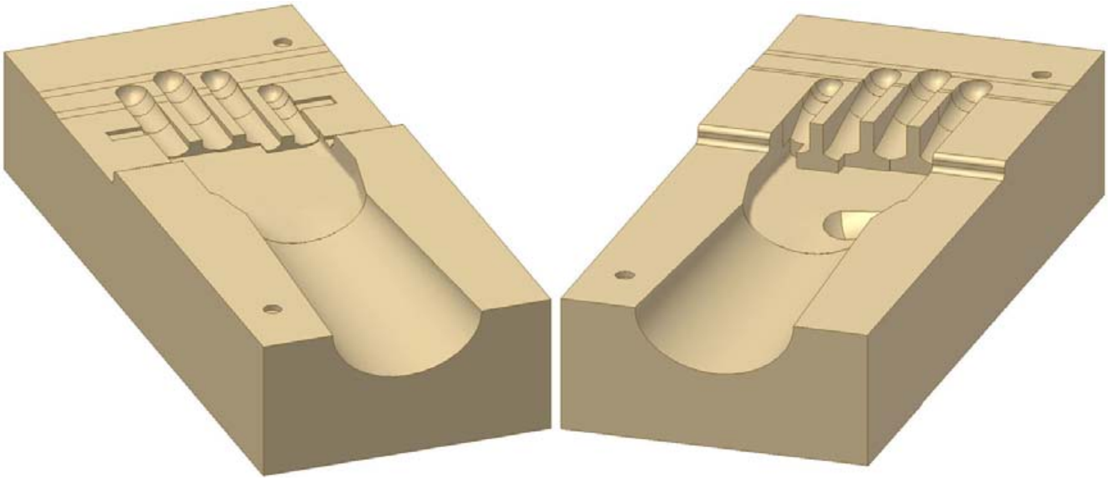


Figure 5.18 – CAD model of mould for CNC routing

To recreate the CAD models of the moulds as physical moulds suitable for casting, a CNC (Computer Numerically Controlled) router was used to machine the shape from a solid block. As with the early stages of the CAD model generation process, only one size of size gauge was created initially to ensure that the processes used were suitable. Once a process had been established and developed, the remaining sizes could then be produced. A size three hand model was used for the preliminary stages of the manikin production. CAM software was used to create machine code necessary to control the CNC router. The code is generated from the profile of each mould and controls the X Y and Z position of the router tool as well as the linear and rotational speed. Figure 5.19 shows the top mould of a size three hand being produced on the CNC router. The two halves of the mould were created independently, with two separate CAD models and two different machine codes. Therefore, details such as the split line and location holes needed to be precise to ensure that the two halves were aligned correctly. The CNC router was unable to create all the features of the mould CAD model due to the type of the tool that was used. The 6mm ball nose cutter that machined the shape of the mould could not create the sharp edges on the inside which represented the edge of the palm. As a result a small 3mm radius was created along this edge and subsequently on the finished manikin.

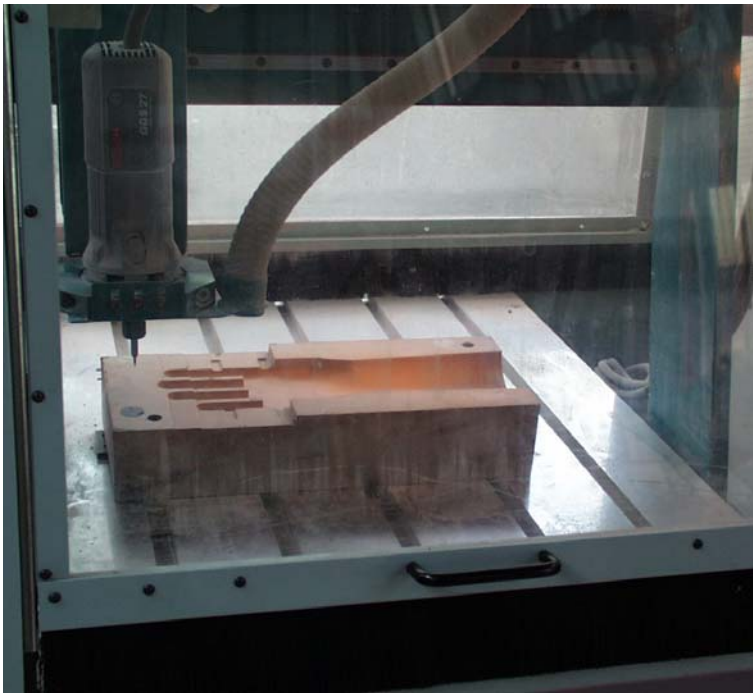


Figure 5.19 – Modelboard mould created on CNC router

Figure 5.20 shows the two halves of the CNC machined mould ready for the casting process. The material chosen for the moulds was a polyurethane modelboard. This material is commonly used for this type of prototyping application because it has a relatively rigid structure but can be machined quickly and easily to give a rapid production cycle.

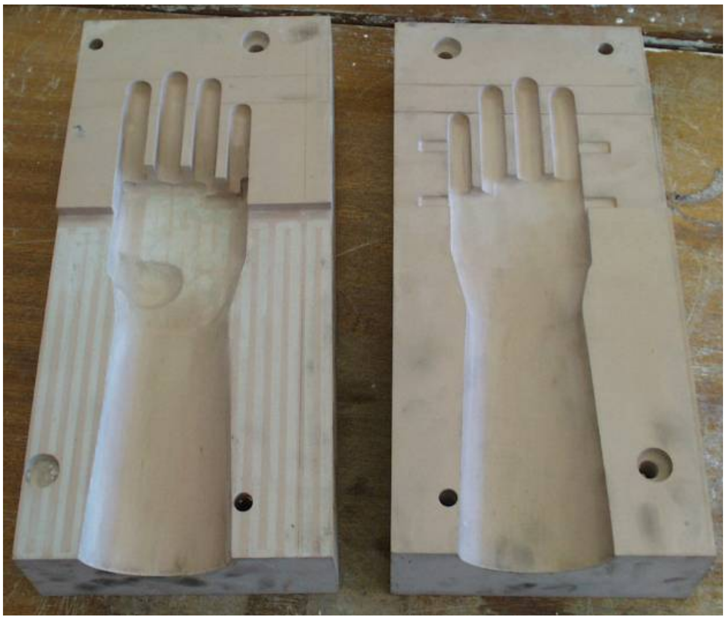


Figure 5.20 – Size 3 hand mould

The casting process was the final stage in producing a 3D representation of the CAD model. It was a relatively straight forward process, but needed to be performed cautiously to ensure the finished cast was as accurate as possible. The process entailed aligning the two halves of the mould together and pouring in an epoxy resin into the cavity. Once cured the resin formed the shape of the finished manikin and could be removed from the mould. The casting material selected was a polyurethane epoxy tooling resin, EPO 4030 manufactured by Axson. This material has good heat, abrasive and shock resistance properties which produced a dense, durable representation of the CAD model that would be a robust tool when integrated into the design and evaluation environment for handwear.

This was a successful method of recreating the CAD model as a 3D manikin and capable of producing an accurate representation. However, examination of the manikins after completing several cycles of the full process revealed that there were inherent problems within each stage of this approach. Firstly, adding to the CAD model generation process increased the time needed to generate the models for each size and increased the possibility of errors and inaccuracies occurring. Adding four CAD models for each size tripled the amount necessary for a full set to represent the size range. A total of 36 models were now required, six for each size. Although generating the additional models was a simple process and primarily performed by the CAD software, user input was required and each model for the mould needed to be created individually as no automated procedures could be applied. A more efficient option would be to use the original models directly as a process had been developed to ensure they were to the correct size and sufficient accuracy.

The CNC machining stage had two main disadvantages. Firstly, the machining process did not create a smooth, even surface on the moulds which subsequently gave a poor surface finish to the manikin. Small ridges created by the tool paths of the router remained on the surface of the moulds which created grooves on the surface of the finished cast. To obtain the surface finish required the ridges needed to be removed manually on each individual mould which increased the time needed for their completion. This manual process was vulnerable to introducing errors into the mould, as there was limited control over how much material was removed and the areas from which it was removed. The CNC machining also had issues with accuracy and repeatability. It was difficult to ensure that both moulds were correctly aligned, as the pre-determined location holes did not always correspond to one another on each half of the mould. This led to a ridge forming along the split line of the finished cast where one half of the mould had overlapped the other. This again could be resolved with hand finishing, but was open to similar problems occurring when hand finishing the moulds.

The most significant drawback of this initial method of recreating the CAD models occurred during the de-moulding process. Once the polyurethane resin had cured it was extremely rigid and because the moulds were of similar rigidity, problems occurred when attempting to remove the finished cast. Although there were no undercuts present in the mould and the appropriate release agent was used during the casting process, de-moulding the manikin was difficult and cumbersome. The moulds and the manikins were often damaged during de-moulding stage because of the difficulties experienced, which meant repairing the moulds and manikin after each cast. To overcome this problem it would be necessary to incorporate draft angles along the vertical edges of the mould to allow the resin cast to be removed easily. However, this was not an option as it would be necessary to change the shape of the moulds which would mean they would no longer accurately represent the dimensions within the size data.

The problems with this approach meant that although it was capable of producing a 3D representation of the CAD model, in practice it was not a repeatable, accurate process. It was unable to produce a batch number of manikins to the same degree of accuracy and therefore a revised method needed to be developed. Professional mould tool manufacturers may have been able to produce the moulds and manikins to the required standard. However, this option was not explored due to the inevitable increase in time and cost associated with adopting this approach. The problems of producing the moulds in-house were largely due to the choice of material used. The concept of using moulds to create reproductions of the same size manikin remained feasible as it was the most effective method to produce the manikins in a suitably resistant material. This meant that a new material and a different method of creating the moulds needed to be specified.

The optimum material for the moulds was a flexible semi-rigid material that is resistant to the polyurethane resin used in the casting of the manikins. Silicon rubber provides these properties as it is an extremely flexible material that can be easily removed from the resin once it has cured. Silicon, however, cannot be machined in the same way as was used for the polyurethane modelboard which led to an alternative method of creating the moulds. As opposed to generating extra CAD models, the original models were used directly with RP technology employed to replicate 3D versions of each size. A 3D Systems InVision™ 3D printer (3D Systems, 2003), was used to produce an acrylic photopolymer resin part. This gave a quick, accurate 3D representation of the CAD model with a smooth, uniform surface finish. As with the initial approach, a size three hand model was used initially to determine if this method was suitable. The 3D printer takes the information required directly from the 3D CAD model with minimal input from the user. It can quickly produce an accurate part that, unlike the CNC router method, requires very little post-processing. Some minor hand finishing was required to remove support structures formed during the creation of the part and further improve the quality of the surface finish by removing any imperfections that may be present. Figure 5.21 shows the RP part of a size three hand CAD model.

Figure 5.21 – RP model of size 3 hand model

The maximum model size that the 3D printer could create was smaller than the overall length of the CAD model. This meant the RP part was created in two pieces, joined just below the wrist. The accuracy of the 3D printer meant that once the two pieces were attached there was no indication of a join and so would not be visible on any subsequent manikins. The part was then used to create the silicone moulds. Silicon rubber is a two-part mix that is a highly viscous liquid which, similarly to the polyurethane resin, is poured into a mould and left to cure. It was therefore, necessary to enclose the RP part in a container into which the silicon could be poured and form the shape of the mould. Once the silicon had cured the container was separated to reveal the RP part encased in silicon. To remove the RP part and create the two halves of the mould, the silicone was cut in two along the same split line used in the CNC router method. Figure 5.22 shows the two halves of the silicon tool, with the outline of the cavity highlighted in yellow. The cavity created is an exact replica of the RP part as the silicon captures every detail and has very low shrinkage properties, 0.08%. The silicon tool could be used to cast the polyurethane resin immediately after the RP part had been removed, it was not necessary to carry out any hand finishing or post-processing of the moulds.

Figure 5.22 – Silicon mould created from RP model

The casting process followed a similar procedure to the one developed for CNC machined moulds. The two halves of the silicon mould were securely aligned together and the resin poured into the cavity. An accurate and secure alignment was attainable because the mould was originally one piece of silicon. When separating the mould into two pieces an undulating profile was created on the outer edge of the split line, which meant the two halves firmly interlocked with each other and could only be positioned in the correct orientation. This ensured that the problems of misalignment and inconsistent split lines on the resin cast, experienced when using the CNC machined moulds, were avoided and a more accurate, precise manikin could be produced. The problems with the de-moulding process were also eliminated when using this method. Once cured, the resin could be easily and quickly removed from the silicon without causing damage to the cast or the mould tool. This enhanced the repeatability of this process as, although flexible and elastic, the mould was durable and capable of producing a batch number of manikins to the same level of accuracy before the curing process of the resin begins to degrade the silicon. This is typically between 16 and 20 casts depending on the amount of resin used, as larger sizes require more resin. Figure 5.23 shows a finished resin cast of a manikin from the silicon mould tool. Due to the accuracy and design of the split line and the detail captured from the RP part, there was very little hand finishing required after it was removed from the silicon tool. The surface finish did not require any further processing; the only necessary finishing was to remove small pieces of resin that had leaked along the split line of the mould which could be easily removed by hand.

Figure 5.23 – Resin cast from silicon tool

This method of creating a 3D representation of the CAD model proved successful and overcame the problems and limitations experienced when using the initial approach of the CNC machined tools. The quality and precision of the manikin was significantly improved, producing a sufficiently accurate replica of the CAD model. The RP technology used produced a part with a high quality surface finish that was accurately captured in the silicon mould tool and so could be recreated in the resin casts. However, the primary function of the method developed to recreate the CAD models was to maintain the dimensional accuracy throughout the various stages. It was essential that the anthropometric data used in the generation of each CAD model was accurately represented in the manikin to enable it to play an influential role in the design and evaluation of handwear. A procedure to verify the accuracy and repeatability of this method was developed and is described in Chapter 7. This procedure entailed comparing the resin gauge with the original CAD model. It was able to determine that the mean difference in size between the CAD model and the finished resin gauge was -0.375mm. The negative value calculated means the former is smaller than the CAD model but the value indicates there are very minor differences in size and shape.

The RP and silicon tool method was used to produce a set of all six sizes with the same processes used for both the hand model and the finger and thumb model. An RP part of each CAD model for each size was produced and silicon moulds created from these parts. An addition to the casting process was to insert a metal ‘skeleton’ inside the mould before pouring the resin. The shape of the skeleton replicates the shape of the cavity within the silicon mould. The size was smaller to ensure the metal structure would fit in the mould and not protrude from the manikin after the casting process. The outer edge of the skeleton was 3mm smaller than the edge of the mould cavity to create a border between the skeleton and the mould. Holes were also drilled into the surface of the skeleton to enable the resin to flow around it evenly and reduce of air pockets occurring during the curing process which would weaken the finished manikin. The skeleton was hand made from 18-gauge sheet steel and brazed to a 1.5mm thick mild steel, hollow rectangular bar, figure 5.24.

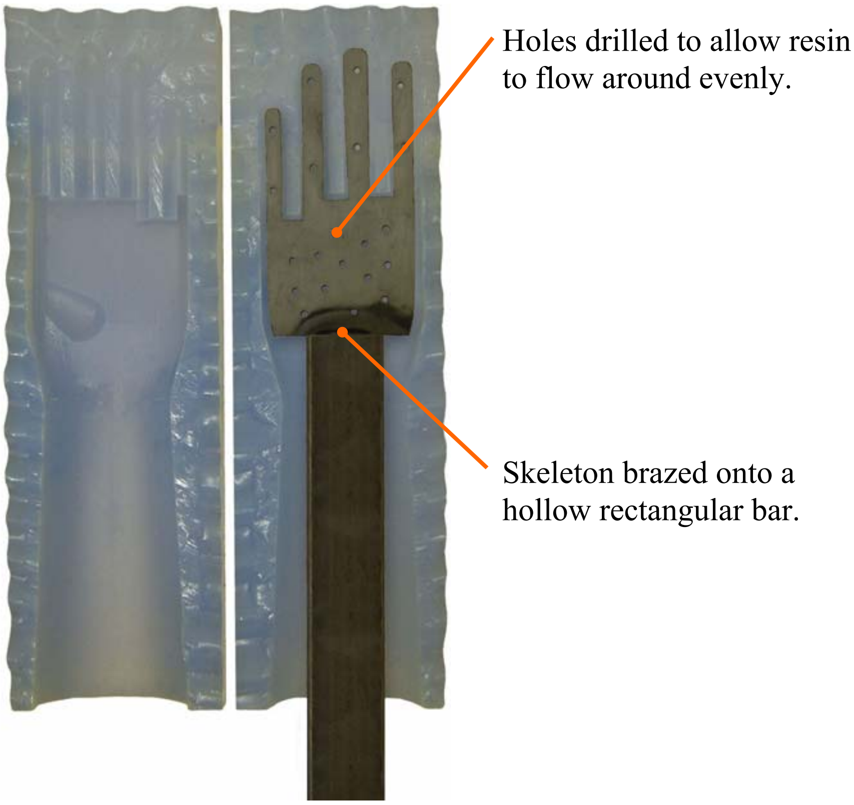


Figure 5.24 – The skeleton positioned inside the silicon mould before casting.

The skeleton was placed inside the silicon mould and the two halves aligned together. During the casting process the skeleton was suspended in the mould using a clamp and visually checked to ensure it was located correctly, figure 5.25. The resin was then poured into the mould and allowed to cure.

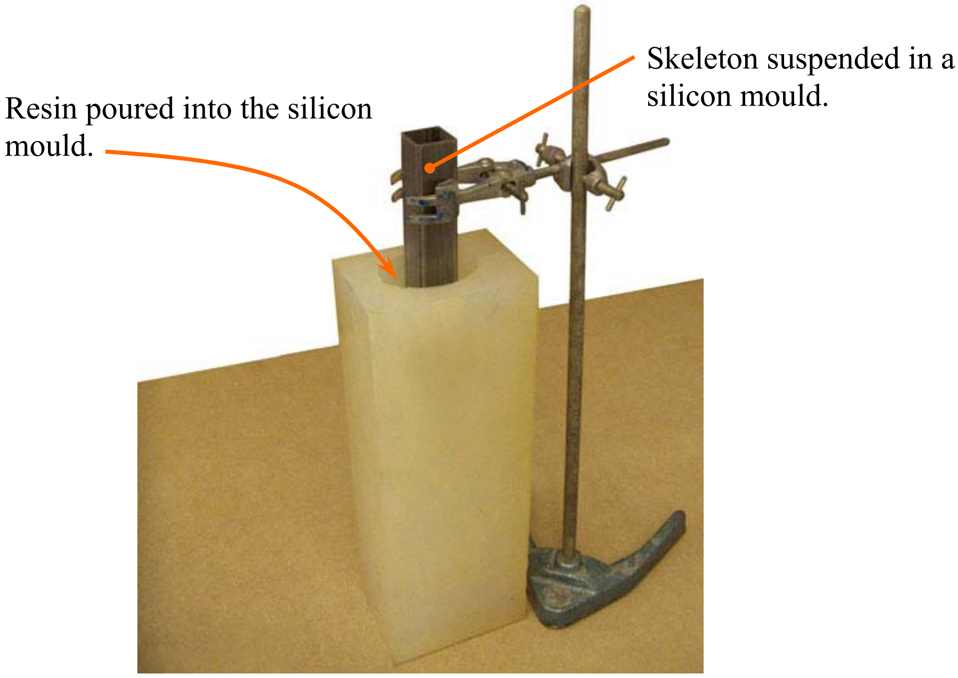


Figure 5.25 – The skeleton held in place during the casting process

The skeleton gave added rigidity to the manikins and enabled them to be mounted on a frame, figure 5.26.

Figure 5.26 – A size 3 right- handed size gauge (manikin)

The next stage of the case study was to introduce the manikins into a handwear manufacturing environment and integrate it into the design and evaluation processes of glove manufacture. It was envisaged that the manikins would be used as part of a quality control process, used as to asses the size of a glove. The manikin would act as a Go-NoGo gauge used by operators of sewing machines during the manufacture of a glove to identify areas of incorrect fit. The gauge would determine if a glove was to the correct size but would also give feedback to the operator on the accuracy of the size and, if necessary, indicate where adjustments were needed. Highlighting where these errors occur allows necessary modifications to be made when manufacturing subsequent gloves, minimising and controlling the tolerances involved and maintaining a consistent level of accuracy. However, the function of the manikin was changed following discussions with handwear manufacturers who expressed concerns with this initial application. There was some capacity for the manikins to be used within a quality control system but at a point after the manufacturing stage, evaluating a sample of gloves from a batch quantity. This would be able to highlight any discrepancies in the manufacturing process and help to maintain the consistent level of accuracy.

The issues raised by handwear manufacturers related to the how the manikin could be integrated into the assembly process of a glove. It was felt that they would obstruct current methods used; adding an unfamiliar procedure to the process and increase the time taken to fully assemble a glove which would impact on production cycles. It was also apparent that the operators of the sewing machines had the expertise and ability to produce the gloves with sufficient accuracy and to an acceptable quality. Suggestions made by handwear manufacturers indicated that the manikins would be more influential during the pattern designing process for manually machined stitched gloves. It is at this stage in the manufacture of this type of glove that errors and inconsistencies can occur. It was also felt that this was the appropriate point in the manufacturing process where errors should be eliminated, identifying them at early stages in the process rather than during latter stages when it would be more difficult and expensive to implement any necessary changes.

This was the first opportunity to discuss the use of the manikins with a handwear manufacturer and gain an insight into the thoughts and opinions they had on introducing it into glove production. It was necessary to use their knowledge and experience to develop the manikins into a feasible tool. The discussions included the shape and configuration of the CAD models to determine if any modifications were needed to these features of the manikins. The manufacturers felt that this aspect was practical and did not require any modification to be integrated into the manufacturing process. The discussions, therefore, concluded that the manikins would operate as a size gauge, used to assist the pattern designer during the generation of new glove patterns. Integrating the size gauges (manikins) into this process at this stage also integrates the anthropometric data as a 3D tool, allowing it to have a direct influence on the design of handwear.

5.5 Size gauge testing and evaluation

The evaluation process for this case study was in two phases. Having determined how the size gauges were to be integrated into a handwear manufacturing environment, it was necessary to use a gauge to design and manufacture gloves and assess these gloves for fit and user performance. This enabled a comparison to be made of how anthropometric data could be used in a design process and determining the influence it had on the final product produced. The first phase entailed collaboration with a handwear manufacturer, Bennett Safetywear Limited (BSL). This company has extensive experience in the design and manufacture of handwear, establishing itself as a European market leader in the manufacture of safety gloves and other forms of PPE for a wide variety of applications (Bennett, 2006). A size gauge was used by a pattern designer from BSL to generate a new glove pattern. The pattern designer was able to refer to the gauge during the generation of the new design, making necessary alterations at each stage in the iterative process. For comparison, the pattern designer generated a second pattern without using the gauge, only being able to refer to the 2D dimensions in the size data to determine the size and shape of the pattern. After the pattern generation process had been completed, a pair of gloves was manufactured from each pattern to assess differences, in size, shape, fit and user performance.

Assessing the gloves produced in phase one formed the second phase of the evaluation process. A trial was conducted to compare the gloves manufactured from the two patterns and collect quantitative and qualitative data. The trial consisted of a battery of tests, compiled to analyse users wearing the gloves, evaluating properties of finger dexterity, haptic feedback and hand strength; in addition to measuring perceptions of fit and perceived difficulty to complete a given task. The results of the trial indicate the effect and influence the size gauge has on the design of the gloves. Improvements in performance and perceptions of the glove manufactured using the gauge can be attributed to its introduction during the design and generation of the associated pattern. This demonstrates the concept that anthropometric data and CAD/CAM can be introduced into the design handwear and their integration can enhance the accuracy of this process, conveyed to the user in an improved performance.

5.6 Evaluation phase 1: Pattern design and glove manufacture

5.6.1 Aim and objectives

The aim of this evaluation was to introduce the size gauge into the design process of a new glove pattern. An assessment was developed to observe and record the activities of a skilled pattern designer interacting with the size gauge to establish how it may be used to improve the current design process for glove patterns. By analysing the outcomes of this assessment the objective was to determine the influence the size gauge had on the methods used by the pattern designer and any improvements gained in size and shape of the patterns produced.

5.6.2 The Gunn pattern

The assessment entailed a pattern designer from BSL generating a new size of glove pattern using conventional methods and with the introduction of the size gauge. The type of pattern chosen was a basic Gunn pattern, figure 5.27. This is one of the principle patterns used in current glove manufacture (British Glove Association, n.d.[b]), primarily used for protective handwear rather than fashion or sporting applications.

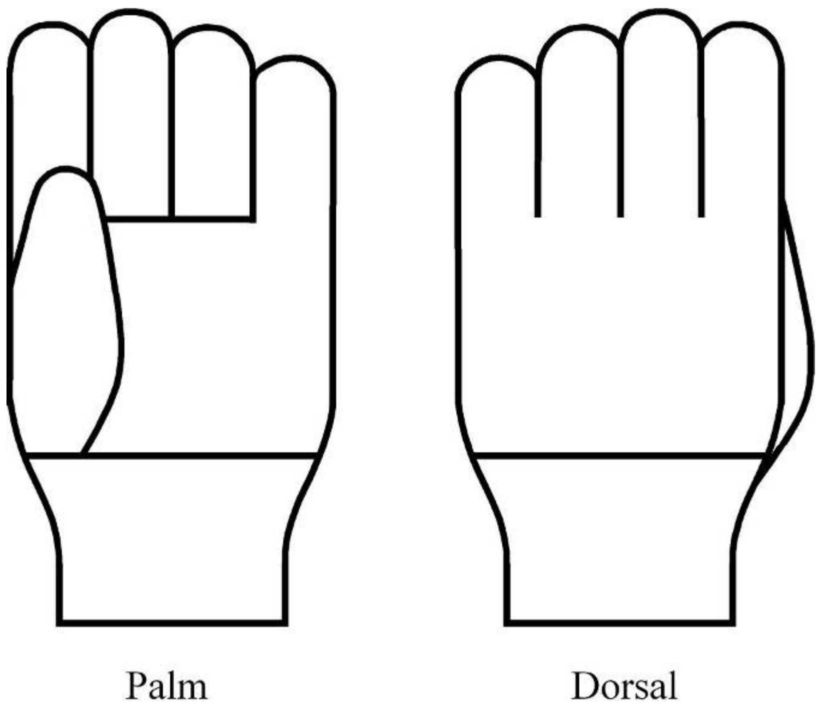


Figure 5.27 – Gunn Pattern

The Gunn pattern consists of four main pieces; however, additional elements can be included depending on the intended use of the glove. For example, reinforcement patches can be added to the palm or digits to increase the abrasive properties of those areas. Figure 5.28 shows the outline of the four main pieces which are colour coded to indicate how they are stitched together to from a fully assembled glove. The two principal pieces are the back and palm. The seamless back piece of the pattern forms the entire dorsal area containing the detail for the back of the glove and the back of each finger. The palm piece forms the palm, the front of digits two and five and contains the seam for attaching the thumb. The two remaining pieces form the front of digits three and four and the thumb. A cuff piece is also added once the glove is assembled; however this varies depending on the type of glove being manufactured and was not included in the evaluation phase.

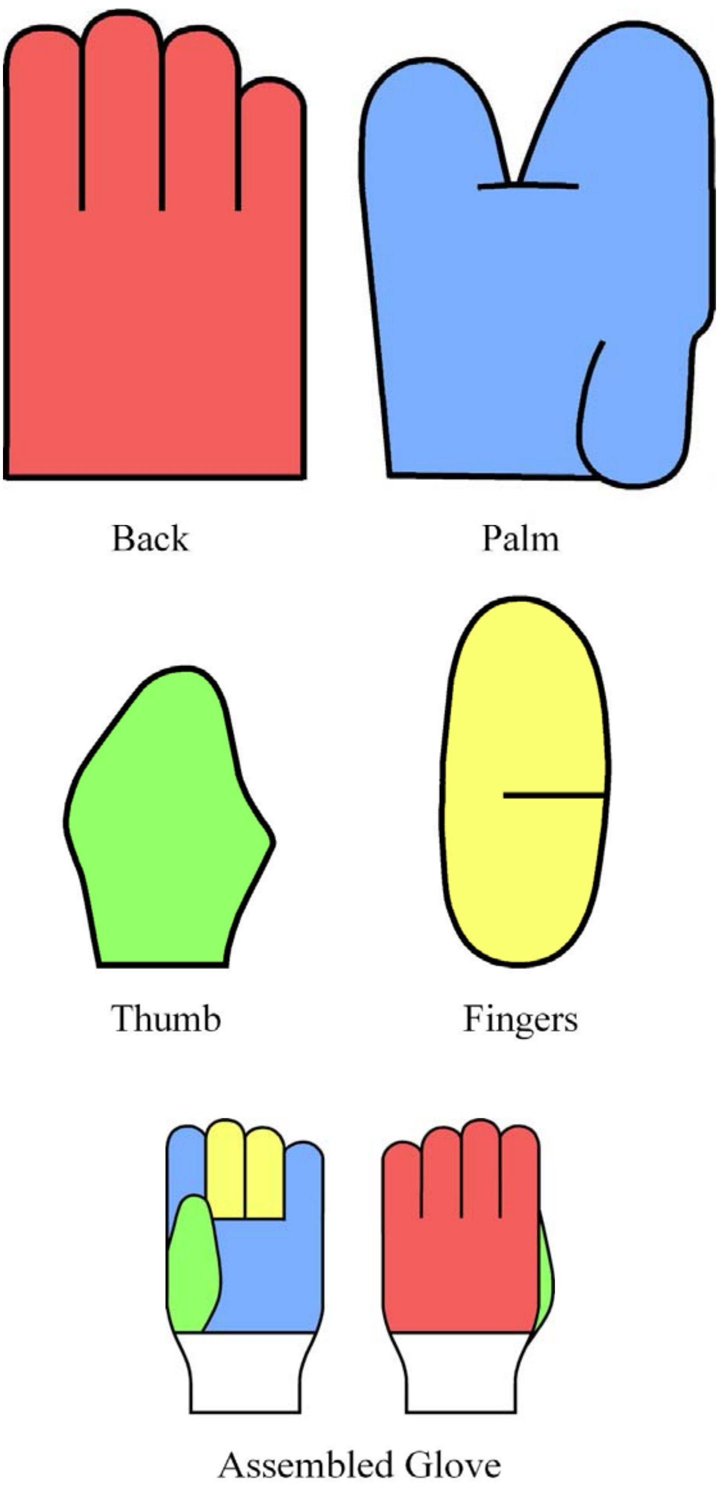


Figure 5.28 – Gunn pattern pieces. Colour coded to indicate their assembly.

5.6.3 Pattern generation process

The assessment was developed through collaboration with BSL, who were given a size gauge to be used in their pattern design process of a cut and sewn glove. The 'cut and sew' manufacturing process uses a 2D pattern to cut out the necessary components of the glove from the appropriate material to the correct size and shape using pattern knives and a hydraulic cutting press. The glove is then constructed by manually machine stitching these components together inside out so that the seams are on the inside.

The process for designing this type of glove pattern is a traditional technique, relying on the experience and empirical knowledge of the designer to produce the accuracy required. It often entails applying rule of thumb methods to create each piece of the pattern correctly in order to generate the required properties of the glove. The patterns and designs generated by BSL have been developed over many years through a trial and error iterative process that encompasses intuitive design skills of the material properties, seam type and assembly methods. This means that although many of the patterns used in this method of glove manufacture are standardised across manufacturers, subtle differences exist between them because it is such a creative skill. For these reasons, the following description of generating a new pattern describes the generic procedures only; no specific details of the pattern design process are revealed. This prevents infringing confidentiality and publicising details of the design process that has been developed by BSL.

Any new pattern is generated by firstly selecting an existing pattern that closely matches the desired shape of the new pattern, figure 5.29. With this as a basis, the designer decides which dimensions require modification and by how much, referring to the required specification for reference, figure 5.30. At this early stage the allowances for the material and seams are considered and taken into account when deciding the level of modification required for each dimension, as these have an influence on the amount of adjustment necessary. Material properties were not a significant issue for this design as the gloves made using the pattern were produced from a cotton twill, which is inelastic and therefore does not stretch or distort. This type of material was chosen because it simplifies the pattern generation process and the glove would not stretch once donned onto the hand or size gauge. This makes it easier to judge whether the glove is to the correct size and shape as the material does not stretch over the hand or gauge to give a false indication of fit.

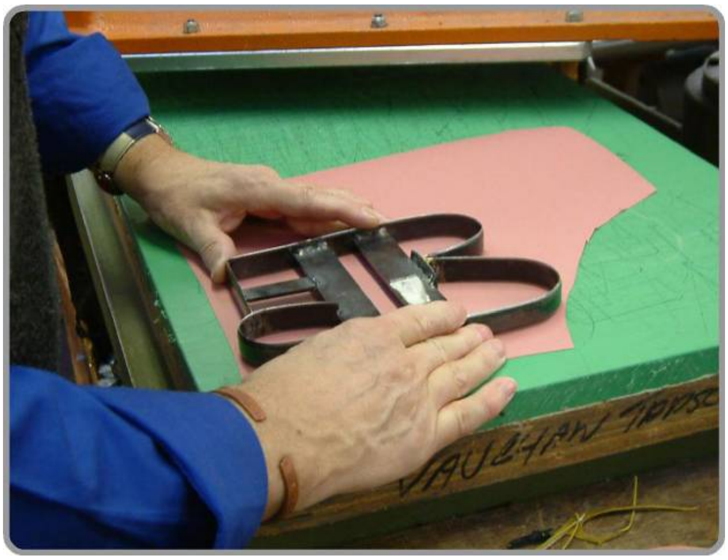


Figure 5.29 – Initial pattern generated from existing designs

Figure 5.30 – Existing designs modified to generate correctly sized pattern pieces

After deciding on the modifications needed to change the existing pattern to suit the required specification, each piece is drafted out onto cardboard to apply the modifications and create the appropriate shape and size, figure 5.31. This stage is the creative part of the generation process. The main issues of material properties, seam position and fit of the glove are all resolved at this stage and is where the experience and knowledge of the designer is utilised most. The designer adjusts lengths, breadths and the profile of each piece to accommodate for the allowances required. After it has been sufficiently modified, each piece then needs to be cut out manually as the individual metal cutting knives are not produced until the size of pattern has been finalised, figure 5.32.

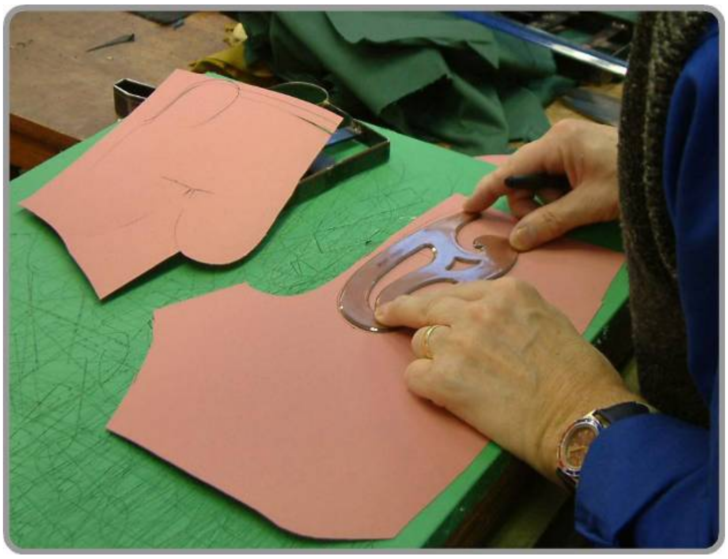


Figure 5.31 – Modifying pattern dimensions

Figure 5.32 – Pattern pieces cut manually

The next stages begin to produce the initial glove. The cardboard pattern is used as a template to mark out each piece onto the material that the glove is to be made from, in this case the cotton twill, figure 5.33. The pieces are then cut out ready to be sewn together, figure 5.34. This procedure would typically be done using cutting knives and a hydraulic cutting press. This eliminates the need to mark out the shape on the material and ensures each piece is duplicated to the correct size. As this was a new pattern and there are no cutting knives, the pieces must again be cut by hand.

Figure 5.33 – Pattern pieces used for marking out on material

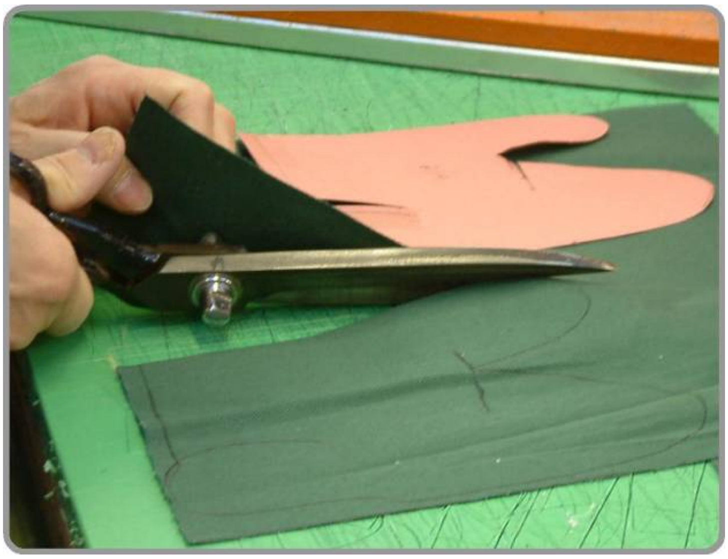


Figure 5.34 – Glove pieces manually cut from material

The glove pieces are then given to a seamstress to be stitched together and create an initial glove from the preliminary pattern, figure 5.35. This stage in the process forms the 3D glove, therefore the seamstress, plays an influential role in the decisions made in the assembly. Discussions between the seamstress and pattern designer determine how each piece should be stitched together to ensure the glove is correctly assembled and forms the required shape. The initial glove produced is then assessed to determine if it is to the correct size, shape and fit. This assessment identifies areas where modifications are required which the designer then applies to the relevant piece or pieces of the pattern. A new glove is then made with the modified pieces, which is again assessed. This cycle of stitching the pieces together and revising the pattern can occur several times until the seamstress and pattern designer are satisfied the glove is correct. Once the glove has been confirmed to be correct, a final pattern is generated which can be used to manufacture a set of cutting pattern knives to mass produce the gloves. The pattern for this type of glove is the same for both left and right hands. To create the opposite hand, the pattern can simply be reversed. The pattern knives have cutting blades on the top and bottom edges so that one set can be used to produce both left and right handed gloves.

Figure 5.35 – Seamstress stitching glove pieces together to form glove

5.6.4 Method

The assessment required the pattern designer from BSL to generate two Gunn glove patterns for producing a glove using the cut and sew manufacturing process. The first pattern was generated using dimensions from the size data and the second pattern was generated with the addition of the size gauge. A size 4 size gauge and the corresponding set of dimensions were used. To confine the assessment to the two-day timescale allocated by BSL, a number of variables were controlled to ensure all the necessary stages could be completed appropriately. The choice of a Gunn pattern with no additional protective elements meant that only four pieces needed to be designed for each of the two patterns. The cotton twill material chosen for the gloves was inelastic and had a uniform consistency, which simplified the procedure for dimensioning the pieces of the pattern. It enabled the pattern designer to specify each piece to the dimensions to the size four data, requiring no modifications to accommodate for material stretch or distortion.

The gloves produced from the patterns were manufactured by hand as it was not possible to produce pattern knives due to only three pairs being created from each pattern. Pattern knives are only practical for mass produced gloves, and this small number did not warrant the high financial and time commitments necessary for their manufacture. The hand made approach was more suited to this assessment as it enabled the gloves to be manufactured immediately after the finished pattern had been finalised, allowing all five pairs of gloves to be completed within the limited time frame.

Before beginning the assessment, the pattern designer was introduced to the testing process by the experimenter to clearly explain the procedures and how the exercise was to be performed. A document of consent was signed by both parties (BSL and Loughborough University), acknowledging that the designer could withdraw from the study at any time and was under no obligation to discuss any confidential or commercially sensitive information. The assessment took place in two locations; a meeting room where the patterns were generated and a workshop where the gloves were manufactured and assessed for fit. Throughout the assessment three different methods were used to record the qualitative data; a video camera, a Dictaphone and a scribe. This ensured that all the necessary information and methods were captured during the generation of the patterns and construction of the gloves.

After all protocols had been explained and were understood by the pattern designer, the assessment could commence. The first phase was to observe the pattern designer generating a Gunn glove pattern using the conventional methods and procedures that would be typically used by BSL for this type of pattern. The designer was asked to generate a pattern using the set of size four dimensions from the size range. The dimensions were presented to the designer in a spreadsheet form, with the same data available to him that was used when generating the CAD model, Chapter 5.3. The task was, therefore, to design a glove pattern that would represent the size four data using conventional pattern generating techniques referring only to 2D dimensions as a guide to the size and shape. With these instructions the pattern designer used the methods described in Chapter 5.6.3 to generate a Gunn glove pattern that he felt correctly represented the set of dimensions he was given. The designer was free to use all the dimensions from the size data that were presented to him on the spreadsheet.

However, when generating the pattern, the designer did not use any circumference dimensions as all the pattern pieces were created using 2D linear measurements. Table 5.2 lists the linear and circumference dimensions within the size range. From the total of 37 dimensions, 11 were circumferences. This meant the designer used 26 dimensions to generate the size of the pattern.

Linear Dimensions		**Circumference Dimensions**	
1	Hand Breadth	4	Hand Circumference
2	DIP Joint Breadth – Digit 2, 3, 4, 5	10	PIP Joint Circumference – Digit 2, 3, 4, 5
3	PIP Joint Breadth – Digit 2, 3, 4, 5	11	DIP Joint Circumference – Digit 2, 3, 4, 5
5	Wrist Breadth	14	Wrist Circumference
6	Hand Length	19	Digit 1 Joint Circumference
7	Palm Length		
8	Digit Length – Digit 2, 3, 4, 5		
9	Digit Crotch Height – Crotch 1, 2, 3, 4		
12	Tip of Digit 2 to Thumb Crotch		
13	Digit 1 Length		
15	Wrist Depth		
16	Hand Depth at MCP Joints		
17	Hand Depth at Thenar Pad		
18	Digit 1 Joint Breadth		

Table 5.2 – Linear and circumference dimensions in the size data

This completed the first phase in the pattern design phase of the evaluation. The next phase was to carry out the pattern design process again with the addition of the size gauge. The designer was given a size four size gauge with the spreadsheet containing the size four dimensions that he used in the first phase. The task was again to generate a Gunn pattern to represent the size four data. As in the first phase, the designer only used the 2D linear measurements from the size data in the spreadsheet. No instruction or demonstration on how to use the size gauge was given to the designer, who was able to use the gauge as little or as often as needed and by any method he preferred during the design process. The pattern generation process was completed a second time and another Gunn pattern was created.

After completing the design of the two patterns, the pattern designer was questioned about the use of the size gauge, discussing how he was able to integrate it into the design process, what the advantages were, and any improvements that could be made. Finally, three pairs of gloves were manufactured from each of the two patterns by a seamstress from BSL to be assessed in the user trials that formed the second evaluation phase of this case study.

5.6.5 Evaluation phase 1 results and discussion

The results of the first evaluation phase are in two sections. Firstly comparisons are made between the patterns generated and the subsequent gloves manufactured during the pattern design exercise. The comparisons analyse the differences in the size and shape of the patterns when the size gauge was used alongside the conventional pattern designing process and how these are manifested in the size and shape of the corresponding gloves. The second section of results examines how the introduction of the size gauge influenced the design process and the decisions made by the pattern designer. Comparisons are again made to determine the differences in the number of stages needed to complete the design of each pattern, indicating how the size gauge has been able to refine this process.

Pattern and glove analysis

The outcome from the pattern design assessment was two separate Gunn patterns, figures 5.36 and 5.37, and three pairs of gloves from each pattern, figures 5.42 to 5.45. The colour of the patterns has been digitally altered from the original pink colour so that they can easily be identified and distinguished from each other. The lines on the pieces indicate where cuts are made to create the seams. The blue pattern in figure 5.36 was the first pattern to be generated, designed using only the anthropometric dimensions from the size data (data pattern). The orange pattern in figure 5.37 was the second pattern generated, designed using the size data and the size gauge (gauge pattern).

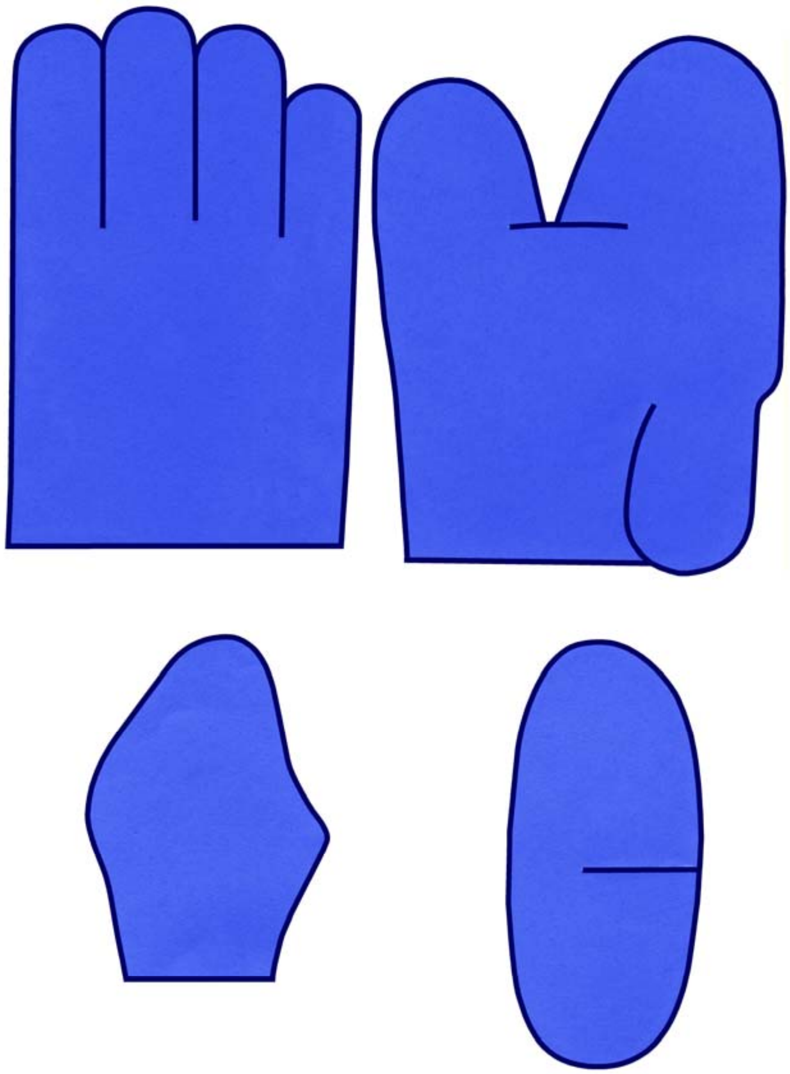


Figure 5.36 – Pattern pieces designed using size data

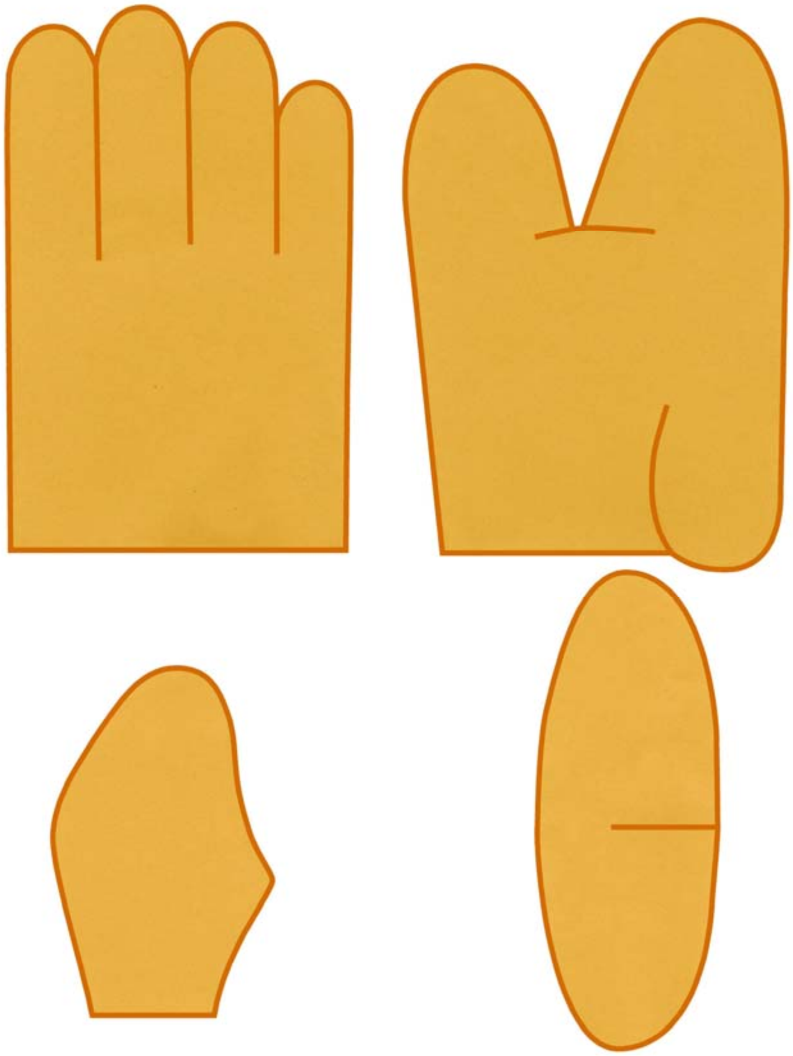


Figure 5.37 – Pattern pieces designed using size gauge

The two patterns are very similar; however, there are distinct differences in the size and shape of each piece which can be analysed more easily when the pieces are overlaid onto each other. Figures 5.38 to 5.41 show the orange gauge pieces superimposed onto the blue data pieces to highlight the differences in the two patterns. The two back pieces in figure 5.38 show the greatest similarity between the four pieces. There is little difference in width and length dimensions; however differences in the length and tips of the fingers are evident. The curvature at the tip of each finger is greater on the data pattern which creates a wide straight finger. Finger length is indicated by the lines representing the cuts necessary for the seams. The length of these cuts creates the crotch heights of the glove. Each of the three cuts is longer on the gauge pattern which creates smaller crotch heights and as a result, longer fingers. Figure 5.39 shows the orange gauge palm piece superimposed onto the blue data piece. There is a significant difference in width dimensions between these two pieces but the lengths are very similar. The data pattern is wider along the two outer edges and on the inner edge of the detail that creates digit two. The curvature on the top of the gauge piece is smaller which coincides with the finger detail on the corresponding back piece. The crotch height is shorter on the gauge piece to match the crotch heights on the back piece. Also visible is a difference in the detail where the thumb piece joins the palm in the lower right-hand corner. The curvature and position of the cut for the seam has been changed by the designer when the size gauge was used in the design process.

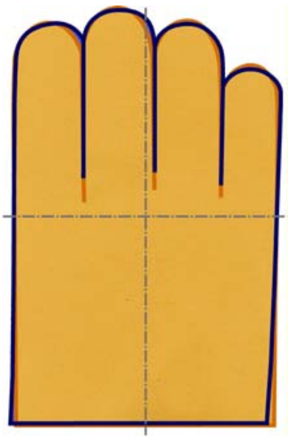


Figure 5.38 – Back pieces superimposed

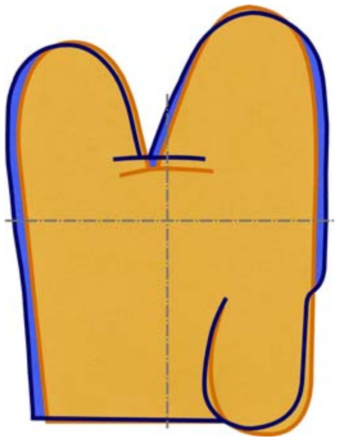


Figure 5.39 – Palm pieces superimposed

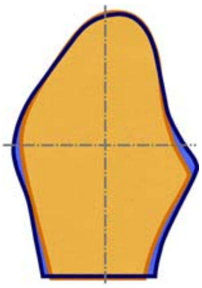


Figure 5.40 – Thumb pieces superimposed

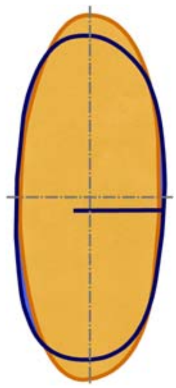


Figure 5.41 – Finger pieces superimposed

Figure 5.40 shows the two thumb pieces. As with the palm the length dimensions remain relatively similar, but in the lower portion particularly, the width of the gauge piece is smaller and follows a different profile to the data piece. The finger pieces in figure 5.41 correspond to the finger detail on the back and palm pieces. Therefore, the length of the gauge piece is significantly larger than the data piece and is slightly thinner.

The variations in the patterns consequently mean the gloves produced from them differ in size and shape. Figures 5.42 and 5.43 show a glove made using the size data (data glove) and figures 5.44 and 5.45 show a glove made using the size data and the size gauge (gauge glove). The difference in the patterns that have been highlighted can be seen when the two gloves are compared.

Figure 5.42 – Data glove (palmar)

Figure 5.43 – Data glove (dorsal)

Figure 5.44 – Gauge glove (palmar)

Figure 5.45 – Gauge glove (dorsal)

The two main differences between the patterns occur in the finger lengths and the overall width of each piece. These differences are reflected in the gloves. The gauge glove has thinner, longer fingers that taper slightly at the tip because of the reduced curvature at the fingertips and smaller crotch heights on the pattern, figures 5.44 and 5.45. In contrast, the data glove (figures 5.42 and 5.43) has much wider shorter fingers due to the pattern having a greater curvature at the fingertips and longer crotch heights. The difference in the width of the palm pieces of the two patterns correlates to the difference in the width of the two gloves. The gauge glove is smaller across the knuckles and palm than the data glove due to these areas being created by the palm piece. A similar variation is visible on the thumb. The thumb is thinner on the gauge glove particularly at the lower portion where it joins the palm and has a lower crotch height. These differences are created by the variations in width of the thumb pieces and the changes in the curvature and position of the cut to form the seam on the palm piece.

Pattern generation analysis

The variations of the patterns and consequently the gloves can be attributed to the use of the size gauge during the pattern design. The gauge was the only variable introduced into the pattern generation process and the differences highlighted above indicate that the gauge has changed the design method and had an influence on the outcome. The two patterns show clear differences in both size and shape in specific areas of the pattern pieces. These differences are a result of the gauge and not due to variations in the consistency of the methods used by the pattern designer. It is inevitable that some differences would exist between two patterns made by the designer using the same dimensions even without the use of the gauge. However, the skills and experience of the designer means he is able to maintain a consistent level of accuracy to generate two patterns that have similar size and proportions. The differences that occur in the two patterns shown above indicate that some areas of the pieces have remained the same shape and size, while other areas are considerably different.

Reviewing how the size gauge was used in the pattern generation process demonstrates the role it played and the influence it had on conventional design methods. The size gauge was utilised in the latter stages of the pattern generation. The preliminary stages of selecting an appropriate existing pattern and modifying the dimensions to produce an initial pattern were similar in both of the design processes. However, the designer did refer to the gauge when modifying the dimensions to better visualise the shape the glove needed to be and how the dimensions relate to each other. The key role the gauge played was after the initial pattern had been recreated in 3D, i.e. the first glove produced. The conventional method of assessing this glove is achieved by identifying a colleague within the company who has the approximate sized hands to fit the glove. This person then wears the glove to allow the designer to determine where the glove requires modification and then change the pattern pieces accordingly. The size gauge replaces this person and introduces an accurate reference to give the designer a more precise guide when assessing the glove. After donning the glove onto the gauge, areas of incorrect fit are easily identified by excess amounts of material or where material does not come into contact with the surface of the gauge. Figures 5.46 and 5.47 illustrate how the designer used the gauge to assess a glove and the markings indicating where modifications are necessary.

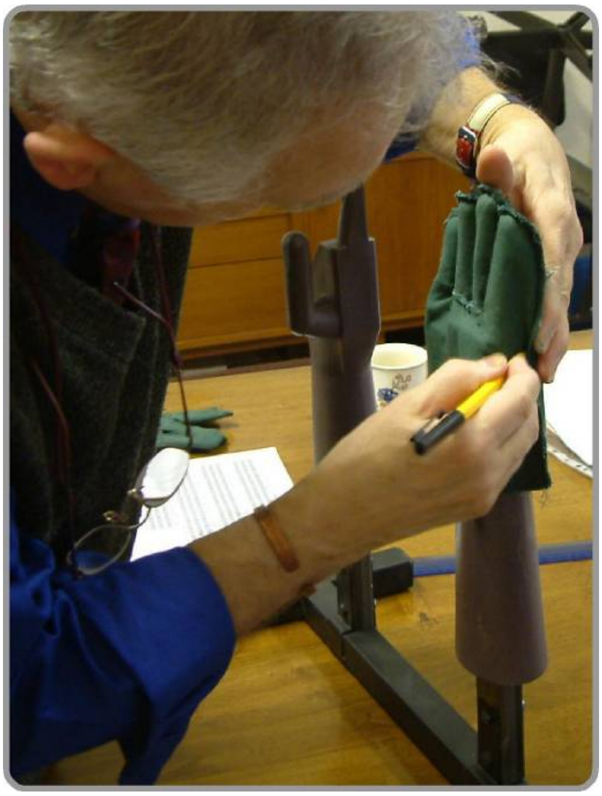


Figure 5.46 – Pattern designer using size gauge for fit analysis

Figure 5.47 – Markings on glove to identify fit errors

This assessment is similar when using a persons hand as a reference. Areas of incorrect fit are identified in the same way and used to modify the size of the glove. The designer also used this method to gain feedback on the wearer's perception of how the glove fits, which is not a feature of the size gauge. Although this feedback may appear to be a useful means of evaluation, the perceptions of one wearer may be unreliable and not indicative of the population the glove is intended for. In addition, the selection of this person is only an approximation and unlikely to be the correct size in all portions of the glove. Identifying people that can assess different sizes is a further drawback with this method as a full range sizes may not be represented. These factors mean that modifications made when using this type of reference are susceptible to incorporating errors into the patterns and therefore the gloves. Using the size gauge overcame these issues, by introducing a reliable, accurate tool into the design process, available in a full range of sizes.

Figure 5.48 illustrates the two design processes, comparing the number of stages required when assessing and modifying the glove to generate the final pattern. The overall effect of the size gauge has been to decrease the number of steps needed to complete the process by allowing the designer to better evaluate the size of the glove and more accurately determine the changes necessary. It is possible that some of this improvement could be attributed to a learning effect caused by the designer generating the two patterns immediately after each other. This was a consequence of the design of the trial, which meant the process of generating the first pattern may have influenced the designer when using the size gauge during the design of the second pattern. Due to the limited availability of the pattern designer it was necessary to perform the trial within a specified time period and to some extent this issue was unavoidable. However, the use of the size gauge has introduced a specific tool during the key stages of assessing the fit of a glove. This has resulted in a more efficient design process by reducing the amount of time and resources needed. The Gunn pattern is a relatively simple pattern, other more complicated patterns with a greater number of pieces and intricate assembly would benefit further from the introduction of the size gauge.

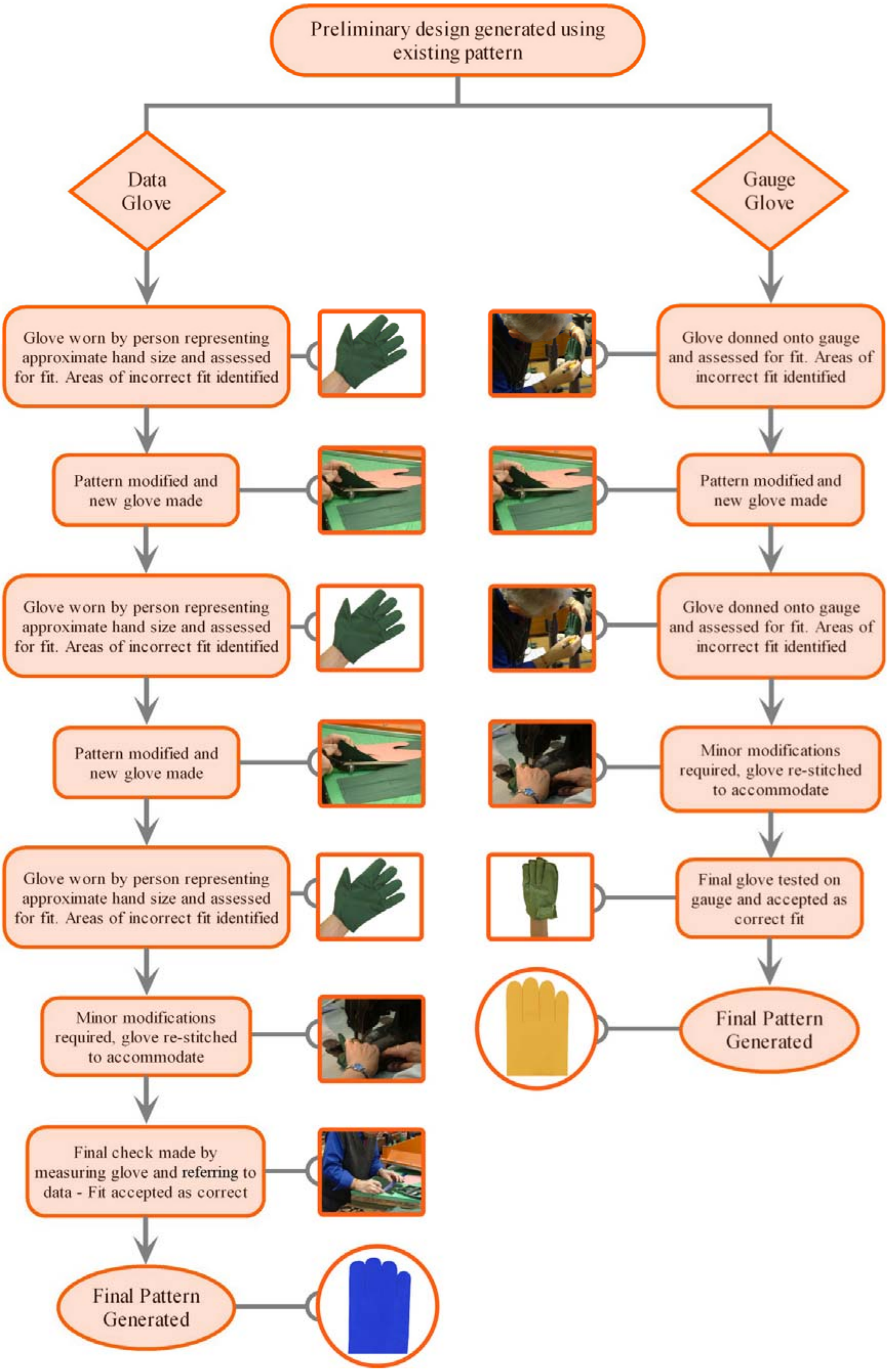


Figure 5.48 – Design process comparisons for data and gauge gloves

5.7 Evaluation phase 2: Glove assessment

The second phase of the size gauge evaluation assessed the gloves produced during the first phase. The aim of the size gauge is to improve the fit of gloves by increasing the accuracy of the design process used for their manufacture. The comparison of the two sets of gloves and patterns has shown differences in their size and shape as a consequence of using the gauge, but did not determine how these differences would affect the performance of the wearer. Therefore, a user trial was conducted to assess whether the variations that exist in the two sets of gloves will enhance fit and improve the ability of the wearer when undertaking a given task.

5.7.1 Method

The assessment of the gloves consisted of analysing participants performing a series of tests. The tests were performed in four different conditions; using bare hands, the data gloves, the gauge gloves and latex gloves. These conditions were compared to determine the affect they had on the ability of the participant to complete the test and give an indication on how the fit of a glove can influence the performance and perceptions of the wearer.

There were a total of six tests used in the assessment. Two tests analysed hand strength by taking grip and pinch strengths of participants, and four tests analysed dexterity and haptic feedback using a modified Purdue pegboard, a nut and bolt disassembly/assembly task, a pin pick up task and by evaluating keyboard typing skills. A full explanation of each test and why it was chosen is given below and in Appendix III.

Grip strength. This was tested using a Baseline® hydraulic hand dynamometer set on the second level of adjustment to record the maximum value in kilograms, figure 5.49. This apparatus was chosen because it has been proven to measure equivalently to the Jamar® dynamometer which gives the most accurate measure of grip strength and therefore is the recommended instrument to be used, (Mathiowetz *et al* 2000). As a result, normative data could be used for comparison if required. To ensure accurate recordings for each trial, all measurements were recorded using the same apparatus, (Mathiowetz *et al* 2000).

Figure 5.49 – Baseline® hydraulic hand dynamometer

A standardised method of measuring grip strength was adopted as recommended by the American Society of Hand Therapists (ASHT). The participant was seated upright in a chair leaning against the back with their feet supported. The dynamometer handle was gripped by the participants in their dominant hand, with their shoulder adducted and neutrally rotated and their elbow fully extended. Continuing to grip the handle, the participant was then instructed to flex their elbow to approximately 90^{o} keeping their forearm and wrist in a neutral position and apply the maximum load that they could with no verbal encouragement by the experimenter, see figure 5.50 (Fess and Moran 1981, cited by Mathiowetz, *et al,* 1984; Mathiowetz *et al* 1985[b]; Spijkerman, Snijders *et al,* 1991). This value was then recorded by the experimenter. The test was performed twice, prior to and after the dexterity tests, with a mean value calculated.

Figure 5.50 – Recording grip strength

Pinch strength. Two-point tip pinch strength (Smith, 1985) was tested using a Baseline® hydraulic pinch gauge which recorded the maximum load in kilograms, figure 5.51.

Figure 5.51 – Baseline® hydraulic pinch gauge

The participant was positioned in the same posture as the recording of grip strength to ensure the recordings could be repeated accurately. Hook and Stanley (1986) found that during the recording of this pinch grip strength, the result was influenced by the remaining fingers. An additional procedure was therefore used to ensure each participant performed the same pinch grip during each trial. The participant formed a fist with their dominant hand, then extended their forefinger and thumb, placing the finger pad on the pinch meter and the thumb below. With the gauge supported by the experimenter, the participant pressed as hard as they could with their finger tip, figure 5.52. Again the maximum load was recorded by the experimenter and two tests were performed, prior to and after the dexterity tests.

Figure 5.52 – Pinch strength being recorded

Evaluating grip and pinch strengths of the participants gives an indication to the influence the gloves have on impeding their grip and pinch patterns and therefore their ability to grip and manipulate objects effectively. Since both the standard glove and prototype glove were manufactured from the same material thickness and had the same material properties, any differences in grip and pinch strength can be attributed to the fit of the glove.

Pegboard Test. Using a modified Purdue pegboard test, subjects were instructed to remove a pin (40mm in length and 8mm in diameter) with their dominant hand from a board and place it in a corresponding cup, figure 5.53 (Tiffin and Asher, 1948). A total of 20 pins were removed individually and placed into separate cups. Once all pins were removed from the board they were replaced back one at a time, figure 5.54 and Appendix III. The total time taken to remove and replace all pins successfully was recorded by the experimenter. Dexterity at the fingertips plays a key role when manipulating and assembling small objects, this test aimed to discover the effect that wearing a glove had on dexterity and the improvements that exist if the glove has improved fit afforded to the wearer. The Purdue Pegboard test is a multiple-operational manual test of gross- and fine-motor movements of hands, fingers, arms and the fingertips (Sweetland and Keyser, 1991), and was used to analyse the effect of gloves on the participant's capability of handling small objects. This would highlight any difference in fit occurring between the standard glove and prototype glove and the influence this has on dexterity. A modified pegboard was designed to be a simplified version, more suited to the evaluation of handwear. The Purdue pegboard uses pins with a smaller diameter and is designed for testing bare handed dexterity. The simplified version enabled the participant to complete the test easily with all gloved conditions within a short period of time to ensure fatigue did not become a factor.

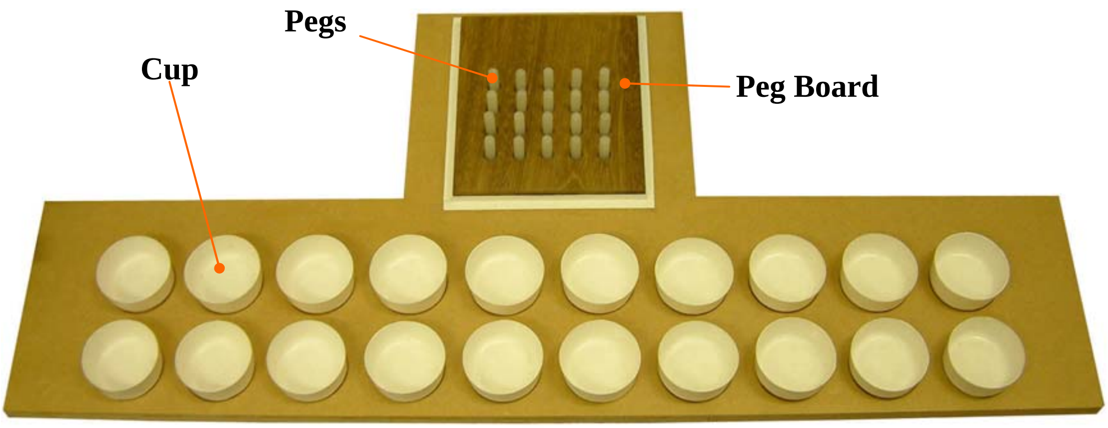


Figure 5.53 – Pegboard test apparatus

Figure 5.54 – Subject performing pegboard test

Nut and bolt assembly. Participants were instructed to unscrew two nuts and bolts from a vertical plane and place them into separate cups in front of them, figure 5.55. Once both nut and bolt sets had been removed and placed into their respective cups, they were replaced into the hole that they had been taken out of, tightening the nut until it could not be turned any further, figure 5.56 and Appendix III. The time taken to successfully disassemble and assemble the two bolts was recorded by the experimenter. The participant is blinded from the nuts and bolts by facing a vertical plane perpendicular and attached to the plane which the nut and bolt is screwed into. This ensures that they are unable to view them while disassembly and assembly takes place. This test evaluated the manipulative skills of the participant, giving a more precise measurement of how the gloved conditions impaired haptic feedback and dexterity as no visual input could be used to complete the task successfully.

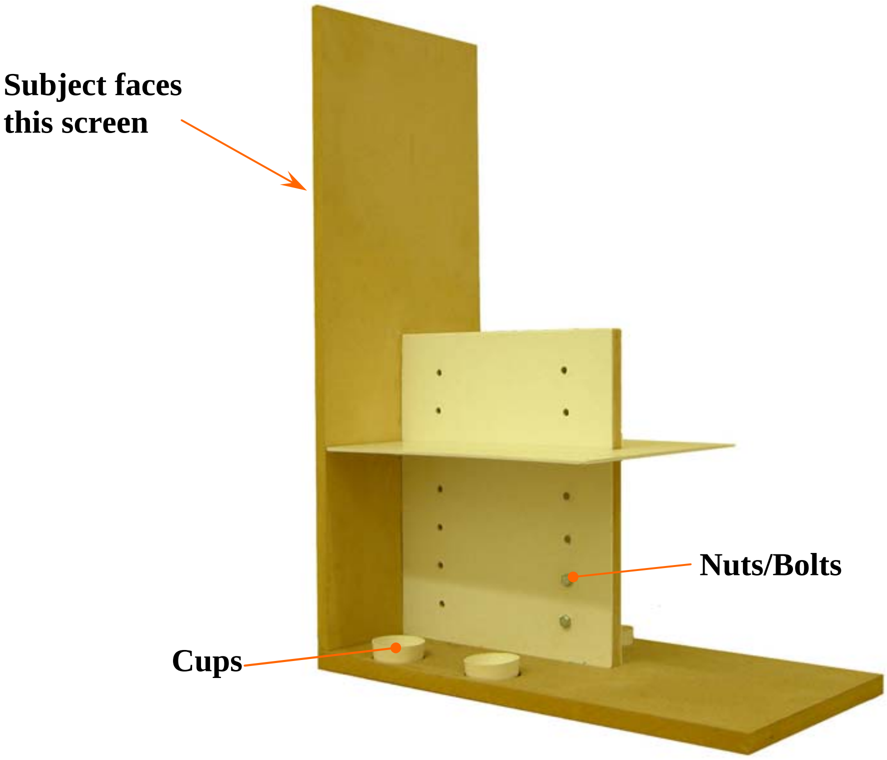


Figure 5.55 – Nut and bolt test apparatus

Figure 5.56 – Subject performing nut and bolt assembly test

Pin pick up test. This test has been adapted from a British Standard (BS EN 420:2003), and is a method for determining gloved finger dexterity. Four solid, steel pins each 40 mm long and with a diameter of 1.5mm 3mm 4mm and 6mm respectively were used, figure 5.57, table 5.3. The pins were placed on a flat, smooth surface and each subject was asked to pick up each pin, with their dominant hand, by its circumference between their index finger and thumb. The subject had three attempts to pick up each pin, without undue fumbling and within 30 seconds, figure 5.58 and Appendix III. The results of this test gave an indication to the level of dexterity the participant had for each gloved condition. The smaller the pin picked up the greater the level of dexterity.

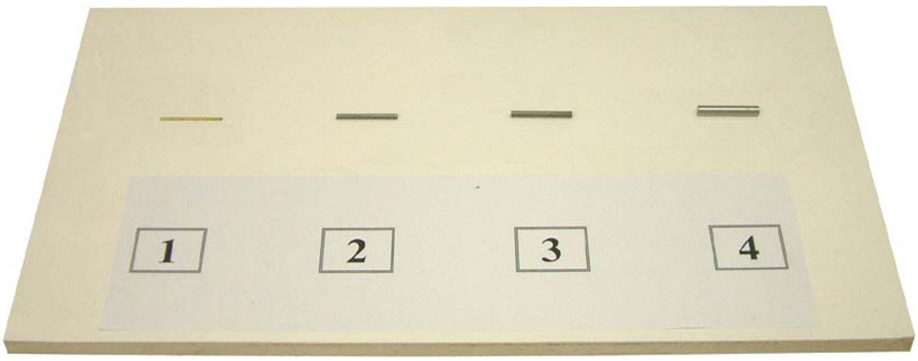


Figure 5.57 – Pin pick-up test apparatus

Pin No.	1	2	3	4
Diameter	1.5mm	3mm	4mm	6mm

Table 5.3 – Key to pin diameters, pin pick-up test

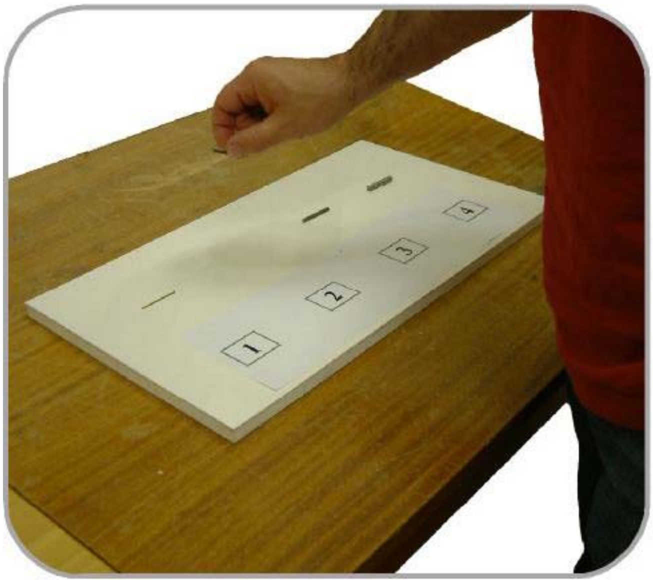


Figure 5.58 – Subject performing pin pick-up test

Keyboard typing test. The participant was asked to type a short paragraph (Appendix VIII) of text using a standard QWERTY keyboard connected to a laptop computer, figure 5.59. They were instructed to type using their own technique that was familiar to themselves and to not correct any errors that they were aware of during the test. The time taken to complete the task and the number of errors within the paragraph were recorded, figure 5.60 and Appendix III. This test was added to the trial to ensure a task that participants were more accustomed to was included. Most of the participants were unfamiliar with the battery of dexterity tests and although a familiarisation condition was included, it was necessary to analyse the effect the gloves had on an activity of daily living (ADL), where each subject would have there own individual technique.

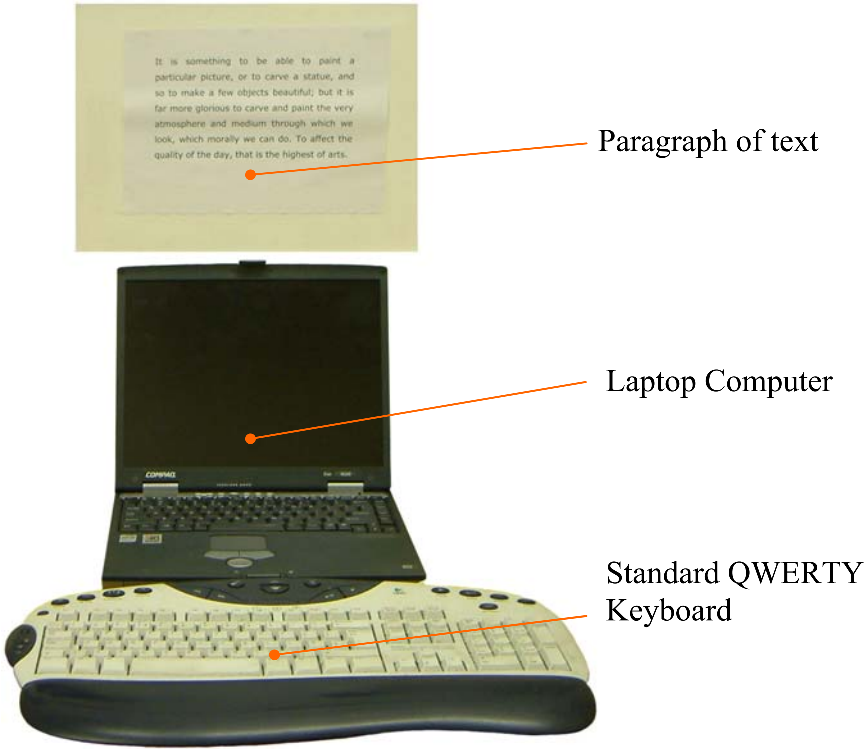


Figure 5.59 – The apparatus for the keyboard typing test

Figure 5.60 – Participant performing the keyboard typing test

The battery of tests chosen have been used in previous studies to asses the fit of handwear. Bishu and Muralidhar (1999) recommends that a glove evaluation protocol should include strength tests (grip and pinch), standardised tests to assess dexterity, tactility and manipulation; and functional tests that simulate actual tasks that the user may perform when wearing gloves. This type of protocol for handwear assessment has been adopted by Scanlan *et al* (2004), Weihrer, S. and Tremblay-Lutter (2000), Torrens and Newman (2000), Muralidhar *et al* (1999), Bishu and Klute (1995) and Bensel (1993) to successfully evaluate the performance of users when wearing different types of gloves. In addition, studies by Rock *et al* (2001), Tsaousidis and Freivalds (1998), Batra (1994), and Hallbeck and McMullin (1993) have used grip and pinch strength tests to evaluate gloves and determine the effects they have on the strength of the participants wearing them. All these studies have been able to demonstrate how wearing gloves that vary in thickness, material and size can have a detrimental effect on a person's ability to carry out tasks that rely on dexterity, tactility and strength. A task that would be relatively straightforward when completed bare handed is significantly more demanding because of the effect the gloves have on these three skills.

5.7.2 User trials

Twelve male volunteers selected from students and staff at Loughborough University participated in the glove evaluation, under conditions approved by the Loughborough University Ethical Advisory Committee. All participants were male, aged between 19 and 40 years (mean 23 ± 5.5 years). Two of the participants identified themselves to be left handed and the remaining ten identified themselves as right handed. None of the participants reported any hand abnormalities or infections that would restrict their normal range of movement. The selection of each participant was determined by their hand size. Only one glove size, size four of the size range, was produced during the pattern design and evaluation phase of the evaluation. Participants in the user trial needed to have similar sized hands to the dimensions in the size four data in order to fit into the gloves sufficiently. It was unlikely, however, that participants would be found that exactly matched each dimension; therefore, the criteria for selecting appropriate participants were based on the hand dimensions deemed critical for protective handwear with enhanced performance, as described in Chapter 4. The dimensions in the criteria were digit 2 length, digit 3 length, hand length and hand breadth (see table 4.2, figure 4.3 and Appendix I). A participant was selected for the user trial if these measurements of their hands matched the corresponding dimensions within the size four data of the size range.

Preceding each trial the participant was informed of the procedures and understood that they could leave at anytime with no obligation to give reasons for their withdrawal. Most of the tests within the trial were unfamiliar to the participants. Therefore, to become accustomed to the battery of tests, each participant performed a familiarisation condition which involved completing of each test under instruction from the experimenter. This served two purposes. Firstly, the participant was able to fully understand how each test was performed properly, so that the correct procedure was followed when it was completed with one of the four gloved conditions. It also reduced the learning effects due to the repeated exposure of the test programme. The gloves worn for the familiarisation condition were blue Nitrile™ chemical protective gloves. This glove was selected because it was unlike any of the other gloves in the user trial, which meant each participant would become accustomed to the tests in a completely different gloved condition.

The trial entailed the participant donning the appropriate glove (if applicable) and completing each of the six tests as directed by the experimenter. The participant was instructed when to start and stop each test to facilitate the timing and recording. All times were recorded with a digital stopwatch. The participants were tested individually and each trial lasted approximately 30 minutes, inclusive of rest breaks between each test to avoid fatigue.

To ensure a fair and unbiased trial, a test design was generated which reduced the effects of presentation order of the tests and gloves to the participants. The design was pseudo-balanced as the number of tests and gloved conditions were insufficient to create a completely unique combination of variables for all participants. The four types of gloved conditions (bare handed, data glove, gauge glove and latex glove) meant there were 24 possible combinations. This meant that each of the twelve participants were tested using a different order of gloved condition. Similarly, each participant performed the timed tests in a different order for each gloved condition. This meant for each participant four different test orders were needed. However, there were not a sufficient number of tests for each participant to have a unique series of test orders. This was because each test was performed four times, once for each gloved condition. As with gloved conditions, there were only 24 possible combinations of tests. Therefore, some participants performed a same test order as other participants; however no participant performed the same test order twice.

These tests gathered quantitative data on each condition in the form of kilograms for the strength assessments and time (seconds) in the dexterity tests. Data was also collected on the perceptions of the participants on the ease at which they could perform the test. After each of the four dexterity tests in each condition, the participant was asked to rate how difficult they thought it was to complete. They were instructed to give an immediate response and rate the test from 1 to 7; 1 indicating very easy and 7 indicating very difficult, figure 5.61.

Very Easy		Easy		Difficult		Very Difficult
1	2	3	4	5	6	7

Figure 5.61 – Difficulty rating scale

In addition to the difficulty ratings, quantitative data on the participants' perception of fit was also assessed. To record this, the hand was divided into five zones. The zones represent different areas of the hand and were used to identify the quality of fit for specific sections of the glove. Each zone corresponds to certain dimensions within the size data. Zone 1 represents the digits; corresponding to the dimensions digit length, PIP breadth and circumference, and DIP breadth and circumference. Zone 2 represents the digit crotches, corresponding to the dimension digit crotch height. Zones 3 and 4 correspond to the palm and the back of the hand respectively. These two zones relate to the hand depth dimensions; hand depth at thenar pad and hand depth at MCP joints. Zone 5 corresponds to the knuckles and relates to hand breadth. Analysing fit in these 5 zones indicated how the dimensions affected the size and shape of the gloves. For both the data and gauge gloves, each participant was ask to rate the fit of each zone as well as give a rating for the overall fit and on the range of motion experienced. Figure 5.62 and table 5.4 illustrate the location of each of the five zones and how they were presented to the participants. A left hand was shown in the diagrams; however, the participants were instructed to consider both the left and right when giving a rating.

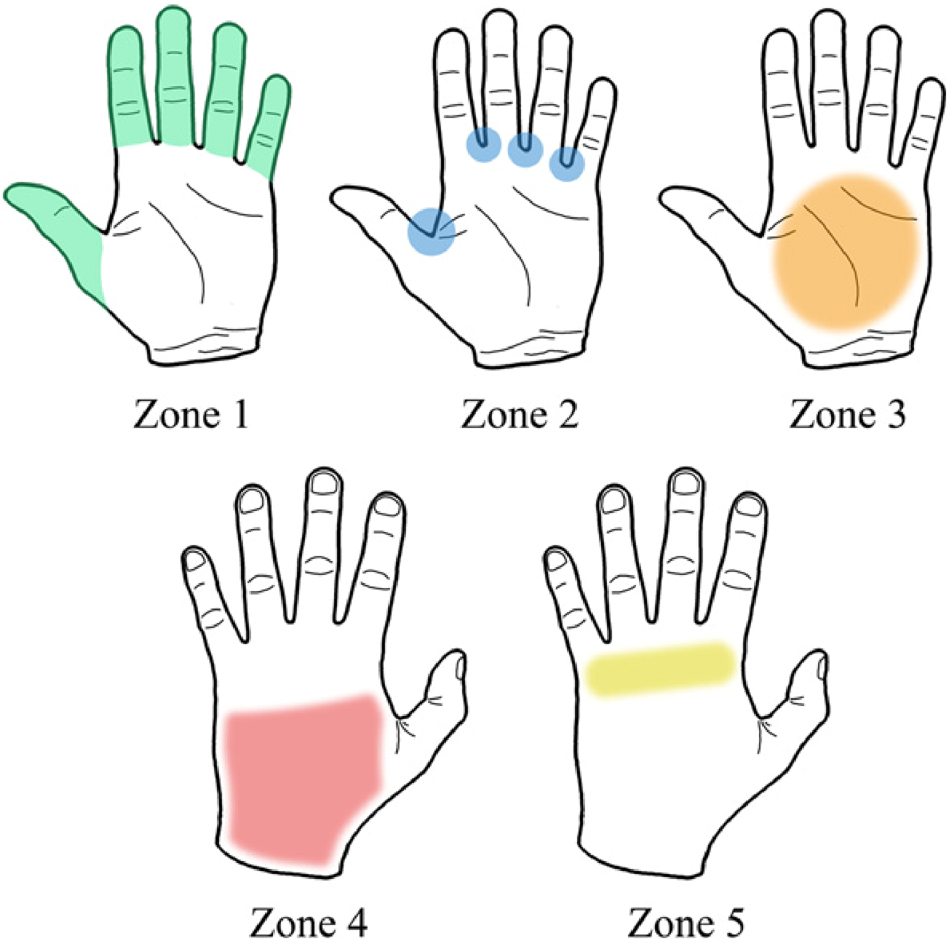


Figure 5.62 – The five zones selected to analyse glove fit

Zone	**Area of Hand**
Zone 1	Digits (Fingers and Thumb)
Zone 2	Crotches
Zone 3	Palm Area
Zone 4	Dorsal Area (Back of Hand)
Zone 5	Knuckles

Table 5.4 – Key to five zones selected to analyse glove fit

A similar rating scale to the difficulty ratings was used, figure 5.63. When asked to give a rating the participant could chose between 1 and 7; 1 indicating a very poor fit and 7 indicating a very good fit.

Very Poor		Poor		Good		Very Good
1	2	3	4	5	6	7

Figure 5.63 – Fit rating scale

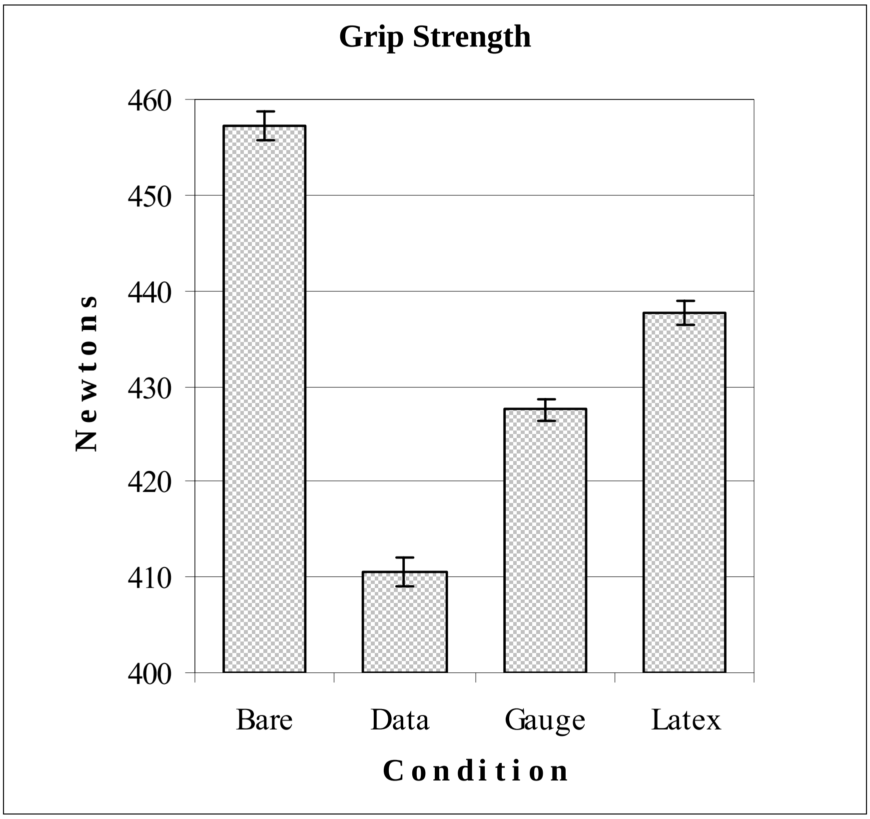
The fit perception assessment was carried out twice. First when the participant initially donned the glove and a second time once all the tests had been completed. An average score was then taken. This gave the overall perception of fit from the participant as it was possible this could differ once they had experienced the movements and activities required to complete the tests.

The forms used to record all the information from the tests can be seen in Appendix IV and the data collected from the tests are presented in Appendix V. After all the trials had been completed the results were compiled into a spreadsheet to facilitate the comparisons between the different conditions and to generate graphs, means, standard deviations and standard errors.

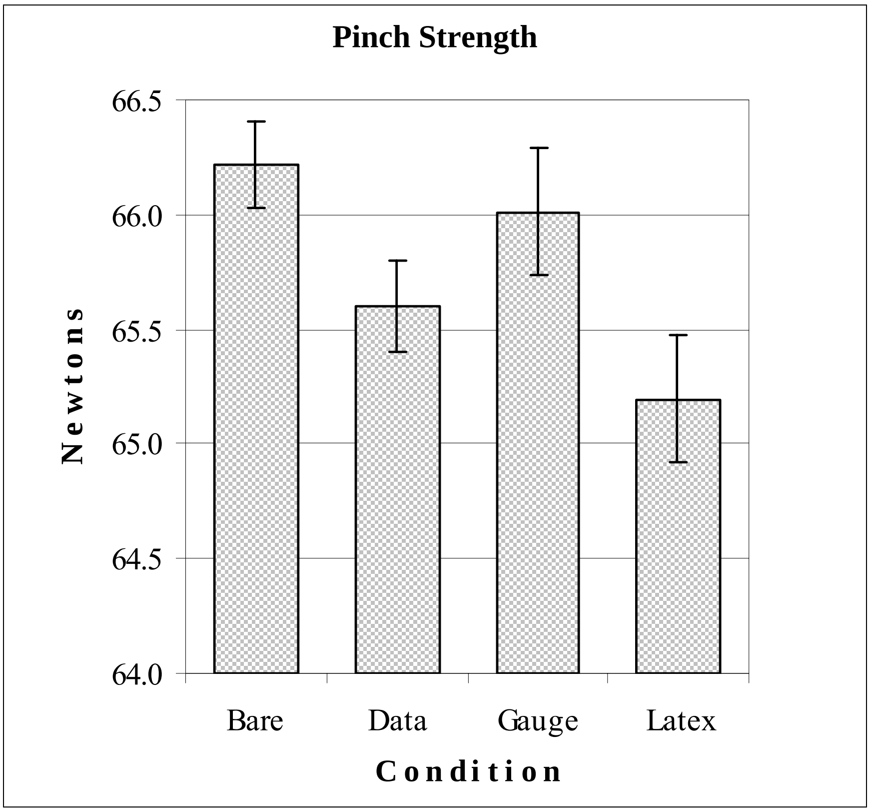
5.7.3 Evaluation phase 2 results and discussion

The results from the glove evaluation are presented below. They are discussed in three separate sections; dexterity and strength assessments, difficulty ratings and fit perceptions.

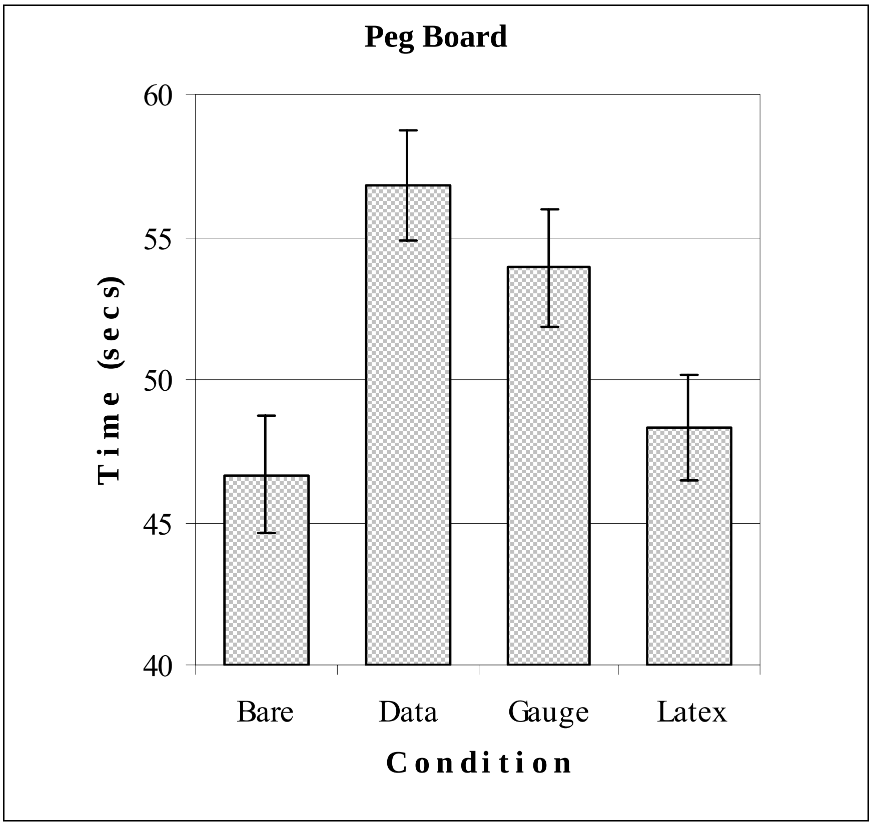
Dexterity and strength assessments



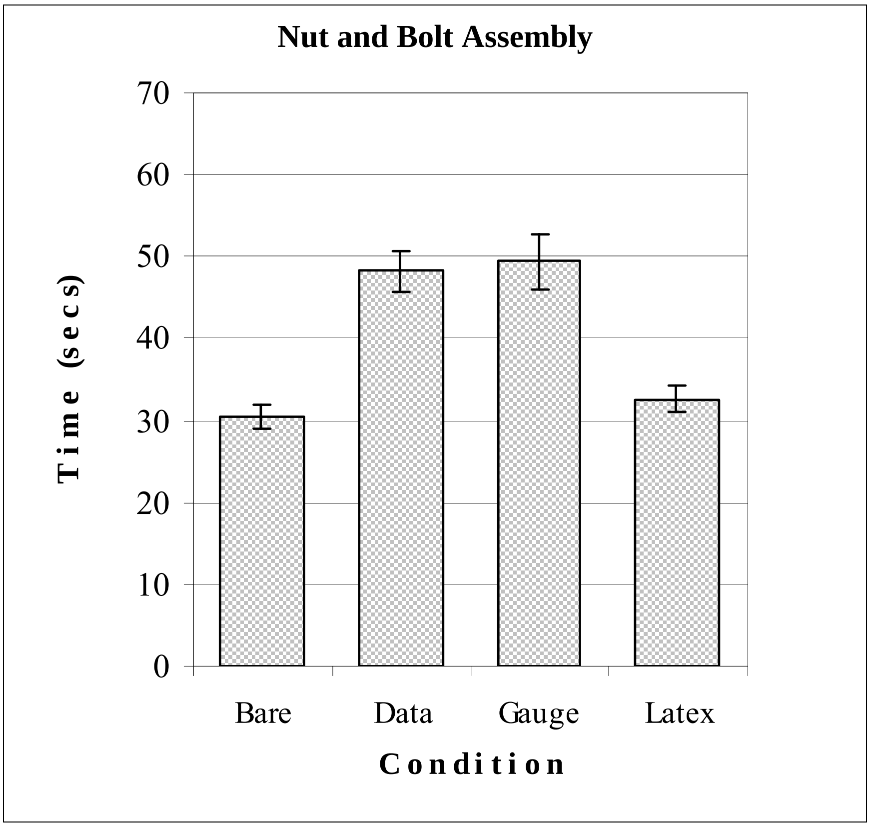
Graph 5.1 – Grip strength results with standard error



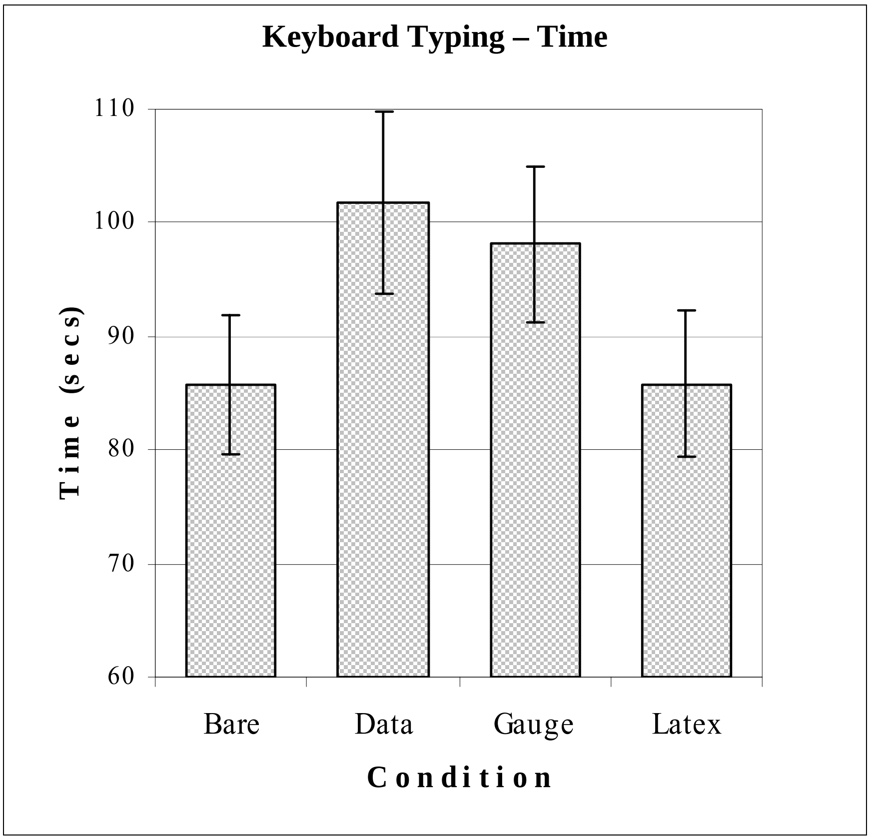
Graph 5.2 – Pinch strength results with standard error



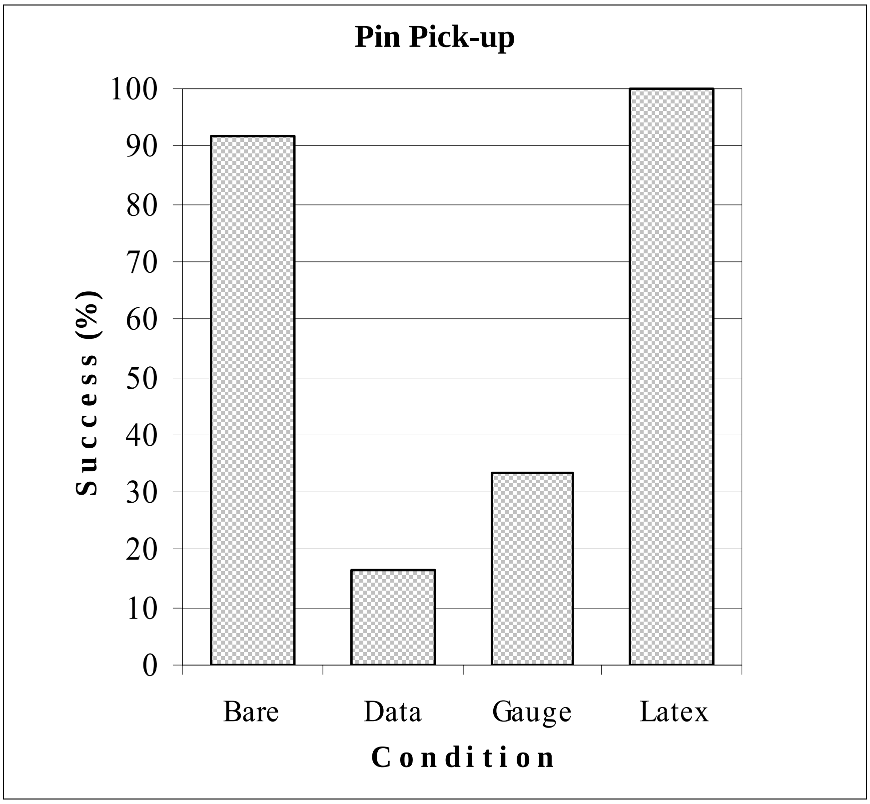
Graph 5.3 – Peg board test results with standard error



Graph 5.4 – Nut and bolt assembly test results with standard error



Graph 5.5 – Timed keyboard typing test results with standard error



Graph 5.6 – Pin pick-up test results

Condition	Keyboard Typing - Total Number of Errors
Bare Hands	39
Data Glove	65
Gauge Glove	58
Latex Glove	41

Table 5.5 – Total number of errors during keyboard typing test

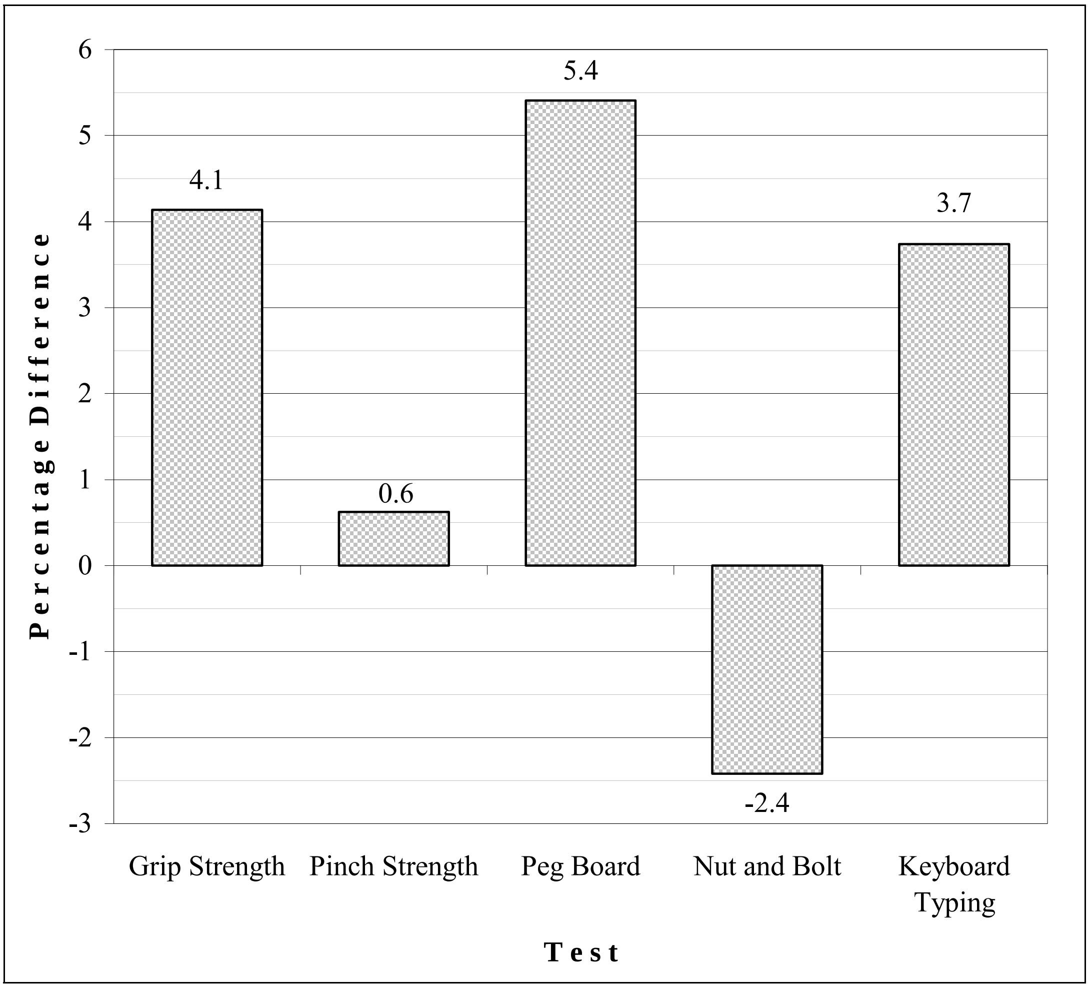
Test	Condition Rank			
	Bare	**Data**	**Gauge**	**Latex**
Grip Strength	1	4	3	2
Pinch Strength	1	3	2	4
Pegboard Test	1	4	3	2
Nut & Bolt Assembly	1	3	4	2
Pin Pick-up Test	2	4	3	1
Keyboard – Time	1.5	4	3	1.5
Keyboard – Error	1	4	3	2
Sum Of Ranks	**8.5**	**26**	**21**	**14.5**

Table 5.6 – Each condition ranked for each test

The results of the strength and dexterity tests indicate distinct variations between the different conditions. As expected, in almost all of the tests the participants performed best when completing them bare handed, table 5.6. The latex glove was the best performing glove, followed by the gauge glove with the data glove which showed the poorest performance in all but one of the tests, table 5.6 and graph 5.4. Grip strength, graph 5.1, was significantly affected when wearing gloves. This is consistent with previous studies (Bishu *et al*, 1995; Bishu and Klute, 1995; Riley, 1985; and Bhuman, 2000) that demonstrate how wearing gloves reduces the grip strength capability of the wearer. In this study the greatest difference in performance was 46.8N between bare hands and the data glove. The gauge and latex gloves performed better than the data glove but participants continued to show a considerable decrease in grip strength compared to bare hands. Pinch strength showed some variation, graph 5.2, but was far less significant. Similarly, the greatest strength occurred in the bare handed condition, but the difference between this and the worst condition, the latex glove, was only 1N. The gauge glove did perform better than the data glove but the difference was only 0.4N.

Overall in the timed dexterity tests, the participants showed a decrease in performance when wearing the data and gauge gloves. The latex glove performance was better, but the participants performed best when using their bare hands. There were, however differences between the data and gauge gloves. The mean time taken for participants to complete the timed dexterity tests was greatest when wearing the data gloves in two of the three tests, graphs 5.3 and 5.5. There was an improvement in performance when wearing the gauge glove by a mean average of 2.9 seconds in the pegboard test and by 3.7 seconds in the keyboard typing assessment. The timed test where the gauge glove did not show an improvement over the data glove was in the nut and bolt assembly test, graph 5.4. Participants wearing the data glove were able to complete the task faster than wearing the gauge glove, but the times for the two gloves were similar, differing by only 1.1 seconds. Although the differences in the times were small, it must be noted that the tests were simple and could easily be completed. This is evident in the mean times to complete the pegboard, nut and bolt assembly and keyboard typing tests with bare hands, which were 46.7, 30.5 and 85.8 seconds respectively.

The improvements in performance are more apparent when comparing the percentage difference between the gloves for each test. Graph 5.7 shows the differences between the gauge glove and data glove for the strength and timed tests as a percentage. The percentage difference for the grip strength, pinch strength, pegboard test and keyboard typing indicate an improved performance when wearing the gauge glove. Only a minor improvement (0.6%) was found for the pinch strength, which is a reflection of the small difference in the results found for this test, graph 5.2. The greatest improvement between the two gloves was in the pegboard test. The 2.9 seconds difference in time when wearing the gauge glove corresponds to a 5.4% improvement in performance of the participants, compared to the data glove. The data glove performed better than the gauge glove in the nut and bolt assembly test, as indicated by the negative value. In this test the participants showed a 2.4% improvement in performance compared with the gauge glove.

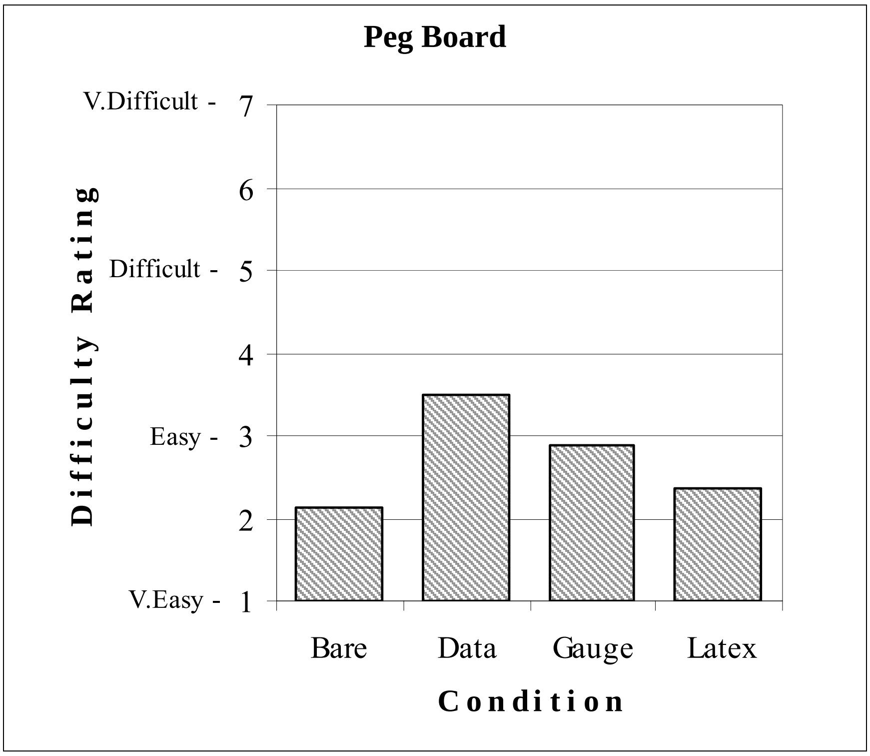


Graph 5.7 – Percentage differences between the gauge glove and data glove.

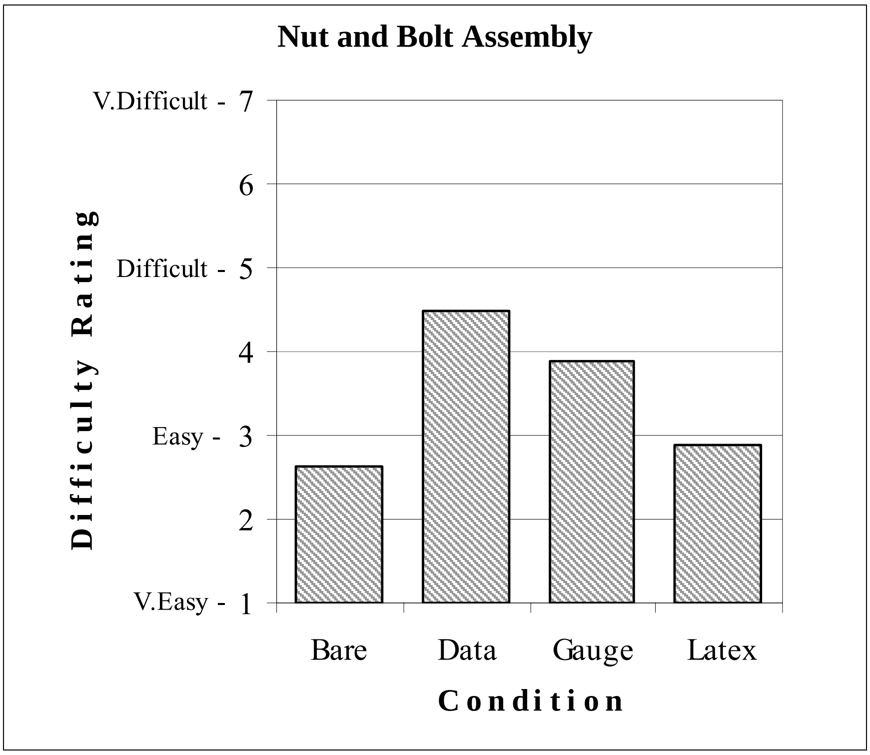
An example of one of the paragraphs written during the keyboard typing test is shown in Appendix IX. This paragraph was written while wearing the data glove and highlights the types of errors incurred. Analysing these paragraphs indicates that wearing the data and gauge gloves significantly affected the participants' normal typing ability. In addition to increasing the time taken, graph 5.5, the gloves also increased the number of errors each participant made, table 5.5. The latex glove had a minor effect on the participants typing ability, causing a slight increase in the number of errors made but not increasing the time taken to type the paragraph. When comparing the data and gauge gloves, the participants made fewer errors when wearing the gauge glove. Combined with the time taken to type the paragraph, this indicates that the participants had greater accuracy and speed when wearing this glove rather than the data glove.

The latex glove was the highest ranked condition in the pin pick up test, with participants 100% successful in picking up the pins, graph 5.6. This was the only test where the bare handed condition did not independently rank as the best condition with a 91.67% success rate. The data glove clearly caused problems for the participants in this test, with only two (16.67%) being able to pick up all four pins when wearing the glove. The gauge glove showed a slight improvement, 33.33%, but also caused problems for the participants.

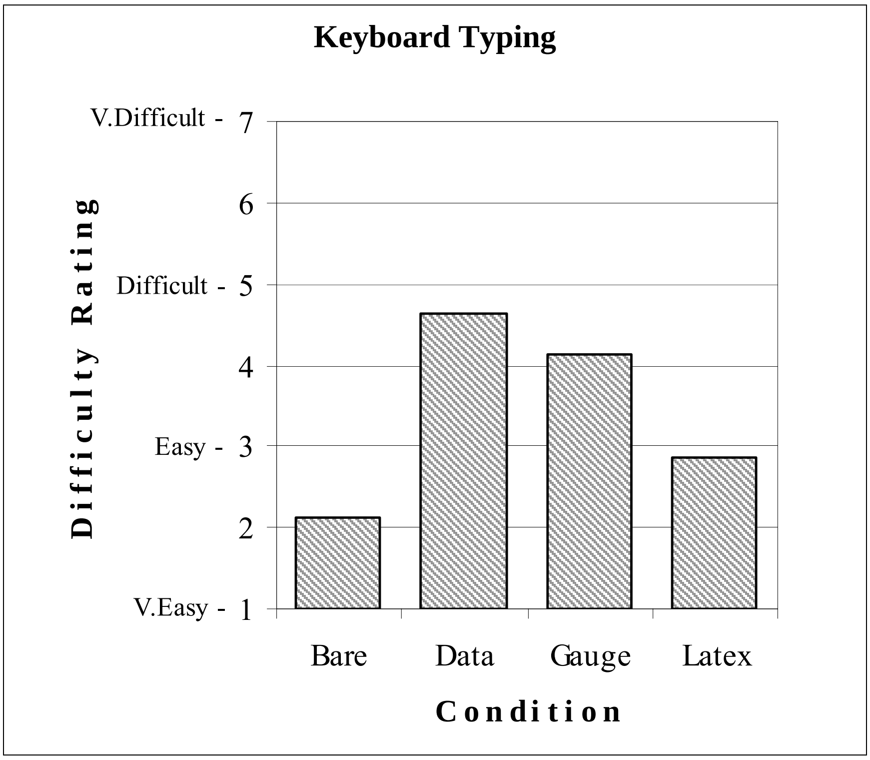
Difficulty Ratings



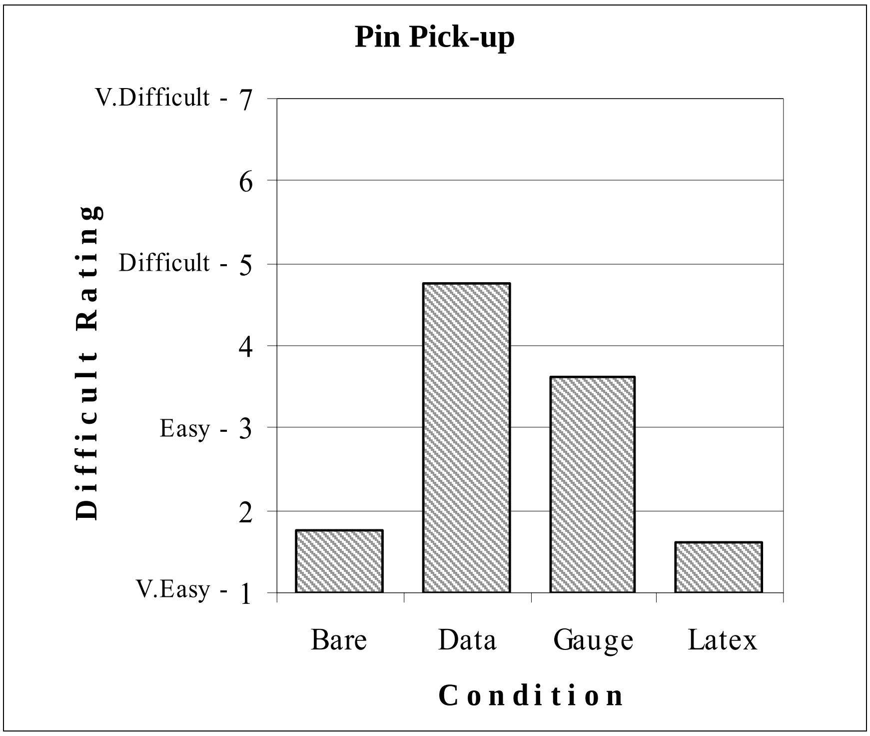
Graph 5.8 – Peg board difficulty ratings



Graph 5.9 – Nut and bolt assembly difficulty ratings



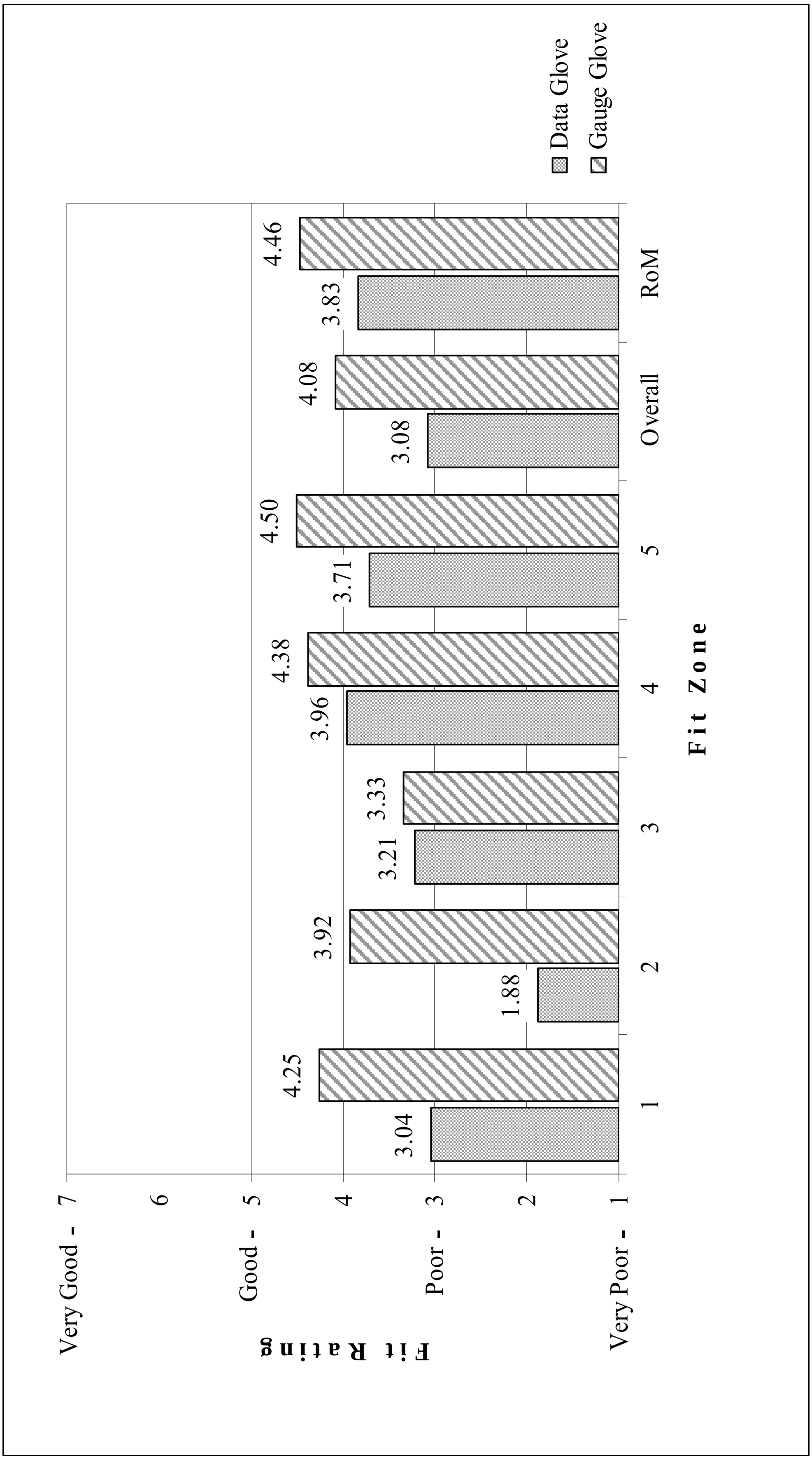
Graph 5.10 – Keyboard typing difficulty ratings



Graph 5.11 – Pin pick-up difficulty ratings

The results of the difficulty ratings generally relate to the results of the dexterity tests, graphs 5.8, 5.9, 5.10 and 5.11. The less time taken to complete the test, or greater success rate in the pin pick up test, equates to a lower (easier) rating in the perceived difficulty. For example, the times taken in the pegboard test (graph 5.3) illustrate that participants took longer to complete the test when wearing the data glove and were quickest when using their bare hands. The corresponding results for the difficulty rating (graph 5.8) reflect this, with participants rating the data glove as the most difficult condition and the bare handed condition as the easiest. Two exemptions to this trend can be seen in the times taken to complete the keyboard typing test, graph 5.5 and the nut and bolt assembly, graph 5.4. The latex glove and bare hand conditions in the keyboard typing test have the same time, however participants found the test more difficult to complete when wearing the latex glove, graph 5.10. Similarly, in the nut and bolt assembly, participants took longest to complete the task when wearing the gauge glove, but found it more difficult when wearing the data glove, graph 5.9.

Fit Perceptions



Graph 5.12 – Fit ratings of Gauge and Data gloves

The fit perception assessment shows the participants rated the fit of the gauge glove higher than the data glove in all areas analysed, graph 5.12. Participants rated the overall fit of the gauge glove higher and experienced a greater degree of flexibility, as indicated by the higher score in the range of motion ratings. The palm and the dorsal area were the two zones where the fit of the gloves were closely matched, the palm in particular, having very similar ratings. The knuckles, zone 5, showed a greater difference in fit perception, with the fit of the gauge glove having the highest mean rating in the assessment. The areas of greatest difference in perceived fit were found at the digits and crotches, zones 1 and 2. The mean rating for the crotches of the data glove was by far the lowest in the assessment, indicating the participants found the degree of fit to be severely deficient in this area of the glove. The substantial difference in these zones coincides with the differences highlighted in the patterns during the analysis of the pattern pieces and gloves after the first phase of the evaluation. This analysis indicated noticeable variation in the length and widths of the fingers and heights of the crotches, which subsequently has affected the perceived fit of the gloves.

When reviewing the ratings for each glove collectively, the gauge glove shows a more consistent trend than the data glove which displays a greater fluctuation in the ratings between each of the areas analysed. This indicates a more constant fit for the gauge glove with participants experiencing a similar degree of fit in all if the 5 zones. In contrast, the perceptions of the participants for the data glove vary between the zones, reflecting an inconsistent, inadequate fit.

5.8 Conclusions

The aim of this case study was to examine the methods of integrating anthropometry and CAD/CAM; analysing the benefits this introduces to the design and manufacture of handwear. This has been demonstrated by developing a tool that allows designers to produce gloves with an enhanced fit by improving the accuracy and efficiency of the handwear design process. This tool is the outcome of integrating anthropometric data into a CAD model, generating a 3D representation of 2D manually collected anthropometry. The design and development of these models demonstrated how data from an independent anthropometric survey can be an influential resource in the design of a new product, but also identified issues relating to appropriately applying this resource. The original size range did not contain sufficient data to represent the hand to the necessary level of detail required for the size gauge, evident in the shape of the preliminary CAD model. It was necessary to use the revised size range to ensure the CAD models contained the features applicable to gauge. The objectives of the anthropometric survey did not include design specifications of the size gauge. This meant additional data were required after the completion of the survey to include these considerations. This highlights the necessity to consider and understand the use of the data being collected during an anthropometric survey, to ensure the correct type and amount of data is obtained. It also emphasises that whilst anthropometric data is a significant resource it must be utilised correctly to become a suitable tool.

Using methods of CAM and RP the computer models were accurately reproduced as 3D manikins, able to be incorporated into the design process of gloves. The designer was able to use the manikins as a size gauge when generating glove patterns, and determine if the design of the pattern was to the correct size. The introduction of a size gauge made a distinct difference to the design method used by the designer. The gauge gave the ability to visualise what the 2D pattern should resemble in 3D and could accurately analyse the fit of the glove to indicate to the designer any necessary changes that were required, which resulted in a more accurate, efficient design process. The size gauge enhanced the iterative design cycle by reducing the number of times the designer needed to refine the initial design to produce a final pattern, as indicated by the comparison made in figure 5.48. Figure 5.64 shows the initial glove made during the pattern generation after it had been donned onto the size gauge, highlighting the markings used by the designer to identify where modifications are needed. This type of analysis was only possible with the size gauge and meant that the iterative process could be refined enabling the pattern to be generated quicker and with greater accuracy.

Figure 5.64 – Fit errors identified on glove following analysis with size gauge

The effect of the size gauge on the outcome of the pattern generation process was to produce a glove that had an improved fit for the wearer. This improvement can be attributed to the use of the gauge because it was the only variable introduced into the pattern design evaluation phase. The improvement was quantified in the user trials, where participants wearing the gauge glove showed an increase in performance and perceived fit over the data glove, produced using conventional methods. This is because of the enhanced fit around the digits and at the crotches which gave the participants a greater ability to complete the tests due to the increased range of motion and enhanced dexterity. The less accurate fit of the data glove meant there was an excess of material around the digits. This lead to a failure of the interaction between the hand and the glove material, meaning the digits were able to move independently within the glove. This resulted in a loss in sensitivity, giving false or misleading feedback to the wearer. The subsequent effect is that the manipulation of small objects and recognition of different textures or surfaces is deficient, cumbersome and time consuming.

As highlighted, when discussing the results of the dexterity tests, the differences in times between the gauge and data glove were minimal. This was due to the type of tests used which were quick and simple for the participant to complete. The tests were specifically chosen because of these reasons, ensuring the duration of each trial was only 30 to 40 minutes and fatigue did not become a factor to consider. These small differences, however, were an indication to an enhanced performance. Participants showed improvements in almost all tests when wearing the gauge glove compared to the data glove, suggesting an increased degree of fit was present. The difficulty and fit perception ratings support this by indicating the participants found the tests easier to complete when wearing the gauge glove and that this glove had a superior fit in all areas.

The glove assessment illustrated the importance of fit and the areas where it is necessary to ensure accuracy in order to improve the performance of the wearer. The two patterns generated were very similar with only minor differences between them but in areas where the fit of a glove is critical. Using the size gauge, the designer was able to identify that these areas required modification which was not highlighted using the conventional methods. In practice, these types of gloves are PPE handwear and are worn when undertaking tasks that would take several minutes, possibly hours to complete in a wide range of different environments. If a clear reduction in performance time for a simple, short task is possible, it is conceivable that a greater reduction in time and improvement in performance for a much longer, more complicated task can be achieved.

The cut and sew glove manufacturing process is the traditional method for glove manufacture. As described in the pattern generation analysis, many of the methods rely on the knowledge and experience of the pattern designer and seamstress to create the pattern and glove to the correct size. This often involves using rule of thumb techniques, specific to the pattern designer and enhanced over many years through trial and error of the iterative design process. Attempting to document and quantify the design decisions will help maintain this knowledge making it accessible among other pattern designers. This will ensure that the cut and sew process has the accuracy and efficiency equivalent to other new developments in glove manufacture. The dimensions of a glove are primarily governed by the dimensions of the hand. However, there are a variety of modifications and design decisions that must be made to develop the original anthropometric dimension into a glove dimension. These include allowances for the elasticity and thickness of the material, the position of the seams, the type of stitch used and any inner liner that might be used with the glove. The knowledge and experience of the designer is able to adjust the anthropometric data to accommodate for these properties and is aware of how the change of a dimension on one piece of the pattern affects the other pieces. Quantifying this knowledge can formulate an equation to derive the required pattern dimension from the anthropometric data. Such an equation may look like the following;

Pattern dimension = anthropometric data ± material thickness ± material properties ± seam position ± stitch type ± liner allowances ± manufacturing requirements

Identifying this knowledge illustrates the type and quantity of design decisions made during the generation for a new pattern. The anthropometric data are subject to many different modifications to convert it into suitable dimensions for the design of a new glove pattern. The size gauge has been shown to aid this design process by allowing the designer to better visualise and interact with the anthropometric data. This equation can further aid the design process by ensuring the data are appropriately modified, principally by designers who do not have the necessary experience and skills. Understanding what variables are applicable for a specific type of glove, the equation can be used together with the anthropometry to ensure the pattern is generated correctly and the glove has an accurate fit.

The outcomes of this case study have begun to fulfil the research objectives outlined in Chapter 1.4, addressing two of the objectives that were set. It has developed and validated a suitable design method to improve fit through appropriate tools of action research. It has also implemented this method and considered its effectiveness. This has been achieved by demonstrating how information from the user can be processed and integrated into a product to benefit their performance. It has investigated the use of anthropometry and CAD/CAM to increase the accuracy of protective handwear manufacture, leading to an improvement in the fit of manually machined stitched gloves. Figure 5.65 is a cycle of stages used in the case study. It illustrates how the information taken from the user has been processed to contain critical properties of handwear which are then fed back to the user in the form of the finished glove.

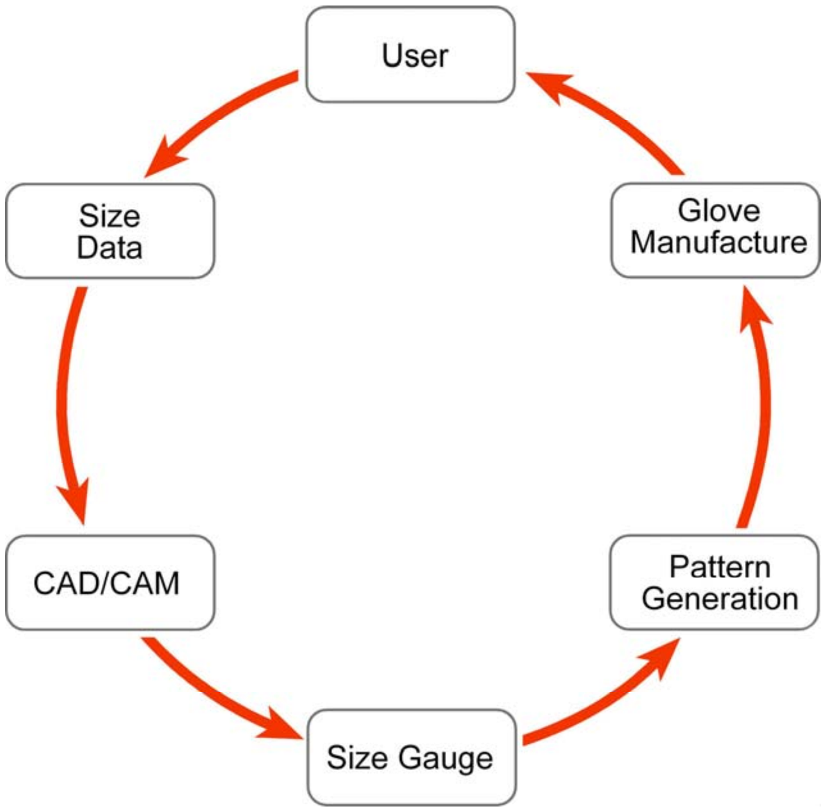


Figure 5.65 – The cycle of stages for case study one

Progressing to each stage in the cycle entailed integrating the relevant knowledge, rule of thumb principles and characteristics of good glove fit to create a glove with enhanced fit for the target user. When developing the size range, the original anthropometric data was processed to include glove design properties and was not only a database of the male and female percentiles. This required the empirical knowledge of the consultant ergonomist and designer to make the value judgements needed to integrate the correct glove characteristics and deciding on critical dimensions that needed to be prioritised. Creating the 3D CAD models and subsequent size gauge manikins from the size range required the awareness of how the size data was generated and to ensure the models were generated accurately. The pattern generation process was heavily dependant on the rules of thumb principles and empirical knowledge of the pattern designer. The designer used these skills to make the value judgements necessary to generate each piece of the pattern to the correct size and with the appropriate accommodations for material properties and seam positions. This ensured the assembled glove was to the correct size and shape, and accurately represented the size data. The evaluation of the manufactured glove demonstrated that the characteristics of good glove fit had been afforded to the target user population through the results of the assessment trials. The improvements shown compared to conventional methods of glove manufacture have demonstrated the performance of the size gauge and the link it provides between the 2D anthropometric data and the glove manufacturing process.

The second case study continued to use this cycle and investigate how the method developed in this cases study can be applied to other forms of handwear manufacture. It demonstrates that the use of CAD models representing hand anthropometric data can produce a dip moulding tool for the manufacture of handwear and is an improvement on current conventional methods.

Chapter Six:
Case Study Two – Designing a mould tool to manufacture handwear with improved fit

6.1 Case study objectives

The first case study (Chapter 5) demonstrated how integrating anthropometry and CAD/CAM can enhance the processes of 2D pattern generation for handwear design. To further examine this integration and investigate additional manufacturing processes, a second case study was designed to develop the methods and outcomes originating from the design of the size gauge. This case study had the same aim as the first, to develop and validate a tool which enhanced the fit of handwear. Therefore, the same research questions were addressed;

- **b)** Is it feasible to modify current methods of apparel design and manufacture to create a novel design tool for the design and manufacture of handwear that improves the quality of fit?
- **c)** What would be the efficacy of the tool in terms of cost effectiveness and functional effectiveness?
- **d)** What improvement in the quality of handwear fit and subsequent task performance can be achieved?

The approach for this case study was to investigate the design of a tool for the manufacture of handwear, specifically focussing on a dip moulding process. The objectives of this case study were as follows;

- To further develop the computer models generated in the first case study, incorporating necessary properties of dip moulding glove formers while retaining the specifications of the size data.
- To accurately produce a prototype glove former from these computer models using methods of RP and CAM.

- To use a prototype glove former in a commercial dip moulding environment to manufacture high quality gloves.
- To evaluate the gloves manufactured through user trials to assess their fit.

The methods used in this case study and preliminary results found in the user trials have been published in a human factors and ergonomics journal (Williams *et al,* 2004[b]), and presented at an international conference, (Williams *et al,* 2005). This provided feedback and discussion on the issues involved.

6.2 Introduction

The aim of this case study was the same as case study 1, but used the integration of anthropometry and CAD/CAM to manufacture handwear mould tools. This was demonstrated through collaboration with a handwear manufacture which enabled the CAD models generated in the first case study to be developed into a mould tool for use within a conventional glove manufacturing process. Using the CAD models ensured that detailed hand anthropometric data were incorporated into the tool and subsequently integrated into the gloves that it produced. This enhanced the fit of the gloves; evident from results of user trials which assessed the performance of participants when wearing them. Following a similar format to that used in the first case study, the user trials compared the gloves made by the new tool with gloves made using current mould tools and assessed attributes of hand strength, dexterity and haptic feedback.

This case study again highlights the benefits of integrating anthropometry into the design of handwear and how adopting methods of CAD/CAM can enable all the necessary details to be represented correctly and to the required accuracy. It also addresses the significance of current design knowledge and its contribution within the development of the CAD models to ensure they had the appropriate features to be suitable for glove manufacture.

6.3 CAD model development

The CAD models designed for the size gauges during the first case study needed significant modifications to be capable of producing a tool suitable for the manufacture of gloves. In their current form the models represented 2D anthropometric data in a 3D volume, this created a geometric configuration because of the limited amount of data available. This shape lacked the necessary properties for a glove mould tool and therefore, needed additional detail to be incorporated. The manufacturing process that uses a tool of this type for glove manufacture is dip moulding. Unlike the cut and sew process examined in the first case study, dip moulding is a process that accurately mass-manufactures gloves with no seams or stitching. It is possible to manufacture a variety of different products and is used extensively in the PPE handwear market as it can produce gloves of uniform thickness in a variety of different types of materials. It is therefore, a common method for manufacturing gloves protecting against chemical, electrical and abrasive hazards. The basic process entails a mould tool shaped to the internal dimensions of the required part, in this case a glove, to be immersed (or dipped) into the appropriate combination of plastisol materials and release agents, then cured using heat in an oven. The mould tool therefore, has a major influence on the shape and size of the final product. This means that the shape and size of the mould tool, or glove former, is critical as it dictates the fit of the glove. This also means that it is possible to influence the fit of a glove by introducing detail such as anthropometric data into the design of the glove former.

To demonstrate how this can be achieved, the size gauge CAD models were modified to introduce the characteristics of a current glove former tool and generate a completely new set of models. As can be seen in the first case study, the shape of the size gauge is determined by only using anthropometric data. Additional details of glove former properties needed to be incorporated into the CAD models to enable them to produce a tool suitable for glove manufacture. A glove former cannot contain any sharp, angular edges and must have a more conventional hand shape as it defines the shape of the glove, figure 6.1. This meant introducing a greater complexity into the CAD models, which initially proved difficult. There was insufficient anthropometric data within the original survey to produce such an intricate shape. Collecting additional data was not a feasible option as the amount required would be too great. The crucial dimensions for good dexterity for a glove have been identified in Chapter 4 when describing the processing of the anthropometric data. The size data contain the necessary dimensions to manufacture a glove with enhanced fit, therefore adding additional data would overcomplicate the CAD model, increase the time required to generate it and increase the difficulty of the adjustment process for creating different sizes. The additional detail needed was to adapt the CAD models for glove manufacture and therefore, was taken from current glove formers.

Figure 6.1 – Ceramic former used in glove dip moulding

Collaboration with a glove dip moulding manufacturer, Comasec Yate Limited, provided access to a wide range of glove formers that could be analysed for size and shape to identify areas where the detail could be taken from. The process of extracting the required detail entailed digitising a current former so that it could be used within the CAD software along side the CAD models. This was achieved using two approaches. Initially D-Sculptor was used to create a 3D surface model of the former and import it into the CAD environment. D-Sculptor is able to create a 3D model by comparing a series of photographs taken from various angles and extracting a polygonal mesh. In each of the photographs a set of individually numbered reference markers are located around the object, in this case the ceramic former, see figure 6.2. By processing each photograph to identify each marker and mask the former to highlight its outline, D-Sculptor was able to extract each mask and align them to create a 3D mesh. Although this software has a number of limitations (see Chapter

2.3.1) it could quickly create a 3D representation of the ceramic former which could be viewed using the CAD environment.

One of the main advantages of D-sculptor is its capability to extract the texture and colour from the photographs and apply it to the surface model. This tool was used to aid the generation of the additional detail required for the glove former CAD model. Prior to taking the photographs, a series of lines were drawn by hand on the former as a guide to the shape and location of construction splines for constructing surfaces. The lines were drawn on the palm, the back of the hand and in the finger crotches, as these were the main areas that required the additional detail. The shape of the lines followed the curvature of these areas to approximate their structure and how they combined with one other. A key consideration when drawing the lines was to ensure they would be able to construct a smooth continuous 3D surface within the CAD software. This meant it was necessary to maintain a smooth, rounded profile and avoid any intersection of the lines which would cause creases in any surface generated.

Applying the colour from the photographs to the wireframe surface model enabled the lines to be visible on the surface of the 3D model. This consequently meant that when the D-Sculptor model was imported into the CAD software used for the glove former development, the lines could be used in the process to generate the additional detail. Figure 6.2 shows two of the photographs used for creating the D-sculptor model, 28 photographs were used in total. The two photographs show a front and rear view of the former and the lines drawn on by hand. The former was placed on a piece of paper which was printed with the set of 16 reference markers.

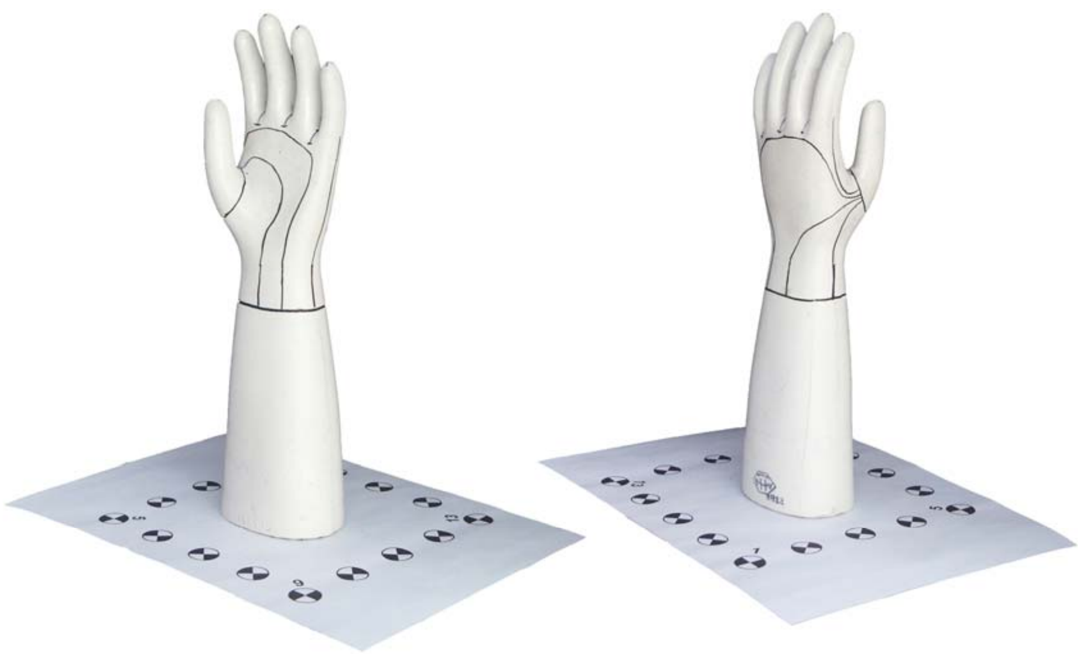


Figure 6.2 – Photographs taken of ceramic former used with D-Sculptor

The D-Sculptor model was a suitable visualisation of the ceramic former; however, was not an accurate 3D representation as the creation process of the surface model can have a tolerance of +/- 5mm. A more accurate 3D surface model was generated using 3D scanning. The process used for this followed the same procedures used during the validation of the size gauges and glove former described in Chapter 7. This produced an accurate, detailed CAD model of the ceramic former that was imported into the CAD software to manipulate and extract the required properties. The 3D scanning process could not capture the lines drawn on the ceramic former, which meant the D-Sculptor model and the 3D scanned model were used in conjunction with one another to create the additional detail needed to develop the size gauge CAD model into a glove former.

A different software program to the one used in the first case study was chosen for the generation of the glove former CAD models. The software used, Rhinoceros 3D, is a NURBS (Non-Uniform Rational B-Spline) modelling package that can accurately generate, edit and analyse CAD models. It was able to generate and manipulate the complex surface geometry necessary to create the required shape. Unlike the size gauge CAD modes, the models for the glove formers were not formed from individual components assembled together, they were constructed from one continuous surface to ensure that a smooth, even finish was generated. Rhinoceros 3D can more easily control this type of CAD model, and is able to modify the surface to create the required shape. Figure 6.3 shows the surface model of the ceramic former created using the 3D scanning method in the CAD environment. Once in this format, the former could easily and accurately be referred to, which enabled the additional details and data required for the adaptation of the CAD models to be extracted.

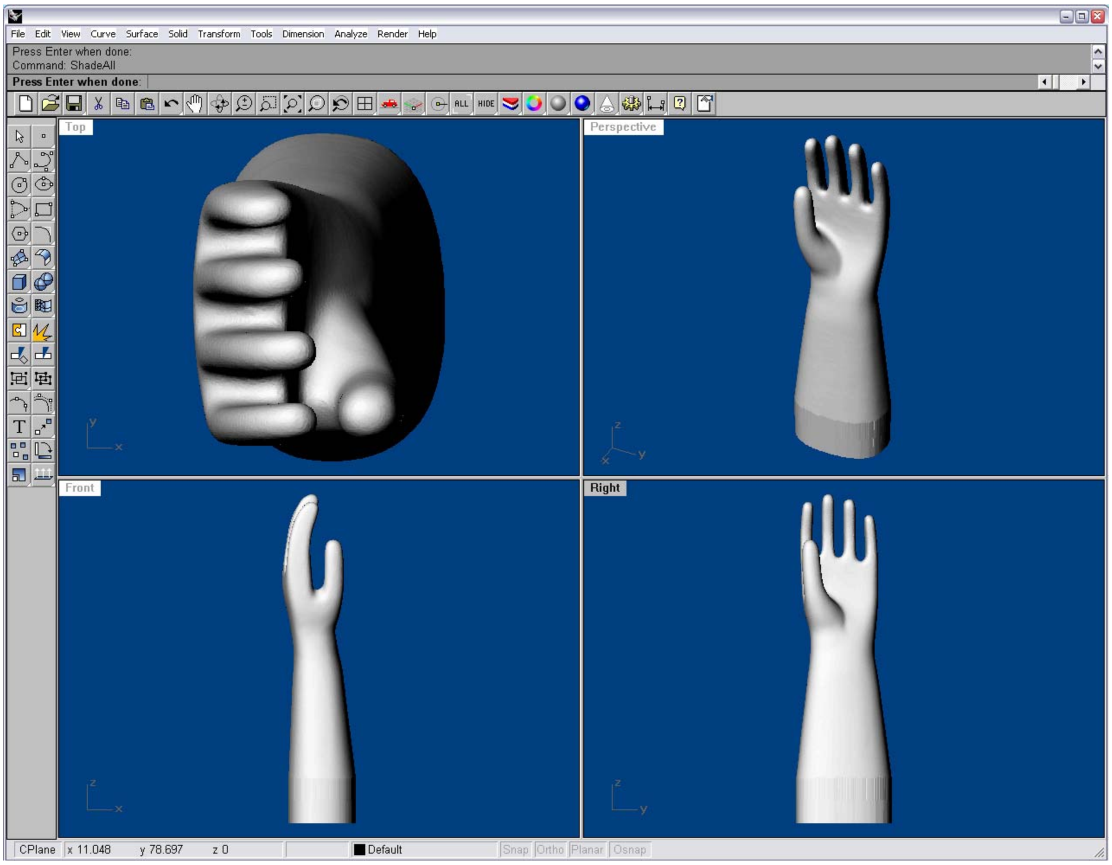


Figure 6.3 – The digitised glove former in the CAD modelling environment

The glove former models were constructed from a series of surfaces which represented the various parts of the hand. Once all the surfaces had been assembled into the correct position, they were joined to create one continuous surface. During the modelling process the size gauge CAD models, in conjunction with the dimension in the size data, were used as a reference to construct and align each surface, ensuring the new models continued to represent the size data correctly. The main areas requiring the additional detail from the current former were the palm, the digit crotches and the shape of the digit tips.

The approach to the modelling processes followed a similar method as the size gauge models. A CAD model using data from size 4 of the size range, and the corresponding size gauge model, was initially used to verify the modelling and CAM/RP procedure. This was because size 4 was considered a common size and gloves produced using the CAD model could be evaluated using a larger number of subjects. A framework structure of splines was drawn using the dimensions within the size data which were then used to create 3D surfaces. Using the size gauge CAD model as a reference along with the size data, the surfaces could be assembled to generate the correct shape. The main stage in this modelling process was the integration of the additional detail from the digitised former. The palm was significantly under developed due to the limited number of dimensions it was generated from. Using the CAD model of the digitised former, construction splines were generated directly from a current glove former and used to create the new palm. The lines drawn on the former prior to it being scanned were used as a guide during the creation of these splines. Figure 6.4 shows the orthographic views of the former within the CAD software.

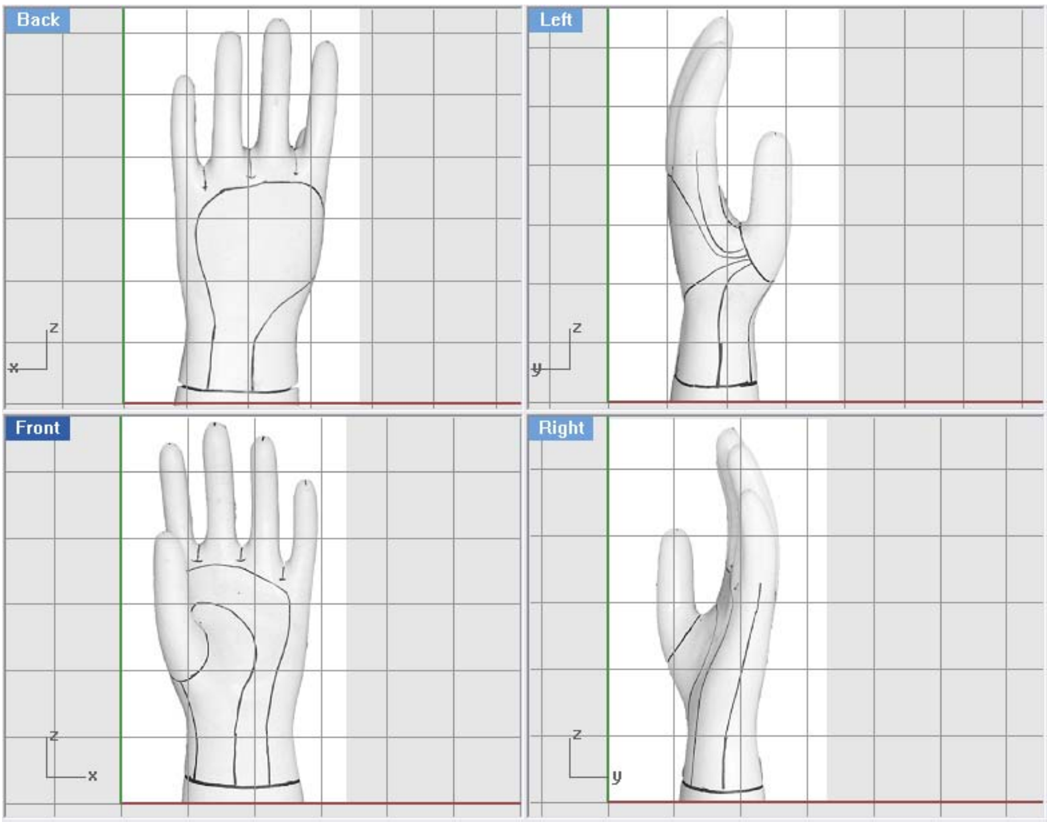


Figure 6.4 – The original former placed within the CAD software to draw construction splines.

Using these views as a guide, the shape and location of the splines could be approximated and adjusted to replicate the black lines drawn on the former. By tracing a line in one viewport, it could be modified in another viewport to obtain the correct 3D shape. This resulted in the 3D framework of splines and curves that can be seen in figure 6.5.

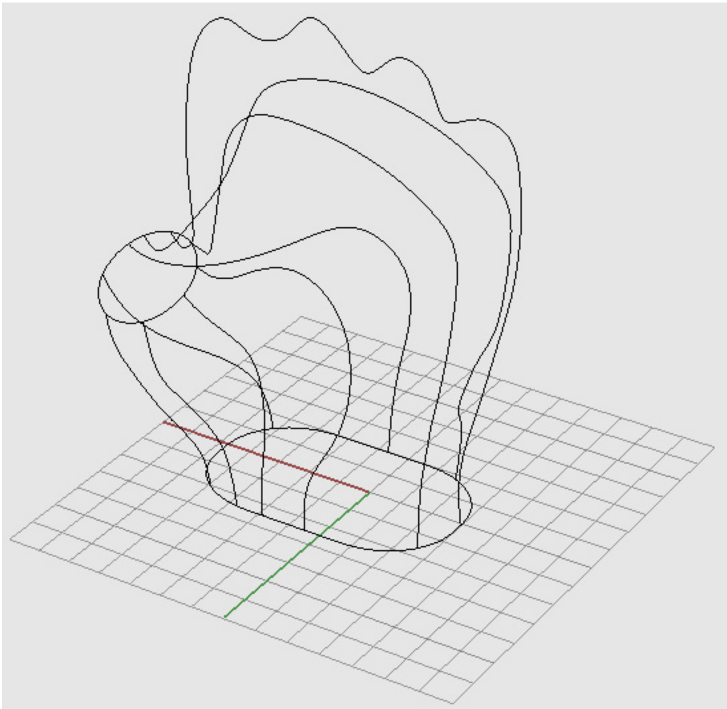


Figure 6.5 – Splines created from tracing lines on original former.

This framework could then be used to construct a 3D surface which would form the basis of the palm for the glove former CAD model. Figure 6.6, below, is the initial surface generated. This surface represented the size and shape of the original former and therefore needed modifying to include dimensions from the size data. The dimensions from the size 4 data used to make the necessary modifications were;

- Hand Breadth
- Crotch Height 1, 2, 3, 4
- Depth at MCP Joints
- Depth at Thenar Pad
- Wrist Breadth
- Wrist Depth

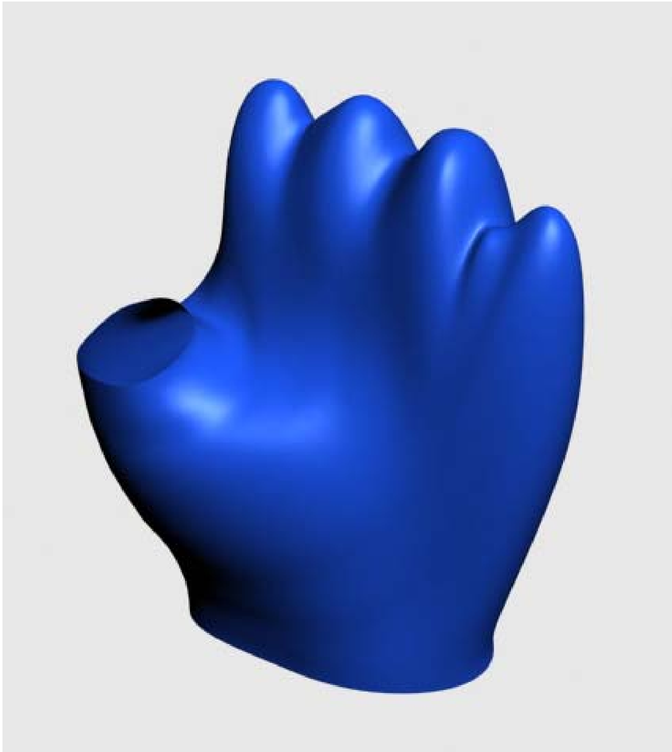


Figure 6.6 – Initial surface of palm generated from framework of splines and curves

Figure 6.7 illustrates how these dimensions relate to the 3D surface. Each dimension was measured on the surface model within the CAD software and adjusted to the correct size.

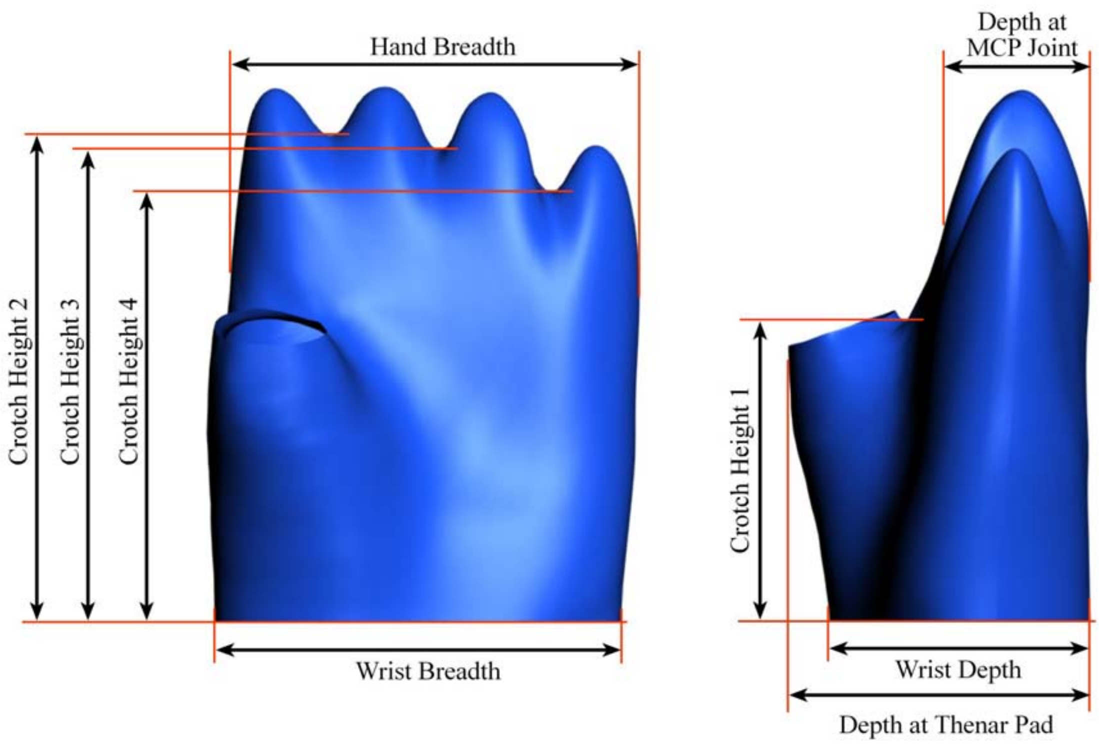


Figure 6.7 – Dimensions from size range used to modify the shape of the palm.

Changing the relevant section of the surface was done by modifying the size and position of the curves and splines in the 3D framework as this controlled the shape of the surface. In addition, the corresponding size gauge CAD model was imported into the same workspace and used as a 3D reference to ensure the appropriate shape and proportions were maintained correctly. Figure 6.8 shows the completed palm surface which had been modified to represent the dimensions within the size 4 size data.

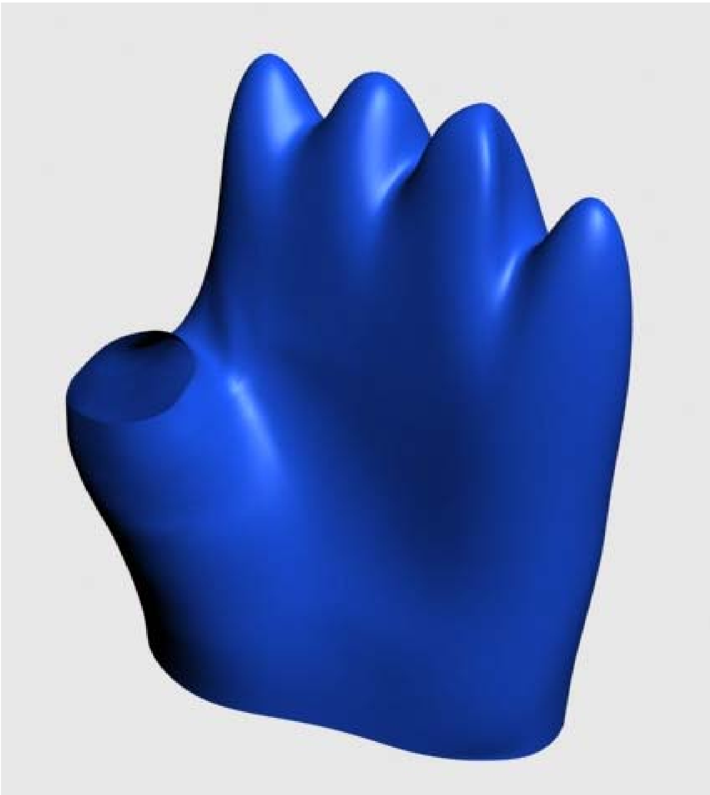


Figure 6.8 – Completed pal surface modified using dimensions from size data.

After generating the palm shape, the next stage was to model the digits and attach them to the relevant area of the palm to create a complete hand. Each of the five digits was generated using a similar approach developed when generating a digit for the size gauge CAD model. A framework of splines and curves was drawn to build a 3D surface which would represent the digit, figures 6.9 and 6.10.

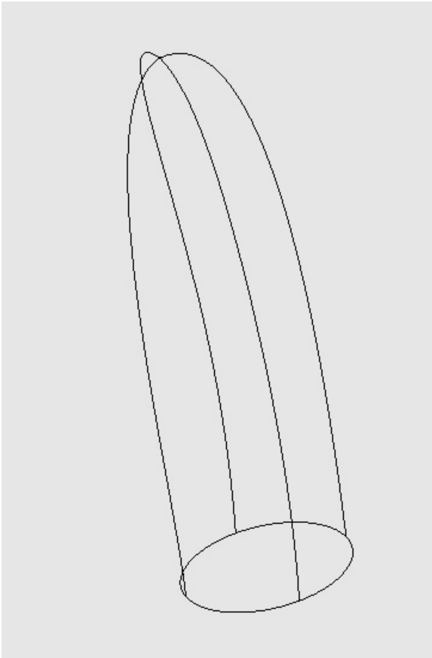


Figure 6.9 – Framework of splines and curves used to generate a digit.

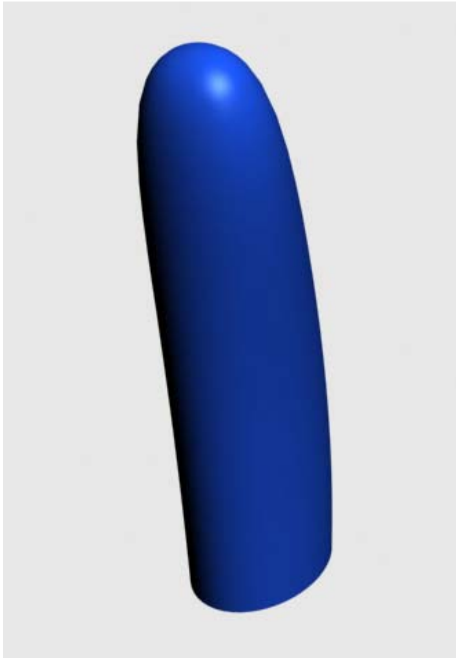


Figure 6.10 – 3D surface of a digit.

The base of a finger was an ellipse, drawn using the dimensions PIP joint breadth and DIP joint breadth to specify the major axis and minor axis, respectively. The base of the thumb was a circle with the diameter equivalent to the digit 1 joint breadth dimension. The length and shape of the digits was created using a series of splines that matched the shape of the digit on the original former. The distance of each of the splines above the ellipse or circle determined the length of the digit and therefore corresponded to the relevant digit length dimension. The splines and curves within this framework were then used to generate a 3D surface to create the shape of the digit.

Each digit was aligned relative to the palm using the corresponding size gauge CAD model and dimensions in the size data. The dimensions used for this process were the digit crotch heights and hand breadth. The bottom of digit 1 was aligned using crotch height 1; the bottom of digits 2 and 3 using crotch height 2; the bottom of digit 4 using crotch height 3; and the bottom of digit 5 using crotch height 4. The fingers were spread evenly across the width of the palm using hand breadth. Figure 6.11 shows each of the digits aligned with the palm surface.

Figure 6.11 – Digits aligned with palm.

Figure 6.12 – Intersecting surfaces trimmed

To connect the palm and the digits it was necessary to trim the intersecting surfaces to enable all the surfaces to be joined. Trimming the surfaces entailed drawing 2D curves and projecting them onto the relevant surface to create a boundary and split the surface to remove the unnecessary piece. Figure 6.12 shows how the digits and palm were modified to eliminate any intersecting surfaces. For the digits this process meant shortening the surfaces slightly by removing the section that intersected with the palm. The palm was modified to create the shape necessary to represent the digit crotches. This shape was created by using the digitised glove former as a guide to match the curvature in this area and ensure a smooth, consistent join. The gaps created by trimming the surfaces were filled using an additional surface which combined each digit with the palm, creating an even transition between them, figure 6.13.

Figure 6.13 – Digits and palm surfaces blended together to create the completed hand shape.

The final feature added to the CAD model was the forearm. There were no dimensions within the size data to specify the shape and size of the forearm, therefore, the length and shape was modelled to match the forearm of the digitised former. The shape of the forearm on current glove formers is specifically designed to allow them to be clamped onto a rig during the dip moulding process. Recreating this shape for the forearm of the CAD model would enable it to be introduced into the same dip moulding process without the need for individual, customised clamps to be produced. Figure 6.14 shows the completed CAD model for the glove former.

Figure 6.14 – Fully assembled glove former CAD model

The completed CAD model was an integration of glove former detail from the digitised former and the dimensions of the size data. This meant the 3D form was a combination of the size gauge and current glove formers, figure 6.17. The CAD model contained properties for a suitable glove former as well as anthropometric data of a known population. Therefore, gloves made from a former produced using this CAD model would contain the necessary characteristics for enhanced fit.

Figure 6.15 – Integrating current glove former detail and size gauge 3D shape into the glove former CAD model.

Using a current glove former as a guide during the CAD modelling process enabled areas of the hand that lacked sufficient data within the size range to be generated in greater detail. The main regions requiring this detail were the digit crotches, the area where thumb joins the palm, the thumb crotch, and the thenar pad. All these regions needed to have a smooth, gradual blend into the palm to create the appropriate shape for a glove former mould tool. Figure 6.16 illustrates how finger crotches of the size gauge and glove former CAD models differ due to the integration of this detail.

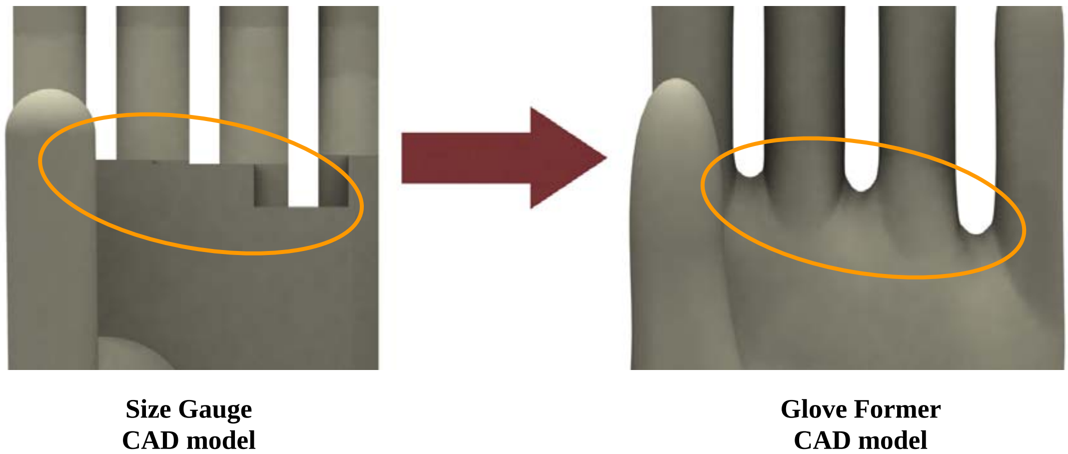


Figure 6.16 – Differences in finger crotch detail between the size gauge CAD model and glove former CAD model.

Figure 6.17 highlights the differences between the thumb crotch and thenar pad regions. The dimensions contained with the size data to specify the detail of these regions meant the configuration of the size gauge CAD model was limited. Using the digitised glove former as a guide to extract the necessary curvature enabled more detailed 3D surfaces to be generated. This better represented the shape of these regions, creating a more natural form that blended the thumb and palm together.

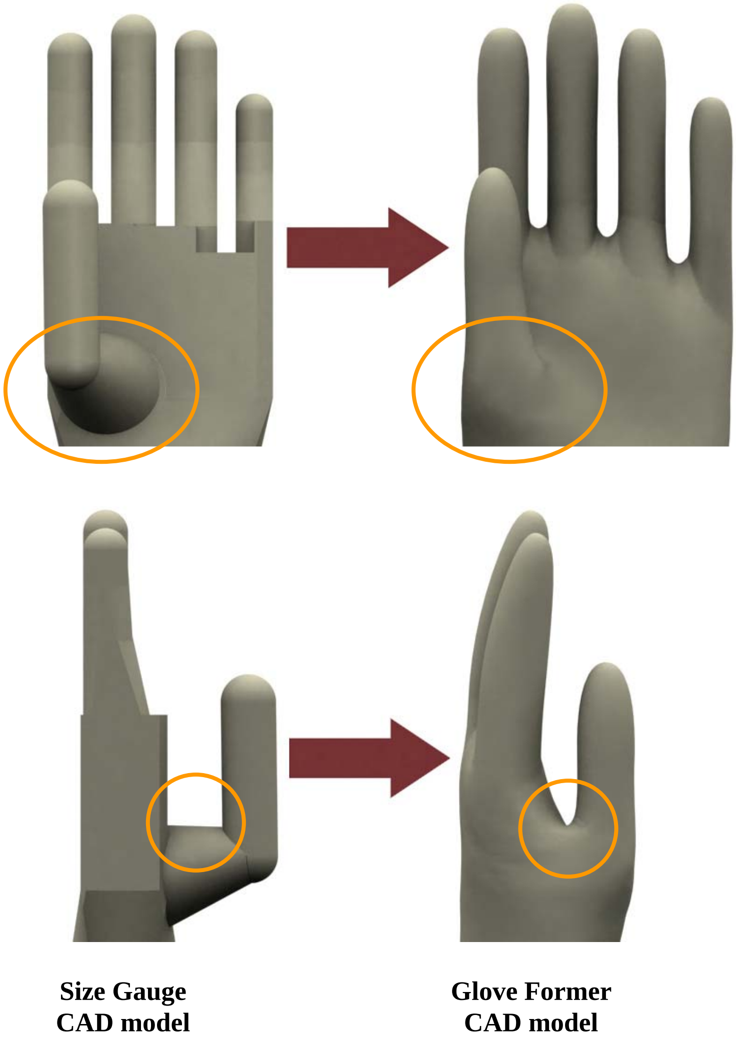


Figure 6.17 – Differences in thumb crotch and thenar pad detail between size gauge CAD model and glove former CAD model.

Two further characteristics of a glove former were taken from the digitised model. On current formers the fingers are slightly curved to recreate the natural, neutral position of the hand. This curvature was added to the fingers of the glove former model and can be seen in the side views in figure 6.17. The other feature to be added was a reduction to the radius of the digit tips, also illustrated in figure 6.17. Current formers have digit tips that are slightly pointed to reduce the occurrence of drips or runs on the glove while it is being manufactured. This feature of the former produces a glove that does not adequately fit the end of the digit. An inconsistent fit in this area of a glove hinders dexterity and tactile perception which is vital for manipulating small objects. This element needed to be reduced for the prototype former, however, could not be eliminated completely as fully rounded digits would cause manufacturing problems. Therefore, the radius that formed the tips of the digits was increased by 20% to create a more pointed shape; incorporating some of the mould tool properties from the glove former, but retaining the dimensional accuracy of the size data. This ensured the prototype former could be used as a dip moulding tool but produce a glove with good qualities of dexterity and tactile perception.

There were two main issues to consider during the generation and assembly of the 3D surfaces that constructed the glove former CAD. The first was to ensure that the integration of the detail did not mean any deviation from the size data. Secondly, it was necessary to consult with Comasec Yate Limited regularly to ensure the detail from the current former was integrated correctly. As this detail was developing the CAD model to be used as a dip moulding tool it was important to have the advice from experts in the field of dip moulding to verify that what was being generated could successfully manufacture a glove. The versatility of the CAD package allowed modification of the CAD model to be completed while discussing the issues with the experienced production engineers from Comasec Yate. The ability to integrate the detail alongside sources of expert knowledge was vital in generating the CAD model accurately and efficiently. The final configuration of the glove former model can be seen in more detail in Appendix II.

The initial modelling method was successful in generating a glove former model that sufficiently represented the size data accurately and contained the necessary characteristics of a glove former. Due to the more complex configuration of this model, the resizing process that facilitated the generation of subsequent sizes for the size gauge CAD models could not be applied. The Rhinoceros 3D software did not have the capability of linking a database with the size data dimensions to the 2D framework structure. This meant that the CAD models for the remaining sizes needed to be generated using the same method for creating the initial CAD model, by modifying each part manually using the relevant dimensions from the size data and the corresponding size gauge CAD model.

6.4 Prototyping a glove former

To use a developed CAD model in the manufacture of gloves, it needed to be produced into a physical glove former that could be used within a dip moulding manufacturing process. Current glove formers are made from ceramic or aluminium as they must withstand the extremes of heat and various chemicals they are exposed to during the dip moulding process. The timescales and costs typically required to manufacture these formers would be unsuitable for producing a prototype former from the CAD models, therefore, the methods of CAM and RP developed in case study one were used. In contrast to the first case study only one model for each size was generated. The separation of the thumb to form an extra model which was necessary for the function of the size gauge was not possible for the glove former, as it needed to be one complete part. This affected the design of the silicon tool which needed to have a split line that separated the tool into three pieces in order to de-mould the cast without causing damage to the mould or the prototype tool.

The other stages of producing a resin cast remained the same. The size 4 CAD model was used to produce the prototype former and manufacture gloves which would be used in the user trials to evaluate their fit. Using the 3D Systems InVision™ 3D Printer, an RP master part was produced of the CAD model, from which the silicon tool was created. Figure 6.18 shows the RP part inside the silicon tool. The top part of the mould was split into two pieces around the thumb and thenar pad area, which created the three-piece tool. The same polyurethane resin was used to cast into the mould to create the finished prototype glove former, figure 6.19. The CAD models were of the left hand due to them being generated using the size gauge models as a reference, which were also of the left hand. To produce both left and right handed formers the models were mirrored within the CAD software and the same CAM and RP methods used to produce right handed prototype formers. This enabled pairs of gloves to be manufactured for assessment in the user trials.

Figure 6.18 – The RP model in the silicon tooling

An important feature of a glove former is a smooth even surface finish, necessary to manufacture gloves with a consistent material thickness. The ceramic and aluminium formers have highly polished surfaces with no imperfections that would cause defects in the gloves they manufacture. This high quality surface finish needed to be reproduced as closely as possible on the prototype former to enable it to produce gloves to a similar degree of quality. The 3D printer was able to recreate the CAD models with an even surface finish, but some hand finishing was required to create the smooth finish required. The silicon tool was able to maintain this level of surface finish and reproduce it on the resin cast which required only minimal hand finishing to prepare it for use within the dip moulding process.

Figure 6.19 – Size 4 resin cast of a prototype former

6.5 Glove evaluation

The aim of this case study was to determine if a mould tool, designed using hand anthropometric data, could produce gloves with enhanced fit. Therefore to fully evaluate the prototype former it was necessary to manufacture gloves using it. The gloves produced were evaluated by conducting a user trial similar to the one undertaken in the first case study, using a battery of tests to assess the accuracy of their fit. To compare the prototype former against a current former, gloves made using conventional manufacturing techniques were also tested at the same time using the same tests. The evaluation procedure involved using subjects with relevant sized hands to undertake a series of tests that evaluated finger dexterity, haptic feedback and hand strength.

6.5.1 Manufacturing prototype gloves

The size and shape of the resin prototype former was verified to ensure it was a sufficiently accurate representation if the CAD model. The methods and results of this procedure are described in Chapter 7. This analysis found that the difference in size between the resin former and the original CAD model was -0.369mm. The negative value calculated means the former is smaller than the CAD model but the value indicates that there are very minor differences in size and shape. After establishing the prototype former was suitably accurate, it was given to Comasec Yate Limited and used within their manufacturing facilities to produce a batch quantity of prototype gloves, figure 6.20. A sample of the polyurethane resin used to produce the former was exposed to the temperatures and chemicals used in the dip moulding process to ensure the former would successfully manufacture a batch sample of gloves suitable for evaluation. The material chosen for the glove was a lightweight Flexigum black natural rubber, which has good flexibility and dexterity properties, with a smooth surface finish. This was selected because it had no significant shrinkage after being stripped from the former, resulting in the glove representing the exact shape. To evaluate the prototype glove against current dip moulded gloves a standard size nine glove former was used to produce a sample batch of gloves from the same material, figure 6.21. This size of former is the equivalent to the size four prototype former and would provide a comparison of what level of fit is currently provided for this type of glove. The two sets of dip moulded gloves in the user trial had the same material properties and were the same thickness, differing only by the type of glove former used, see table 6.1.

Figure 6.20 – Prototype glove

Figure 6.21 – Standard glove

6.5.2 User trials

Sixteen male volunteers selected from students and staff at Loughborough University participated in the glove evaluation, under conditions approved by the Loughborough University Ethical Advisory Committee. All participants were male aged between 18 and 38 years of age (mean 22.31 ± 5.5 years), two identified themselves to be left-handed and fourteen as right-handed. None of the participants had any hand abnormalities or infections that would restrict their normal range of movement. The criteria for selecting appropriate participants were the same for the trials in the first case study, based on the hand dimensions deemed critical for protective handwear with enhanced performance, as described in Chapter 4. These dimensions were digit 2 length, digit 3 length, hand length and hand breadth (see table 4.2 and figure 4.3). A participant was selected if these dimensions matched those in the size four data range.

The trial followed a similar procedure used to assess the gloves generated in the size gauge evaluation. It consisted of four gloved conditions; each participant tested wearing the standard glove, the prototype glove, a latex glove and with bare hands. To become accustomed to the battery of tests, each participant performed a familiarisation condition to reduce the learning effects due to repeated exposure to the test programme. The gloves worn for this condition were blue Nitrile™ chemical protective gloves. Table 6.1 gives the thicknesses of each of the gloves at the palm and at the fingertip.

Glove Type	Thickness (mm)	
	Palm	Fingertip
Standard Glove	0.67	0.65
Prototype Glove	0.69	0.67
Latex Glove	0.12	0.15
Familiarisation Glove	0.52	0.55

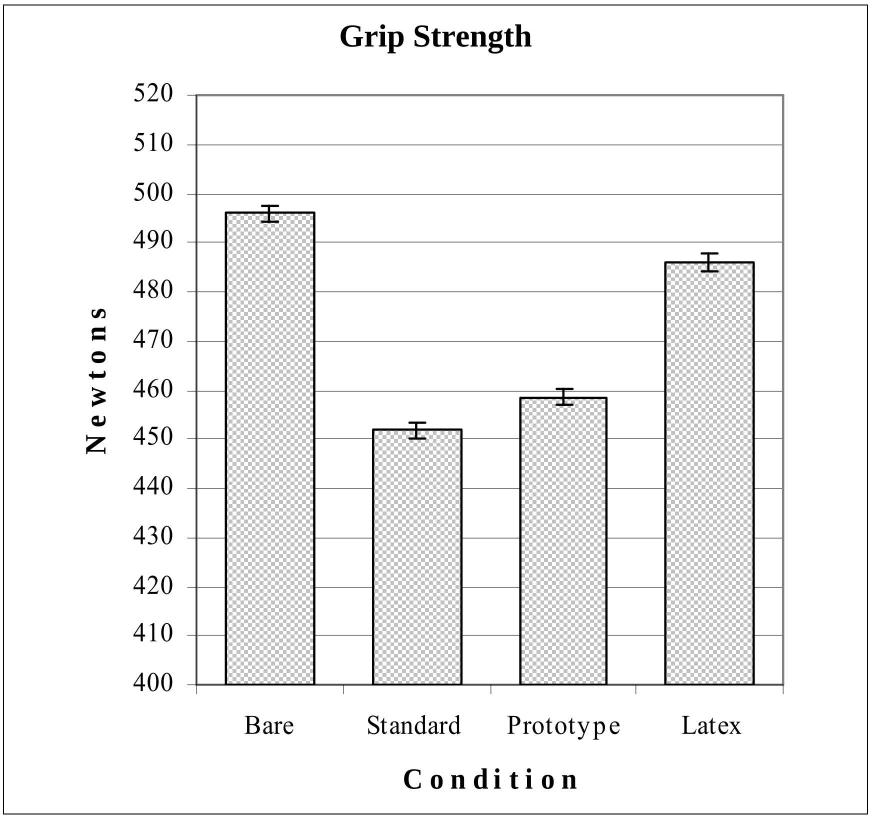
Table 6.1 - Glove thickness of each glove used for the evaluation testing

Four different tests were performed with each gloved condition; a pegboard test, a nut and bolt assembly, a pin pick-up test and a keyboard typing test. Each participant was also tested for grip strength and pinch strength for each condition. A description of each test and why it was chosen was given in Chapter 5.7.1 and in Appendix III. The user trial followed the same pseudo-balanced test design used in the user trial for the first case study to ensure a fair and unbiased trial. This was to reduce the effects of presentation order of the tests and gloves to the participants.

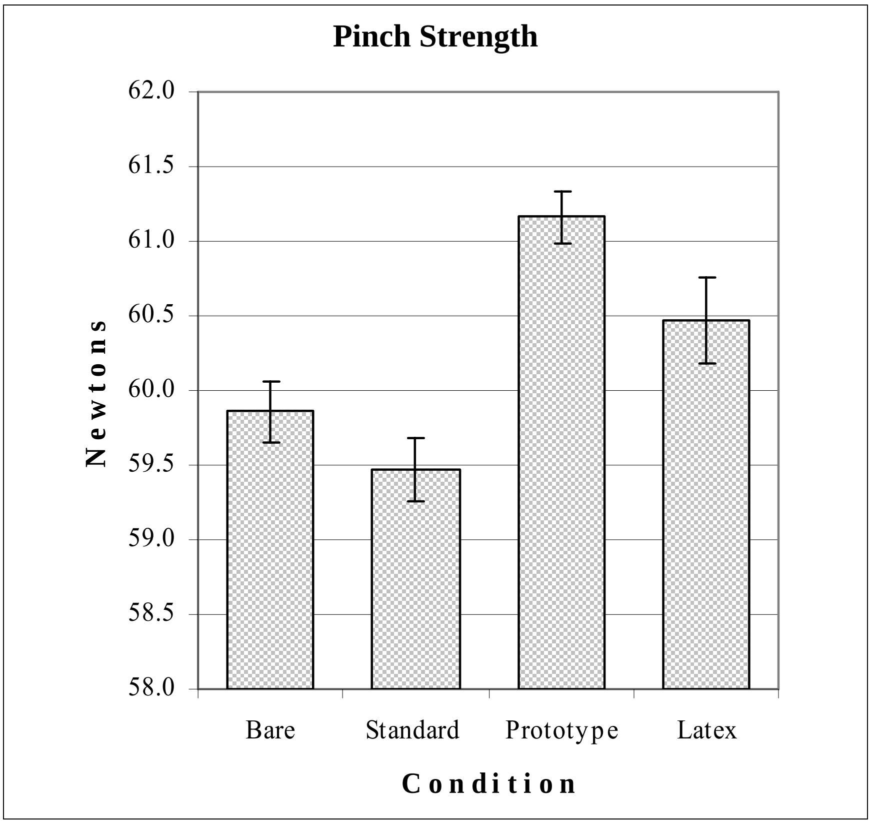
Before each trial the participant was informed of what was entailed and understood that they could leave at anytime with no obligation to give reasons for their withdrawal. They were asked to don the appropriate glove (if applicable) and carry out the test as directed by the experimenter. The participant was instructed when to start and stop each test to facilitate the timing and recording. All times were recorded with a digital stopwatch. The participants were tested individually and each trial lasted approximately 30 minutes, inclusive of rest breaks between each test to avoid fatigue. The forms used to record all the information from the tests can be seen in Appendix VI and the data collected from the tests are presented in Appendix VII.

6.5.3 Results and discussion

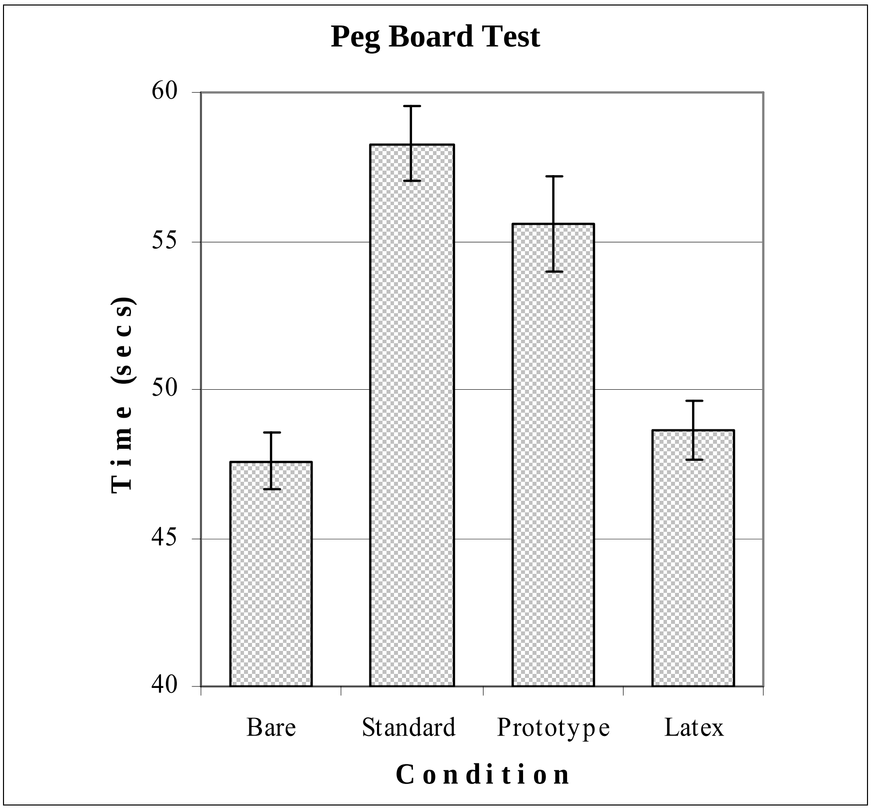
The results of the glove evaluation are presented below.



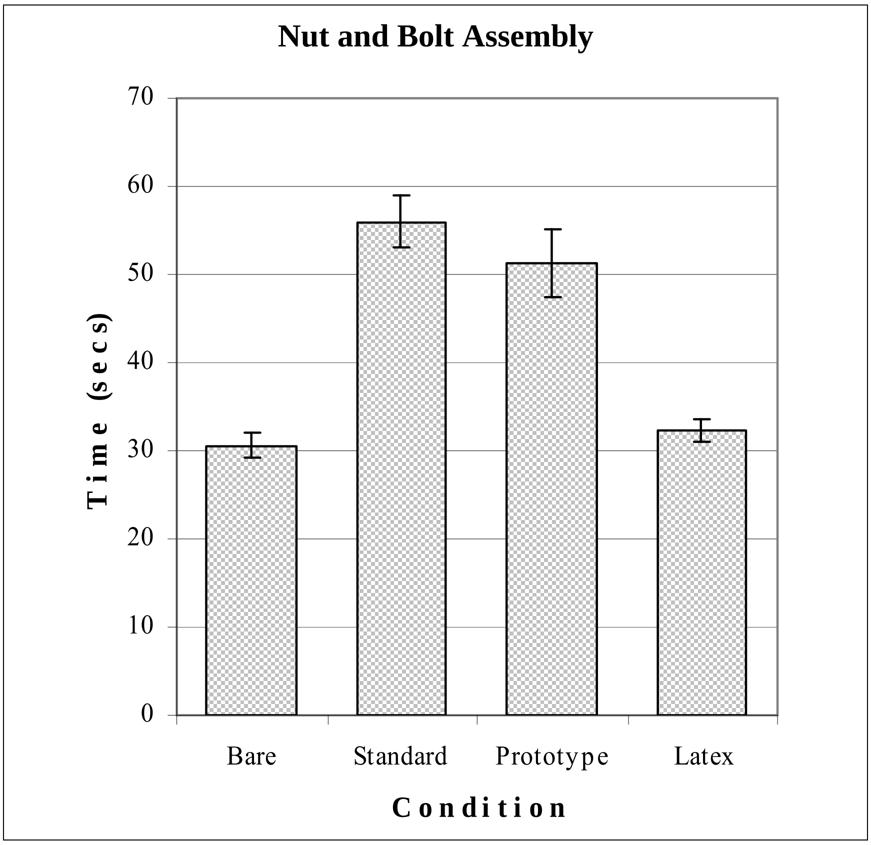
Graph 6.1 – Grip Strength with standard error



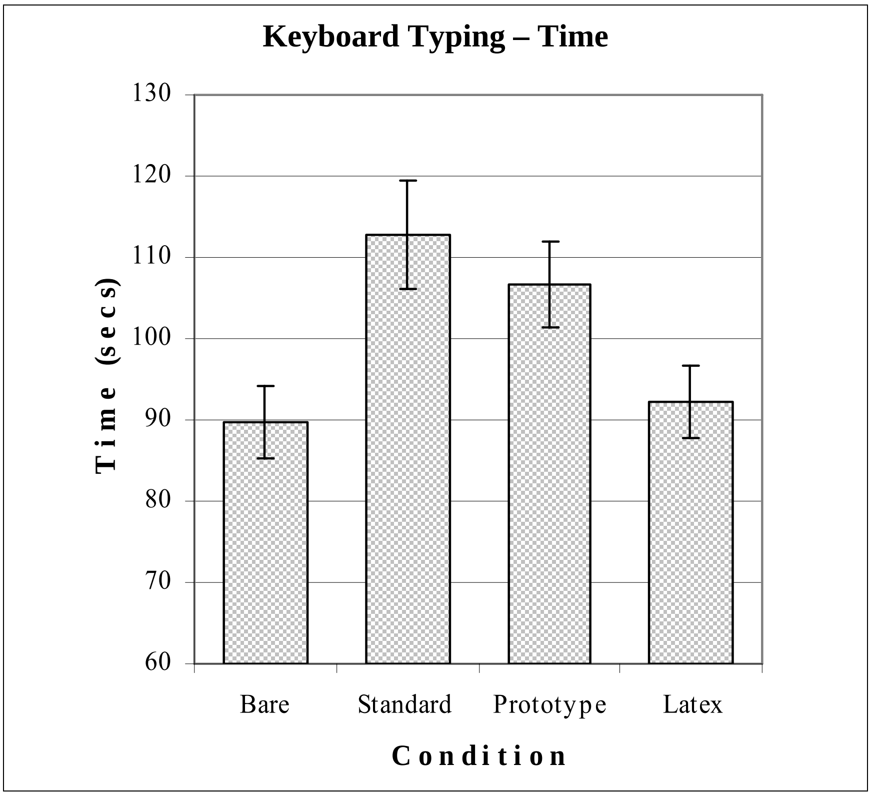
Graph 6.2 – Pinch Strength with standard error



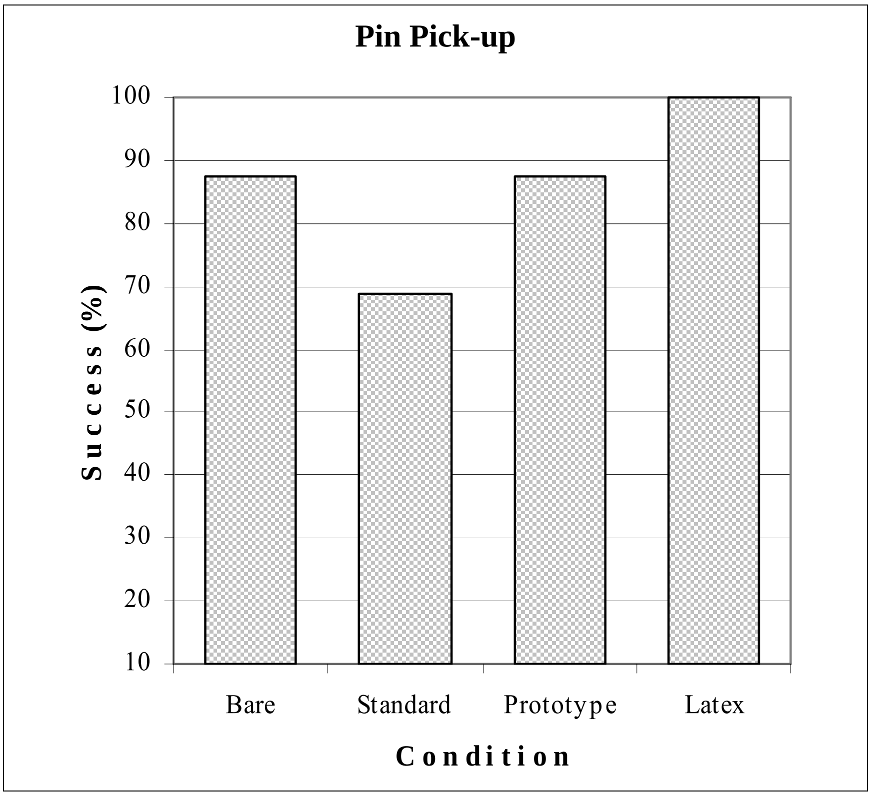
Graph 6.3 – Pegboard test results with standard error



Graph 6.4 – Nut and bolt assembly test results with standard error



Graph 6.5 – Timed keyboard typing test results with standard error



Graph 6.6 – Pin pick-up results

Condition	Keyboard Typing - Total Number of Errors
Bare Hands	49
Standard Glove	108
Prototype Glove	80
Latex Glove	57

Table 6.2 – Total number of errors during keyboard typing test

Test	Condition Rank			
	Bare	Standard	Prototype	Latex
Grip Strength	1	4	3	2
Pinch Strength	3	4	1	2
Pegboard Test	1	4	3	2
Nut & Bolt Assembly	1	4	3	2
Pin Pick-up Test	2.5	4	2.5	1
Keyboard – Time	1	4	3	2
Keyboard – Error	1	4	3	2
Sum Of Ranks	**10.5**	**28**	**18.5**	**13**

Table 6.3 – Each condition ranked for each test

In summary, all of the participants had a reduced ability to perform the tests when wearing gloves (graphs 6.1-6.6), due to the lack of finger dexterity, haptic feedback and tactile perception experienced. As expected participants performed best with bare hands in almost all of the tests, followed by the latex glove condition, then the prototype glove, with the standard glove performing the worst in each test, table 6.3

Grip strength was considerably affected when wearing gloves, graph 6.1, which is consistent with other findings, Bishu *et al* (1995), Bishu and Klute (1995), Riley (1985) and Buhman (2000). Participants experienced a significant reduction in strength while wearing the prototype glove, standard glove and latex glove compared to the bare handed condition. There was, however, an increase in grip strength between the prototype glove and the standard glove, 6.7N. The results from the pinch strength show that there is a negligible difference between the gloved conditions with only a 1.7N difference between the highest and lowest mean pinch strengths. Possible conclusions made from these results are that that the fit of a glove has little effect on a the strength of persons pinch, as this is a precise movement limited to the index finger and thumb (Tsaousidis, 1998; Hallbeck, 1993).

There was a distinct difference in the results between the bare handed condition and the two Flexigum gloves; the prototype glove and the standard glove. However, participants wearing the prototype glove showed an improvement in performance compared to the standard glove, following a similar trend to the results in the size gauge glove evaluation where the gauge glove out performed the data glove, Chapter 5.7.3. The results in this evaluation show a greater increase between the gloves produced using integrated anthropometric data than the current standard glove, indicating a further improvement in fit has been achieved. Participants took, on average, 11 seconds longer to complete the pegboard test while wearing the standard glove when compared to bare hands, whereas the difference was 8 seconds when wearing the prototype glove, graph 6.3. Similar results are shown in the nut and bolt assembly, (graph 6.4) where the mean time taken to complete the task when wearing the standard gloves is 5 seconds longer than it is when wearing the prototype glove. The keyboard typing test (graph 6.5 and table 6.2) revealed that wearing gloves clearly affects a person's individual typing style, increasing the amount of time required and introducing a high number of errors. An example of one of the paragraphs written during the keyboard typing test is shown in Appendix IX. This paragraph was written while wearing the prototype glove and highlights the types of errors incurred. When wearing the prototype glove there was a dramatic difference in the time taken to complete the task and the number of errors made. The mean average for participants to complete the task was 16.8 seconds longer compared to bare hands, with an additional 31 mistakes made. However, the performance was further hampered when wearing the standard glove. Participants took an extra 23.1 seconds to complete the task making a mean average of 108 errors.

The pin pick up test (graph 6.6) is the only test where the prototype glove performed as well as the bare handed condition with the latex glove showing the best performance. A possible explanation for this could be the added grip that a glove provides the wearer, which is enhanced if the glove fits correctly. This would enable some participants to pick up all pins with their bare hands and while wearing the prototype glove as the dexterity and tactility required is at a similar level to complete the task. It may account for the 100% success rate of the latex glove condition and would also explain why, when wearing the standard gloves, only 68.75% of the participants could successfully pick up all four pins as the fit of the glove was inadequate, experiencing too much excess material at the fingertips.

6.5.4 Statistical analysis

The data from the glove evaluation were analysed to determine if there were significant differences between the variables for each of the tests. Due to the nature of the data, a parametric test was most applicable. A students t-test was used to statistically measure the significance of difference between the means of two distributions at $p \leq 0.05$. All analysis was done using the statistical analysis software SPSS for windows, version 12.0. The results of the statistical analysis are presented in tables 6.4 – 6.9.

The grip strength, pegboard test and nut and bolt assembly show significant differences between all conditions except for the bare/latex and prototype/standard pairings, tables 6.4, 6.6 and 6.7. There were significant differences in the times for keyboard typing test for all conditions except for the bare/latex pairing, whereas there are only significant differences between the number of errors made during the test for the prototype/latex and prototype/bare pairings, tables 6.8 and 6.9. There were no significant differences between any of the conditions for the pinch strength, table 6.5. This supports the finding discussed previously (Chapter 6.5.3) that the fit of a glove has little influence on a person's pinch strength.

Grip Strength

	Bare hand		**Standard**		**Prototype**		**Latex**	
	t-score	Sig.	t-score	Sig.	t-score	Sig.	t-score	Sig.
Bare			5.52	**0.00**	3.68	**0.00**	1.46	0.17
Standard					-0.82	0.43	-4.00	**0.00**
Prototype							-3.32	**0.00**
Latex								

Table 6.4 – Student t-test results for grip strength

Pinch Strength

	Bare		**Standard**		**Prototype**		**Latex**	
	t-score	Sig.	t-score	Sig.	t-score	Sig.	t-score	Sig.
Bare			0.29	0.77	-1.08	0.30	-0.42	0.68
Standard					-1.34	0.20	-0.47	0.64
Prototype							0.35	0.73
Latex								

Table 6.5 – Student t-test results for pinch strength

Pegboard Test

	Bare		Standard		Prototype		Latex	
	t-score	Sig.	t-score	Sig.	t-score	Sig.	t-score	Sig.
Bare			-8.96	**0.00**	-6.95	**0.00**	-1.45	0.17
Standard					2.03	0.06	9.75	**0.00**
Prototype							5.57	**0.00**
Latex								

Table 6.6 – Student t-test results for the pegboard test

Nut and Bolt Assembly

	Bare		Standard		Prototype		Latex	
	t-score	Sig.	t-score	Sig.	t-score	Sig.	t-score	Sig.
Bare			-11.96	**0.00**	-6.84	**0.00**	-1.03	0.32
Standard					1.37	0.19	9.12	**0.00**
Prototype							5.73	**0.00**
Latex								

Table 6.7 – Student t-test results for the nut and bolt assembly

Keyboard Typing Test – Time

	Bare		Standard		Prototype		Latex	
	t-score	Sig.	t-score	Sig.	t-score	Sig.	t-score	Sig.
Bare			-4.98	**0.00**	-5.59	**0.00**	-1.44	0.17
Standard					2.12	**0.05**	5.07	**0.00**
Prototype							5.00	**0.00**
Latex								

Table 6.8 – Student t-test results for the timed keyboard typing test

Keyboard Typing Test - Errors

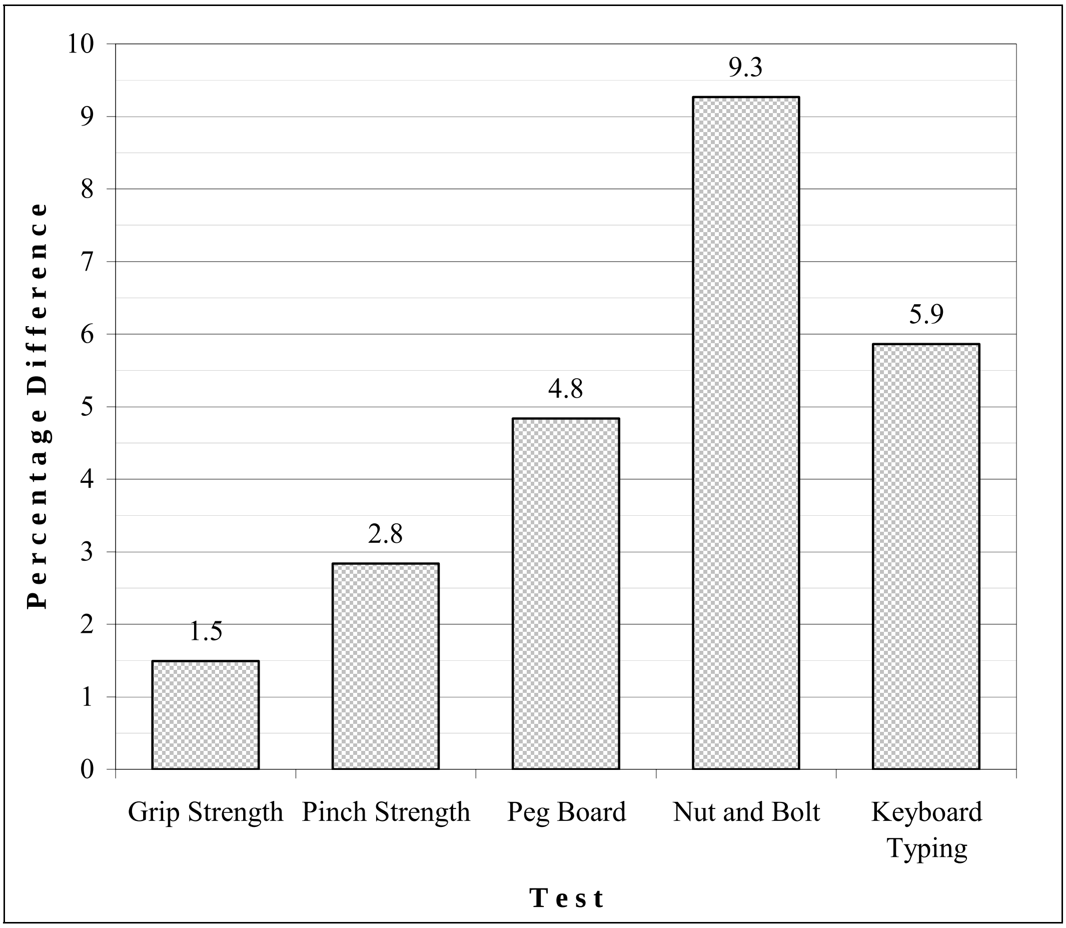
	Bare		Standard		Prototype		Latex	
	t-score	Sig.	t-score	Sig.	t-score	Sig.	t-score	Sig.
Bare			-1.91	0.08	-2.44	**0.03**	-0.97	0.35
Standard					0.93	0.37	1.79	0.09
Prototype							2.56	**0.02**
Latex								

Table 6.9 – Student t-test results for the number of errors during the keyboard typing test

6.6 Conclusions

From the results of the glove evaluation it can be determined that when wearing gloves manufactured using the prototype former there is an increase in performance when conducting tests that asses dexterity, haptic feedback and tactile perception, compared to gloves manufactured from a current former. The lack of anthropometric detail related to the end user within current formers results in a glove that does not have a high degree of fit, with areas of relatively large amounts of excess material occurring, particularly around the fingers. This leads to a loss in sensitivity in this area and can give false or misleading senses to the wearer. The subsequent effect is that the manipulation of small objects and recognition of different textures or surfaces is deficient, cumbersome and time consuming.

The statistical analysis of the user trial results indicated very little statistical significance between the prototype glove and standard glove. Only the timed keyboard typing test recorded any significance between the two gloves, table 6.8. However, the user trial was able to determine measurable differences in the performance of the participants when wearing these gloves. For each test, the participants wearing the prototype glove demonstrated an improved performance when compared to the standard glove. Although these differences were small in the context of these experimental conditions, they could have a considerable influence when applied to practical situations. Graph 6.7 shows the percentage differences between the prototype glove and the standard glove for the strength and timed tests.



Graph 6.7 – Percentage difference between the prototype glove and standard glove.

These results highlight a clear improvement in performance achieved by wearing the prototype glove. The improvement is consistent for both the strength tests and all three timed tests, with the greatest improvement seen in the nut and bolt assembly test. Both gloves were manufactured from the same material and are the same thickness (table 6.1); therefore, this improvement can be attributed to the fit of the glove. The design of the prototype former has produced a glove which reduces the adverse effects that impair hand strength and dexterity, experienced when wearing protective handwear. Within the environments that these types of gloves would be worn in, any enhancement of these abilities can have a significant effect on overall task performance. The difference of only a few seconds for a short, simple task like the nut and bolt assembly test can mean a greater difference in time for longer, more complicated tasks. If the percentage difference for the nut and bolt assembly is applied to task lasting thirty minutes when wearing the prototype glove, it would take an additional 2 minutes 47 seconds to complete wearing a standard glove. The improved performance can increase further when the differences in time are combined from a succession of several tasks which vary in complexity. This means that although the differences in performance found in the user trial were not statistically significant, they have significance within the context of affording an enhanced fit for protective handwear.

As with the size gauge, the CAD models created for the prototype glove former have been designed to allow anthropometry from different populations to be used for their generation. The dimensions from the size data were used to control the size and shape of the various parts of the CAD model, chapter 6.3. Similar dimensions from other sources of hand anthropometric data can be used in the same way and therefore be represented in a 3D format. The greater detail needed for CAD models and the inability of the CAD software to link an anthropometric database consequently causes the resizing process to be a time intensive and complicated procedure. The CAD models however, can be modified to include specific design characteristics that are often necessary within the manufacture of dip moulded handwear. For example, certain types of plastisol materials can shrink once cured and stripped from the former. This means that the former must be enlarged to take this shrinkage factor into account. This was not an issue with the prototype gloves as a specific material was chosen that did not have any significant shrinkage. However, this can easily be accommodated, by scaling the CAD model by the necessary percentage in the required areas to ensure that the glove that is produced is to the correct size and shape.

This case study has fulfilled two of the research objectives. It has developed and validated a suitable design method to improve the fit of handwear through appropriate tools of action research and implemented this method to consider its effectiveness. This has been achieved by demonstrating that designing CAD models of the human body can accurately manufacture protective handwear. By integrating anthropometry and CAD/CAM a mould tool for the manufacture of handwear has been designed and prototyped which has successfully been used in the production of gloves. These gloves have been evaluated and show an increased fit and consequently an improved performance for the wearer, when compared to those manufactured using current formers. Figure 6.22 shows each of these stages, illustrating how they interact to create the process which resulted in the new glove. This process followed a similar method to the first case study as can be seen in figure 5.44, Chapter 5.8. The same tools of integrating the relevant knowledge, rule of thumb principles and characteristics of good glove fit were used in order to progress through the cycle and create the enhanced fit for the new glove.

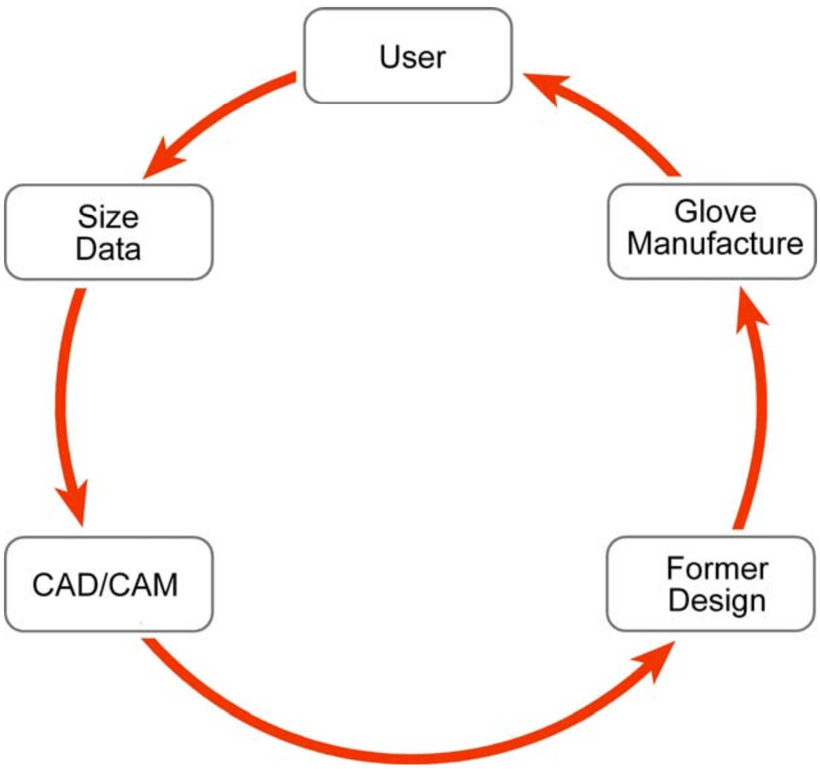


Figure 6.22 – The cycle of stages for case study two

This case study has also demonstrated how to incorporate the traditional craftsmanship of designing clothing into a CAD/CAM process. Detailed information has been taken from current glove formers to develop CAD models for prototype formers to ensure they contain the necessary properties to successfully manufacture handwear. Current formers contain a substantial amount of detail pertaining to high quality former and glove design; however lack anthropometric detail of the end user. The integration of these two resources has resulted in a mould tool capable to accurately manufacture handwear possessing specific data of the hand as well as existing traditional design and manufacturing knowledge.

Chapter Seven:
Validating Accuracy

7.1 Introduction

The main function of the size gauges and glove formers was to accurately design, evaluate and manufacture handwear. This was achieved due to the detailed anthropometric data and design knowledge integrated into the CAD models that they originate from. For this reason, it was essential that the combination of CAM and RP processes used to recreate the CAD models transferred this data and knowledge as accurately as possible. This would ensure it was correctly incorporated into the gauges and formers, and ultimately into the gloves they produce. If the CAD models could not be accurately represented in a 3D form, the gauges and formers would not be an adequate evaluation of their capability to produce handwear with enhanced fit for the wearer. It was necessary to validate the prototyping methods chosen and ensure the approach adopted represented the CAD models with sufficient accuracy. It was accepted that the processes and combination of processes used would not generate an exact reproduction; there would be some differences between the original CAD model and the subsequent resin cast from the silicone mould. Analysing each of the stages within the prototyping method enabled these differences to be measured and identified where they occur.

The approach to analysing the prototyping methods involved measuring the size gauges and glove formers used in the evaluation phases of case study one and two, respectively. The results of this analysis gave an indication to the level of accuracy achieved using the RP model and silicone mould method to produce the resin tools. This needed to be carried out prior to the evaluation phase to ensure the anthropometric data and necessary design knowledge had been correctly integrated into the tools from the CAD models.

The accuracy of the size gauges and glove formers is primarily dependant on the accuracy and validity if the anthropometric data used in the generation of the CAD models. These data are the key reference for the creation and assembly of the pieces that structure each of the CAD models. The anthropometric data used was primarily collected and recorded from an independent source and, therefore, there was no control over the accuracy and validity. The purpose of this validation was to examine the prototyping method used in the case studies, ensuring the approach selected was suitable and capable of reproducing the CAD model to the required accuracy.

7.2 Method

The same manufacturing approach was used for both the size gauges and glove former, summarised in figure 7.1 and detailed in Chapter 5.3. The CAD models were used to create master RP models using a 3D printer, which were then used to create silicone moulds into which the more resistant polyurethane resin could be cast. This meant the same approach could be used to validate the accuracy of both the size gauges and the glove formers.

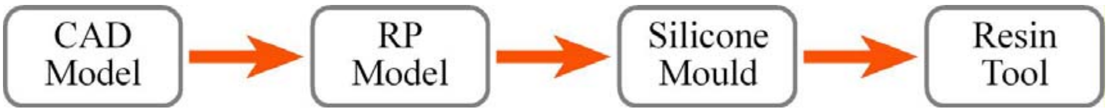


Figure 7.1 – Stages for resin tool manufacture

To determine the differences between the resin tool and the corresponding CAD model it was necessary to compare the two versions to highlight how the size and shape had changed during the various stages of manufacture. In addition, the CAD models were also compared to the RP models to examine the accuracy of the 3D printer and the silicone moulds. This indicated how the changes had accumulated during the prototyping process and at which stage they occurred. The main procedure that required validating was the hand finishing of the RP model prior to creating the silicone mould and the resin cast after de-moulding. The quality of a RP model is dependant upon the type of model, the system, the build parameters, the material and the operator (Grimm, 2005). These variables remained constant for both the size gauge and glove former; however, the hand finishing process was far less controlled. Although this process was a minor procedure, it was necessary to ensure that it did not have any significant affect on the dimensional accuracy of the size gauge and glove former RP models.

To make the necessary comparisons the RP models and the resin tools were digitised using a method of 3D scanning. This enabled them to be placed into the same environment as the CAD models where they could be accurately aligned and evaluated using Computer Aided Inspection (CAI) software. This process involved three main stages; the first was the 3D scanning process which required capturing the surface detail of the size gauges and glove formers. This was the most significant stage as all the relevant detail needed to be captured correctly to enable accurate comparisons to be made. The 3D scanning process generates a series of points that form the shape of the scanned object; the next stage was to process these points to create a surface model to represent the size gauge/glove former within the CAD environment. The final stage was to align the surface model with the corresponding CAD model and assess the differences between them by using the CAI software to calculate the levels of deviation.

This chosen method for making the necessary comparisons is a more accurate approach than a manual method of measuring the RP models and resin tools using callipers or micrometers to determine dimensional accuracy (Yao, 2005). The use of a non-contact 3D scanner enables precise and reliable measurements to be taken in both 2D and 3D from an unlimited number of points. Conventional manual measuring techniques entail identifying specific datum points on the models and tools which would be inaccurate and, therefore, difficult to repeat the same measurements on the different versions of size gauge and glove former. This is particularly true for the glove former as the complex curvature and detail means it would be not be possible to accurately analyse and compare the free-form shape with the CAD model.

Validating the accuracy of the glove former entailed making two comparisons to the CAD model, figure 7.2. The left hand RP model and resin tool used in the dip moulding process to manufacture the gloves were 3D scanned to determine what differences existed between them and the equivalent CAD model.

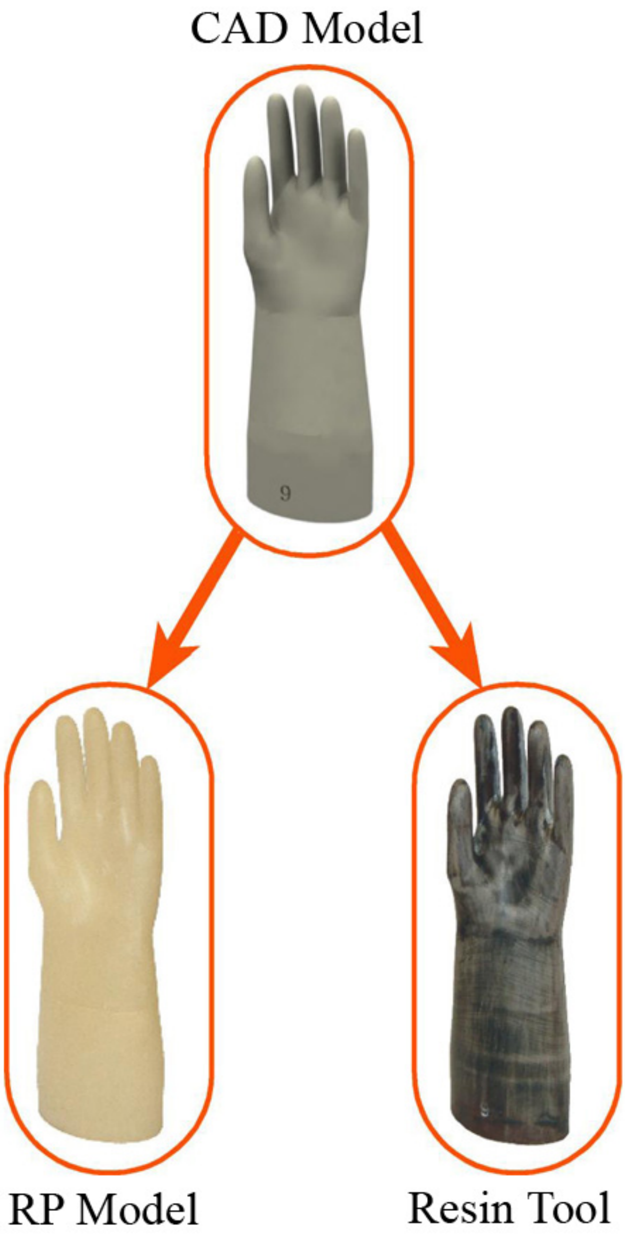


Figure 7.2 – Glove former comparisons

The validation for the size gauge was similar but further comparisons were made to determine the capability of the silicone mould to produce multiple parts with the same degree of accuracy. The silicone rubber used for the moulds was only suitable for producing a sample batch of size gauges and glove formers. The polyurethane resin has a detrimental effect on the silicone, deteriorating the mould during the curing process. This effect is only evident over a repetitive cycle of casting and de-moulding and was therefore not a significant issue during the case studies as only a small number of parts were produced from each mould. However, to fully determine that this did not become a factor, two versions of the resin size gauge (Resin A and Resin B) were scanned in addition to the RP model to compare to the original CAD model, figure 7.3. This process was performed on two sizes of the size gauge, size 1 and size 5 to assess any variation between the different RP models and resin tools.

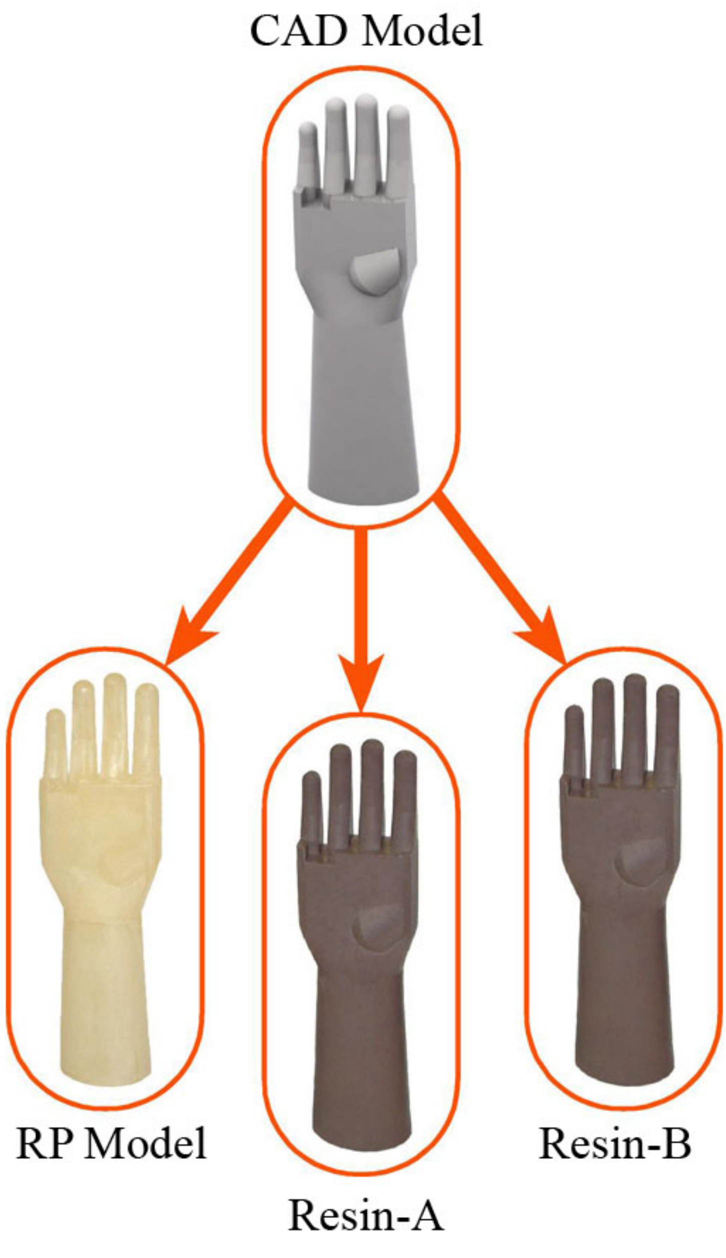


Figure 7.3 – Size gauge comparisons

7.2.1 3D scanning

The 3D scanning process used a non-contact 3D Scanners ModelMaker-Z system mounted on an articulating arm allowing a wide range of motion to easily manoeuvre the head of the scanner around the part to be scanned. The scanner projects a laser stripe across the surface of the object which is viewed by a camera. When the scanner is manoeuvred around the object the shape of the laser stripe changes accordingly, and replicates the shape of the objects surface. The changes in the shape of the laser are detected by the camera which forms a profile made up of several hundred points. The articulating arm measures the position of each profile enabling them to be accurately located in 3D space and form a 3D point cloud which represents the shape of the scanned object (3D Scanners, 2001). These point cloud data can then be manipulated and processed to generate a surface for applications of reverse engineering and computer aided inspection.

The method for scanning the size gauges and glove formers followed this process. There were a total of eight objects scanned; each RP model and two resin tools for size 1 and size 5 of the size gauges (figure 7.3), and the RP model and resin tool for the glove former (figure 7.2). Figure 7.4 shows the scanning procedure in process for the RP model of the glove former. The 3D scanner was manually moved over the RP models and resin tools to project the scanner laser over their entire surface and capture the required detail to generate the 3D point cloud. The object to be scanned was securely mounted onto a uniform plane to eliminate the possibility of any movement during the scanning process. This ensured the various profiles did not become misaligned, which would cause difficulties during the post-processing phase.

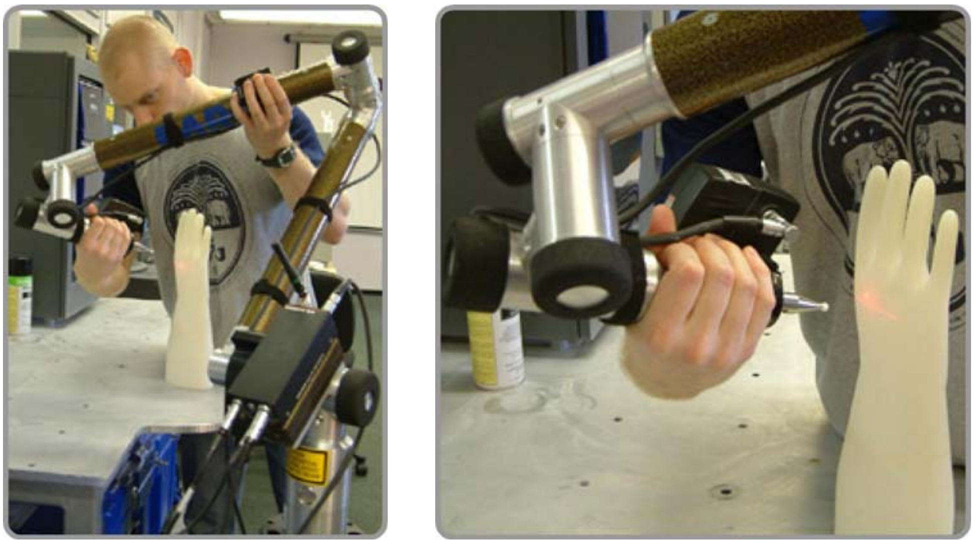


Figure 7.4 – Scanning a glove former RP model

The aim of the scanning process was to capture the entire shape of the object; however, this was not always possible. The areas between the fingers on both the size gauges and glove former were difficult to capture due to the limited space available to manoeuvre the 3D scanner. The laser could not be projected onto the surface of these areas as it was obstructed by the adjacent fingers. This lead to areas on the inside of each finger without any data within the point cloud on all the objects scanned. The missing data were supplemented during the post processing phase to enable the generation of complete surface models for all the RP models and resin tools.

7.2.2 Post processing the point cloud data

The post processing phase developed the point cloud data created during the 3D scanning process to generate a surface model which could be compared to the CAD models during the computer aided inspection phase. Although the point cloud data for the various objects scanned differed in shape and size, the post processing followed a similar procedure for both the size gauge and glove former. It entailed three main stages; editing the point cloud to identify and delete erroneous data points, applying a surface to the points and finally cleaning this surface to fill any holes and remove defects to create a smooth uniform finish. Figures 7.5 to 7.8 show the stages of transition from a point cloud data set to a completed surface model.

Processing point cloud data can sometimes be a very complex and time consuming procedure. Depending on the amount of data captured and the intended use of the processed surface model, it may be necessary to use several different techniques to obtain the desired finish. Similar types of problems were encountered when processing the data of all of the scanned objects from both the size gauges and prototype glove former. These were mainly a result of an insufficient number of points between the fingers. However, enough detail was captured to ensure an accurate representation could be generated. The software used for the post processing phase was Geomagic Studio, which gives the ability to interact with the point cloud data and generate the necessary surface models required.

The first stage was to edit the point cloud, identifying erroneous data so it could be deleted. Figure 7.5 shows the point cloud of a size 5 size gauge RP model captured during the 3D scanning process.

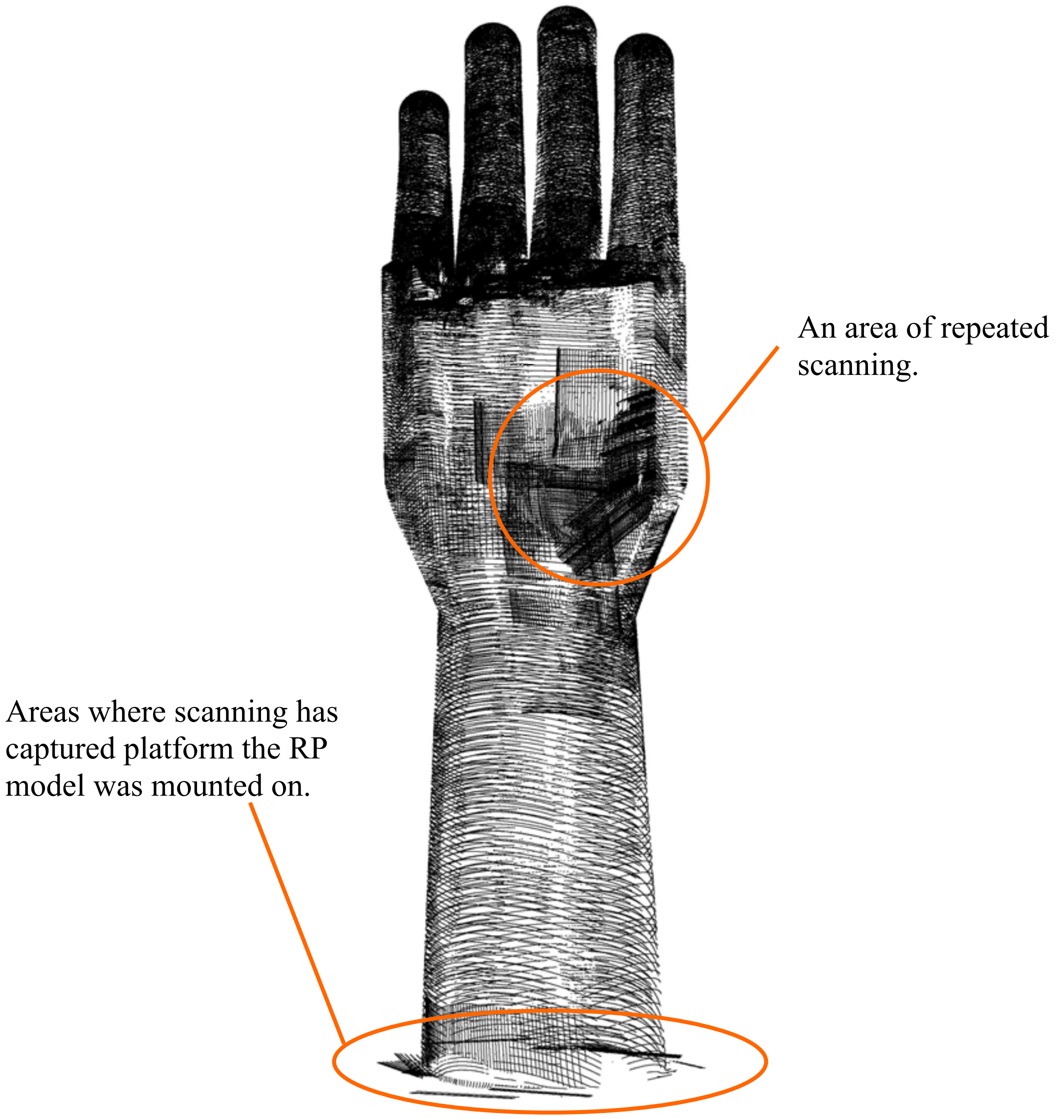


Figure 7.5 – The point cloud captured during the 3D scanning process

The data file was loaded into the software where each of the individual points captured could be viewed and manipulated. The raw point cloud contains a large amount of points; the point cloud for the RP model in figure 7.5 contains over 3 million points. The initial processing stage was to remove unnecessary and duplicated points to reduce the number and create a more organised structure. During the 3D scanning process, the laser often captures detail that is not part of the object being scanned and is therefore not required when creating a surface. In this instance, part of the platform that the object was mounted onto was captured by the scanner. This detail was not required and could therefore be removed. The appropriate points could easily be identified and removing them from the point cloud was a simple procedure of manually selecting and deleting them. Identifying and removing other erroneous points was not as straightforward. The scanning method often required the same area of the object to be scanned several times to capture the necessary surface detail. This resulted in a repetition of points being captured for some areas. To generate a smooth consistent surface from the point cloud it was necessary to create an even distribution of points and therefore remove any repetition created by scanning the same area of the object several times. It was not possible to manually identify and delete these points; therefore, an operation within the software was used to select the appropriate points for removal. This sampling operation within Geomagic Qualify gives control over the amount of points removed depending on the curvature and shape of the point cloud.

The variation in the shape of the size gauge and glove former meant that a different sampling method was required for the two sets of point cloud data. The type of sampling was determined by the geometry of the scanned object. Areas of flat uniform surfaces require fewer points than curved areas to represent the required shape and generate a surface. The glove former has a complex form with no flat surfaces or angular edges. This required using a curvature sampling operation to the point cloud which preserved the areas of intense curvature, i.e. the digits and digit crotches, while removing points on larger more consistent surfaces, i.e. the palm and back of the hand. Conversely, the size gauge is mainly constructed from flat surfaces with the only areas of curvature occurring at the digit tips and, therefore, required a different approach to refining the distribution of points. To maintain the flat areas and defined edges where these surfaces meet, a uniform sampling operation was applied.

This uniformly reduced the number of points on the flat surfaces, but preserved areas of curvature by specifying their significance within the point cloud data. This ensured that there were sufficient data points at the tips of the digits to maintain the necessary curvature and the removal of points on flat uniform areas to create an organised point distribution. Figure 7.6 shows the processed point cloud from figure 7.5. All erroneous and extraneous data points have been removed to create an even distribution of points that contains the detail required.

Figure 7.6 – Processed point cloud data

These operations to 'clean' the point cloud and prepare it for the surface generation phase by removing points that would affect the surface quality. Editing the point cloud, however, requires careful consideration, as each point represents a part of the scanned object. Removing points is, therefore, erasing detail from the point cloud and the more points removed from the point cloud the less accurate the finished surface model would be. Although cleaning the data was necessary, it was essential to maintain the accuracy of the scanned data throughout this process. This was achieved by choosing the most appropriate post processing techniques based on the type of geometry and shape of the point cloud data. Using a curvature sampling operation for the glove former point cloud and a uniform sampling operation for the size gauge enabled the removal of unnecessary, duplicated points while preserving the required detail.

7.2.3 Creating and modifying a surface

After processing the point cloud data it could be used to create a surface. A wrap operation within Geomagic Studio software can automatically generate a polygonised version of the point cloud which is a single surface composed of many triangles. Performing this operation is a simple procedure, however, the initial surface created often requires editing and modifications before it can be used in any further applications, in this instance the comparisons with the CAD models.

The wrap operation was performed on each of the point cloud data models for the RP and resin tools of the size gauges and glove formers. Although the point cloud data differed slightly between the various RP models and resin tools, similar editing procedures could be used to create the required finished surface. After performing the wrap operation on the point cloud the main editing operation required was to fill holes in the initial surface. Figure 7.7 shows the initial surface generated from the point cloud data in figure 7.6. Holes occur where there are insufficient data points to create the necessary geometry and must be filled manually to complete the full surface. A specific tool within Geomagic Studio allows this process to be completed easily and precisely, with the added sections corresponding to the profile of the surrounding surface to maintain its shape and curvature. Once all the holes are filled the quality of the surface finish can be enhanced using various tools that modify and edit the polygons that form the surface.

The only operation performed on these surface models was to decimate the number of polygons and refine the surface by removing major dents and spikes. It was possible to further improve the quality of the surface by applying other tools; however, this would deviate away from the original shape of the scanned object and subsequently reduce the accuracy. A similar operation to the sampling performed on the point cloud data, the decimating operation reduces the number of triangles within the surface without compromising surface integrity or detail. Therefore, similar to the sampling operation performed on the point cloud data, the tool was used with caution to ensure the size and shape of the original scanned object was maintained and an accurate representation was generated. A completed surface model of a size 5 size gauge RP model is shown in figure 7.8. This model was then exported from Geomagic Studio to be used in the comparisons with the corresponding original CAD model for the accuracy validation phase.

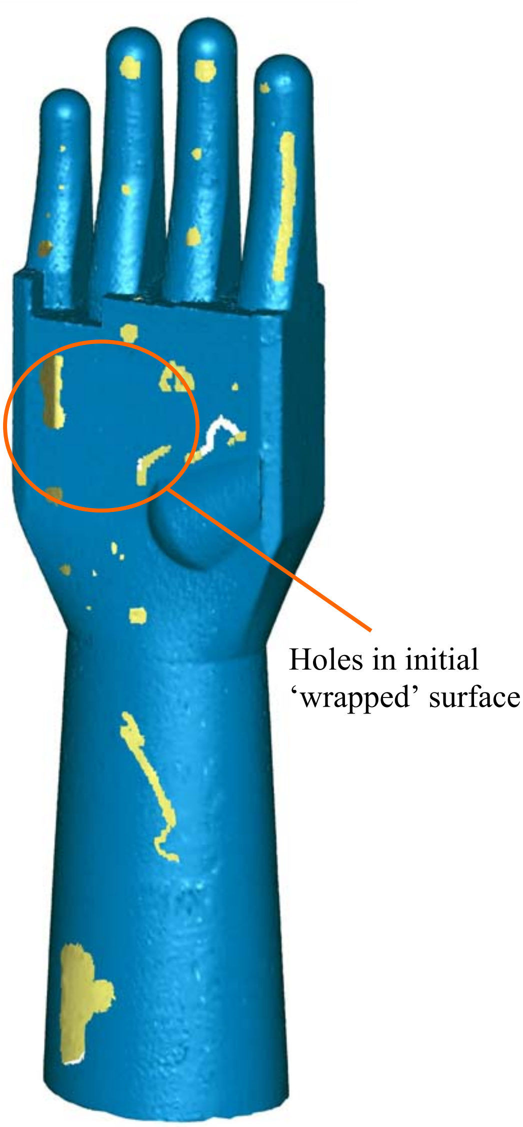


Figure 7.7 – Initial surface created from point cloud

Figure 7.8 – Completed surface model from point cloud data

7.2.4 Computer aided inspection

The outcome of the 3D scanning and subsequent post processing of the RP models and resin tools was a 3D computer model for each of the RP models and resin tools for the size gauges and glove former. To compare each of these models with the corresponding CAD model, computer aided inspection (CAI) software was used to analyse the dimensional differences between them. The CAI software used was Geomagic Qualify which enables the two models to be accurately aligned and validated using various analytical tools. The first stage of the inspection process was to import the relevant 3D models into the software environment. For each comparison made there were two models imported; the original CAD model, referred to as the reference model and the surface model generated from the 3D scanning process, referred to as the test model.

As previously discussed and illustrated in figures 7.2 and 7.3 there were eight comparisons made; six for the size gauge and two for the glove former. Each comparison was completed individually but followed the same procedure. After importing the appropriate 3D models they were accurately aligned to determine the degree of variation in size and shape between the scanned object and the corresponding CAD model. The method used to align the models is primarily governed by their geometry. The most appropriate method for both the size gauge and glove former was a best fit alignment as it was capable of dealing with the combination of curvature and flat surfaces to produce an accurate alignment. The operation automatically aligns the two models using comprehensive calculations that arrange points within the test model to correspond with the same points in reference model. The procedure is completed in three stages; initially a specified number of points are selected to approximately orientate the test model with the reference model. After this first pass, the number of points is increased and the test model is repositioned to find the ‘best fit’ equivalent to the position of the reference model. Finally, fine adjustments are made to ensure all the specified points correspond with each other and the correct alignment is achieved.

After performing the alignment procedure, the two models could be compared and analysed. Several different tools are available within Geomagic Qualify for this analysis using both 2D and 3D methods. These tools convey the level of deviation between the test model and the reference model and the location of where these deviations occur. For the comparisons of the size gauges and glove formers a 3D analysis tool was chosen that creates a colour chart illustrating the deviation between the two models. The chart is generated as a separate model and uses a colour spectrum to indicate where the models deviate, with each colour representing a different level of deviation. A key to the colour spectrum is also generated to assign a numerical value to each of the colours. The colour chart can be modified to optimally display the result of the comparison and ensure the transitions between areas of deviation are precise and accurate. In addition to the graphical view the comparison result gives accurate statistics of the mean deviation, mean positive deviation, mean negative deviation and standard deviation.

The main stages of CAI process are shown in figure 7.9, using the example of a glove former. The 3D colour chart is the final output of this process and gives the necessary information to determine the accuracy of the RP models and resin tools for the size gauges and glove formers.

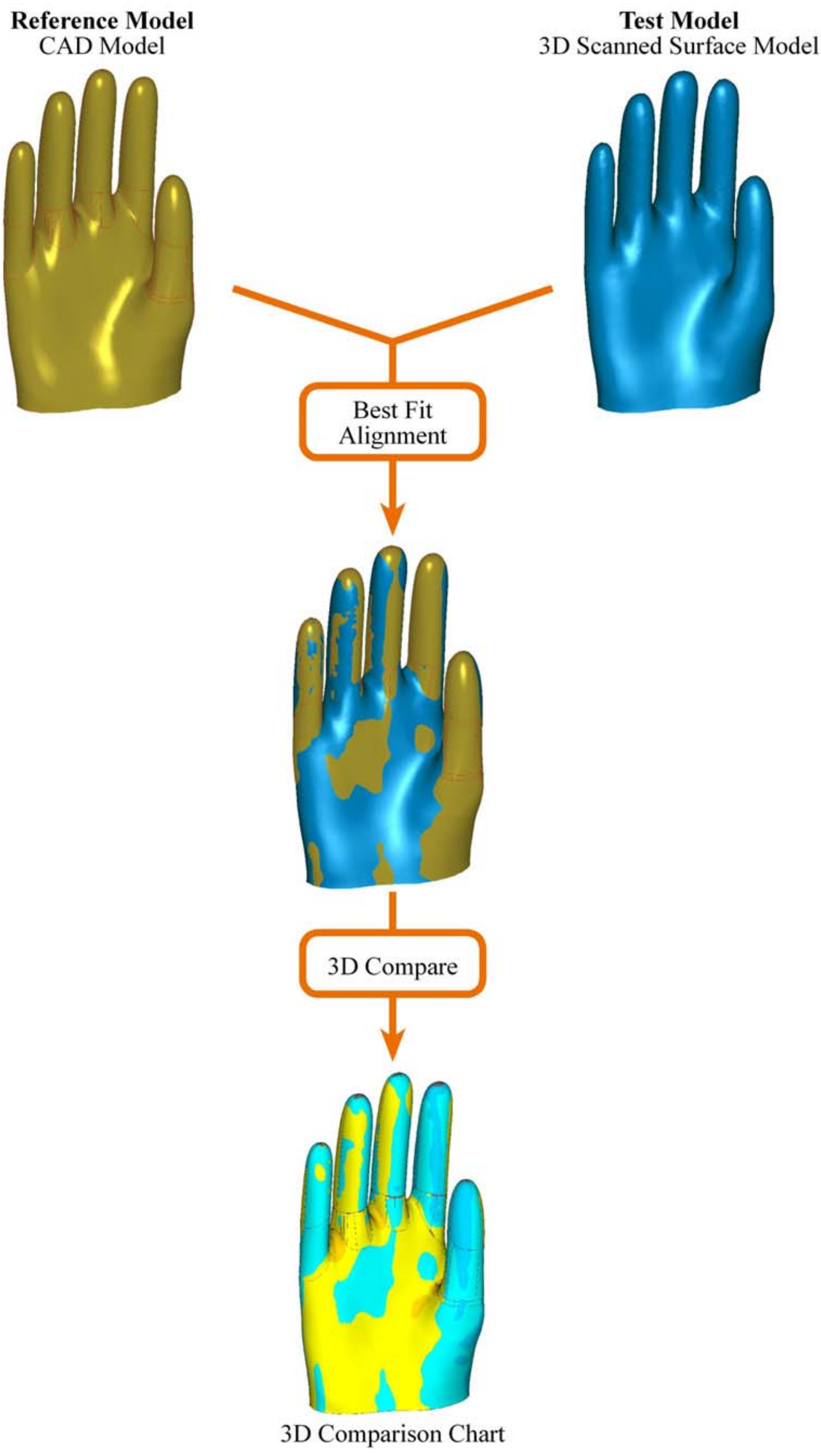


Figure 7.9 – Process of Computer Aided Inspection for a glove former

7.3 Results

The results of the CAI are presented below and are divided into two sections examining the size gauge and glove former separately. For each of the eight comparisons made there is a 3D comparison chart and the relevant statistics to quantify the deviations between the CAD model and the corresponding RP model or resin tool. The comparison charts illustrate the areas where the two models differ in size and shape and are accompanied by a deviation spectrum to indicate the level of deviation occurring. The statistics are in a tabulated format and list the mean deviation, the mean positive deviation, the mean negative deviation and the standard deviation. A positive value indicates the test model (3D scanned surface model) is larger than the reference (CAD) model, negative values indicate the test model is smaller. Also listed is the number of points generated during the initial scan of the object as this gives an indication to the amount of detail captured.

7.3.1 Size gauge

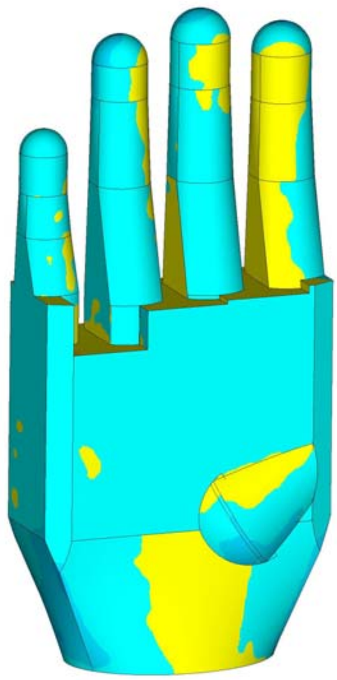


Figure 7.10 – 3D Comparison chart for Size 1 CAD model and RP model

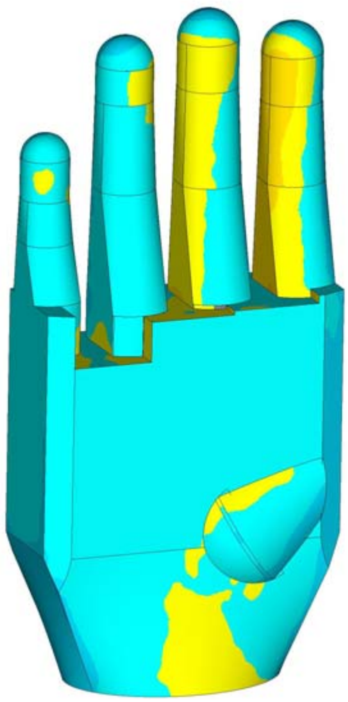


Figure 7.11 – 3D Comparison chart of Size 1 CAD model and Resin-A Size Gauge

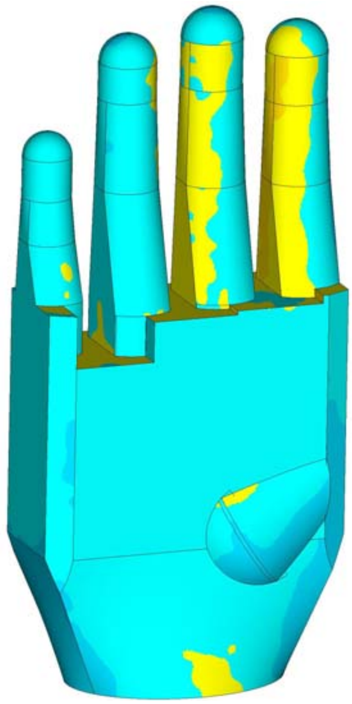


Figure 7.12 – 3D Comparison chart of Size 1 CAD model and Resin-B Size Gauge

Figure 7.13 – Deviation spectrum for Size 1 Size Gauge 3D comparison. Scale in mm

Size 1	Mean Deviation	Mean Positive Deviation	Mean Negative Deviation	Std. Deviation	No. Points Captured
RP Model	-0.186	+0.151	-0.284	+0.329	1,492,998
Resin-A	-0.341	+0.270	-0.443	+0.418	1,943,223
Resin-B	-0.321	+0.218	-0.411	+0.414	1,630,518

Table 7.1 – Accuracy results for size 1 size gauge. Deviation figures in mm

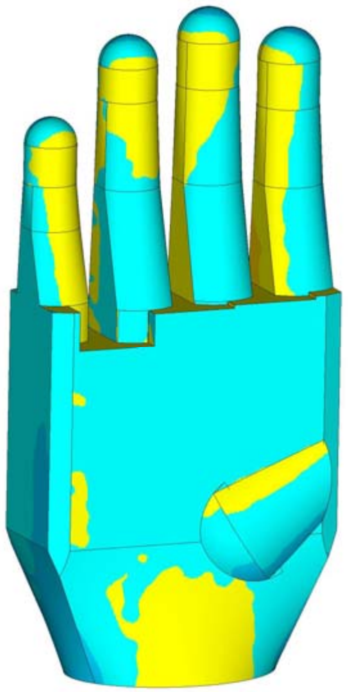


Figure 7.14 – 3D Comparison chart of Size 5 CAD model and RP model

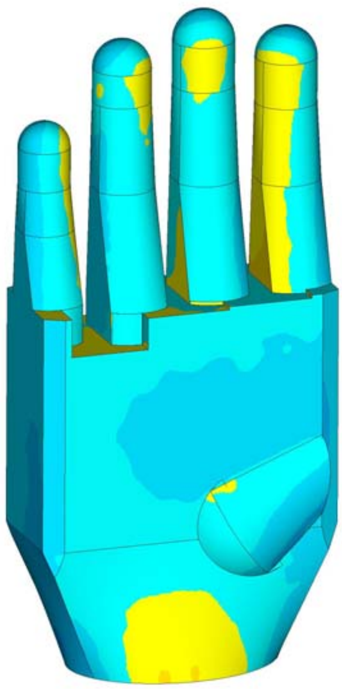


Figure 7.15 – 3D Comparison chart of Size 5 CAD model and Resin-A Gauge

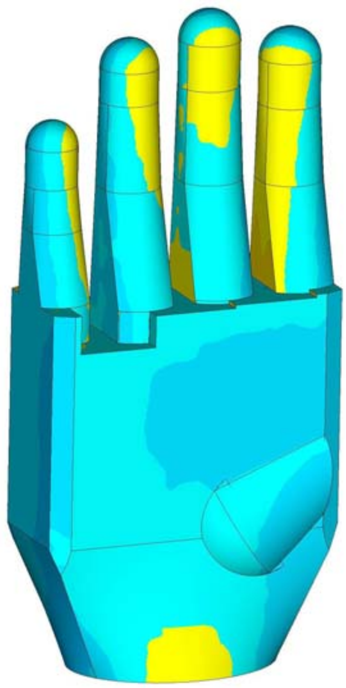


Figure 7.16 – 3D Comparison chart of Size 5 CAD model and Resin-B Gauge

Figure 7.17 – Deviation spectrum for Size 5 Size Gauge 3D comparison. Scale in mm

Size 5	Mean Deviation	Mean Positive Deviation	Mean Negative Deviation	Std. Deviation	No. Points Captured
RP Model	-0.196	+0.277	-0.434	+0.432	1,525,857
Resin-A	-0.443	+0.211	-0.575	+0.456	1,505,040
Resin-B	-0.396	+0.237	-0.531	+0.466	1,549,484

Table 7.2 – Accuracy results for size 5 size gauge. Deviation figures in mm

7.3.2 Glove former

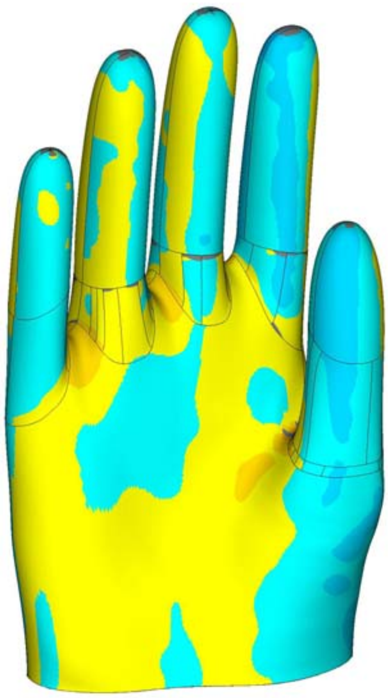


Figure 7.18 – 3D Comparison chart of glove former CAD model and RP model

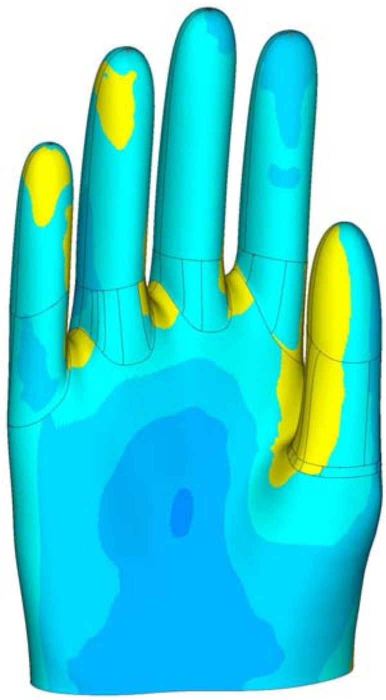


Figure 7.19 – 3D comparison chart of glove former CAD model and resin former

Figure 7.20 – Deviation spectrum for glove former 3D comparison. Scale in mm

Size 4	Mean Deviation	Mean Positive Deviation	Mean Negative Deviation	Std. Deviation	No. Points Captured
RP Model	-0.044	+0.258	-0.311	+0.368	1,702,567
Resin Former	-0.369	+0.298	-0.588	+0.592	1,744,786

Table 7.3 – Accuracy results for glove former. Deviation figures in mm

7.4 Accuracy of 3D scanning and post-processing methods

To validate the 3D scanning and post-processing methods used a procedure to investigate and determine their accuracy was developed. The objective of this exercise was to ensure that the tolerances found would not significantly affect the accuracy results of the RP models and resin tools for the size gauges and glove formers. If any significant variations were found the results would need to be modified accordingly to integrate the tolerances and provide an accurate analysis of the methods chosen to produce the RP models and resin tools.

3D scanning systems are an increasingly popular technology, used in a growing number of varied applications (Grimm 2006), although the accuracy of such technologies is yet to be fully determined. Many studies have been conducted that address this issue spanning a variety of different scanning techniques, (Balzani *et al*, 2001; Boehler *et al,* 2003; Boehnen and Flynn, 2005; Geng *et al,* 2004; Goesele *et al*, 2003; Johansson, 2002 and Lichti *et al,* 2000) however, as noted by Geng *et al* (2004) no standard procedure or test has emerged or been accepted.

As no specific test method to validate the 3D scanning and post-processing techniques has been established a new method was developed that could analyse the overall accuracy of the process. This method was adapted from British Standards (BS EN ISO 10360-2:1996, BS EN ISO 10360 Parts 1-6) which detail the calibration of coordinate measuring machines (CMMs). The assessments within these standards use a series of five test spheres to calculate location error, size error and form error of a CMM system. Using this principle, a series a five slip gauges (figure 7.21) were used as test pieces and subjected to the same scanning and post-processing procedures used when validating the RP models and resin tools. This gave a series of surface models that could be accurately measured and when compared to the corresponding slip gauges, indicate the level of accuracy that had been achieved.

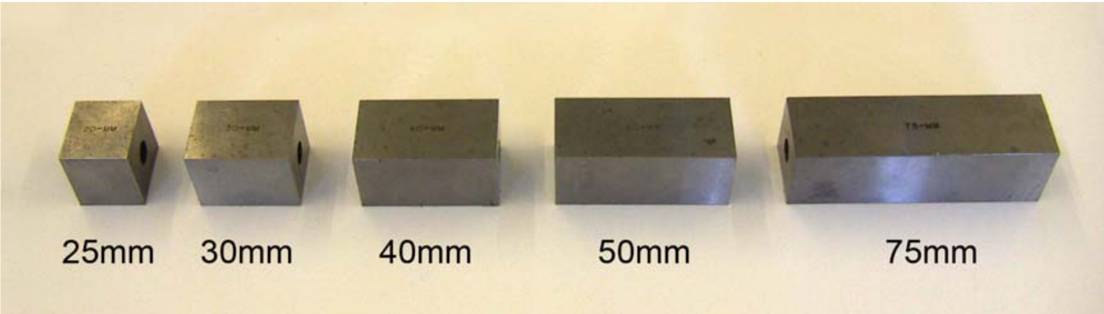


Figure 7.21 – Five slip gauges used for validation of the 3D scanning and post-processing

7.4.1 Method

The five slip gauges varied in length; 20mm, 30mm, 40mm, 50mm and 75mm. Each one was securely mounted to a level platform and scanned three times using the ModelMaker-Z 3D scanner. The 3D point cloud data generated by the scanning process was then edited using the same methods and techniques used when editing the point cloud data of the RP models and resin tools, removing any erroneous and extraneous data points. This enabled 3D surface models of the slip gauges to be created which were then measured using tools within Geomagic Qualify. The same considerations and cautions were taken to ensure that the point cloud data and the surface models were not excessively modified to ensure that accurate representations of the slip gauges were generated. A total of fifteen surface models were created, three for each of the five slip gauges. Measurements were taken across the length of each model and compared to the equivalent slip gauge to calculate a deviation value.

7.4.2 Results

Table 7.4 summarises the results of the exercise to validate the 3D scanning and post-processing methods. For each slip gauge the length and deviation value for each of the models generated is given, together with the mean average length and deviation of the three models. From the mean length, the accuracy as a percentage for each gauge was calculated.

Slip Gauge	Scan Data								
	Model 1		Model 2		Model 3		**Mean**		%
	Lgth	Dev	Lgth	Dev	Lgth	Dev	**Lgth**	**Dev**	
20mm	19.946	-0.054	19.995	-0.005	19.915	-0.085	**19.952**	**-0.048**	**99.76**
30mm	29.974	-0.026	29.945	-0.055	29.926	-0.074	**29.948**	**-0.052**	**99.83**
40mm	39.948	-0.052	39.966	-0.034	39.991	-0.009	**39.968**	**-0.095**	**99.92**
50mm	49.973	-0.027	49.917	-0.083	49.987	-0.013	**49.959**	**-0.041**	**99.92**
75mm	74.956	-0.044	74.902	-0.098	74.991	-0.009	**74.950**	**-0.050**	**99.93**

Table 7.4 – Scanner accuracy results. Length and deviation figures in mm

The results show a high degree of accuracy was achieved using the chosen methods of 3D scanning and post-processing. The mean average deviations range from -0.041mm to -0.095mm (mean -0.057mm), with a maximum deviation of -0.098mm, on the second model of the 75mm slip gauge, and a minimum deviation of -0.005mm, on the second model of the 20mm slip gauge. The mean percentage from all of the slip gauges reveals that, overall, the 3D scanning and post-processing methods are 99.87% accurate. The results, therefore, can conclude that these methods were capable of creating accurate 3D surface representations of the RP models and resin tools. This means that the comparisons made to the CAD models were reliable and not significantly affected by variations accumulated during the processes of editing the point cloud data or creating and modifying the 3D surface.

7.5 Discussion and conclusions

The objective of this validation study was to analyse the prototyping methods used to recreate the size gauge and glove former CAD models as resin tools. This was to ensure that the anthropometric data and design knowledge contained within the CAD models was accurately incorporated into the tools and subsequently the handwear that was manufactured and designed using them. Failure to achieve an accurate representation of the CAD models would be an inadequate evaluation of their capability to produce handwear with enhanced fit for the wearer.

Comparing the CAD models to the RP models and resin tools has identified expected differences between them. Tolerances attributed to the RP machine and processes of hand finishing have meant that variations between the CAD model and the RP model have occurred. The results of the comparisons show, however, that the degree of variation is small and a high degree of accuracy has been achieved. For the size gauge, the mean deviation between the CAD model and RP model is -0.186mm and -0.196mm (tables 7.1 and 7.2), for sizes one and five respectively; and for the glove former, the mean deviation is -0.044mm (table 7.3). This means that the 3D Systems' InVision 3D printer chosen to create a 3D representation of the CAD models was capable of accurately producing the RP master parts used to create the silicone moulds. Previous independent benchmarking of 3D printing systems (Grimm, 2005) using similar methods of validation found the mean deviation of the InVision SR 3D printer ranged from -0.0108in. to -0.0011in. (-0.2743mm to 0.0279mm). The results from this validation fall within this range and, therefore, indicating the printer was operating at an optimum level producing a high quality RP model.

The results from the comparisons between the CAD model and the resin tools show an increase in the deviations. The process of creating the silicon moulds and casting the polyurethane epoxy resin lead to a further reduction in the overall size of the resin tools. The difference however, remains small; across both sizes and versions of the size gauge resin tools the mean deviation ranges between -0.321mm and -0.443mm (table 7.1 and 7.2) from the CAD models, and the resin former has a mean deviation of -0.369mm (table 7.3) from its corresponding CAD model. This further reduction in size is consistent with the effects of shrinkage occurring during the curing process of the silicone rubber and the epoxy resin and the minor hand finishing required after the de-moulding process.

When analysing the repeatability of the silicone moulds the results show they were able to produce a subsequent cast with similar accuracy. For both sizes of the size gauge there was little difference between the deviations of the two resin versions. For size one the mean deviation for Resin-A was -0.341mm and for Resin-B was -0.321mm (table 7.1), a difference of 0.02mm. A similar result was found for size five, the mean deviation for Resin-A was -0.443mm and for Resin-B was -0.396mm (table 7.2), a difference of 0.047mm. In both sizes the deviation was greater on Resin-A meaning that Resin-B was a more accurate tool. The causes of this result are unclear.

It is possible that the de-moulding process slightly increases the size of the cavity within the mould reducing the deviation; however, as the differences were so small this result was not a significant finding.

The pattern of where the deviations occur is highlighted by the 3D comparison charts. The charts for the size gauge comparisons (figures 7.10 to 7.15) show a consistent level of accuracy, with the same areas showing similar levels of deviation, as indicated by the regions of different colour. Large flat areas, i.e. the palm, show the most consistency with a very few variations in colour with areas of more curvature such as the fingers and the thenar pad showing a greater variation in colour and therefore increased levels of deviation.

The glove former comparison charts are less consistent, figures 7.18 and 7.20. The two charts illustrate a clear difference in the deviation pattern, particularly around the palm area. This is possibly due to the different geometry of the glove former which contains no flat surfaces, requiring greater curvature and detail to manufacture the type of glove it is designed for. The inconsistencies in the comparison charts is evident in the deviation figures (table 7.3) with a greater difference in the level of deviation between the RP model and resin former compared to the equivalent deviation figures of the size gauge.

The principle deviation for both the glove former and size gauges is between the CAD model and the resin tools. The CAD models are the original product developed using the anthropometric size data and design knowledge, and the resin tools are the physical representations of these models to evaluate how this data and knowledge can improve the fit of handwear. Figures 7.22 and 7.23 summarise the differences between the CAD models, the RP models and the resin tools. In figure 7.22, mean averages of the mean deviations have been calculated for the glove former and figure 7.23 gives the same data for the size gauge comparisons. These figures give an overview of deviations occurring. This validation study has shown that the resin tools are an accurate representation of the CAD models. Figure 7.22 illustrates that there is only an average -0.369mm difference between the resin glove former and the CAD model. Similarly, in figure 7.23, overall there is only an average of -0.375mm difference between the size gauge CAD models and the resin size gauge.

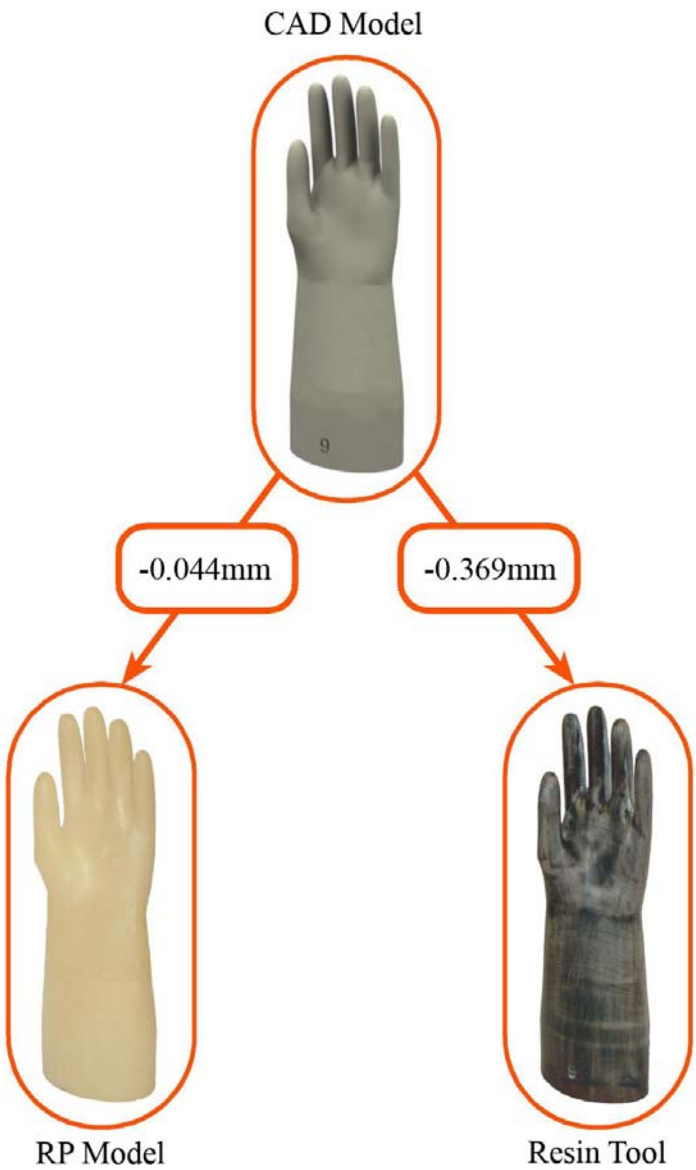


Figure 7.22 – Comparisons made between glove former CAD model, RP model and resin tool

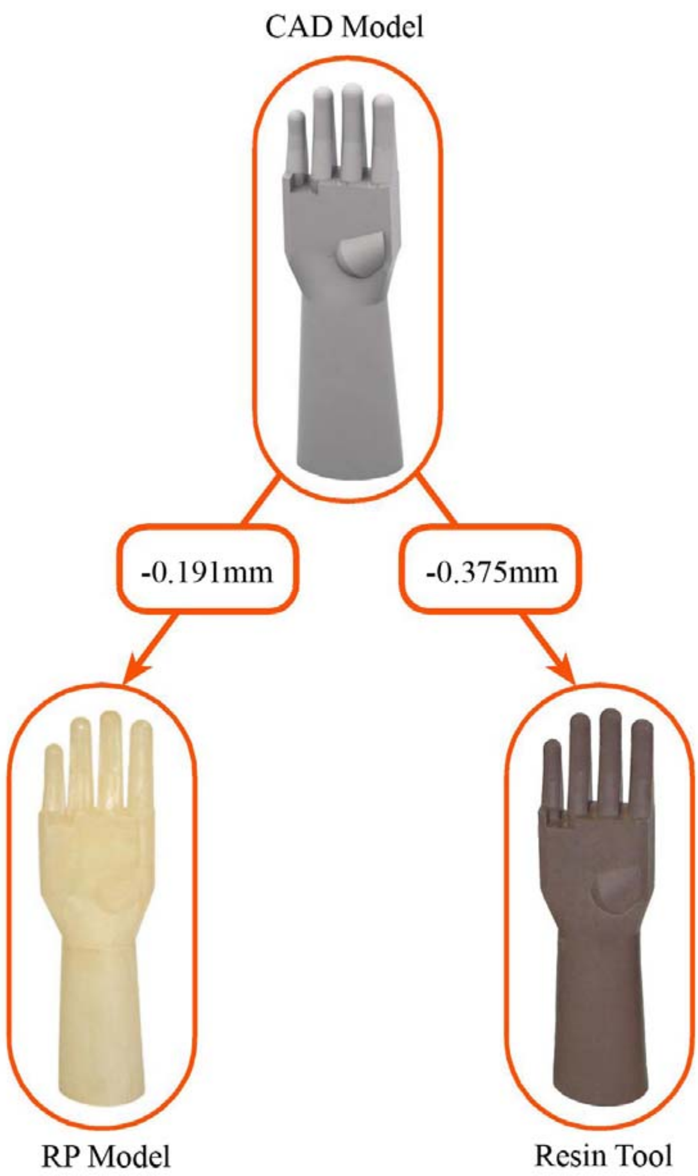


Figure 7.23 – Comparisons made between size gauge CAD model, RP model and resin tool

Additionally, the results show a consistency of the prototyping method used. From all of the five resin tools analysed (two versions of each size of size gauge and the glove former) the deviation between them and the corresponding CAD model ranges between -0.443mm and -0.321mm, a difference of 0.122mm. This indicates the method was suitable for both the size gauge and the glove former, capable of consistently producing the necessary resin versions of the CAD models to a similar level of accuracy. It also confirms that the method was adept to handle the different sizes and geometry that varied between the size gauges and glove former and did not require any major modifications or additions to the processes used within it.

Identifying and quantifying the difference between the CAD models and resin tools has given an understanding as to how the prototyping method affected the size of the gloves designed and manufactured within the evaluation phase of the case studies. In addition, by calculating the amount of deviation that occurs between the CAD model and the corresponding resin tool, it is possible to modify the size of the CAD model to take account of this, further increasing the accuracy. For example, in the case of the glove former, the resin tool was 0.369mm smaller than the original CAD model. By enlarging the CAD model by this amount, the error caused by the shrinkage during the RP and silicon mould process could be eliminated.

The validation process has verified that it was acceptable to use the tools within the case study research, ensuring they were an accurate representation of the CAD models by successfully transferring the design knowledge and anthropometric size data into size gauges and glove formers. This consequently means that the results from the user trials are a true indication of the capability for the CAD models to produce handwear with an accurate fit and an improved performance for the wearer.

Chapter Eight:
Discussion and Conclusions

This chapter assesses the achievements of the case study research, discussing the outcomes and drawing the main conclusions of the study. Each case study chapter discusses the specific results and conclusions found during the evaluation phases. This chapter reviews these results in relation to the research questions formed after the literature review in Chapter 2.8, as well as the research objectives outlined in Chapter 1.3. It discusses these questions and objectives in three separate sections; the research methodology, the case study outcomes, and future research and developments.

8.1 Discussion

8.1.1 Chosen research methodology

The first research question addressed the design of a research methodology suitable for this study.

f) The literature review identified gaps in current knowledge and methodology of designing and manufacturing handwear. What are the appropriate research methodologies to fill these gaps and achieve the research aim?

The literature review fulfilled the first research objective:

- To identify and explore the key issues surrounding the design and manufacture of apparel using anthropometric data and CAD/CAM; identifying gaps in current knowledge and methodology relating specifically to handwear.

It revealed that anthropometric data and CAD methods are used to design customised clothing through means of 3D body scanning. However, it remains difficult to accomplish such results for clothing intended to protect the extremities of the body. This gap in current knowledge and methodology relating specifically to handwear provided the scope to investigate how integrating anthropometry with CAD/CAM can improve handwear fit. The research methodology chosen is described in Chapter 3. The methodology was influenced by five different elements: the form of research; the research purpose; the strategy; the method; and the tools selected. The choices made are summarised in table 3.5, Chapter 3.4. The design of this methodology enabled appropriate research to be carried out to fulfil the research questions and objectives.

Case studies were chosen as the primary research tool. This gave the opportunity to explore how the combination of anthropometric data, 3D computer modelling and computer manufacturing/prototyping could generate tools and introduce them into a manufacturing environment. The collaboration with handwear manufacturers enabled the expert views and experience given to be integrated into the design process, ensuring current knowledge in handwear design was consulted and integrated.

By using descriptive and practical research methods, physical products were produced in the form of the size gauges, dip moulding formers and gloves. To enable the gauges and formers to be used appropriately by handwear manufacturers they needed to be fully developed and prototyped. This meant a complete design process of each tool was carried out. By going through this process it was possible to understand how 2D anthropometric data can be accurately represented as 3D computer models and explore the issues arising from integrating these two disciplines. By practically demonstrating this process, it was also able to verify that the proposed theory of using anthropometry and CAD/CAM to improve handwear fit was feasible.

The product of the tools created in the case studies were the gloves designed and manufactured. They constituted the main evidence that the tools were capable of producing gloves to an industry standard quality and that these gloves afforded an improved fit to the wearer. The user assessments to evaluate them were designed to analyse elements of their manufacture and fit, consisting of a battery of repeatable tests in a controlled environment. This allowed comparisons to be made with other equivalent gloves which concluded that the intended improvements in fit had been demonstrated and consequently the research aim had been achieved.

8.1.2 Case study outcomes

The case studies formed the main part of this study and addressed the following three research questions:

g) Is it feasible to modify current methods of apparel design and manufacture to create a novel design tool for the design and manufacture of handwear that improves the quality of fit?

h) If so, what would be the efficacy of the tool in terms of cost effectiveness and functional effectiveness?

i) What improvement in the quality of handwear fit and subsequent task performance can be achieved?

By addressing these questions, the cases studies were able to produce suitable outcomes that fulfilled the following research objectives;

- To develop and validate suitable design methods to improve the fit of handwear.

- To implement a proposed method(s) and consider its effectiveness.

8.1.3 CAD modelling and CAM/RP

The initial part if the case studies dealt with research question B. The literature review revealed how the use of anthropometric data with CAD/CAM is an increasingly popular approach in the design of various types of apparel. The use of body scanning for collecting anthropometric data and digitising the shape of the human body enables customised apparel products to be created. The case studies were designed to investigate if this approach could be adopted to improve the fit of handwear. This area of apparel has not benefited from the developments in anthropometric data collection due to the inability to capture the detail of the hand using 3D body scanning. The only available anthropometric resource of the hand is 2D anthropometry, collected through conventional manual techniques. The case studies were used to develop novel design tools which used this form of anthropometry with CAD/CAM to improve the fit of handwear. This integration created an avenue for incorporating detailed anthropometric data into the design and manufacture of protective handwear which does not exist within current handwear design and manufacture processes. The outcomes and results from each case study have shown that the tools have enabled designers and manufacturers of handwear to produce gloves with a more accurate fit by using anthropometric data to determine their size and shape.

The initial step in each case study was to generate 3D computer models using the 2D anthropometric data taken from the size range. The creation of this size range was discussed in Chapter 4, explaining the combination of anthropometric quantitative data and qualitative design decision making. The computer models were generated by creating a series of geometric parts that represented each element of the hand and assembling them to create the correct size, shape and proportions. Due to the different objectives of the each case study, the CAD models developed varied in their appearance and structure.

In the first case study the aim of the CAD models was to provide a 3D representation of the size range. Figure 8.1 shows the final configuration of the CAD models, illustrating how the data within the range was represented. The geometric shape of the models is a constraint caused by the number of dimensions contained within the size range. This limited the level of detail able to be created within the CAD model. However, the size range had sufficient characteristics to produce a glove with good fit and the methods used to generate the CAD models meant that these characteristics were accurately integrated.

In the second case study the aim was also to represent the size data, but in addition, key manufacturing properties of a glove former mould tool needed to be incorporated. This led to a very different appearance to the CAD models, as seen in figure 8.2. In order to include this detail it was necessary to analyse existing mould tools to extract the required shapes and contours that form the properties which are needed to enable the moulding process to work. This was achieved through 3D scanning and digital photography to transfer an existing tool into the CAD environment. Using this tool as a guide, the required construction lines could be drawn to modify the size gauge CAD models generated in the first case study.

Figure 8.1 – Size gauge CAD model

Figure 8.2 – Glove former CAD model

In both cases studies the need to easily and accurately modify each element of the CAD models was an important factor in correctly representing each size in the size range. It was necessary to develop a method that enabled a CAD model to be modified into another size rather than being completely re-modelled. This ensured each size was to the same degree of accuracy. This was achieved in the first case study by creating the database that was linked to the wireframe skeleton structure of the CAD model. The database contained all the required data to determine the size, shape and position of each piece. By changing the data within the database, the CAD model could be modified to represent a different size without having to create and assemble new pieces separately.

The database method could not be used to modify the CAD models generated in the second case study. These models had greater complexity due to the added detail needed to simulate the properties of the dip moulding glove former. However, other measures were used to ensure the modification of these models were as accurate as possible. Again, the construction of the models used a wireframe structure which generated and controlled the surfaces that created the necessary shape. This structure could be quickly and accurately manipulated to change its size and shape. Although this could not be done automatically, specific points within the wireframe corresponded to the dimensions within the size data. This meant the wireframe could be changed to relevant dimension and accurately checked to confirm each part of the model was to the correct size and in the correct position relative to other parts.

The construction methods chosen to build and manipulate the CAD models in both case studies successfully enabled the dimensions from the size range to be appropriately represented. Both case studies developed a similar method to generate the 3D models; using a wireframe skeleton structure from which surfaces or solid geometry could be created. This structure was assembled using 2D dimensions, i.e. lengths, breadths, radii and diameters. This was to correspond with the dimensions in the size range so they could be directly used in the construction and modification of the structure, controlling its size, shape and configuration. This meant that when the structure was used to create the 3D surfaces or geometry, the size data was recreated into a 3D form.

After generating the CAD models and finalising their configuration, the next stage in each case study was to recreate these models as physical tools; the size gauges and glove formers. It was important that the combination of CAM and RP methods chosen were able to recreate the CAD models accurately and ensure the anthropometric data, glove characteristics and mould tool properties contained within them were transferred correctly. Using 3D printing technology together with silicone tooling and resin casting, the CAD models were accurately recreated as the required tools. The level of accuracy achieved was verified by the exercise described in Chapter 7. This exercise compared the RP model and final resin tool with the corresponding CAD model to determine the deviations between them. The results of these comparisons found that the combination of methods chosen were able to maintain the size and shape of the CAD models. This consequently meant that the detail within them had been correctly incorporated into the appropriate tool. The glove former CAD model had a mean average deviation of -0.369mm from the resin tool, figure 7.20. The same comparison of the size gauge CAD model and corresponding resin tool showed a mean average of -0.375mm, figure 7.21. These figures indicate the chosen method of producing the resin tools was consistent and able to accurately recreate the CAD models.

8.1.4 Assessment of the size gauge and glove former

The second question addressed by the case studies, question C, concerned the efficacy of the tools produced from the CAD models in terms of cost and functional effectiveness. The tools developed in the case studies were designed to be incorporated into existing handwear designing and manufacturing processes. It was recognised that current manufacturing techniques have been established over many years with extensive use of expert knowledge and experience. The intention was to enhance and strengthen these processes by incorporating the tools into current manufacturing processes. Collaboration with two handwear manufacturers enabled the tools to be used in a commercial environment, giving the opportunity to obtain first hand experience of how the tools performed and how they were able to influence the design and manufacture of new gloves.

The tool designed in the first case study is specifically aimed at improving the design of gloves manufactured from 2D patterns. The size gauge was introduced into a pattern generation process. It enabled the pattern designer to better visualise the size and shape of the finished glove, similar to the use of a mannequin for the design of larger garments. It gave the designer the ability to inspect the dimensions of the pattern at the conceptual design stage of glove manufacture and ensure errors were minimised before the glove went into production.

The assessment of the size gauge was designed to analyse how the conventional method of glove pattern designing was influenced by the introduction of the gauge and what improvements, if any, would be made. Collaborating with Bennett Safetywear Limited, the assessment examined how the designer generated a new pattern, analysing each stage of the process and the design decisions made. The designer was asked to generate two new glove patterns, using the size range data to specify the size of the glove. One pattern was generated using the data only and another using the addition of the size gauge. The results of the assessment showed that the size gauge had a considerable influence on how the designer evaluated the decisions he made concerning the size and shape of each piece of the pattern. Figure 8.3 summarises the comparison of the two methods used to generate the new pattern.

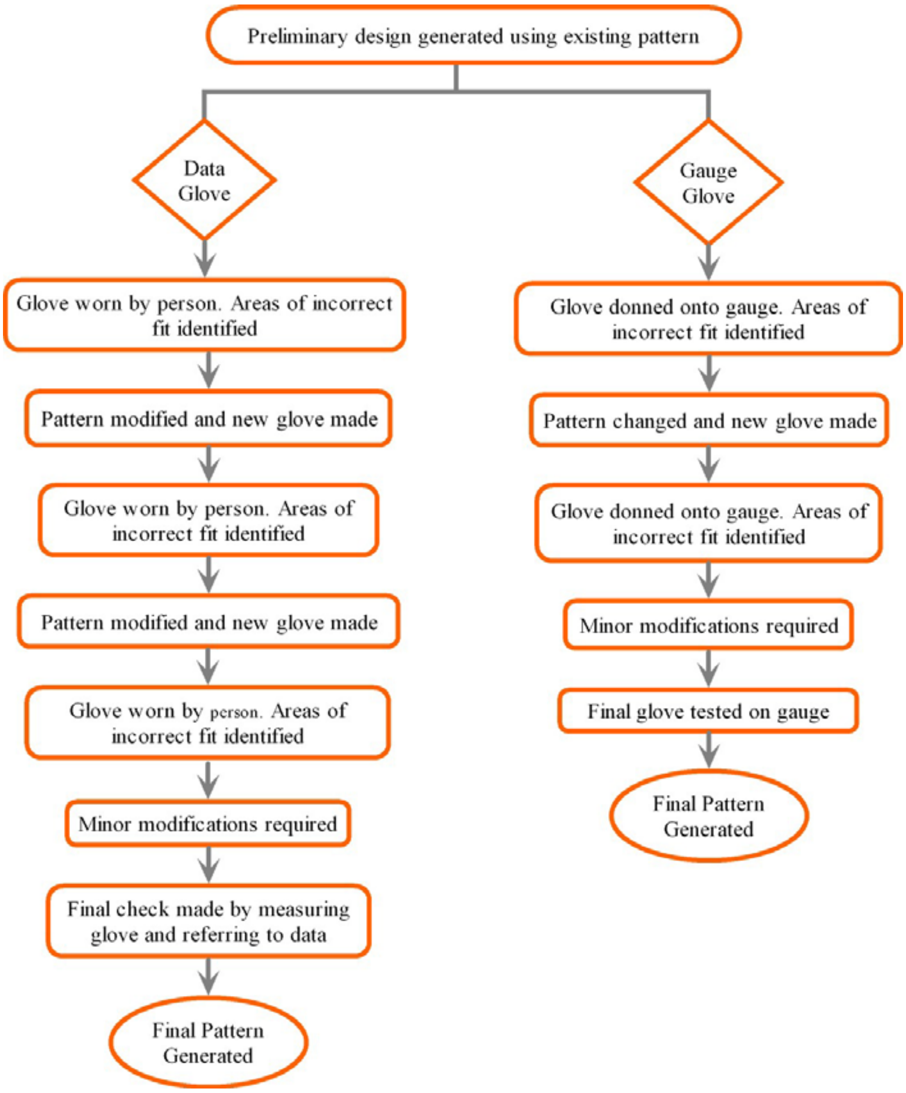


Figure 8.3 – Summary of the design process comparison in case study one.

The size gauge reduced the number of stages the designer needed to produce a pattern that he was satisfied suitably represented the size data. Using the gauge enabled the designer to make more precise adjustments to the pattern by immediately receiving feedback on the fit of the glove. It gave the opportunity to accurately analyse the pattern in 3D, assessing how the assembly of the different pieces needed to be modified to ensure the fit was to the correct specification. This was not available to the designer when only 2D dimensions were used. This meant that more iterations in the design process were needed, making more alterations to the pattern before a satisfactory pattern could be finalised. The only comparable option to the size gauge for the pattern designer was to use a person with hands that closely matched the required size. This method has fundamental flaws, as the selection of this person is only approximate and unlikely to be the correct size in all proportions. The advantage of the size gauge is that it represents the maximum volume within a size. All areas are to the same proportion and consistent across all the sizes in the range. A persons hand is unique, and modifying the size of the pattern using this as a guide will not accommodate the range of users that correspond to that size.

The results of this assessment clearly indicated that the size gauge assisted the pattern designer to generate a pattern in less time, with fewer iterative stages in the design process. In terms of cost effectiveness this would reduce the cost of producing a new pattern due a more efficient design process. In terms of functional effectiveness, the size gauge enabled the designer to assess the glove pattern in greater detail. This improved the accuracy of the glove pattern by being able to determine the fit corresponded correctly to the size data dimensions. This improvement in fit was determined by comparing the two gloves produced during the size gauge assessment the glove evaluation phase of the first case study.

The analysis of the pattern generation process revealed the number of variables involved when creating a glove pattern of this type. It highlighted that this process is heavily dependant on the tacit knowledge and rule of thumb principles of the pattern designer, gained through empirical experience of glove design and manufacture. There are several different allowances and variables that must be considered by the designer when determining the size shape of each piece for the pattern. The anthropometric data used must be modified to accommodate these variables. Producing a pattern that is based purely on hand dimensions will result in a glove that may fit the hand in a static position, but due to the properties of the material will restrict range of motion and not enable the wearer to grip effectively. The designer must consider the properties of the material, to allow the hand to move within the glove. This movement must be controlled to ensure the interaction between the hand, glove and object remains intact, as uncontrolled movement leads to poor fit. Allowing for movement inevitably means introducing excess material to facilitate the extension, flexion and translation of the hand. The designer must decide on the location for this additional material, and its subsequent movement, so that it does not form creasing in sensitive areas of the hand which may cause injury. This leads to an understanding of the potential tasks the wearer might perform when using the glove. Being aware of the different grip patterns associated with these tasks enables the designer to position the excess material in an appropriate place. This ensures it does not interfere with the movement of the hand or impair the performance of the wearer. Finally, the designer must consider the relevant manufacturing requirements to ensure that these variables and allowances are combined and the glove can be made to the correct specification.

The skill of the designer is to understand how all these factors influence each other for a specific pattern to ensure they are all accommodated appropriately in the final glove. Observing the skills of the pattern designer during the size gauge assessment led to formulating an equation that attempted to externalise the tacit knowledge.

$$\text{Pattern dimension} = \text{anthropometric data} \pm \text{material thickness} \pm \text{material properties} \pm \text{seam position} \pm \text{stitch type} \pm \text{liner allowances} \pm \text{manufacturing requirements}$$

By formulating this equation and understanding the tacit knowledge of the pattern designer, it gives the potential for designers new to glove design to apply these skills in the processes for designing new handwear. It also ensures that the expertise and skills continue to be used, by capturing and recreating them through a CAD methodology.

The second case study focussed on the design of a mould tool for the manufacture of handwear using a dip moulding process. This process is a more automated procedure than pattern designing and so there was less opportunity to influence the manufacturing processes involved for this type of glove. Collaborating with Comasec Yate Limited, the prototype glove former developed was directly introduced into a current commercial manufacturing environment. The glove former is the equivalent of the 2D pattern used to construct a glove in the cut and sew manufacturing method. This means that the accommodation for material properties, excess material, material movement etc., is contained within the shape of the tool. The process of combining the size data and the shape of an existing glove former enabled the prototype former to possess dip moulding capabilities and the qualitative design characteristics for good fit. This meant it was able to manufacture a batch quantity of gloves to an industry standard that would provide the wearer with an improved fit. The evidence that these gloves afforded an improvement in fit for the wearer was demonstrated in the glove assessment phase of the case study.

This demonstrated an improvement in the functional effectiveness of this manufacturing process. The prototype former was able to produce gloves using the same method as current formers but with an improvement in fit properties. An improvement in terms of cost effectiveness is possible by reducing the time taken to produce dip moulding glove formers. Currently, production of these tools requires a turn around of many weeks, the CAM and RP methods used to produce the prototype former from the CAD model can reduce this time to a few days. The polyurethane resin used for the former is unsuitable for the mass production of gloves due to the nature of the dipping procedure. The combination of chemicals and repeated heating and cooling degraded the surface finish of the former, leading to a reduction in the quality of the gloves produced. However, the process used to create the resin tools in the case studies would allow for new mould tools to be produced quickly and accurately. An alternative casting material that is more resistant to dipping process would enable the tool to withstand the destructive elements and manufacture gloves on a larger scale. The validation analysis carried out in Chapter 7 analysed the accuracy of this process and verified it was capable of recreating the intricate curvature and surface finish required for a glove former. The use of computer modelling and CAM/RP/RM methods would enable a new type of glove to be manufactured in less time and at a reduced cost by generating an appropriate tool more quickly. It would also enable customised tools for small specific populations to be made which are currently rarely able to be produced due to the timescales and costs involved with existing production methods.

The financial aspect when designing and manufacturing gloves is a high priority for handwear manufacturers. As with all manufacturing industries, it is essential that the costs involved in producing the final product are kept as minimal as possible to ensure it can be sold at a competitive price. For both the ‘cut and sew’ and dip moulding processes, the costs involved at each of the various stages are precisely calculated and closely monitored, as each one can affect the retail price of the gloves and the associated profit margins. Introducing a new tool or method into these processes must be carefully considered, as the proposed improvements in productivity must not mean an excessive increase in manufacturing costs. Implementing changes to the manufacturing process will only be beneficial if it allows the gloves to be produced economically. Therefore, in order for the size gauge and glove former tools to be practical additions to existing handwear manufacturing industries, they must be able to integrate into the efficient costing structures specifically calculated for current design and manufacturing processes.

Time is a major investment within a manufacturing process and can have a significant affect on production costs. Reducing lead times for products is a key priority for manufacturers as it means fewer resources are used within the manufacturing process; reducing costs and increasing the speed of delivery to the customer. The evaluation stages of the case studies demonstrated that incorporating the size gauge and the glove former tools into current processes of handwear manufacture can improve the lead times for a new glove. They are able to reduce the time needed during the design and development stages, which is often part of the manufacturing process where an extensive amount of time is required. However, for handwear manufacturers to fully integrate these tools into their manufacturing procedures some initial financial investment would be necessary.

The primary and most significant of these investments is the production and modification of the necessary CAD models. This would require a CAD designer to generate a series of models to the correct size and shape, using the appropriate anthropometric data and integrating any additional design properties. These models would then need to be recreated into the physical manikins that form the size gauges or glove formers. A suitable material would need to be identified and tested if the polyurethane resin used in the case studies was unsuitable. In the case of the size gauge, it may be necessary to give some additional training to the pattern designers to ensure they use the gauges correctly and understand exactly what they represent. However, this would be minimal as the pattern designer using a size gauge in the first case study was given no instruction and was immediately comfortable when using it to generate a new pattern. In return for this upfront investment, the size gauge and glove former have demonstrated they can provide a significant addition to the design and manufacture of handwear. The trade-off with the costs incurred to initiate the introduction of the tools is a faster, more efficient process which is able to create an improved, more accurate product.

8.1.5 Glove assessment

The assessment of the gloves satisfied research question D. It gave evidence that an enhanced quality of fit was achieved by demonstrating an improvement in task performance of the wearer. The collaboration with handwear manufacturers in both case studies enabled the two tools developed to produce gloves that could be assessed for their fit. In the first case study the size gauge assessment generated a pattern from which four pairs of gloves suitable for evaluation were manufactured by a professional seamstress, figure 8.4. In the second case study a pair of prototype glove formers was used in a commercial dip moulding process to produce eight pairs of gloves suitable for evaluation, figure 8.5.

The assessment of the gloves used a battery of tests designed to evaluate dexterity, haptic feedback, hand strength and fit perception. The participants selected to perform the tests were chosen to closely match the sample population of the original anthropometric data. The results from both assessments were able to conclude that the tools developed in the case studies were able to produce gloves which afforded an improved fit for the wearer. This improvement was determined by comparing the gloves with equivalent gloves manufactured using current manufacturing processes. The assessments also compared the bare handed capabilities of the participants and while wearing a pair of latex gloves. The improvements were measured by the reduction in the time taken to complete the strength and dexterity tests, an increase in hand strength, and an increase in perception of fit of the glove in all areas assessed.

Figure 8.4 – Glove designed using size gauge in case study one

Figure 8.5 – Glove manufactured using glove former in case study two

The results of the size gauge glove assessment in Chapter 5.7.3 illustrated the improvements that the glove designed using the size gauge had over the glove designed using only the size data. Participants wearing the size gauge glove had a greater grip and pinch strength, could perform the majority of the tests in less time and made fewer errors when using a keyboard. The assessment also revealed that the participants found these tests more difficult to complete when wearing the data glove compared to the other conditions assessed. When analysing the perceived fit and range of motion of the data and gauge gloves, the participants experienced a greater degree of fit for the gauge glove for all areas of the hand.

The results of the glove former, Chapter 6.5.2, showed similar results to those in the first case study. Participants wearing the glove produced from the prototype former were able to perform better than they were when wearing the glove produced from a standard current former. None of the dexterity tests could be completed as quickly when wearing the standard and the grip and pinch strengths were reduced.

For both types of gloves in the case studies, the priority was to improve performance fit rather than comfort fit. These two types of fit do not necessarily coincide, as the properties for improving performance may not correspond with qualities that make the glove more comfortable. For example, the size range was generated with shorter digit lengths to ensure there was no excess material of the glove at the digit tips.

While this resulted in a better fit for the gloves at the digit tips, it consequently meant a poor fit around the digit crotches, which may be an uncomfortable sensation for some wearers. This suggests that when the properties for comfort and performance conflict it is necessary for performance fit to be the dominating factor. Comfort is obviously important for handwear; however, the critical factor for protective handwear is how the wearer performs when wearing it. This issue between comfort and performance relates to the appropriate fit for a piece of clothing. As highlighted in the opening chapter, the correct fit is determined by what fit is appropriate for that particular product. It enables the wearer to perform a range of grip patterns and use the optimum pattern(s) to fulfil the required tasks. The size gauge and prototype glove former have enhanced the appropriate fit for this type of handwear. By prioritising areas where good fit improves performance over areas perceived for comfort, the gloves produced have ensured the wearer can perform tasks more efficiently.

The research aim for this study was to demonstrate and validate a method of enhancing appropriate fit for protective handwear. The assessment of the gloves has shown it was possible to improve the fit of current protective handwear by introducing new tools into the design and manufacturing processes. The design process to create these tools has enabled suitable anthropometric data and characteristics of good fit to be integrated into the glove, benefiting the wearer. The cut and sew and dip moulding manufacturing processes are the two most common methods used for PPE handwear. This study has demonstrated that an improvement in the effectiveness of these processes can enhance the fit of these types of gloves. By examining the issues relating to fit the properties for an appropriate fit have been identified. This has contributed towards a better understanding of how fit is integrated into a glove and ultimately minimise the problems and limitations associated with the use of PPE handwear.

8.2 Further research and development

The final research question considered the possibility of applying the methods developed in the case studies to other body worn products and what benefits this might afford to the wearer:

j) Is the method for generating the tool appropriate for designing and manufacturing other products that interact with the human body?

Addressing this question also fulfilled the final research objective; to determine how a proposed method to improve the fit of handwear can be further developed and refined so that it may be applied to other products in the field of body worn PPE.

The sources of data used when generating the CAD models was primarily from military personnel, and initially used in the HDDP with intentions for improving handwear for military use. As stated previously (Chapter 4.3), this does not limit the use of the tools developed from the CAD models to the HDDP, nor does it mean they are specific to military applications. One of the main properties of the CAD models was to ensure they could be modified easily and be adaptable to represent different sources of anthropometric data. Incorporating this property allows the CAD models to represent the hand profile of various populations of different sizes; from a large source, as was demonstrated in this case, to an individual hand. This means similar tools for the design and manufacture of handwear can be developed for these different types and sizes of populations and used for any application where fit is a necessary property to accurately specify. The size gauge CAD models are particularly suited to modification as they are in a basic format, only representing the size data. The database that was designed to easily and accurately modify each model to represent the sizes within the size data means any data can be used to specify their size and shape. The second case study demonstrated that these models can then be adapted to include additional detail relevant to a specific application. Therefore, it is possible that once the correct anthropometric data has been put into the CAD model, any necessary glove manufacturing properties or design knowledge can be applied to create a tool that ensures the correct fit is attained.

Formulating the equation in case study one externalised the tacit knowledge of a glove pattern designer. To apply this equation and generate new designs of glove patterns it could be used to build a database for glove manufacture. The database would contain a series of predefined patterns for different types of gloves. To create these patterns the equation would be used to determine the size and shape needed to accommodate the variables identified in case study one. This type of database would likely contain many thousands of patterns in order to represent the number of different combinations of variables that would exist. To identify the pattern required, information such as anthropometric data, glove type, material and manufacturing processes would be input into the database. By specifying these parameters, a suitable pattern could be retrieved or generated which correctly accommodated the required combination of variables. A system to provide this resource would give access to a wide range of patterns enabling handwear manufacturers to produce gloves with an appropriate fit for various applications and populations.

The methods developed in the case studies for generating CAD models using anthropometric data are not limited to the design and manufacture of handwear. The same methods can be extended to benefit all clothing that is designed to interact with the human body. It is equally important for this to be an accurate interaction and allow the product to fit the contours of the body part. Therefore, the use of appropriate anthropometric data is necessary to ensure a comfortable, secure fit is achieved. A possible development of the size gauge CAD models is their modification to represent anthropometric data of the foot. Size gauges that form a 3D model of these data could be produced that give the same benefits evident in the glove pattern design process to footwear manufacturers and shoe last designers. Similarly, these types of gauges could be introduced into the design and manufacture of any clothing that interacts with the human body, for example facemasks, helmets or load carriage systems. This method can be further extended to apply to any product that has an interface with the human body such as workstations, chairs or control mechanisms. However, it has become apparent throughout this research that the type and amount of anthropometric data available is critical when developing such products. Selecting the appropriate measurements from an anthropometric survey or when conducting a survey assists in the generation of the CAD models.

It is important to utilise the benefits of CAD/CAM and rapid prototyping methods in the design and development of any product that requires the integration of anthropometric data. These methods enable the detail within these data to accurately determine the correct size and shape of the final product, ensuring it meets the needs of the specified population. As CAD software continues to become more powerful in terms of geometry creation and modification, integrating 2D anthropometric data will become less challenging, allowing more complex models to be generated. The level of detail contained within these models combined with the capabilities of 3D body scanning will enable the creation of highly detailed, accurate computer models representing all features of the human body.

8.3 Conclusions

The following points summarise the main conclusions of this study.

- A systematic method of integrating anthropometry resources into a CAD/CAM based design process can enhance the fit of protective handwear; affording an improvement in task performance for the wearer.

- The CAD model development (Chapters 5.3 and 6.3) demonstrated that 2D anthropometric data of the hand can be used to build computer models that represent these data in 3D.

- A method using RP models and silicone moulds can provide an accurate representation of a CAD model. This method was capable of creating the resin tools from the size gauge and glove former CAD models. It maintained the size and shape of the models; accurately transferring the anthropometric data, glove characteristics and mould tool properties contained within them. The level of accuracy attained was verified using a process of 3D scanning (Chapter 7) which determined the differences between the resin tools and the corresponding CAD models.

- Introducing the size gauge into the design of a new glove pattern reduced the number of iterative stages required for this process. This decreased the time necessary to generate the pattern and increased its dimensional accuracy, consequently improving the fit of the glove.

- Highlighted during the assessment of the size gauge was the importance of the tacit knowledge and decision making of the pattern designer during the pattern generation process. Anthropometric data is only one of the resources necessary to design a glove pattern. The knowledge and experience of the pattern designer plays a vital role in combining the data with material properties and manufacturing requirements to ensure the glove is produced to the correct specification.

- Gloves manufactured using the size gauge and glove former offer an enhanced fit over the corresponding gloves manufactured using conventional methods. In user trials, a clear improvement in the performance of participants was recorded when they wore gloves manufactured from the size gauge and glove former. Both types of glove were able to improve the time taken for the wearer to complete a simple task compared with conventional gloves. A 5.4% improvement was recorded for the size gauge glove and a 9.3% improvement was recorded for the former glove. This improvement was a consequence of the enhanced fit of the gloves which afforded greater grip and pinch strength, and an improved ability to perform tasks reliant on dexterity and haptic feedback.

- The CAD models of the size gauge and glove former have the potential to be modified using hand anthropometry from different populations. This will enable the design and manufacture of protective handwear that suit the needs and requirements of individual populations, affording an accurate fit for optimum task performance.

- The method developed for integrating anthropometric data into a CAD/CAM based design process can be used to benefit any product that interacts with the human body. This method enables the detail contained within these data to accurately create the correct size and shape of the final product, ensuring it meets the needs of the target population and associated task performance.

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APPENDICES

Appendix I:
Anthropometric measurements

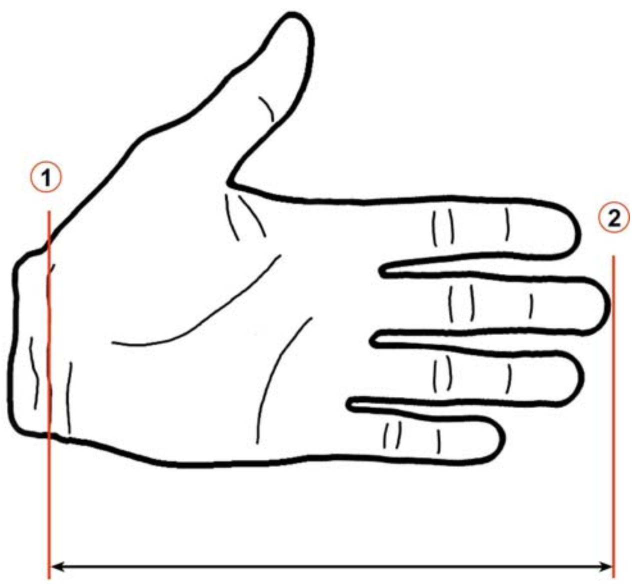
The following gives descriptions of the hand measurements taken in the DERA anthropometric survey and the additional measurements taken Loughborough University students used to generate the size data. The descriptions detail the position the hand during the recording of the measurement and the two location points the measurement id taken between.

Hand length

The measurement is taken with the hand and fingers out straight, palm facing upwards. Overall length of the palm and the fingers is recorded.

Point 1 – Distal wrist crease

Point 2 – Tip of digit three

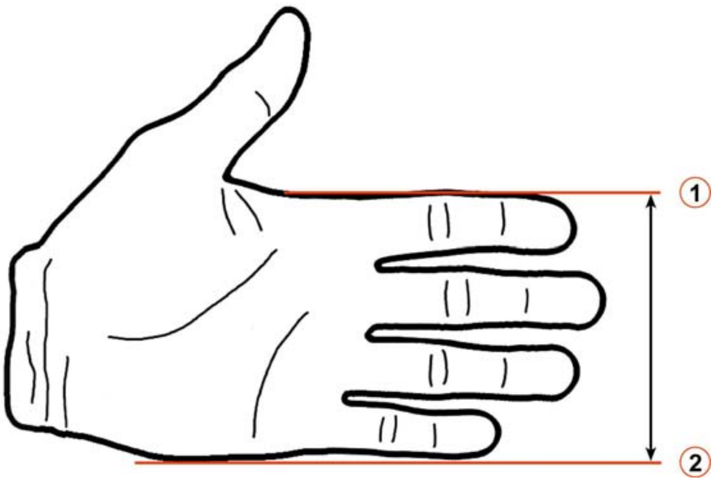


Hand breadth

The measurement is taken with the hand and fingers out straight, palm facing upwards. The thumb is abducted from the palm. Overall breadth of the palm at its widest points excluding the thumb is recorded.

Point 1 – Most lateral aspect of the palm, excluding the thumb.

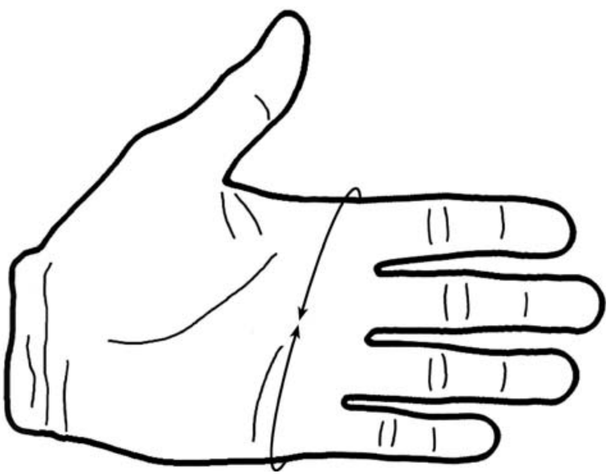
Point 2 – Most medial aspect of the palm.



Hand circumference

The measurement is taken with the hand and fingers out straight, palm facing upwards. The thumb is abducted from the palm.

Points – Measured around the palm at the junction between the palm and the fingers (MCP joints).

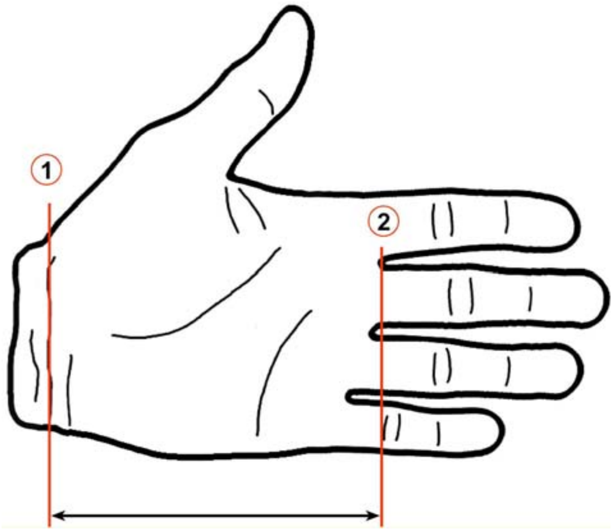


Palm length

The measurement is taken with the hand and fingers out straight, palm facing upwards. The thumb is abducted from the palm.

Point 1 – Distal wrist crease.

Point 2 – Proximal crease of digit three.

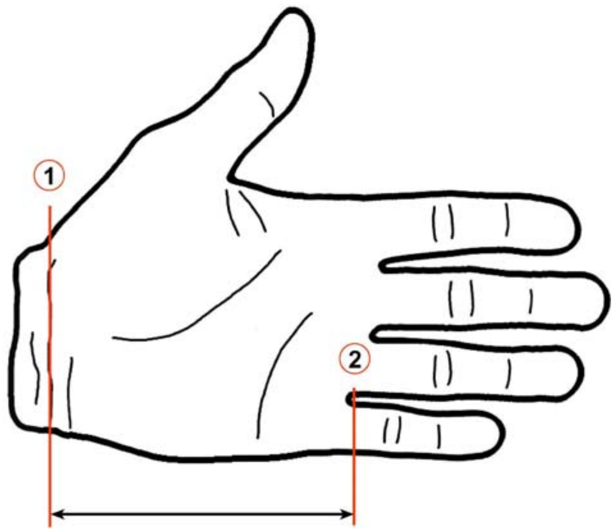


Crotch height

The measurement is taken with the hand and fingers out straight, palm facing upwards. The thumb is abducted from the palm.

Point 1 – Distal wrist crease.

Point 2 – Nearest point on the skinfold of the relevant crotch.

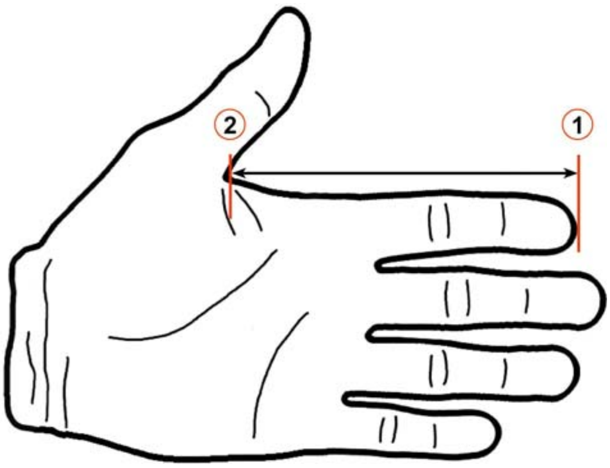


Digit 2 tip to thumb crotch

The measurement is taken with the hand and fingers out straight, palm facing upwards. The thumb should be abducted as far from the palm as is comfortably possible. Ten mm is added to the length to account for the width of the calliper blades.

Point 1 – Tip of digit two (index finger).

Point 2 – Proximal thumb crease.

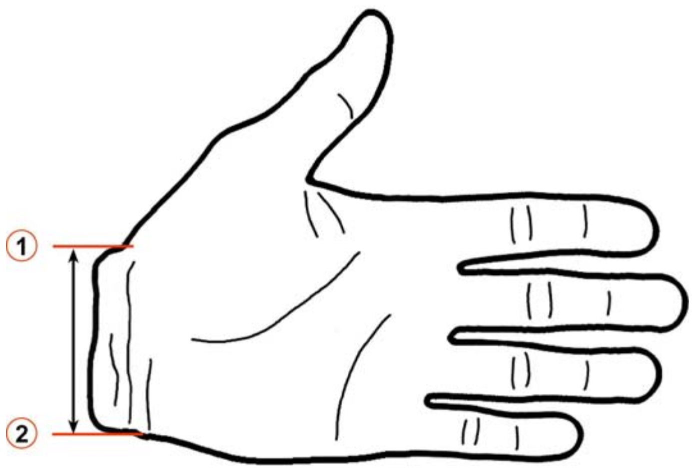


Wrist breadth

The measure meant is taken with the palm facing upwards.

Point 1 – Most lateral aspect of the wrist along the distal crease.

Point 2 – Most medial aspect of the wrist along the distal crease.

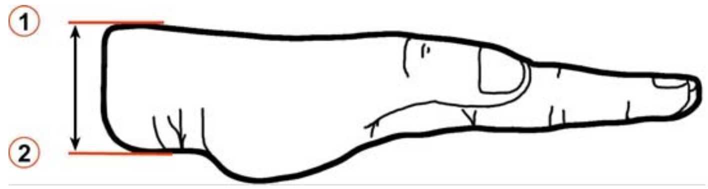


Wrist depth (maximum)

The measurement is taken with the hand straight and a neutral wrist position.

Point 1 – Dorsal wrist surface, distal to styloid process.

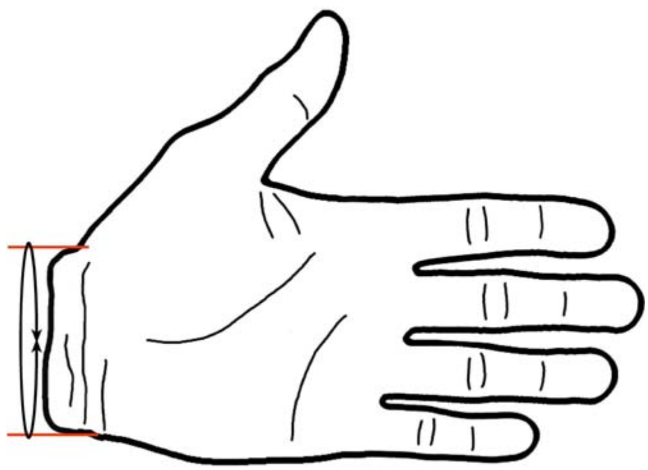
Point 2 – Distal wrist crease on palmar surface.



Wrist circumference

The measurement is taken with the palm facing upwards.

Points – From midpoint of palmar wrist crease around circumference of wrist. The scale of the tape measure lies along the distal wrist crease.

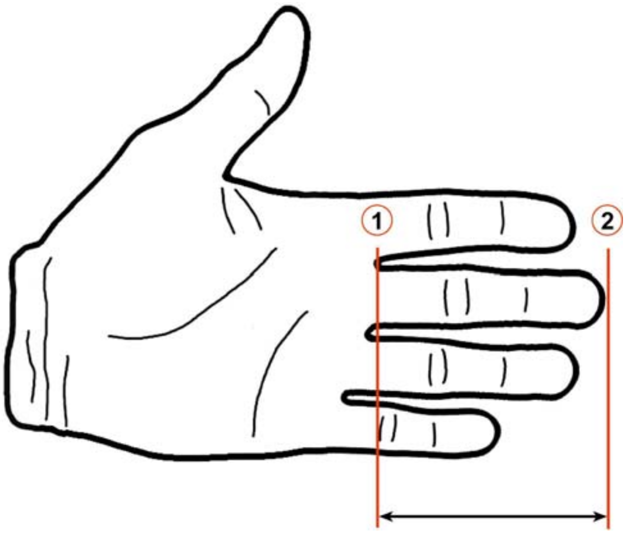


Finger (Digits 2-5) length

The measurement is taken with the hand and digits out straight, palm facing upwards.

Point 1 – Proximal crease of finger.

Point 2 – Tip of finger.

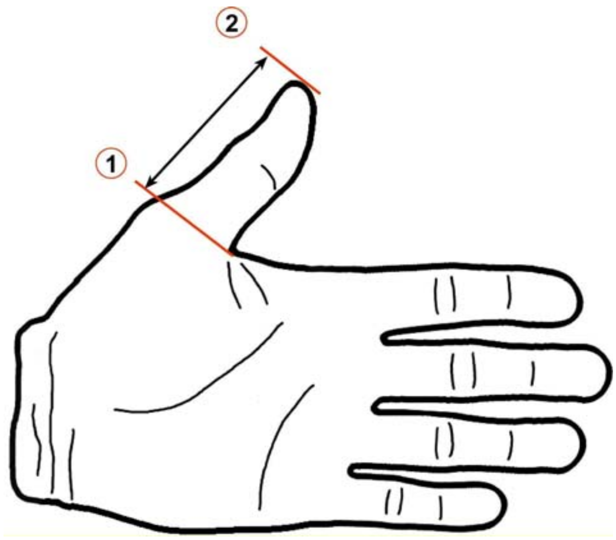


Thumb (Digit 1) length

The measurement is taken with the hand and digits out straight, palm facing upwards.

Point 1 – Proximal thumb crease.

Point 2 – Tip of thumb.

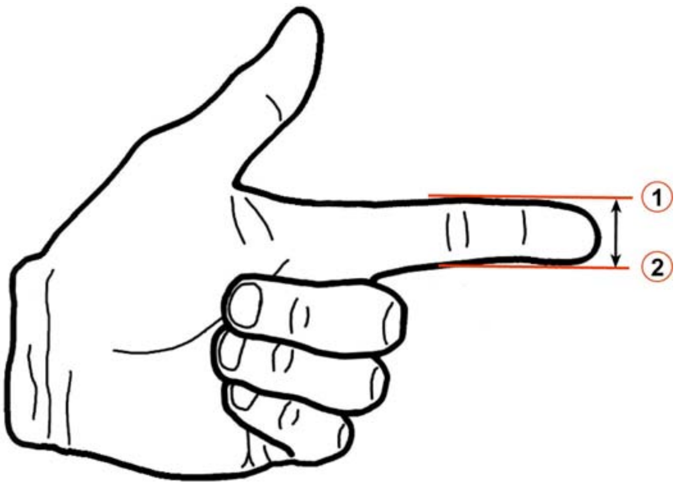


PIP joint breadth

The measurement is taken with the palm facing upwards and the relevant finger extended. The maximal breadth of the proximal interphalangeal joint of the finger is measured.

Point 1 – Most lateral point of PIP joint.

Point 2 – Most medial point of PIP joint.

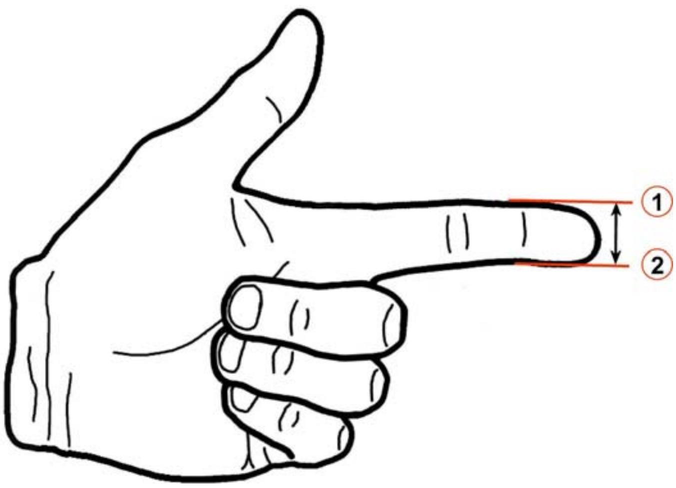


DIP joint breadth

The measurement is taken from the palm facing upwards and the relevant finger extended. The maximal breadth of the distal interphalangeal joint of the finger is measured.

Point 1 – Most lateral point of DIP joint

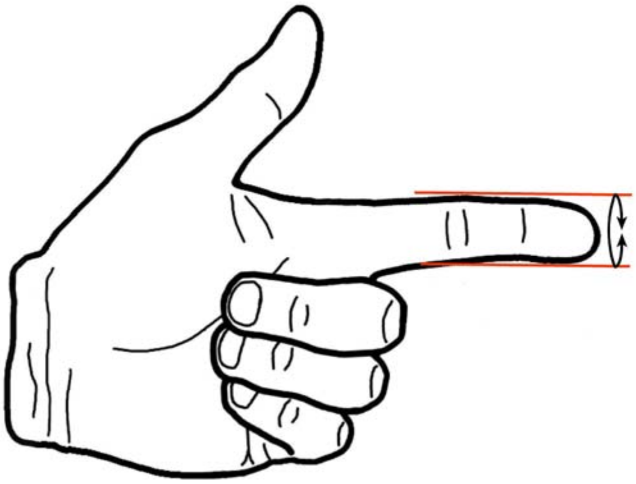
Point 2 – Most medial point of DIP joint



PIP joint circumference

The measurement is taken from the palm facing upwards and the relevant finger extended.

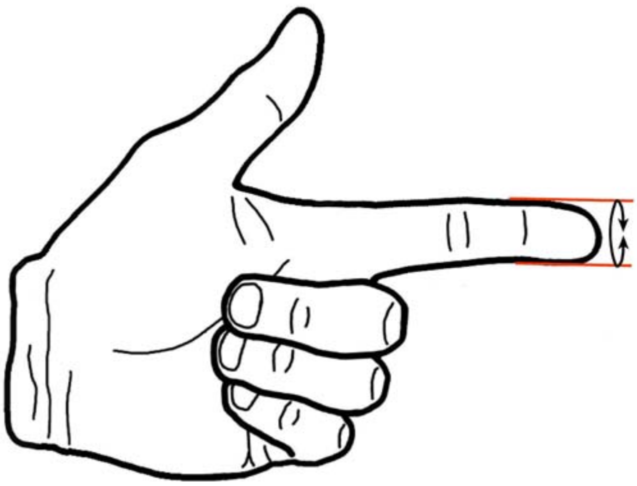
Points – The circumference around the proximal interphalangeal joint of the finger is measured.



DIP joint circumference

The measurement is taken from the palm facing upwards and the relevant finger extended.

Points – The circumference around the distal interphalangeal joint of the finger is measured.

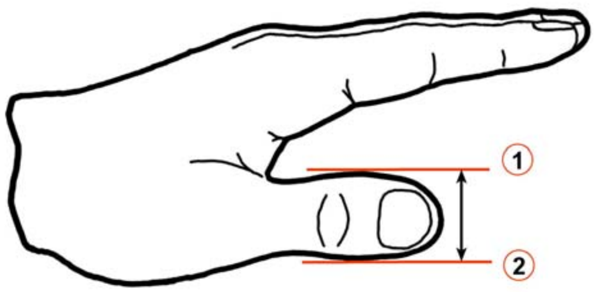


Thumb (Digit 1) joint breadth

The measurement is taken with the thumb facing upwards. The maximal breadth across the interphalangeal joint of the thumb is measured.

Point 1 – Medial aspect of interphalangeal joint.

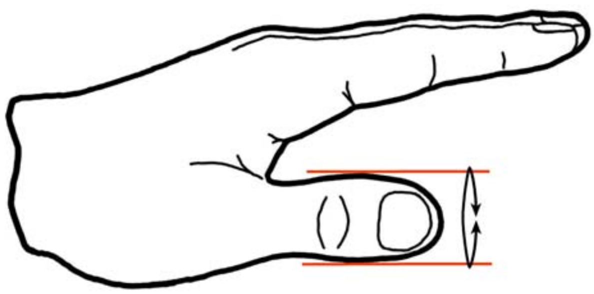
Point 2 – Lateral aspect of interphalangeal joint.



Thumb (Digit 1) joint circumference

The measurement is taken with the thumb facing upwards.

Points – The circumference around the interphalangeal joint of the thumb is measured.

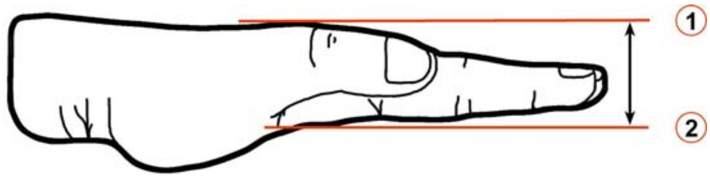


Hand depth at MCP joints

The measurement is taken with the hand placed on a flat horizontal surface, fingers close together and the thumb adducted against the side of the palm.

Point 1 – Highest pint of the MCP joint (knuckles).

Point 2 – Horizontal surface.

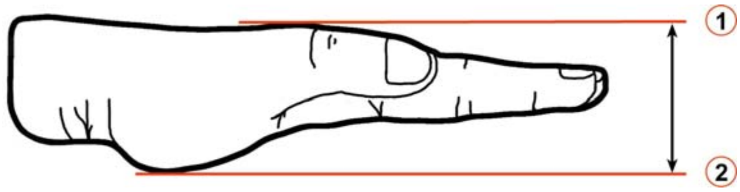


Hand depth at thenar pad

The measurement is taken with the hand placed on a flat horizontal surface, fingers close together and the thumb adducted against the side of the palm.

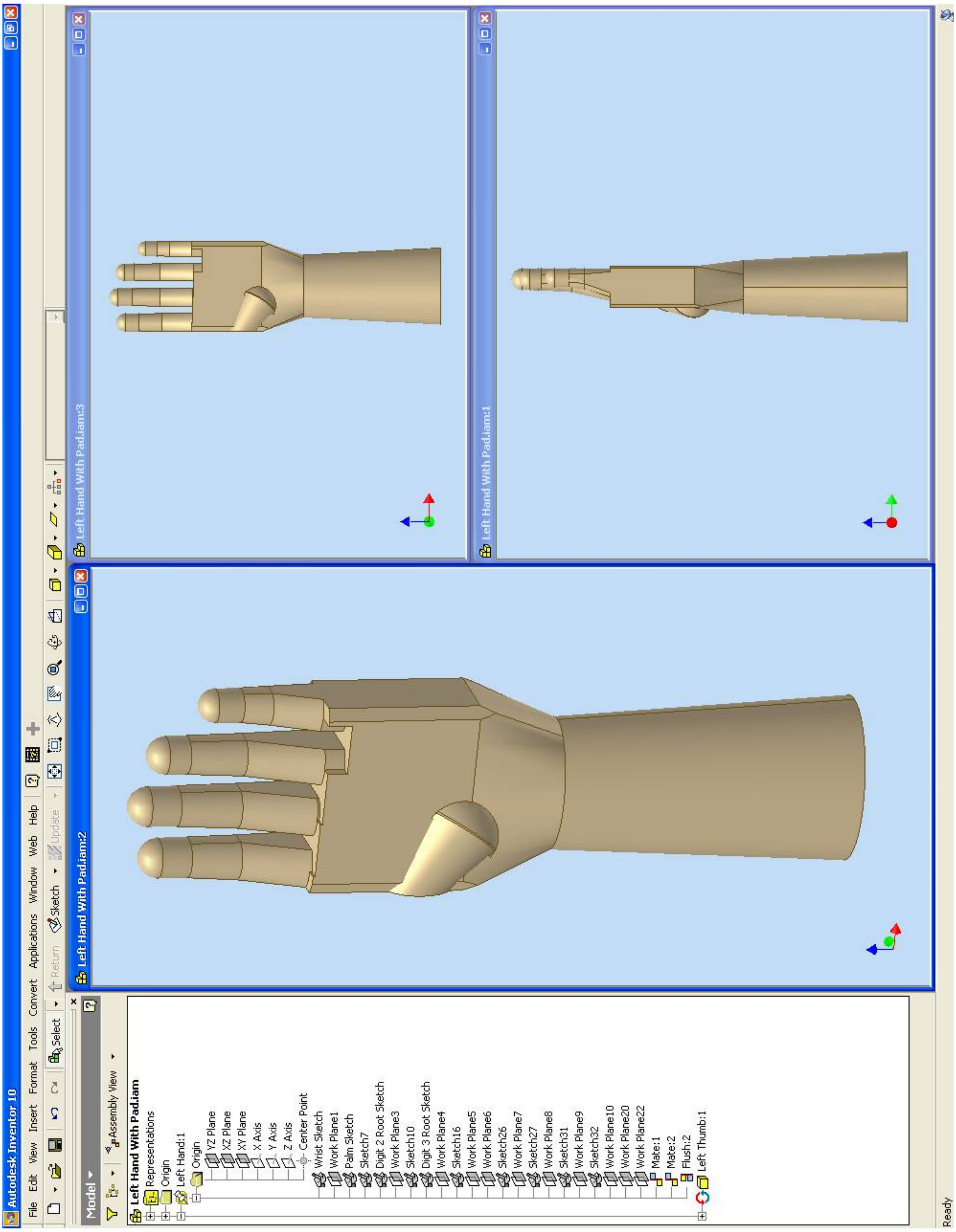
Points – Highest point on dorsum of hand.

Points – Horizontal surface.

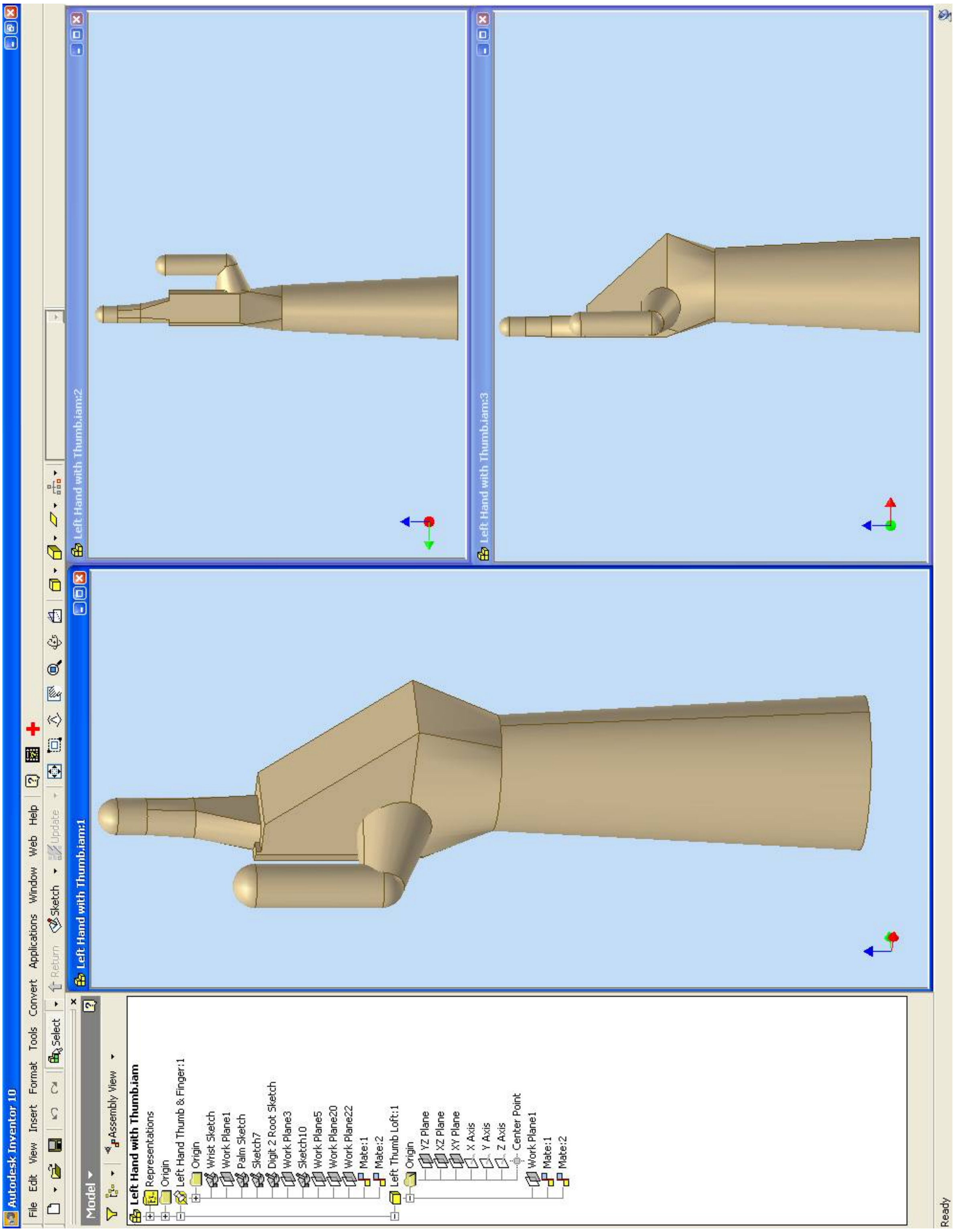


Appendix II:
Views of CAD models in the software environment

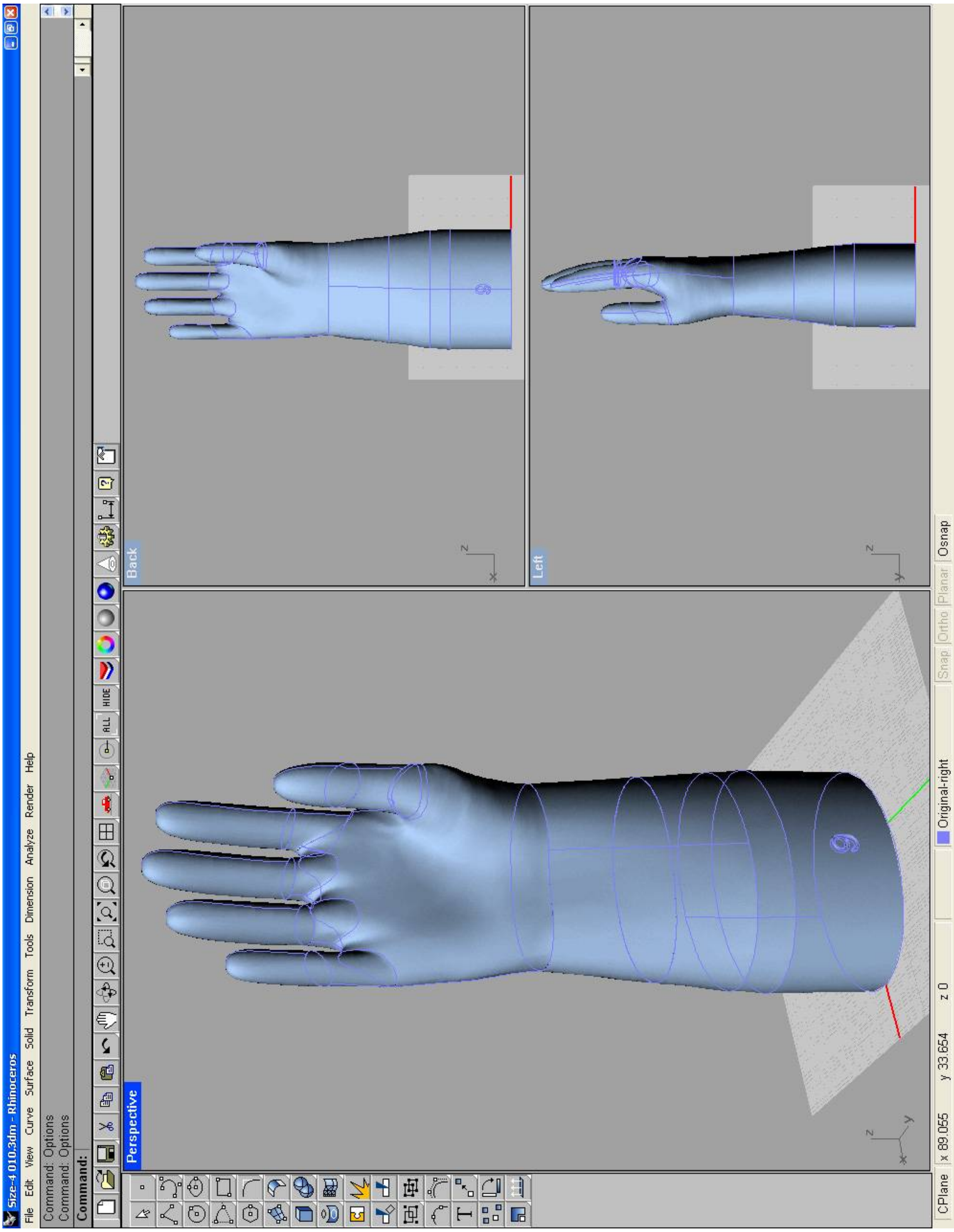
CAD model of size gauge hand model in the Autodesk Inventor environment.



CAD model of size gauge finger and thumb model in the Autodesk Inventor environment.



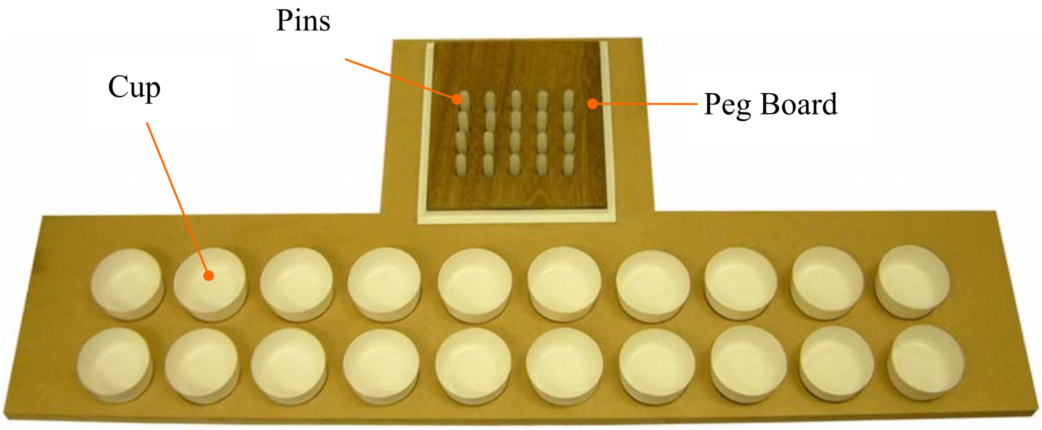
CAD model of glove former in the Rhino3D environment.



Appendix III:
Dexterity tests used in handwear assessments

Pegboard test

Apparatus setup



Test protocol

1

Step 1:

The participant is seated comfortably with their non-dominant hand on their thigh.

2

Step 2:

With their dominant hand, the participant removes each pin from the board individually and places it in one of the empty cups.

3

Step 3:

The participant continues to remove all pins until they are all in a separate cup in front of them.

4

Step 4:

The participant then removes each pin from the cup and places them back into the board, one at a time.

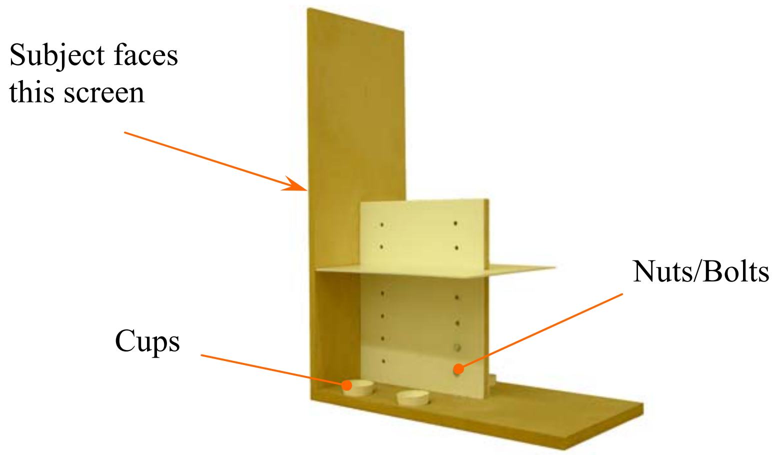
5

Step 5:

The participant continues to place the pins back into the board until they are all replaced correctly. The total time taken for completion is then recorded by the experimenter.

Nut and bolt assembly

Apparatus setup



Test protocol

1

Step 1:

The participant is comfortably seated, facing the vertical screen in front of them.

2

Step 2:

The participant then unscrews the first nut and bolt, placing each piece into a cup, situated on either side of the plane it was screwed into.

3

Step 3:

The same procedure at step 2 is repeated for the second nut and bolt.

4

Step 4:

Once both sets of nut and bolt have been removed they are then reassembled into the plane one at a time.

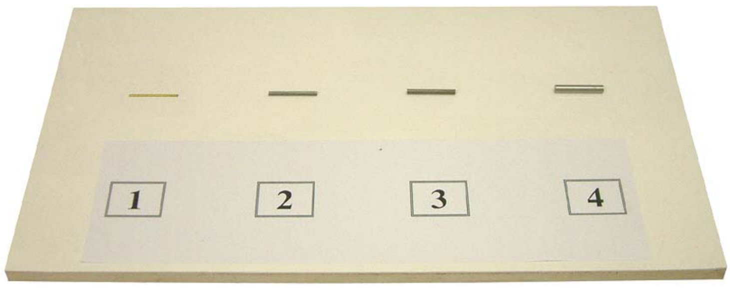
5

Step 5:

The participant screws each nut onto the respective bolt as tight as they can. The total time taken to disassemble and assemble both pairs of nuts and bolts is recorded by the experimenter

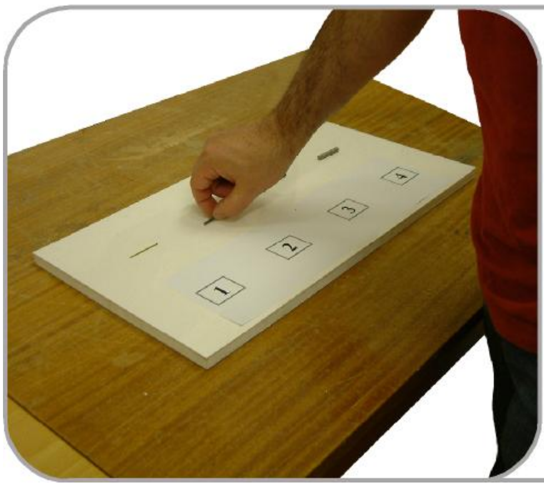
Pin pick-up test

Apparatus setup



Pin No.	1	2	3	4
Diameter	1.5mm	3mm	4mm	6mm

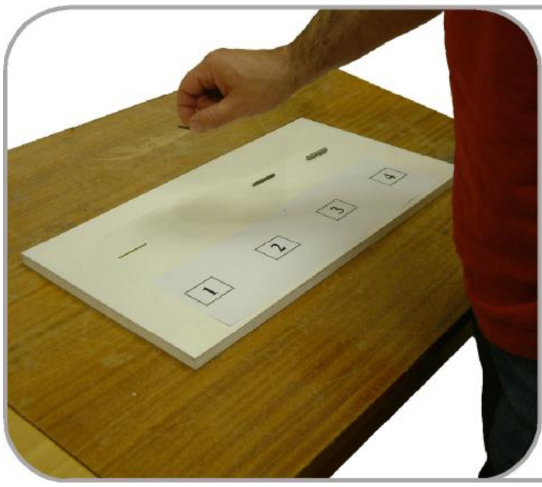
Test protocol



1

Step 1:

The participant stands in front of a flat plane with 4 pins of varying diameters are situated. With their dominant hand, the participant picks up each pin by its circumference between their thumb and index finger.



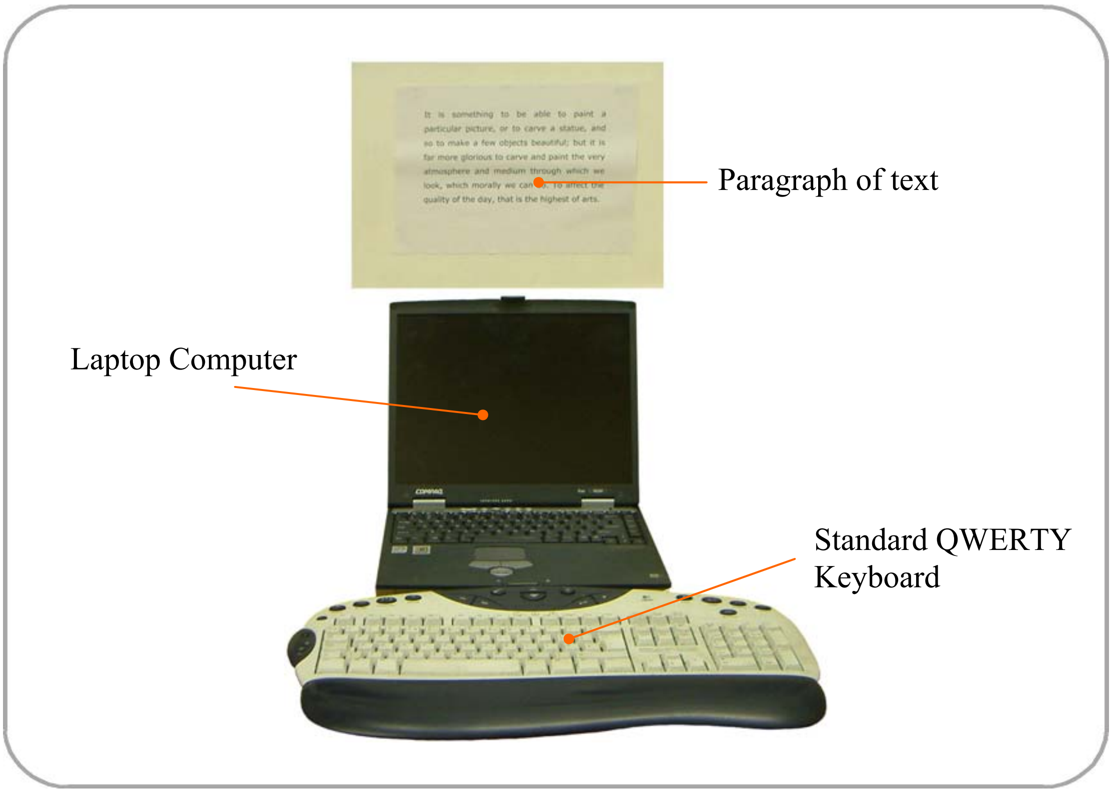
2

Step 2:

The participant has 3 attempts to pick up each pin, without undue fumbling and within 30 seconds, before they can move onto the next. The experimenter records how many pins the participant was able to pick up successfully.

Keyboard typing test procedure

Apparatus setup



Test protocol

1

Step 1:

The participant uses their own typing style to type a short paragraph of text, Appendix III. The time taken to type the paragraph and the number of errors within it is recorded by the experimenter.

Appendix IV:
Recording forms – Glove evaluation case study one

Handwear Assessment Trial
Case Study One

Participant Name:	No.:
Operator:	Date:

C - Data Glove

Test	Order	Time: Split	Time: Finish	Difficulty Rating
A - PegBoard Test				
B - Nut & Bolt Disassembly/Assembly				
C - Keyboard Typing				
D - Pin Pick-up Test *(tick if successful; cross if unsuccessful)*		1 2 3 4		

B - Gauge Glove

Test	Order	Time: Split	Time: Finish	Dificulty Rating
A - PegBoard Test				
B - Nut & Bolt Disassembly/Assembly				
C - Keyboard Typing				
D - Pin Pick-up Test *(tick if successful; cross if unsuccessful)*		1 2 3 4		

A - Bare Hands

Test	Order	Time: Split	Time: Finish	Dificulty Rating
A - PegBoard Test				
B - Nut & Bolt Disassembly/Assembly				
C - Keyboard Typing				
D - Pin Pick-up Test *(tick if successful; cross if unsuccessful)*		1 2 3 4		

D - Latex Glove

Test	Order	Time: Split	Time: Finish	Dificulty Rating
A - PegBoard Test				
B - Nut & Bolt Disassembly/Assembly				
C - Keyboard Typing				
D - Pin Pick-up Test *(tick if successful; cross if unsuccessful)*		1 2 3 4		

Grip and Pinch Strength
Case Study One Glove Evaluation

Condition *(circle appropiate)*			
Bare Hands / Data Glove / Gauge Glove / Latex Glove			
	Kilograms		
	Pre	**Post**	**Mean**
Grip Strength			
Pinch Strength			

Condition *(circle appropiate)*			
Bare Hands / Data Glove / Gauge Glove / Latex Glove			
	Kilograms		
	Pre	**Post**	**Mean**
Grip Strength			
Pinch Strength			

Condition *(circle appropiate)*			
Bare Hands / Data Glove / Gauge Glove / Latex Glove			
	Kilograms		
	Pre	**Post**	**Mean**
Grip Strength			
Pinch Strength			

Condition *(circle appropiate)*			
Bare Hands / Data Glove / Gauge Glove / Latex Glove			
	Kilograms		
	Pre	**Post**	**Mean**
Grip Strength			
Pinch Strength			

Fit Ratings – Pre Testing

Glove *(circle appropriate)*: **DATA / GAUGE**

Zone – 1: Digits

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Zone – 2: Digit Crotches

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Zone – 3: Palm Area

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Zone – 4: Knuckles

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Zone – 5: Dorsal Area

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Overall

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Range of Motion

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Fit Ratings – Post Testing

Glove *(circle appropriate)*: **DATA / GAUGE**

Zone – 1: Digits

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Zone – 2: Digit Crotches

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Zone – 3: Palm Area

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Zone – 4: Knuckles

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Zone – 5: Dorsal Area

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Overall

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Range of Motion

V.Poor		Poor		Good		V.Good
1	2	3	4	5	6	7

Appendix V:
Glove evaluation data – Case study one

Grip Strength

	Gloved Condition			
Subject No.	**Bare handed**	**Data**	**Gauge**	**Latex**
1	40	37	39.5	38
2	47	39	45	43
3	39	44	43	41
4	54	51	50	49
5	47	40	41	41
6	54	49	47	52
7	38	42	35	40
8	50	48	48	49
9	44	40	42	46
10	47	40	43	46
11	49	40	43	48
12	50	35	45	44
Mean (Kg)	**46.62**	**41.85**	**43.58**	**44.62**
Mean (N)	**457.30**	**410.51**	**427.49**	**437.68**
Std Dev	**5.40**	**4.94**	**4.01**	**4.29**
Std Error	**1.56**	**1.43**	**1.16**	**1.24**
Rank	**1**	**4**	**3**	**2**

Pinch Strength

	Gloved Condition			
Subject No.	**Bare handed**	**Data**	**Gauge**	**Latex**
1	6	5.75	5.75	5.5
2	5.75	5.75	6.5	6.25
3	7	6.75	7.25	7
4	7	6.75	7.25	7
5	7.5	7.75	8.5	7.75
6	6.75	7.25	7.25	6.5
7	6	6.5	5.25	4.75
8	6.5	7	7.25	7.75
9	6.5	6	5.75	5.75
10	8	7.5	7.5	7.75
11	6.75	6	5.75	6.75
12	7.25	6.75	7.5	6.75
Mean (Kg)	**6.75**	**6.69**	**6.73**	**6.65**
Mean (N)	**66.22**	**65.60**	**66.01**	**65.20**
Std Dev	**0.66**	**0.69**	**0.97**	**0.96**
Std Error	**0.19**	**0.20**	**0.28**	**0.28**
Rank	**1**	**3**	**2**	**4**

Peg Board Test

	Gloved Condition			
Subject No.	**Bare handed**	**Data**	**Gauge**	**Latex**
1	38	54	51	42
2	44	56	53	44
3	42	50	44	42
4	54	57	60	55
5	48	60	51	48
6	44	49	46	46
7	43	56	51	47
8	51	58	59	51
9	60	74	67	63
10	35	49	47	41
11	53	60	63	52
12	48	59	55	49
Mean (secs)	**46.67**	**56.83**	**53.92**	**48.33**
Std Dev	**7.10**	**6.74**	**7.09**	**6.33**
Std Error	**2.05**	**1.95**	**2.05**	**1.83**
Rank	**1**	**4**	**3**	**2**

Nut & Bolt Assembly

	Gloved Condition			
Subject No.	**Bare handed**	**Data**	**Gauge**	**Latex**
1	30	46	39	29
2	26	46	42	39
3	35	66	53	28
4	31	35	44	33
5	23	42	36	26
6	30	40	46	34
7	25	44	40	35
8	28	45	50	33
9	40	56	78	46
10	27	48	62	27
11	37	51	48	29
12	34	60	55	32
Mean (secs)	**30.5**	**48.3**	**49.4**	**32.6**
Std Dev	**5.14**	**8.75**	**11.66**	**5.65**
Std Error	**1.48**	**2.53**	**3.37**	**1.63**
Rank	**1**	**3**	**4**	**2**

Keyboard Typing Test - Time

	Gloved Condition			
Subject No.	**Bare handed**	**Data**	**Gauge**	**Latex**
1	70	97	93	75
2	48	55	56	46
3	63	74	65	64
4	77	86	102	79
5	106	136	122	94
6	77	72	79	75
7	82	100	94	83
8	82	104	99	86
9	125	149	138	126
10	94	110	95	94
11	102	111	123	122
12	103	127	111	86
Mean (secs)	**85.8**	**101.8**	**98.1**	**85.8**
Std Dev	**21.22**	**27.50**	**23.84**	**22.17**
Std Error	**6.13**	**7.94**	**6.88**	**6.40**
Rank	**1**	**4**	**3**	**1**

Keyboard Typing Test - No. of Errors

	Gloved Condition			
Subject No.	**Bare**	**Data**	**Gauge**	**Latex**
1	1	1	2	0
2	5	16	9	6
3	8	7	6	8
4	10	13	16	8
5	2	8	9	5
6	1	2	2	1
7	2	6	7	4
8	2	1	1	0
9	0	1	2	1
10	3	8	1	4
11	1	2	3	3
12	4	0	0	1
Total	**39**	**65**	**58**	**41**
Std Dev	**3.05**	**5.20**	**4.73**	**2.91**
Std Error	**0.88**	**1.50**	**1.36**	**0.84**
Rank	**1**	**4**	**3**	**2**

Pin Pick Up Test

	Gloved Condition			
Subject No.	**Bare**	**Data**	**Gauge**	**Latex**
1	1	0	0	1
2	1	1	1	1
3	1	0	0	1
4	1	0	1	1
5	1	0	1	1
6	1	0	0	1
7	0	0	0	1
8	1	0	0	1
9	1	1	1	1
10	1	0	0	1
11	1	0	0	1
12	1	0	0	1
Total	**11**	**2**	**4**	**12**
%	**91.67**	**16.67**	**33.33**	**100.00**
Rank	**2**	**4**	**3**	**1**

Difficulty Ratings

Subject No.	Condition	Peg Board	Nut & Bolt	Keyboard	Pin Pick Up
		Test			
1	Bare handed	2	2	2	1
	Data	3	4	4	5
	Gauge	3	3	4	5
	Latex	2	2	3	1
2	Bare handed	1	1	1	1
	Data	3	3	5	2
	Gauge	1	2	4	2
	Latex	2	2	2	2
3	Bare handed	3	5	3	2
	Data	3	6	4	5
	Gauge	3	4	3	4
	Latex	2	4	3	1
4	Bare handed	2	3	3	2
	Data	4	4	6	5
	Gauge	4	5	5	5
	Latex	3	3	4	1
5	Bare handed	3	3	3	3
	Data	4	6	5	5
	Gauge	3	3	5	3
	Latex	3	3	3	3
6	Bare handed	2	3	2	2
	Data	5	6	5	6
	Gauge	3	6	4	4
	Latex	2	3	3	2
7	Bare handed	2	2	1	2
	Data	3	3	4	5
	Gauge	3	3	4	3
	Latex	2	3	3	1
8	Bare handed	2	2	2	1
	Data	3	4	4	5
	Gauge	3	5	4	3
	Latex	3	3	2	2
9	Bare handed	1	1	1	1
	Data	2	4	6	3
	Gauge	3	6	4	3
	Latex	2	3	2	2
10	Bare handed	3	6	4	4
	Data	6	7	6	7
	Gauge	5	7	6	6
	Latex	3	4	4	2
11	Bare handed	2	3	4	2
	Data	2	5	5	4
	Gauge	4	5	6	5
	Latex	2	4	5	1
12	Bare handed	3	2	2	2
	Data	4	5	4	5
	Gauge	3	5	4	3
	Latex	3	3	3	3

Difficulty Ratings - Mean Values

	Gloved Condition			
Test	Bare	Data	Gauge	Latex
Peg Board	2.13	3.5	2.88	2.38
Nut & Bolt	2.63	4.50	3.88	2.88
Keyboard Typing	2.13	4.63	4.13	2.88
Pin Pick Up	1.75	4.75	3.63	1.63

Fit Perception

		Zone						
Subject	Glove	1	2	3	4	5	Overall	RoM
1	Data	3.5	2	3	4	3.5	3.5	5
	Gauge	3.5	3.5	3	4	4	3.5	4
2	Data	3.5	2.5	3.5	5	3	3	3.5
	Gauge	6	5	3	5.5	6	4	5
3	Data	3	1.5	2	4	4.5	3	4
	Gauge	4	5	3.5	5	5	4.5	5
4	Data	4.5	2	3.5	2.5	3	3	3.5
	Gauge	4.5	4	4	4.5	4	4.5	4
5	Data	2	2	3	4	4.5	2	2.5
	Gauge	4	3.5	3	5	5	4	5
6	Data	3	2	4	3.5	3.5	3	3
	Gauge	4	4	3.5	4.5	4	4	4
7	Data	2	1.5	2	3.5	3.5	2.5	5.5
	Gauge	4	6	3.5	5.5	5	5	6
8	Data	3	2	3	5	4.5	3	4
	Gauge	5	4	3	5.5	5	5	5.5
9	Data	3	2	3.5	3	1.5	2.5	3
	Gauge	5	3.5	3.5	3	4	4	3.5
10	Data	2	2	3	4	4.5	3.5	3.5
	Gauge	3	2	2.5	2.5	4	3	3
11	Data	3	1	3	4.5	3.5	3.5	4
	Gauge	4	3	3	3.5	3	3.5	4
12	Data	4	2	5	4.5	5	4.5	4.5
	Gauge	4	3.5	4.5	4	5	4	4.5

Fit Perception - Mean Values

	Zone						
Glove	1	2	3	4	5	Overall	RoM
Data	3.04	1.88	3.21	3.96	3.71	3.08	3.83
Gauge	4.25	3.92	3.33	4.38	4.50	4.08	4.46

Appendix VI:
Recording forms – Glove evaluation case study two

Handwear Assessment Trial
Case Study Two

Participant Name:		No. :
Operator:		Date:

C - Standard Glove

Test	Order		Time Split	Finish
A - PegBoard Test				
B - Nut & Bolt Disassembly/Assembly				
C - Keyboard Typing				
D - Pin Pick-up Test *(tick if successful; cross if unsuccessful)*			1 2 3 4	

B - Prototype Glove

Test	Order		Time Split	Finish
A - PegBoard Test				
B - Nut & Bolt Disassembly/Assembly				
C - Keyboard Typing				
D - Pin Pick-up Test *(tick if successful; cross if unsuccessful)*			1 2 3 4	

A - Bare Hands

Test	Order		Time Split	Finish
A - PegBoard Test				
B - Nut & Bolt Disassembly/Assembly				
C - Keyboard Typing				
D - Pin Pick-up Test *(tick if successful; cross if unsuccessful)*			1 2 3 4	

D - Latex Glove

Test	Order		Time Split	Finish
A - PegBoard Test				
B - Nut & Bolt Disassembly/Assembly				
C - Keyboard Typing				
D - Pin Pick-up Test *(tick if successful; cross if unsuccessful)*			1 2 3 4	

Grip and Pinch Strength
Case Study Two Glove Evalution

Condition *(circle appropiate)*			
Bare Hands / Standard Glove / Prototype Glove / Latex Glove			
	Kilograms		
	Pre	**Post**	**Mean**
Grip Strength			
Pinch Strength			

Condition *(circle appropiate)*			
Bare Hands / Standard Glove / Prototype Glove / Latex Glove			
	Kilograms		
	Pre	**Post**	**Mean**
Grip Strength			
Pinch Strength			

Condition *(circle appropiate)*			
Bare Hands / Standard Glove / Prototype Glove / Latex Glove			
	Kilograms		
	Pre	**Post**	**Mean**
Grip Strength			
Pinch Strength			

Condition *(circle appropiate)*			
Bare Hands / Standard Glove / Prototype Glove / Latex Glove			
	Kilograms		
	Pre	**Post**	**Mean**
Grip Strength			
Pinch Strength			

Appendix VII:
Glove evaluation data – Case study two

Grip Strength

	Gloved Condition			
Subject No.	**Bare handed**	**Standard**	**Prototype**	**Latex**
1	47	40	40	45
2	56.5	48.5	54	55
3	55	53	50	56
4	55	54.5	54	57
5	41	40	46	39
6	45	40	43	46
7	57.5	55	55	55.5
8	55	48	44	47
9	42	41	37	41
10	50	39	41	46
11	60	52	57	64
12	51	50	49	50
13	59	52	48	55
14	40	38	40	41
15	45	42	43	46
16	50	44	47	49
Mean (Kg)	**50.6**	**46.1**	**46.8**	**49.5**
Mean (N)	**496.0**	**451.9**	**458.6**	**485.9**
Std Dev	**6.61**	**6.15**	**6.06**	**6.95**
Std Error	**1.65**	**1.54**	**1.52**	**1.74**
Rank	**1**	**4**	**3**	**2**

Pinch Strength

	Gloved Condition			
Subject No.	**Bare handed**	**Standard**	**Prototype**	**Latex**
1	6	5.5	5.5	5.75
2	7.25	7.125	7.25	7.75
3	6	6.75	6	6.125
4	6.5	6.125	6.25	6.625
5	4.75	4.5	5.25	5
6	6.75	7.5	6.5	6.25
7	5.75	5.5	6.5	5.125
8	6.125	6.5	6.25	6.25
9	5	5.5	5.5	5.5
10	5.25	4.5	4.75	5.25
11	7.75	6.75	7.25	9.25
12	5.5	5.5	5.75	4.5
13	6.75	6.5	6.75	7
14	5.5	6.25	6.75	6.25
15	6.5	6.25	6.75	6
16	6.25	6.25	6.75	6
Mean (Kg)	**6.1**	**6.1**	**6.2**	**6.2**
Mean (N)	**59.9**	**59.5**	**61.2**	**60.5**
Std Dev	**0.81**	**0.85**	**0.72**	**1.15**
Std Error	**0.20**	**0.21**	**0.18**	**0.29**
Rank	**3**	**4**	**1**	**2**

Peg Board Test

	Gloved Condition			
Subject No.	**Bare handed**	**Standard**	**Prototype**	**Latex**
1	46	56	51	49
2	43	51	47	45
3	52	61	54	51
4	47	64	56	52
5	44	58	48	44
6	46	61	52	50
7	42	53	45	44
8	48	52	51	47
9	46	63	57	47
10	56	61	65	59
11	48	56	60	49
12	47	56	56	45
13	44	58	59	50
14	48	53	61	44
15	53	59	59	49
16	51	70	68	53
Mean (secs)	**47.6**	**58.3**	**55.6**	**48.6**
Std Dev	**3.81**	**5.03**	**6.42**	**4.03**
Std Error	**0.52**	**0.68**	**0.87**	**0.55**
Rank	**1**	**4**	**3**	**2**

Nut & Bolt Assembly

	Gloved Condition			
Subject No.	**Bare handed**	**Standard**	**Prototype**	**Latex**
1	31	61	43	31
2	27	36	38	33
3	41	80	47	32
4	28	64	49	32
5	30	51	33	28
6	22	53	42	33
7	20	43	28	22
8	26	45	37	27
9	37	58	54	30
10	29	42	51	34
11	37	70	72	37
12	32	51	64	30
13	27	59	47	42
14	37	57	75	29
15	28	56	60	34
16	38	70	80	43
Mean (secs)	**30.6**	**56.0**	**51.3**	**32.3**
Std Dev	**5.99**	**11.59**	**15.31**	**5.25**
Std Error	**0.95**	**1.83**	**2.42**	**0.83**
Rank	**1**	**4**	**3**	**2**

Keyboard Typing Test - Time

	Gloved Condition			
Subject No.	**Bare handed**	**Standard**	**Prototype**	**Latex**
1	108	117	109	100
2	85	98	102	84
3	120	136	128	119
4	88	93	95	94
5	77	88	90	68
6	94	165	128	102
7	86	107	91	91
8	61	86	84	65
9	73	118	110	76
10	116	161	140	123
11	103	118	113	103
12	105	116	131	98
13	78	80	83	85
14	64	79	71	63
15	81	105	96	94
16	97	139	135	110
Mean (secs)	**89.8**	**112.9**	**106.6**	**92.2**
Std Dev	**17.52**	**26.60**	**21.00**	**18.00**
Std Error	**2.53**	**3.84**	**3.03**	**2.60**
Rank	**1**	**4**	**3**	**2**

Keyboard Typing Test - No. of Errors

	Gloved Condition			
Subject No.	**Bare handed**	**Standard**	**Prototype**	**Latex**
1	0	0	2	1
2	2	6	5	5
3	0	8	0	1
4	1	5	6	4
5	7	4	13	9
6	7	37	11	10
7	4	11	5	2
8	4	7	4	3
9	2	0	1	0
10	3	2	2	1
11	4	3	2	4
12	2	7	10	6
13	1	4	4	2
14	5	8	11	4
15	3	3	2	3
16	4	3	2	2
Total	**49**	**108**	**80**	**57**
Std Dev	**2.14**	**8.61**	**4.08**	**2.83**
Std Error	**0.34**	**1.38**	**0.65**	**0.45**
Rank	**1**	**4**	**3**	**2**

Pin Pick Up Test

	Gloved Condition			
Subject No.	**Bare handed**	**Standard**	**Prototype**	**Latex**
1	1	1	1	1
2	1	1	1	1
3	0	1	1	1
4	1	0	0	1
5	1	1	1	1
6	0	0	1	1
7	1	1	1	1
8	1	0	1	1
9	1	1	1	1
10	1	1	1	1
11	1	1	0	1
12	1	1	1	1
13	1	1	1	1
14	1	1	1	1
15	1	0	1	1
16	1	0	1	1
Total	**14**	**11**	**14**	**16**
%	**33.33**	**26.19**	**33.33**	**38.10**
Rank	**2.5**	**4**	**2.5**	**1**

Appendix VIII:
Keyboard typing test paragraph

The following paragraph was used in the keyboard typing test as part of the glove assessments performed during the evaluation phase of the case study research.

It is something to be able to paint a particular picture, or to carve a statue, and so to make a few objects beautiful; but it is far more glorious to carve and paint the very atmosphere and medium through which we look, which morally we can do. To affect the quality of the day, that is the highest of arts.

Appendix IX:
Keyboard typing test paragraph examples

Case Study One Glove Assessment. Keyboard typing test – Number of errors.

Participant 03 – Data Glove

It is something tto be able to paint a particlaur picture, or to carve a statue, and to so to make it a few objects beautiful; but is far m,omore glorious to carve and paint the very atmosphere and medium trhough which we look which morally we can do. To affect the quality oif day , that ios the highest of the arts.

7 errors made

Case Study Two Glove Assessment.

Keyboard typing test – Number of errors.

Participant 08 – Prototype Glove

It Is something to be able to pain t a particular picture , or to carve a statue, and so omake a few objects beautiful; but it is a far more glorious to carve and paint the very atmosphere and medium through which we look, which morally we casn do. To affect the quality of the day, that is the highest of the arts.

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4 errors made