BIOMECHANICAL DATA IN THE DESIGN PROCESS:

A STUDY OF THE HANDS AND WRISTS OF OLDER ADULTS DURING PACKAGE OPENING

BRUCE CARSE

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Copyright Statement

‘This thesis is the result of the author’s original research. It has been composed by the author and has not been previously submitted for examination which has lead to the award of a degree.’

Signed: Date:

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Abstract

A multi-method approach was adopted to investigate how biomechanical data and testing techniques can be used in the design process, specifically focussing on inclusive design, package opening and older adults.

Interviews with design professionals were conducted to establish their current use of both traditional ergonomic data and biomechanical data. Then a series of studies were made to develop a set of information on the interaction of older adults with packaging. These included a survey on packaging use, an ethnographic packaging study and biomechanical testing of package opening activities. Designers were interviewed a second time to establish the best way of presenting biomechanical data for integration in the design process.

Designers did not routinely follow principals of inclusive design. They did not have suitable information or tools to facilitate such a process and there was a lack of demand from commissioners. An extensive set of questionnaire, video and quantitative motion and force data was collected describing package opening tasks for young and older adults.

Older adults accepted the difficulties faced during package opening and rarely complained. Jars and bottles were examined in detail using a novel, dynamic load sensing device which mimicked real life packaging. Significant kinetic and kinematic differences between young and older adults were measured at the wrists during jar opening.

Although detailed biomechanical data can be developed on the interaction between person and product, designers could not see how this could be effectively integrated into the design process. When offered a range of different data types they demonstrated a strong preference for data to be presented to them in a visual manner.

Further validation and standardisation of the biomechanical model of the hand and wrist is required, as are practical steps to ascertain the best techniques for introducing basic biomechanical data and principles into designer’s working practice.

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List of Abbreviations

AD	Assistive device
ADL	Activity of daily living
CAD	Computer-aided design
CMC	Carpometacarpal joint
COR	Centre of rotation
CRC	Child resistant closure
DIP	Distal interphalangeal joint
DoF	Degree of freedom
HWA	Hand or wrist ailments
IP	Interphalangeal joint (of the thumb)
LH	Left hand
MCP	Metacarpophalangeal joint
MRI	Magnetic resonance imaging
PIP	Proximal interphalangeal joint
RH	Right hand
ROM	Range of motion
WJC	Wrist joint centre

Data Presentation

Throughout this thesis data will be presented in the following format: Mean (± Standard Deviation). The level of statistical significance will be denoted by the probability statistic for the test carried out as follows, with $p<0.05$ considered to be significant.

Glossary of terms

Inclusive Design: “Inclusive design is not a new genre of design, nor a separate specialism, but an approach to design in general and an element of business strategy that seeks to ensure that mainstream products, services and environments are accessible to the largest number of people” (Design Council, 2009)

Gerontology: “The study of all aspects of the aging process, including the clinical, psychological, economic, and sociologic issues encountered by older persons and their consequences for both the individual and society” (Mosby, 2009)

Biomechanics: “Anatomy, physics and mathematics are used to determine and measure the quantities of motion (time, space and force) and to fully understand the movement of living things” (Adrian and Cooper, 1995)

Ergonomics: “Ergonomics, also known as human factors, is the scientific discipline that seeks to understand and improve human interactions with products, equipment, environments and systems. Drawing upon human biology, psychology, engineering and design, ergonomics aims to develop and apply knowledge and techniques to optimise system performance, whilst protecting the health, safety and well-being of individuals involved. The attention of ergonomics extends across work, leisure and other aspects of our daily lives” (Ergonomics, 2009).

Ethnography: “The scientific description of peoples and cultures” (Oxford English Dictionary, 2009)

Chapter 1 Introduction

1.1 Background

The population of our society is ageing. While longevity is generally considered to be an indicator of successful public health policies and socioeconomic development (World Health Organisation, 2000), it is already beginning to have far reaching implications on the way we live our everyday lives. Provision of care for the elderly, pensions, economic change, shifting family dynamics, longer working lives and maintaining independent lifestyles are all important issues which need to be addressed, both by our governments and the society in which we live.

It is the latter of these issues, maintaining independence, with which this thesis is primarily concerned. Given the proliferation of manmade buildings, spaces, transportation systems and products we interact with on a daily basis, it follows that the design of these should reflect any significant changes in our society. It is for this reason that design has a responsibility to respond to the needs, aspirations and abilities of older adults.

Inclusive design is a design approach and business strategy that encourages designers to make mainstream products, services and environments accessible to the largest number of people. Traditionally this has focussed on minimising the ‘design exclusion’ of disabled and older people but this has recently been expanded to include “economically vulnerable groups and those affected by changing technologies and work practices” (Design Council, 2009).

The design activity by its nature is a series of informed decisions based on the designer’s experience and the information they have available. If designers are required to design products to suit older adults’ physical abilities, they need the appropriate data and information at the correct point in the design process.

Although there is much data being produced by life sciences (such as biomechanics) which could be useful to designers, little of it seems to filter through from those narrow scientific fields to the design community. Therefore, it is the main theme of this thesis to generate new and appropriate data and information for designers about older adults' physical abilities.

For the purposes of this thesis it was necessary to choose both a specific region of the body and a particular activity that could be studied using biomechanical testing techniques. These testing techniques would be used to describe how any age-related decline in physical ability affected normal daily life. The hand and wrists were selected as the region of the body, as they frequently come into direct contact with various products. It was also decided that consumer package opening represented an ideal activity to study as it involved the use of the hands and wrists, and it formed part of the key activity of daily living (ADL) of being able to feed oneself. It was also an activity that would be encountered on a fairly regular basis, and involved an object that was designed (the article of packaging) and could potentially be redesigned.

1.2 Key Research Areas

The work described in this thesis will involve three principal areas of research; inclusive design, biomechanics and packaging design, alongside two secondary areas of research; ergonomics and gerontology. These are illustrated below in Figure 1.1. The diagram shows how these various research fields overlap and are interrelated, which would have implications for the overall methodology adopted during the course of the project.

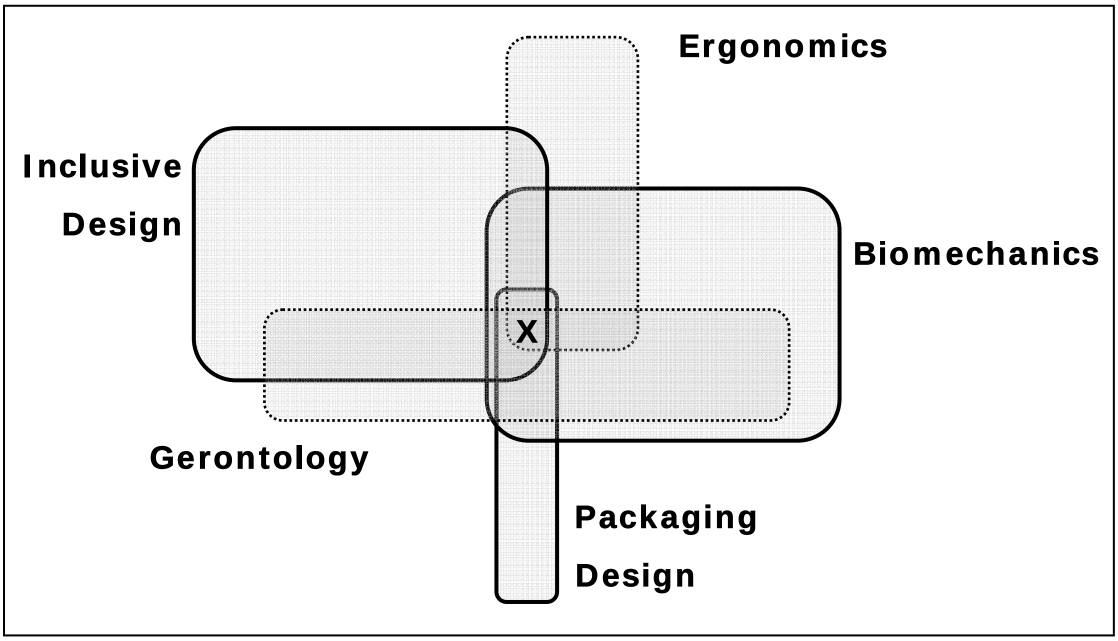


Figure 1.1 Diagram of research space. Core areas bold line, secondary areas dotted line

Throughout this thesis various types of data will be referred to. The term ‘ergonomic data’ is a general term that refers to a number of different types of data including; anthropometric, maximal isometric strength, range of motion and biomechanical data. The term ‘biomechanical data’ is data that specifically describes the kinematic movement of various body segments, and the forces and moments experienced during a particular activity.

1.3 Project Aim and Objectives

With the project background in mind, the overall aim of the project was defined as being:

To investigate how biomechanical data on the hands and wrists of older adults can be used by packaging design professionals in the inclusive design process.

Having defined this broad aim for the overall research project, three more specific research questions were formulated:

a) Is it viable to use biomechanical testing techniques to gather information about people's physical abilities to aid better product design?

b) In terms of how they manipulate products with their hands, are there any significant differences between young healthy adults and older adults? Can these be characterised?

c) How can biomechanical principles and data most effectively be presented to designers such that they use it to offer consumers better products?

These three research questions were then further broken down into five more attainable research objectives:

1. Explore the working practices of designers involved in packaging design paying particular attention to their use of ergonomic data and their attitudes towards inclusive design.

2. Investigate the attitudes and opinions of older adults towards the problem of package opening.

3. Establish if there are significant differences in the way that young and older adults perform package opening tasks.

4. Assess whether or not it is realistic to use biomechanical testing techniques and/or biomechanical data in the product design process.

5. Determine the most effective way of presenting biomechanical data to designers.

These five research objectives will be referred to throughout this thesis, with each individual piece of work described in terms of how it contributes towards answering them. The following chapters will each have their own more specific objectives in the form of smaller, more manageable research micro-objectives. The five main objectives will combine to answer the three broader research questions listed above.

1.4 Overall Methodology

Due to the varied nature of the aim and objectives of this project, it was necessary to develop a 'Mixed Methods' (Creswell, 2003) methodology which combined established research methods, calling on both qualitative and quantitative techniques. Mixed methods approaches to research have been discussed in the literature, with some arguing that researchers adopting the pragmatist viewpoint have the ability to examine problems in fine detail using quantitative methods, and then take a broader view (with indefinite scope) using qualitative methods (Onwuegbuzie and Leech, 2005) . The same authors therefore argued that the two approaches complement one another:

"Pragmatist researchers are in a better position to use qualitative research to inform the quantitative portion of research studies, and vice versa" (Onwuegbuzie and Leech, 2005, pp.219)

It was clear from the outset that the answers to the three main research questions could not be derived through a single series of experiments. This methodology allowed for an exploration of the main research questions from a number of different perspectives. The overall methodology is shown in Figure 1.2 and indicates how the earlier research activities were related both directly and indirectly to the latter research activities.

A predominantly pragmatic approach was adopted, whereby the problem was considered to be the most important thing, and the researcher was free to use all approaches to understand the problem (Creswell, 2003).

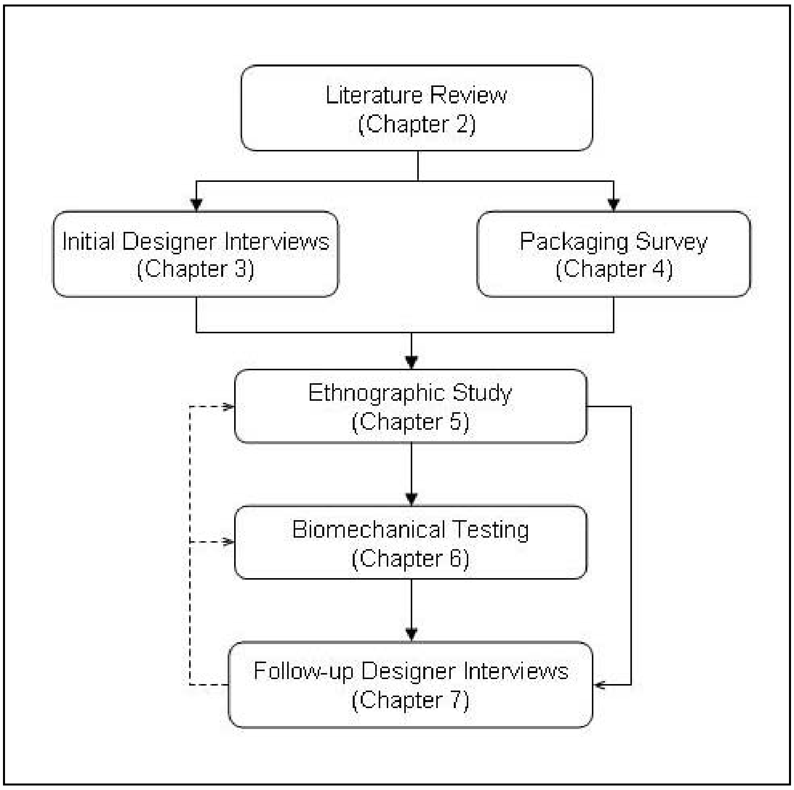


Figure 1.2 Diagram of overall research methodology and thesis structure

Initially a literature review was employed to provide a comprehensive review of current knowledge in the areas of inclusive design, package opening and the biomechanics of the hand and wrist. These three main areas were studied with particular attention paid to the secondary themes of ergonomics and gerontology. The literature review highlighted key gaps in the knowledge and pertinent issues that would influence the remainder of the methodology. One of the key issues that required focussed research effort was that before any data was generated for inclusive design, two of the key stakeholders in the design process must be consulted; design professionals and older adults.

Consultation with design professionals was achieved by conducting a series of face-to-face structured interviews to establish the context in which any data collected during this study might be used. This represented an inductive approach to the problem, whereby observations were gathered and a hypothesis was developed, as opposed to traditional deductive research where a hypothesis is confirmed by observations. (Trochim, 2000). Interviews were selected as the research method in this case as they allowed for a deeper exploration of the environment in which data might by used, and also allowed the interviewer to establish direct contact with the interviewee. The advantage of this approach over, for example, postal surveys or telephone interviews was that clarification of questions could be provided to the interviewee, insuring a higher quality of response. The high quality responses led to an accurate description of how designers worked and their attitudes towards data. The benefit of this work was that subsequent data collection was focussed directly on the views and opinions expressed by the design professionals interviewed. This part of the study helped to meet objective number 1, and contributed towards objectives number 4 and 5.

Consultation with older adults was accomplished through a packaging survey which explored the problem of package opening difficulties and how they impact their lives. Adopting a deductive approach, a face-to-face questionnaire was designed to carry out this descriptive research (Kumar, 2005) as it allowed the collection of quantitative data which was then used to portray the attitudes and opinions of the older adults surveyed. This method was quick enough to deploy that it allowed for a large number of respondents as well as providing a high level of accuracy thanks to the face-to-face manner in which it was conducted. With a large number of respondents and categorical answers given to questions, subjective quantitative data was generated for statistical analysis. In addition to establishing the older adults' viewpoint, the survey also identified what they considered to be the most difficult type of packaging to open which was then used to inform the subsequent ethnographic packaging study. This part of the study focussed exclusively on objective number 1.

A video-based ethnographic study of package opening activities was performed in order to generate various types of ergonomic data on the physical interaction between people and packaging. In conducting this deductive research, the problems experienced during package opening were explored and correlations which would account for these problems were investigated. In favouring a laboratory based 'observer-as-participant' approach over covert ethnography, the researcher was offered more control over the video data collected, ensuring it was comparable between subjects and could therefore generate reliable subjective quantitative data. The overall aim of using this technique was to understand more about the various strategies used by both young and older adults to complete package opening tasks. It achieved this through a new video footage analysis technique which yielded ergonomic data that could be presented to design professionals at a later stage. Furthermore, this part of the study proved pivotal in ensuring the following biomechanical testing phase was as lifelike as possible. This part of the study contributed to the achievement of objectives 3 and 5.

Biomechanical testing of young and older adults was carried out to generate more in-depth objective data on the physical interaction, specifically the kinetics and kinematics of the hands and wrists during dynamic package opening activities. Motion analysis (with simultaneous force measurement) was chosen as a method as it offered the unique opportunity to collect objective ex-vivo data on human movement. This then allowed an inverse dynamics approach (Winter, 2004) to be used to calculate the forces and moments at various parts of the hand and wrist. The work involved the design of some novel dynamic force sensing equipment which was used in conjunction with a motion analysis system to realistically recreate jar and bottle opening activities, similar to those observed previously in the ethnographic study. It was thought that alternative measurement techniques such as goniometry and static force measurement did not provided a similarly integrated approach to data collection as the motion analysis approach. The objective quantitative data generated allowed for the direct comparison of groups of young and older adults. Biomechanical testing contributed significantly to objective 3 and provided secondary information for objective 4.

Using data generated in the ethnographic study combined with data from previous biomechanical studies a second series of semi-structured face-to-face interviews was conducted with design professionals. In these interviews designers were presented with various pieces of data in a number of different formats. Their preferences for certain types of data and reservations about others were recorded. A semi-structured interview style was chosen to allow a more conversational tone to the interview, where the interviewee was free to ask questions and interact with the data presented to them. The multifaceted qualitative data obtain using this method would not have been achieved using questionnaires or online surveys. It was also felt that focus groups may not have offered the interviewees the level of freedom to ask questions and explore ideas compared with the confidentiality offered by a one-to-one interview. These interviews helped to close the loop between data collection and the design process by presenting data to design professionals who could offer qualified feedback on how and when they might use it, and how it might be improved. These interviews served to help achieve objectives 4 and 5.

Table 1.1 Types of research method used as part of 'mixed methods' methodology, based on ‘types of research’ described in Kumar (2005).

Research activity	Application	Objectives	Knowledge base	Inquiry mode
Literature review	Secondary	Exploratory		Qualitative
Initial designer interviews	Primary	Descriptive Explanatory	Inductive	Qualitative
Packaging survey	Primary	Descriptive	Deductive	Quantitative (subjective)
Ethnographic study	Primary	Correlation Exploratory	Deductive	Quantitative (subjective)
Biomechanical testing	Primary	Correlation Exploratory	Deductive	Quantitative (objective)
Follow-up designer interviews	Primary	Descriptive	Descriptive	Qualitative

As indicated in Figure 1.2, the structure of this thesis is made up of five key parts which will be described sequentially following the literature review. Each of these chapters will describe in more detail the specific methods used for each part of the project, going beyond the overall methodology presented here. These five chapters will be followed by an overall discussion, drawing together the discrete findings and offering a broad view of what these findings collectively imply for ageing research and inclusive design.

Chapter 2 Literature Review

2.1 Literature Review Outline

The following literature review will discuss the context in which biomechanical data might be used. Three distinctly different perspectives are explored.

Initially, it will discuss inclusive design and the tools and resources which are currently available to designers, which ergonomic data they favour and whether or not any biomechanical data is used. Secondly, it will describe the hand and wrist and evaluate related biomechanical data, with differences in physical capability between young and older adults identified. It will also review the biomechanical models of the hand and the force sensing equipment currently available. Finally, the package opening research will be discussed in terms of how it relates to inclusive design and biomechanics, and how the research can be expanded to be more useful to the design community.

2.2 Inclusive Design Literature

Inclusive design has come to fruition in the UK, and other countries, through the collaborative efforts of industry, designers and researchers. This section will explain inclusive design and its origins, the main barriers to achieving it, what tools, techniques and resources are currently available to designers and finally what implications this has for the design community and other research fields.

2.2.1 Inclusive Design Explained

To introduce the inclusive design approach and its origins, it is crucial to establish a clear definition:

"Inclusive design is not a new genre of design, nor a separate specialism, but an approach to design in general and an element of business strategy that seeks to ensure that mainstream products, services and environments are accessible to the largest number of people" (Roger Coleman, Design Council)

The above definition may sound like a logical approach that should be commonplace in all design activity. However, over the past 20 years it has become increasingly apparent that many products and services have been designed mostly with young, fit and able people in mind, consequently excluding many older and disabled users. Given that graduate product designers are predominantly male, and between 20-25 years of age, a lack of empathy with older and disabled users is understandable (Warburton, 2003). It was suggested that this lack of understanding is not intentional and is instead simply a result of living in a society that does not value age and which is heavily influenced by the power of popular culture through advertising.

Inclusive design firmly acknowledges its links to similar concepts such as design-for-all, universal design and transgenerational design, describing itself as a "framework and growing body of practise"(Coleman et al., 2003a). Design-for-all was defined as *"A European term that promotes inclusion, equality, and socially sustainable development. Supports access to environment, usability of products and access to services. Focus on user involvement"* (EDeAN, 2009). Universal design was defined as *"The design of products and environments to be usable by all people, to the greatest extent possible, without adaptation or specialized design"* (Mace, 1998, Preiser and Ostroff, 2001). And finally transgenerational design was defined as *"The practice of making products and environments compatible with those physical and sensory impairments associated with human aging and which limit major activities of daily living"* (Pirkl, 1994).

What these definitions show are how the concept has evolved, moving away from specifying older adults or those with impairments as the only excluded groups, and by stipulating that it should not be an afterthought whereby adaptation or specialised design is required for inclusion. Inclusive design is the first incarnation of the concept whereby stakeholders, other than just designers, are mentioned in its definition with inclusive design described as “an element of business strategy”. It is within this framework that it is expected that business decision-makers as well as design practitioners will be able to understand and respond to the needs and desires of their diverse users. Inclusive design represents a significant step forward, as it appears to be removing some of the responsibility from the designer, stipulating a wider business strategy which involves all of the stakeholders; customers, designers, engineers, manufacturers, distributors, and business decision-makers.

A final important characteristic of the definition of inclusive design is the clear distinction between itself and assistive technology. Assistive technology is primarily concerned with aiding short-term recovery from illness or injury, and also providing long-term functional support (Newell, 2003). In contrast, inclusive design aims to develop products that can be used by the widest range of people possible, instead of designing specifically to overcome one impairment, illness or injury. It is acknowledged that inclusive design will never be able to include 100% of the population, so there will always be a need for assistive technologies even if inclusive design does slightly reduce the need for them. Newell argues that the assistive technology sector should also adopt the inclusive design ethos, and design assistive technologies to be usable by a broader range of users. Criticisms of the assistive technology sector have been made by some academics, claiming that many products are ugly, too functional in appearance and because they are usually produced for very small markets there is a significant lack of choice for the consumer (Green and Jordan, 1999). In an appraisal of products designed specially for the older adult, many of the products assessed were heavily criticised for being of poor quality, limited functionality, over-priced, and some were described as being unsafe (Gardner et al., 1993).

2.2.2 Our Changing Population

There has been widespread publicity recently of the fact that our population is getting older. In fact, it is estimated that by the year 2020 almost half of the UK's population will be over the age of 50 years old. Similar trends have been forecast in other developed countries across the world, with 20% of the United States' and 25% of Japan's populations expected to be over the age of 65 by the year 2020 (Coleman, 1993).

The implications of this changing population for business leaders are of paramount importance, as it represents a clear opportunity to develop products and services for the only consumer sector which is showing significant growth (Coleman, 2003). Coleman also argues that there is strong evidence to suggest that older adults in the UK, particularly around the age of 65, have a great deal of disposable income combined with an abundance of free time in which to spend it.

Increased life expectancy and the emergence of a growing group of older adults with disposable income is a complex issue. Firstly, due to advances in medical science (Cassel, 2001), healthy life expectancy is not increasing at the same rate as overall life expectancy (Figure 2.1). The implications of this trend are that people are more likely to spend a larger portion of their retirement in poor health.

The second complex issue surrounding the ageing population is the appreciation that as people age they become more diverse, because they will have encountered divergent experiences, interests, activities and capabilities throughout the course of their lives. This would suggest that categorising people by chronological age represents rather short-sighted thinking. It assumes that they have similar attitudes, tastes, behaviours, lifestyles and economic status, which is quite clearly not the case (Haslam, 2005).

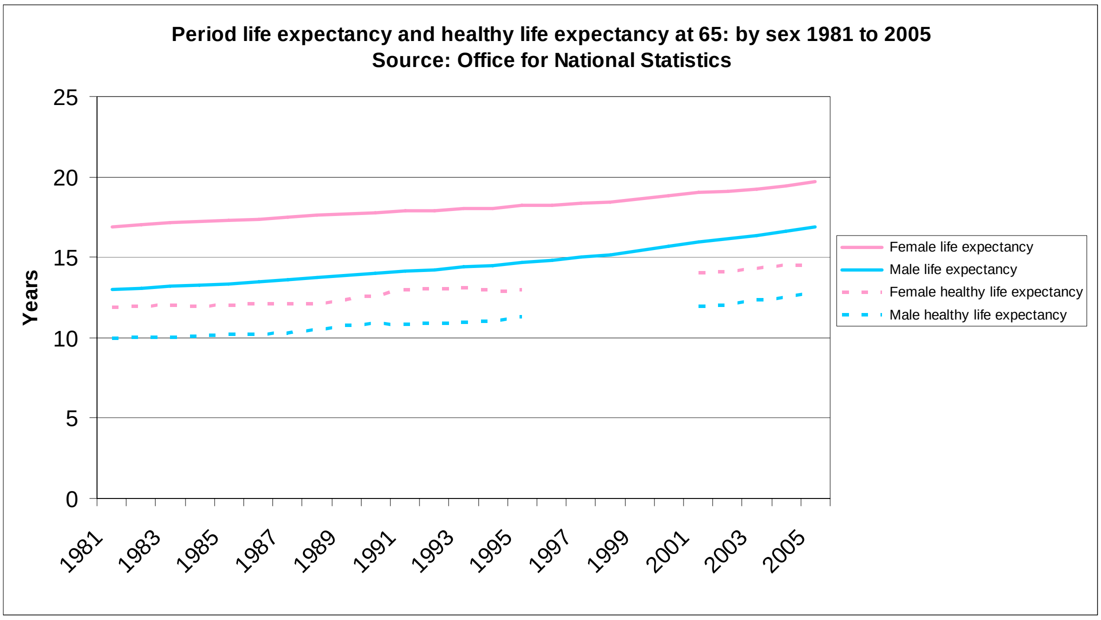


Figure 2.1 Overall life expectancy and Healthy life expectancy

While inclusive design offers a broad framework, aiming to include people from every group that may be excluded by design, this thesis will focus specifically on the exclusion of older adults.

2.2.3 Barriers and Incentives for Inclusive Design

The argument for inclusive design is irrefutable, but it has not yet become common practice for designers, with few of the available tools and resources being utilised. It is recognised that ignorance on the part of the designers is certainly not the cause (Sims, 2003) as the vast majority were aware of inclusive design, suggesting there must be an alternative explanation; either the barriers are too sizeable, or the incentives are too weak.

In terms of encouraging design students to embrace inclusive design, the ‘Design for Our Future Selves Award’ (Royal College of Art, London) provides an example of an initiative, introduced in 2000, to encourage students to address the needs and aspirations of older people through design. Independence, mobility, health or working life are the four award categories. Architecture, design, or communication students can enter.

Also established in 2000 was the 'DBA Inclusive Design Challenge' which is an inclusive design competition for industry, run jointly by the Design Business Association (DBA) and the Helen Hamlyn Research Centre. Businesses from a range of design disciplines are invited to "create a mainstream product, service, environment or communication, which can be enjoyed equally by consumers of all abilities". This not only raises awareness of inclusive design in industry, it also encourages businesses and design professionals to gain practical experience of following an inclusive design approach.

By way of generating consumer demand for inclusive design a standard trade mark, called the 'Owl Mark', was given to products that are thought to be older adult-friendly (Nayak, 2002). This was awarded to products which passed evaluation tests under the expectation that consumers would start to recognise it and demand it, and then designers would then strive to achieve it through their design work. The thinking behind the introduction of the Owl Mark is certainly sound, however such an initiative requires widespread media coverage, and the recruitment of designers and business leaders to champion the idea. Unfortunately this has not yet happened for the Owl Mark

Recent investigations into the perceived barriers and incentives for adopting an inclusive design approach have yielded some valuable, and consistent results (Dong and Clarkson, 2007, Freudenthal, 1999). Dong and Clarkson found through their postal survey of 35 designers the main incentives were *'client requirements for inclusive design'*, *'consumer demand'* and a *'successful business case'*. In the same survey, designers also expressed a need for external support, in the form of *'data and tools'* and *'standards and guidelines'*. The designers then went on to describe the main barriers as *'Lack of requirements from clients', 'Lack of budget and time'* and *'Lack of knowledge/information/method'*. Interestingly the barriers and incentives seem to mirror one another, with demand from consumers and clients acting as incentive when present, and barrier when absent, making this a highly important requirement. A lack of time and budget is closely related to this, as if there's no direct demand for inclusive design, designers will find it hard to justify spending time and money on it. Successful business cases are seen as an important incentive, which assumedly is lacking, as they may help designers argue the case for inclusive design. It seems that even if there were an increase in demand for inclusive design, there are still the barriers of a lack of knowledge, information and methods to be overcome. Consequently, the most conscientious of designers who wish to practise inclusive design are often confronted by a series of obstacles (Freudenthal, 1999):

1. Lack of available information
2. Information difficult to find, with much of it embedded within specific scientific research fields
3. Unfamiliar terminology
4. Impractical formats

Furthermore, there is the argument that the majority of tools and resources developed for inclusive design have not been based on a requirements capture of what designers want, and were instead developed based on the notion that they might be useful (Dong et al., 2004).

In summary, there are currently two main barriers to inclusive design; on one side a lack of tangible demand from consumers and clients (who will commission design work), and on the other there is a lack of data, information, tools, resources and methods. It is the latter barrier, specifically the lack of data, that will be addressed by this thesis.

"Design for All will remain only a philosophical approach for most designers unless they have access to appropriate design tools that complement their working methods" (Porter et al., 2004)

2.2.4 Tools and Resources for Inclusive Design

With the importance of inclusive design already established, the following section will describe and discuss the various tools (a thing used to help perform a job) and resources (a stock or supply of materials or assets that can be drawn on in order to function effectively) that are available to designers who want to practise inclusive design.

2.2.4.1 Resources for Inclusive Design

The reference book Older Adultdata (Smith et al., 2000) details a large amount of data collected from a variety of sources, with both anthropometric and strength data. It offers a limited amount of brief guidelines on how to use the data. Bodyspace (Pheasant, 1996) provides an introduction to ergonomics and is widely regarded to be one of the primary teaching texts in the field of ergonomics. Like much of the ergonomics literature it concentrates mainly on people's working lives. In addition to anthropometric data it also provides an explanation of how the designer should use the data by drawing on some practical examples. It also introduces and discusses many of the statistical techniques that can be used in ergonomic design.

Design-Relevant Characteristics of Ageing Users (Steenbekkers and Beijsterveldt, 1998) represents the first published attempt to collect data, with respect to the older adult, specifically with product design in mind. The work carried out had three key aims:

1. Describe and quantify physical, psychomotor, sensory and cognitive characteristics of the users of consumer products in the age groups 20 to 30, and 50+, providing a databank of relevant human characteristics.

2. Compare the capacities of different age groups of adults, which might enrich various theories on the ageing of capacities.

3. To generate design guidelines for designers of durable daily-life products based on the measurement of capacities.

The work was conducted on a large scale, with 750 Dutch volunteers tested, and aimed to gather more comprehensive data than previous studies. The text clearly recognises that it is not only physical characteristics (body dimensions and strengths) that affect the older user's interaction with products, but that there are other equally important physiological variables involved. The physiological differences between old and young adults have been apparent for many years (Welford, 1958), but this publication by Steenbekkers and Beijsterveldt is the first time anybody has attempted to collect a set of data to quantify these physiological variables specifically for designers. Despite offering the designer a wide range of relevant data, and corresponding design guidelines, there was no evidence in the literature to suggest that this text is widely used or referenced (Sims, 2003). A great deal of the data is presented in Older Adultdata (Smith et al., 2000), although this is restricted to anthropometric and strength data. In a survey of 29 design professionals, none reported actually using the information in Older AdultData (Sims, 2003).

In addition to the traditional hardcopy resources described above, designers also have a number of web-based electronic resources at their disposal. The Design Council internet resource (Design Council, 2009) provides both a general introduction to inclusive design, explaining the business case, as well as an inclusive design education resource which showcases a number of case studies generated by the Helen Hamlyn Research Centre. This collection of case studies is valuable as it describes real design projects from initial project brief through to final design solution. The European Design for All e-Accessability Network provides a source of information, methods, tools and examples for design students, their tutors, design professionals, design managers and policy makers across Europe (EDeAN, 2009). It aims to act as an advice hub, cataloguing documents, links and references to most of the available inclusive design resources and allowing users to access them. Ricability is an independent research charity providing free information for older and disabled consumers based on rigorous professional research (Ricability, 2009). They produce a number of consumer reports each year, providing practical, unbiased information for older and disabled consumers on both assistive technologies and the inclusivity of mainstream products. This is a useful resource for designers as it provides an idea of what competing products are on the market and how well they performed in consumer tests, and most importantly gives them an insight into the criteria commonly used for assessing these products.

The Inclusive Design Toolkit was developed by the University of Cambridge Engineering Design Centre (EDC) to provide support to designers and anyone involved in product development, as well as providing an outline of the business case for inclusive design (Inclusive design toolkit, 2009). It includes valuable information on user capabilities including; vision, hearing, thinking, locomotion, reach and grasp, dexterity and communication. It also illustrates a variety of tools to both facilitate inclusive design and evaluate the inclusivity of a design.

2.2.4.2 Tools for Inclusive Design

One important design tool for helping designers achieve inclusive design, HADRIAN (Human Anthropometric Data Requirements Investigation and Analysis), was developed by the University of Loughborough’s Department of Design and Technology in 2004 (Marshall et al., 2004, Porter et al., 2004). The aim of this tool was to make it easier for designers to use ergonomic data, and to allow for multivariate analysis which cannot be achieved using standard anthropometric data. It also has the benefit of using data from their own data collection sessions, which focussed specifically on older adults and people with disabilities. Porter et al. (2004) argue that standard anthropometric data can be easily misinterpreted since they imply that people come in standard sizes and proportions, and that they are all healthy and able bodied. The traditional anthropometric data presentation format, using tabulated percentile tables, makes it impossible for the designer to reconstruct any real individual subject recorded in the survey.

Porter et al. (2004) also argue that because standard anthropometric data is poorly correlated, designing for the 5th and 95th percentiles can actually lead to the ‘designing out’ of more than the intended 5%. This occurs when more than one anthropometric variable is being considered – the man with the largest hands will not necessarily have the longest arms and the strongest handgrip. This information is simply not conveyed in other currently available data.

HADRIAN was designed as an evaluation tool to work with SAMMIE CAD (Case et al., 1991) which is a computer based human modelling tool that allows the designer to import CAD models from other CAD packages and assess their ergonomic suitability. The latest incarnation of this work is Accessibility and User Needs in Transport for Sustainable Urban Environments (AUNT-SUE) which aims to provide the socially inclusive design and operation of public transport (Marshall et al., 2005).

InclusiveCAD (Loudon and Macdonald, 2004) is the first CAD software tool to attempt to directly use data on older people’s biomechanical capabilities to aid product development. It concentrates on analysing the moments (turning effect of external forces) caused around each of the virtual user’s joints by importing a given design from a CAD package and applying it to the virtual user. The software calculates the moments caused around the joints in question as a percentage of the selected age group’s maximal moment capability. This software is still very much in its infancy and has therefore not been fully evaluated by designers. It does, however, represent an innovative new ergonomic design tool in that it offers an alternative way of assessing designs in terms of the users’ strength capabilities, rather than focussing solely on their anthropometric measurements.

One of the most frequently cited methods of assessing the level of design exclusion of any given design was to conduct a user trial. User trials offer the design team the opportunity to have direct contact with the potential end users of their product, providing them with a rich source of feedback. The user trial sample group should include older adults and the disabled, with as many ‘edge-cases’ (those who are on the borderline of being able to use the product) as possible. The rationale behind including these ‘edge cases’ is that if they can use the product, it should follow that the rest of the population should be able to use it as well (Keates and Clarkson, 2003).

There is a lack of theoretical framework for user/product interaction, so it seems that usability testing is the only available technique for avoiding a user/product mismatch. Unfortunately though, it is thought that usability testing has a number of important limitations (Green and Jordan, 1999).

Transferability of results, or rather the lack of it, was cited as a significant problem. It is a problem because any data gathered in a user trial will only be truly relevant to the context in which it was collected. User trialling, therefore, becomes a one-off technique that will only be capable of highlighting some localised, case-specific problems. This problem may not prove to be considerable if user trialling is viewed as a bottom-up approach, whereby a body of findings can be gathered and eventually amalgamated into a workable set of principles or theories (Green, 1999). It has also become apparent that professional ergonomic designers do not have any documented evidence of the reliability and validity of the usability tests they regularly use, and that many methods are used only by the very people who invented them (Stanton and Young, 1998).

There were no guidelines in the literature on how to record the results of user trials, or instructions on how best to present the results to designers. It is assumed that if they are summarised, then vital details, clues, comments, attitudes or behaviours could be lost in the process. Conversely, if they are not summarised, the designer may become swamped with results and be unable to rationally interpret them.

Furthermore, it was not known what happens when the results of the user trials are given to the designer. They may be enhanced, they may be compromised – nobody knows – and as yet there is no published evidence to support or refute either claim. Any designer is faced with a number of points of judgement, where they must do what they consider to be best, given their experience, and the nature of the information they have to hand. The designer has always been responsible for these decisions, so it should logically follow that the better informed the designer is, the better their ergonomic decisions will be. The status quo with regards to user trialling is summed up (Green, 1999) quite eloquently as follows:

"Thus we have a process of questionable value which may or may not be known, or if known not applied, or if applied ineffectively" (Green and Jordan, 1999)

From this it seems that although user trials are regularly used by designers and ergonomists, nobody truly knows how effective they are.

Empathic tools can be described as tools used by designers that allow them to empathise with, or better understand their target audience and capture various pieces of unarticulated information which may be unattainable when using other tools (Evans and Burns, 2007). Empathic tools are important in the design process, particularly when you have one group (designers) trying to include an unfamiliar group (older adults) in their design considerations. The majority of the empathic techniques available to the designer are fairly informal by nature, and simply involve spending time with the subjects, talking to them and watching what they do. User forums have been used, whereby groups of older adults were able to meet with design students where they participate in focus groups, talk through ideas, develop concepts, test prototypes, and were given the opportunity to discuss consumer issues with professional designers and industry managers. Working one-to-one with the users often results in the designers bonding with them, and subsequently empathising with them, giving the designers greater motivation to come up with design solutions that engage with their aspirations and lifestyle goals, enhance self-esteem and offer pleasure in use (Coleman et al., 2003b). These benefits can all be achieved in addition to meeting the primary aim of addressing the physical issues of capability.

In order to empathise with the physical issues of reduced capability and literally 'feel' what it is like to suffer from some of the impairments faced by older adults, designers can employ a number of simulation techniques. The earliest evidence of this technique was first introduced by Loughborough University and Ford in 1994, with their Third Age Suit (Figure 2.2a) developed for young designers to experience the difficulties faced by older users getting into and out of a car (Cardroso et al., 2003). In 2006 the research team from Loughborough University went on to launch the Osteoarthritis Suit (Figure 2.2b)

Figure 2.2 (a) Loughborough University's Third Age Suit and (b) Osteoarthritis Suit

There are a number of other emerging physical simulation techniques, for example, it is possible to buy goggles that simulate a range of vision impairments, from glaucoma to tunnel vision, and hand movements can be restricted by binding them or using gloves with stiffeners in the fingers. The EDC at the University of Cambridge has developed some devices that limit finger motion (Figure 2.3) and elbow extension. As part of the Inclusive Design Toolkit, previously mentioned in Section 2.2.4.1, there are also software-based visual and hearing impairment simulators (Inclusive design toolkit, 2009) that allow designers to find out, for example, how someone with macular degeneration might see a certain image. It allows designers to upload images of their own designs to assess them, and make necessary changes to make them easier to use for that particular group. Furthermore, using preloaded disability prevalence data, the same tool can calculate what percentage of the population designers might be excluding with any given design.

Figure 2.3 University of Cambridge EDC's finger restricting device

Not only are these popular techniques with young designers, it is thought that they could also form the basis of an absolute quantitative scale for measuring inclusivity (Keates and Clarkson, 2003). One criticism of these techniques is that the designers can easily remove the simulator(s) and carry on their lives as normal, so they fail to fully understand the longitudinal implications of impairment, such as attitudinal problems, and what coping strategies might be developed. While the simulations can be valuable there can be no substitute for getting end users, such as older adults, involved (Warburton, 2003).

2.2.4.3 Summary of Tools and Resources

While there appears to be a plethora of tools and resources available to designers who wish to practice inclusive design, there is little published empirical evidence, or indeed industrial case studies, that show these having a direct effect on designs either by making them more inclusive or by providing the company in question with higher profit levels. It seems that the majority of publicised success stories are anecdotal in nature (Mueller, 2003) and rarely feature facts and figures, which does not make for a very robust argument supporting inclusive design. It is likely that these tools and techniques do work, and there may well be evidence of their success out there, it’s just that this evidence does not appear to have been gathered and documented, if it does exist. It is logical to assume that the more data, tools and resources designers have at their disposal the better. They can mix and match them as appropriate and will eventually find ones which they consider to be most useful.

Another important issue here is that of access. While the Inclusive design toolkit (Inclusive design toolkit, 2009) is freely available to all via the internet, most other tools and resources are not freely available to designers, which is likely to deter them from using them particularly when they are working with limited time and money.

2.2.5 Inclusive Design Summary

Inclusive design is still in its early stages. It has the strong backbone of a good moral argument combined with an excellent business opportunity of a new, relatively untapped and lucrative market. Unfortunately there are two key barriers blocking its success; a lack of demand from design commissioners, and insufficient data, information, tools and resources for designers to achieve inclusive design.

2.2.6 Inclusive Design – Implications for Thesis

There are a number of tools and resources available to designers, but there is no strong evidence to suggest that they are being used, and if they are being used how effective they are. It was therefore considered to be crucial that this research project remain focussed on delivering data that was not only accurate, but was also accessible and easily understood by the inclusive design community.

Tentative steps have been taken towards introducing biomechanical data to the design community in the form of an inclusive design tool (Loudon and Macdonald, 2004, Macdonald and Loudon, 2007). Given the complex nature of the data used within the tool, it seems that this was perhaps too complex for designers who are not familiar with biomechanics, hence this is now being used as a tool to facilitate cross-disciplinary design workshops (Macdonald et al., 2009).

Biomechanics can provide a deeper understanding of how people manipulate and interact with products, more so than the data currently available to designers. The key is to find a way of presenting such complex data to an unfamiliar audience simply, but without diluting it. A thorough review of the biomechanical data, specifically data regarding the upper limb and older adults' physical ability, was therefore deemed necessary.

2.3 The Biomechanics of the Hand and Wrist

A clear need for new ergonomic data to enable designers to achieve inclusive design was established in the previous section. It was reasoned that biomechanics could offer alternative insights into how people manipulate products and the resultant forces that are applied to their bodies and presumably therefore provide more meaningful data to designers. Biomechanics offered the ability to go beyond traditional anthropometric and static maximal strength data. Most importantly it provided a set of methods for quantifying the differences in posture, motion and resultant forces between groups of people; in this case a comparison between older adults and young healthy adults.

Using biomechanics for ergonomic and inclusive design purposes is by no means a novel idea. It has been used for some time in occupational ergonomics (Chaffin et al., 2006, Nussbaum et al., 1999) and in various other ergonomic contexts, such as car design (Zhang and Chaffin, 2000) and the design of hand tool handles (Seo et al., 2007). As discussed previously, the most significant use of biomechanics for ergonomics and inclusive design is the software tool InclusiveCAD (Macdonald and Loudon, 2007, Macdonald et al., 2009). This represented an important attempt to take data on older adults from one established research field and present it, in a novel format, to an unfamiliar audience of designers. One limitation of this work was that it concentrated on the whole body so was therefore more suitable for the design of large products. It is assumed that designers should similarly be interested in finding out more about the biomechanics of the hand and upper limb, as it is this part of the body that is most likely to physically interact with smaller products such as packaging.

"Just as our eyes and skin do, the hand serves as an important sensory organ for the perception of our surroundings. The hand is also the primary effector organ for our most complex motor behaviours. And, the hands help to express emotions through gesture, touch, craft and art……. The hand functions as a highly specialised instrument performing very complex manipulations, requiring infinite levels of force and precision." (Neumann, 2002, p.194)

One of the most important aspects of the hand is that it offers people autonomy, as it has been shown that diminished hand functionality is a strong predictor of dependence in older adults (Hughes et al., 1997). The following section of the literature review will describe the hand and its capabilities, the effects of ageing on the hand and key research on the biomechanics of the hand.

2.3.1 Basic Anatomy of the Hand and Upper Limb

The arm and hand together can be likened to a machine which has three major aspects: 1) the muscles fulfil the role of 'motor', 2) the tendons, bones, joints and ligaments act as the 'transmission' and, 3) the skin and pulp tissues provide the means of 'application' to the objects the hand has to contact, control and manipulate (Brand and Hollister, 1999).

2.3.1.1 Bones and Joints of the Upper Extremity

The upper extremity is made up of 32 bones in total; the clavicle, scapula, humerus, radius, ulna, carpal bones (8), metacarpals (5) and phalanges (14) as shown in Figure

2.4a. The carpal bones are detailed in Figure 2.4b. The thumb will be referred to as digit I, and the other digits numbered sequentially through to the little finger which will be digit V.

Moving distally from the trunk the main joints of the upper extremity are; the shoulder, the elbow, the radiocarpal joint, five carpometacarpal (CMC) joints, five metacarpalphalangeal (MCP) joints four proximal interpahalngeal (PIP) joints, four distal interphalangeal (DIP) joints and one interphalangeal (IP) joint (digit I). The joints of the hand and wrist are illustrated below in Figure 2.5.

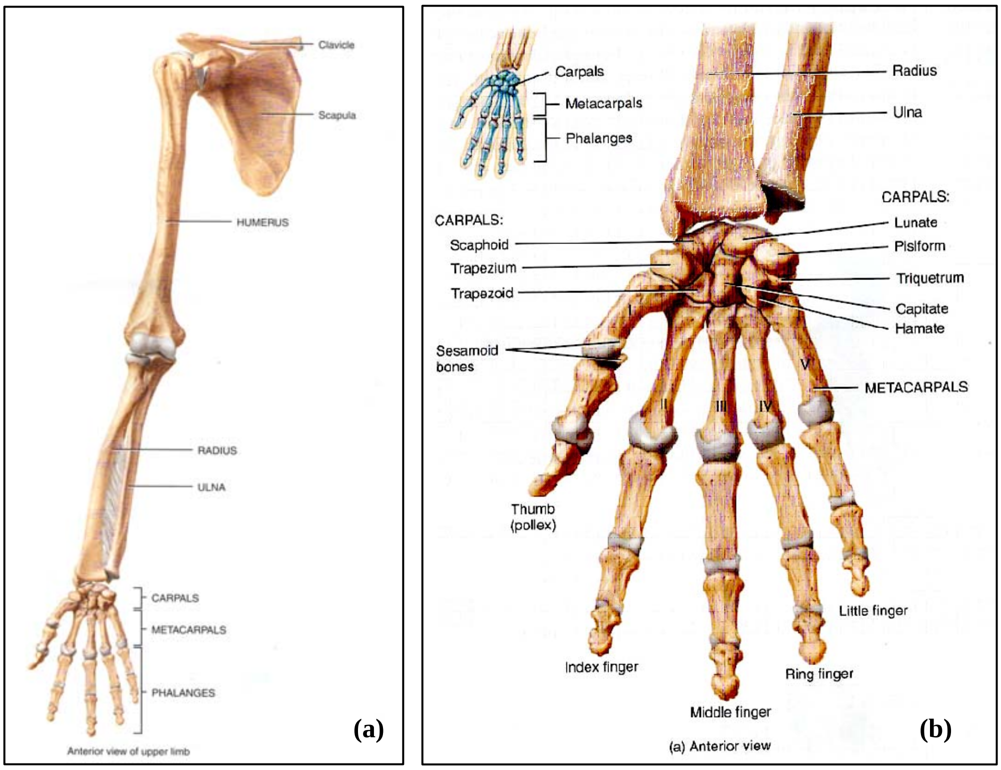


Figure 2.4 (a) Bones of the upper extremity and (b) Detailed view of bones of the hand and wrist. Adapted from (Tortora and Derrickson, 2009).

The wrist complex consists of multiple articulations between the eight carpal bones, the distal aspect of the radius and the metacarpal bones. The eight carpal bones can be divided into proximal (scaphoid, lunate and triquetrum) and distal (hamate, capitate, trapezoid and trapezium) rows, articulating with the distal radius and five metacarpal bones respectively (Nordin and Frankel, 2001). The proximal and distal rows of the carpal bones are highlighted in Figure 2.6.

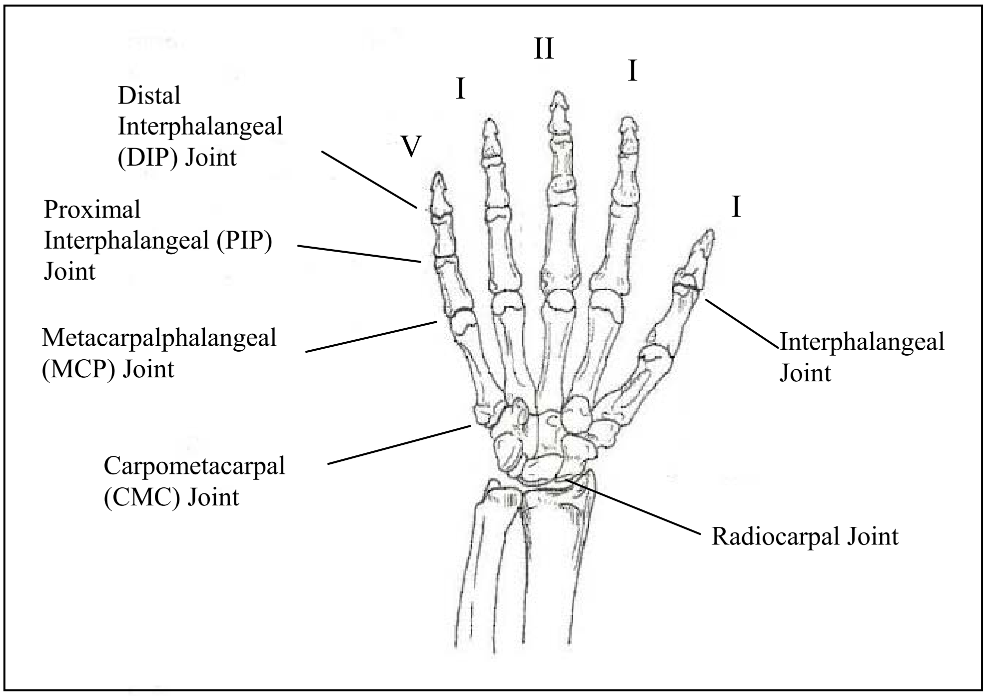


Figure 2.5 Joints of the digits (numbered), hand and wrist. Adapted from Nordin (2001).

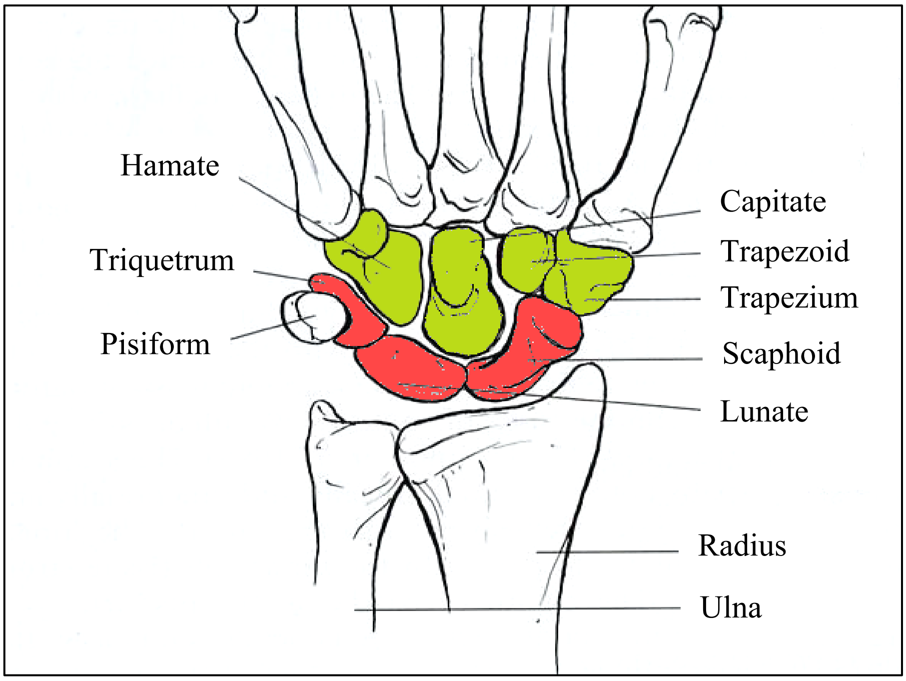


Figure 2.6 The carpal bones, showing proximal (red) and distal (green) rows. Adapted from Nordin (2001).

As illustrated in Figure 2.7, the bones of the hand are arranged into two arches traversing the hand (the proximal and distal transverse arches) and one longitudinal arch (the longitudinal arch). The longitudinal arch starts at the proximal carpal bones and extends through the second and third metacarpals (the non-articulating section of the arch) and on to digits II-V. It is this rigid section which connects the two transverse arches. Using the capitate as its foundation, the proximal transverse arch lies at the distal end of the carpal bones and is relatively imobile. The distal transverse arch passes through distal metacarpal heads II-V and is relatively mobile. It is the co-ordination of the three arches that allows the hand to be held in a cup shape (Nordin and Frankel, 2001).

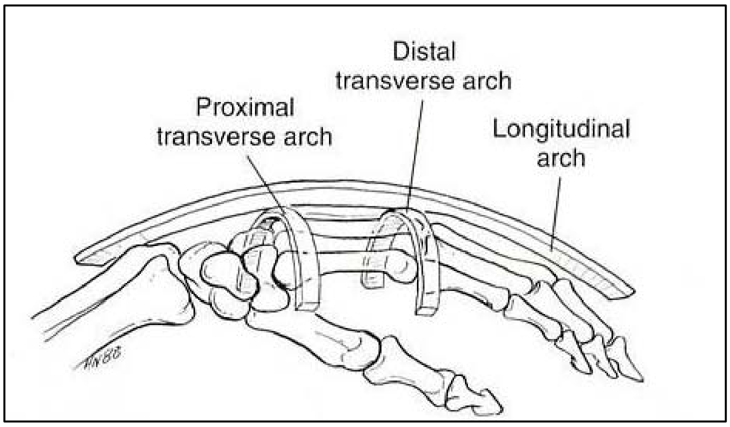


Figure 2.7 The three arches of the hand; proximal transverse, distal transverse and longitudinal. Adapted from Nordin (2001).

Each of the joints in the upper extremity has a number of degrees of freedom, from one to three and these are detailed below in Figure 2.8. It should be noted that this represents a simplified model of the upper extremity, with the radiocarpal joint and CMC joints II-V being generalised under the label of ‘wrist’. Figure 2.8 describes the thumb (digit I) CMC joint as having just two degrees of freedom however, due to its unconstrained nature and the extensor pollicis longus muscle’s point of insertion, as the thumb adducts it also supinates, thus giving it a third degree of freedom (Brand and Hollister, 1999, Hollister et al., 1992). Another simplification is that the MCP joints are described as having only two degrees of freedom (flexion-extension and abduction-adduction) when they can actually experience a small amount of pronation-supination which is particularly prominent in digits IV and V (Krishnan and Chipchase, 1997) . (Speirs et al., 2001) argue that when using a motion analysis system it is acceptable to assume no pronation or supination as this will have no effect on the other angles being measured.

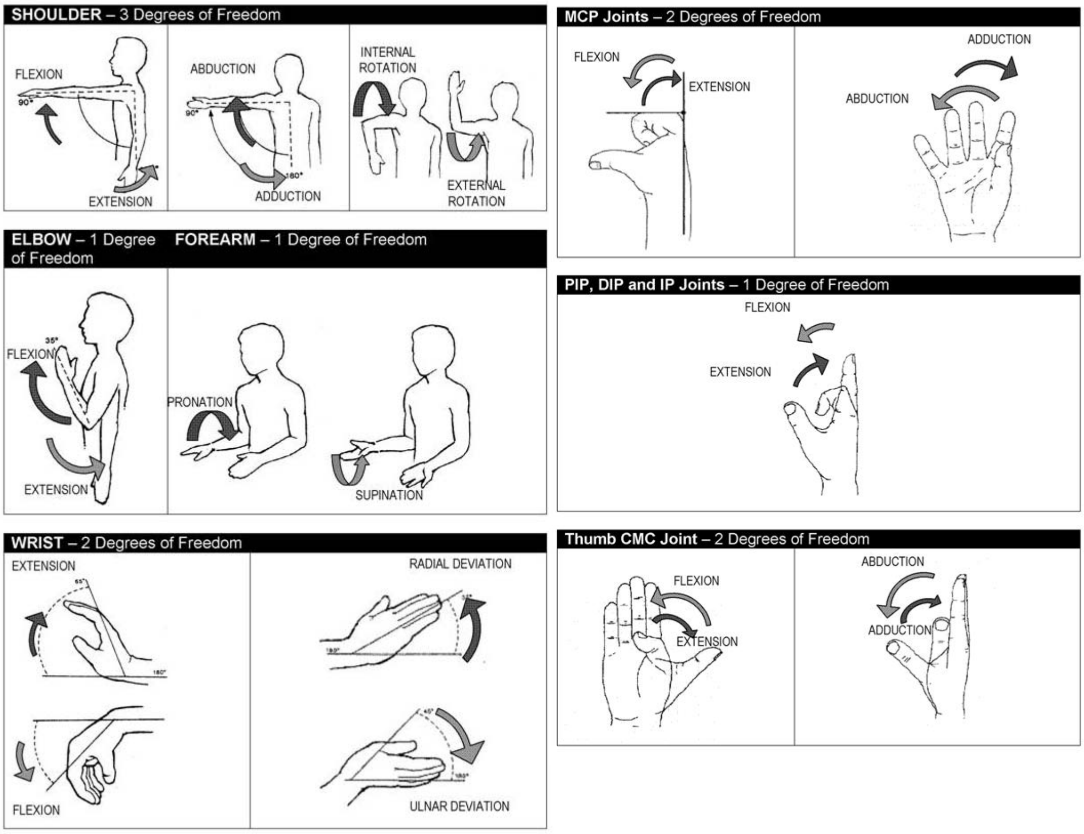


Figure 2.8 Degrees of freedom of the upper extremity. Adapted from Adrian and Cooper (1995).

2.3.1.2 Muscles of the upper extremity

Muscles can be likened to the motors of the body as they allow the movement and stabilisation of joints and limbs, control how the body applies forces to the objects it encounters and generally allow people to interact with their environment. With tension as their main output, muscles are able to shorten on demand and through the combination of active contraction and passive elastic recoil after being stretched, facilitate coordinated movements of the joints and limbs (Brand and Hollister, 1999). Tendons are the dense connective tissue structures that attach muscle to bone and ligaments join one bone to another to create joints

The muscles of the upper extremity control and coordinate movements within the degrees of freedom outlined in Figure 2.8. The muscles of the upper arm control the flexion and extension of the elbow joint as well as contributing to the pronation and supination of the forearm. The muscles of the forearm, also known as the extrinsic muscles of the hand, serve a number of purposes; moving the wrist, pronating and supinating the forearm, contributing to flexion and extension of the elbow, and playing a large role in the flexion and extension of the five digits. The effects of these extrinsic muscles are closely associated with actions of the intrinsic muscles of the hand, with few if any functional movements requiring either group to act in isolation. The intrinsic muscles of the hand can be classified into the four functional groups; the primary intrinsic movers of the thumb (digit I), the primary intrinsic movers of digit V, the interossei and the lumbrical muscles (Oatis, 2004). A detailed table of the various muscles and the upper extremity movements they contribute to can be found in Appendix A, alongside corresponding anatomical illustrations.

2.3.2 Capabilities of the Upper Extremity

Having identified and described the main components of the upper extremity and how they combine to allow coordinated movement with multiple degrees of freedom, it was considered important to summarise its functional capabilities. Functional capabilities are described in terms of joint range of motion, strength and dexterity with comparisons made between young and older adults.

2.3.2.1 Joint Range of Motion

Joint range of motion (ROM) is important because it determines the number of different positions a person can move their body segments into, and therefore directly affects the number of functional tasks they can perform normally. Table 2.1 shows the normal ranges of motion for all joints of the upper extremity and where possible the data for young adults is compared with that of older adults.

Table 2.1 Range of motion of the joints of the upper extremity. Young adults compared with older adults. See legend for data sources.

		Normal range of motion (degrees)	Older adult range of motion (degrees)
Shoulder[1]			
Flexion		170 ± 2 (M) 172 ± 1 (F)	165 +/- 2 (M) 170 +/- 1 (F)
Extension		57 ± 3 (M) 58 ± 3 (F)	55 ± 2 (M) 61 ± 2 (F)
Abduction		178 ± 1 (M) 180 ± 1 (F)	178 ± 1 (M) 178 ± 1 (F)
Internal Rot^{n}		49 ± 3(M) 53 ± 4 (F)	59 ± (M) 56 ± 2 (F)
External Rot^{n}		94 ± 2 (M) 101 ± 2 (F)	82 ± 4 (M) 94 ± 2(F)
Elbow[2,3]			
Flexion		140.6 ± 4.9	143 ± 11
Forearm			
Supination		88.1 ± 4	74 ± 14
Pronation		75.0 ± 5.3	71 ± 11
Wrist[4]			
Flexion		71 ± 8 (M) 77 ± 9 (F)	64 ± 9 (M) 65 ± 9 (F)
Extension		67 ± 10 (M) 75 ± 9 (F)	58 ± 12 (M) 64 ± 10 (F)
Radial Dev^{n}		21 ± 7 (M) 24 ± 6 F	20 ± 7 (M) 21 ± 6 (F)
Ulnar Dev^{n}		44 ± 6 (M) 46 ± 9 (F)	42 ± 7 (M) 43 ± 8 (F)
Thumb CMC[5]			
Flexion		15	-
Extension		20	-
Abduction		40	-
Thumb MCP[6]			
Flexion		57 ± 12 (M) 60 ± 11 (F)	-
Thumb IP[6]			
Flexion		65 ± 10 (M) 68 ± 11 (F)	-
Extension[7]		35.2 ± 16.4 (M) 25.8 ± 14.4 (F)	-
Finger MCP[8,9]			
All digits	Abduction	~20	
	Adduction	~20	
Index	Flexion	75 (M) 75 (F)	-
	Extension	22 (M) 24 (F)	-
Middle	Flexion	80 (M) 79 (F)	-
	Extension	19 (M) 23 (F)	-
Ring	Flexion	74 (M) 76 (F)	-
	Extension	17 (M) 18 (F)	-
Little	Flexion	72 (M) 72 (F)	-
	Extension	15 (M) 21 (F)	-
Finger PIP[9]			
Index	Flexion	106 (M) 107 (F)	-
	Extension	11 (M) 19 (F)	-
Middle	Flexion	110 (M) 112 (F)	-
	Extension	10 (M) 12 (F)	-
Ring	Flexion	110 (M) 108 (F)	-
	Extension	14 (M) 20 (F)	-
Little	Flexion	111 (M) 111 (F)	-
	Extension	13 (M) 21 (F)	-

[1] (Murray et al., 1985); 20 male and female subjects (25-36 years) and 20 male and female subjects (56-64)

[2] (Boone and Azen, 1979); Data from 56 males (34.9±3.4 years)

[3] (Walker et al., 1984); Data from 30 Male and 30 Female subjects aged 60-84 years

[4] (Steenbekkers and Beijsterveldt, 1998); 750 male and female subjects, 50-80+ years. Young adult data 20-30 years, older adult data 70-74 years.

[5] (Gerhardt and Rippstein, 1990)

[6] (Jenkins et al., 1998); 50 male and 69 female subjects. Mean age 35 (range 16-72) years

[7] (Apfel, 1986); Mean passive ROM based on the right hands of 19 males (35.7±14 years) and 12 females (33.7±6)

[8] (Batmanabane and Malathi, 1985)

[9] (Mallon et al., 1991); Mean passive ROM from 60 male and 60 female subjects aged 18-35. No SD reported.

The data shown in Table 2.1 was collected using traditional goniometry (the measurement of joint angles) techniques. It shows that with age one can generally expect a decrease in range of motion at most joints of the upper extremity, although this decrease is not dramatic. Of particular interest to this study was the age-related decrease in range of motion in the forearm and wrist, as this highlighted a partial loss of upper extremity functionality. Steenbekkers and Beijsterveldt (1998) found large age-related decreases in ROM of the flexion and extension of the wrist, which was more prevalent in female older adults. Data on the range of motion of older adult's digits would have been useful but could not be located in the literature.

In a novel study using motion analysis, instead of traditional goniometry, to measure joint range of motion it has been shown that the most significant differences between young and old, with regard to range of motion, are found in the trunk, neck and shoulder (Doriot and Wang, 2006). The same study found no significant differences in the range of motion of the elbow, forearm and wrist, however the study was limited by its sample size when compared with the studies mentioned in Table 2.1. In contrast, a much larger study on forearm rotation found that there were significant age-related decreases in range of motion, with the effect starting earlier and being more pronounced in the female population (Rickert et al., 2008). The authors of this paper went on to argue that supination ROM is functionally more important, as subjects with limited supination reported significantly more interference with activities of daily living compared to those with limited pronation.

2.3.2.2 Strength

In addition to the muscles and the joints of the upper extremity combining to allow controlled kinematic movement, they also allow the body to exert forces and moments onto the objects it encounters. Strength can be measured in a number of ways, with muscles generating a series of forces that act as levers around the joints, allowing the measurement of a moment at each joint. More importantly for the functionality of the hand is the combination of these joint moments in the form of various prehensile grips. Upper extremity strength will therefore be described in two ways; joint moment strength and grip and pinch strength.

Joint moment strength data from various sources (Askew et al., 1987, Delp et al., 1996, Murray et al., 1985) within the literature are presented in Table 2.2.

Table 2.2 Maximal joint moment strengths. Young adults compared with older adults. See legend for data sources.

Joint	Degree of Freedom	Joint Moment (Nm)			
		Young Adults		Older Adults	
		Male	Female	Male	Female
Shoulder[1]	Flexion	79.7 (3.9)	52.6 (2.9)	74.1 (2.9)	35.2 (2.3)
	Extension	103.8 (4.6)	50.4 (1.7)	83.6 (4.1)	37.7 (2.8)
	Abduction	55.5 (2.4)	33.2 (1.6)	46.9 (2.3)	22.0 (1.8)
	Adduction	55.1 (2.3)	27.0 (1.5)	41.8 (2.1)	21.8 (1.6)
	Internal Rotation	103.1 (5.8)	55.0 (3.2)	81.7 (4.8)	38.0 (2.5)
	External Rotation	58.1 (2.6)	28.4 (1.2)	43.6 (1.7)	22.5 (1.5)
Elbow[2]	Flexion	71.1 (15.1)	33.0 (7.8)		
	Extension	41.3 (10.7)	20.6 (6.0)		
Forearm[2]	Pronation	7.2 (1.8)	3.5 (0.8)		
	Supination	8.9 (2.3)	4.3 (1.2)		
Wrist[3]	Flexion	12.2 (3.7)			
	Extension	7.1 (2.1)			
	Radial Deviation	11 (2)			
	Ulnar Deviation	9.5 (2.2)			

[1] (Murray et al., 1985); 20 male and female subjects (25-36 years) and 20 male and female subjects (56-64)
[2] (Askew et al., 1987)
[3] (Delp et al., 1996)

As with ROM data, there are some noticeable gaps in the literature concerning data collected specifically on older adults. The data shows a general decline in shoulder joint moment strength with age which appears to be more pronounced in female older adults.

Prehensile grip and pinch strengths of the thumb and fingers are important as they can act as a measure of ability to seize, hold, secure and pick up objects. In a prehensile grip all digits are used, whereas in a prehensile pinch it is usually the thumb and another digit (usually digit II) that are used. ‘Power grip’ is used when large forces and stability are required for the task, and precision is not important. A ‘power pinch’ is used when large forces are needed to stabilise an object between the thumb and digit II (and often digit III). Examples of power pinch grips include the lateral pinch grip, pulp pinch grip and the three jaw chuck grip (Neumann, 2002). A summary of power grip and various pinch grip strengths for young and older adults are shown in Table 2.3.

Studies have shown that power grip strength diminishes with age for both males and females (Steenbekkers and Beijsterveldt, 1998) and loss of strength is curvilinear in its nature and is therefore more apparent in the oldest groups (80 years and older) (Desrosiers et al., 1995). Desrosiers et al. (1995) also found that in addition to age, hand circumference and body height are good predictors of power grip strength. Power pinch grips have also been shown to weaken with age (Nayak and Queiroga, 2004), and body size was not found to be a consistent predictor across age and gender groups (Imrhan and Loo, 1989). One study found that in addition to maximal power pinch grips declining with age, a loss in the ability to hold a steady sub-maximal pinch grip occurs in both men and women, although this deterioration is more apparent in the latter (Ranganathan et al., 2001).

Table 2.3 Comparison of selected prehensile grip and pinch strengths of young and older adults. Data taken from multiple sources, images adapted from Neumann (2002) and Edwards and Buckland (2002).

Grip/pinch type	Image	Study	Strength (N)			
			Young Adults		Older Adults	
			Male	Female	Male	Female
Power Grasp		Imhran[1]	487.6 (17.3)	308.0 (11.2)	294.3 (18.5)	210.9 (9.7)
		Mathiowetz[2]	537 (102.3)	331.5 (61.9)	335.1 (95.7)	220.7 (52.1)
		Steenbekkers[3]	543 (85)	343 (58)	392 (74)	246 (52)
Lateral Pinch[1]		Imhran[1]	92.2 (3.4)	63.8 (1.7)	65.7 (3.4)	48.1 (3.0)
		Mathiowetz[2]	118.8 (21.8)	78.8 (9.3)	85.9 (10.7)	64.5 (12.9)
Chuck Pinch[1]		Imhran[1]	92.2 (2.2)	68.7 (2.3)	57.9 (4.4)	45.1 (2.6)
		Mathiowetz[2]	115.7 (19.1)	78.8 (14.2)	80.5 (15.1)	64.1 (11.6)
Pulp Pinch[1]		Imhran[1]	71.6 (2.8)	46.1 (1.7)	42.2 (2.6)	29.4 (2.0)
Tip Pinch		Mathiowetz[2]	81.4 (13.4)	53.0 (8.0)	61.4 (11.6)	44.9 (11.6)

[1] (Imrhan and Loo, 1989)
[2] (Mathiowetz et al., 1985)
[3] (Steenbekkers and Beijsterveldt, 1998)

2.3.2.3 Manual Dexterity

An important aspect of hand functionality, in addition to ROM and strength, is manual dexterity. While there are a number of definitions for manual dexterity in the literature, this thesis will use "the skilful and controlled manipulation of a tool or object by the fingers" (Chan, 2000). As with other aspects of hand functionality, studies have shown that manual dexterity tends to decline significantly with age (Hackel et al., 1992, Hughes et al., 1997, Ranganathan et al., 2001). The effect of this decline in fine motor skill tends to be exhibit itself in difficulties performing a number of everyday tasks such as fastening buttons, putting on jewellery, hand writing, tying shoe laces and retrieving objects from a purse (Ranganathan et al., 2001).

2.3.3 Reduced Upper Extremity Function in Older Adults

It is thought that the reduction in upper extremity function in older adults is due to a series of localised structural changes combined with more distal changes in neural control. The localised structural changes can involve the joints, muscles, tendons, bones, nerves and receptors, blood supply, skin and fingernails. Furthermore, with age comes the additional risk of underlying pathological conditions such as osteoporosis, osteoarthritis, rheumatoid arthritis and Parkinson's disease (Carmeli et al., 2003). So, it is the combination of these age related changes that result in the reduced range of motion, loss of strength and decline in manual dexterity that clinicians and researchers have measured and investigated.

2.3.4 Biomechanical Measurement for the Hand and Upper Limb

The literature has shown that reduced range of motion, loss of strength and decline in manual dexterity are suffered to varying degrees by older adults. What is not clear is how this loss of hand function directly effects the way older adults handle and manipulate consumer products differently from younger adults. As stated previously, biomechanical testing offers a unique method of simultaneously capturing the motion of various body segments during activity (kinematics) and the forces which act upon these segments (kinetics). In order to achieve both kinematic and kinetic analysis of any given activity, both an accurate biomechanical model of the hand and wrist, and force measuring equipment are required.

2.3.4.1 Biomechanical Models of the Hand

There have been a number of kinematic models of the hand and wrist proposed, along with validation studies to prove that they are viable when using a series of reflective surface markers and a motion analysis system. The relative merits and drawbacks of each of these models will now be discussed.

Before any complete biomechanical models of the hand were proposed, early investigations into the feasibility of using surface markers to measure various joint angles of the hand and wrist compared 3D motion analysis with 2D lateral fluoroscopy. These studies showed that using motion analysis was as accurate as the fluoroscopy techniques for both finger flexion (Rash et al., 1999), similarly for wrist flexion/extension (Small et al., 1996) and also for the flexion of the thumb joints (Kuo et al., 2002), with the latter study concluding that with an accuracy of ±5°, motion analysis is clinically acceptable.

The studies mentioned above all used single markers placed above each joint's centre of rotation, which were used to create a series of segment axes. An alternative approach taken in other studies was to use rigid clusters, or triads, of three markers attached to each segment (Degeorges et al., 2005, Fowler and Nicol, 2001). While it is thought that using such a marker system provides more accurate segment axis definitions, there were a number of drawbacks including having too many markers in such a small capture volume, and also having to conduct a large number of static calibration trials to define the location of joint centres. As Fowler and Nicol (2001) and Degeorges et al. (2005) only studied the motion of one digit, it is likely that the problem of having too many markers would be exaggerated if this approach were to be taken for all digits simultaneously. Furthermore, it appeared from the published illustrations that the use of triads of markers would likely impede free, natural movement. Three of the most recent and comprehensive biomechanical models of the hand and wrist all use a single marker system (Carpinella et al., 2006, Cerveri et al., 2007, Metcalf et al., 2008) and all reported high levels of accuracy, repeatability and inter-rater reliability.

Cerveri et al. (2007) proposed a biomechanical model of the hand and wrist with 22 functional degrees of freedom which are show in Figure 2.9. One criticism of the proposed model is that it does not explain how the wrist joint centre is defined relative to the rigid wrist band with four markers (Figure 2.9c). Its linkage system also connects, in a straight line, the four MCP joints to the wrist joint centre (WJC) which is not anatomically accurate as the metacarpals do not lie at such large angles of ab/adduction that they would converge at the WJC. The method of using a rigid cluster of markers on the forearm to locate the wrist joint centre is however preferable to the method proposed by Metcalf et al. (2008), which relies on placing markers on the distal head of the ulna, dorsal aspect of the ulna, distal head of the radial styloid process and the dorsal aspect of the radius in order to form a plane for the forearm. The limitation of this method is that the two markers on the dorsal aspects of the radius and ulna are both likely to move relative to the other two markers during forearm rotation, causing the forearm plane to distort. The same model also proposes that metacarpals II-V be considered which as one plane, given the mobility of both the proximal and distal transverse metacarpal arches, seems to be an over simplification. The model proposed by Caprinella et al. (2006) is restricted in that it does not consider the motion of the wrist. Only one study offered a detailed explanation of how the joint centre of rotations (in flexion/extension) can be calculated using the surface markers (Zhang et al., 2003).

A standard set of joint co-ordinate systems for the upper limb has been proposed (Wu et al., 2005) however it is thought that these are based on bony landmarks that are not easily identifiable through the application of surface markers, so marker application may prove to be time consuming and laborious during subject trials (Metcalf et al., 2008).

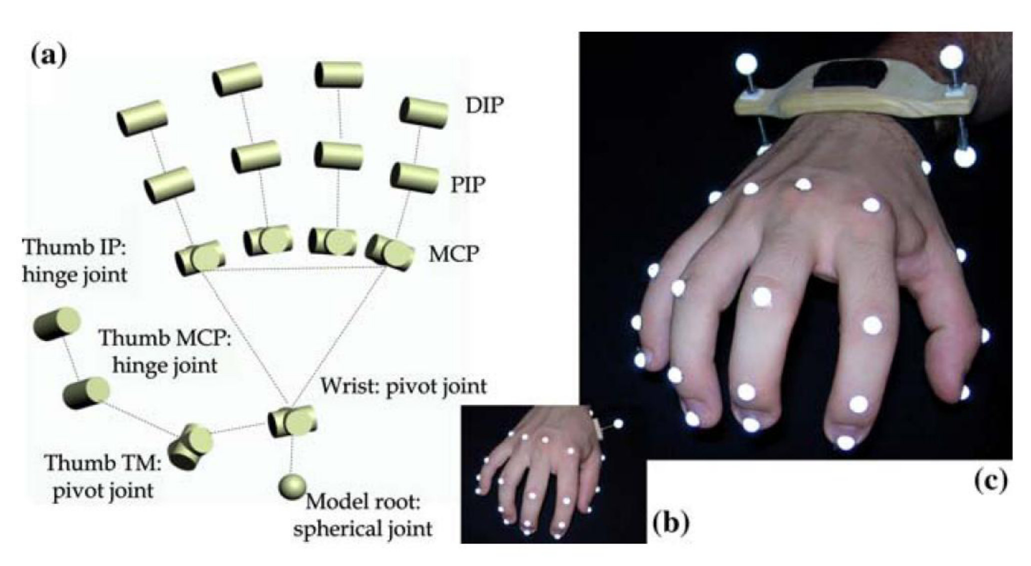


Figure 2.9 Biomechanical model of hand and wrist (Cerveri et al. 2007). a) DoFs and linkages of the model, b) surface marker layout, c) surface markers and rigid wrist band

2.3.4.2 Force Measuring Equipment

There are a plethora of force measuring devices described in the literature, most of which use strain gauges to convert applied loads into electrical signals, with the strain gauges incorporated in realistic products and devices. The relative benefits and shortcomings of some devices that measure loads applied by the hands and wrists will now be discussed.

One of the most relevant studies on measuring the individual finger loads during typical ADL's (Fowler and Nicol, 1999b) used a novel 6 DoF force transducer in conjunction with a motion analysis system. The force transducer was adaptable such that it could measure the loads on digit II during jar opening, tap twisting, kettle pouring and key turning (Fowler and Nicol, 1999a). While this study offered precise data on the loads at the PIP and DIP joints, one criticism is that in doing so the test apparatus appeared to dictate the positions and postures that the subject adopted during testing, and therefore did not necessarily support subjects' natural strategy for completing these tasks. For example, it is rare that one finger would be acting completely independently of the others, instead they tend to be bunched together to provide a combined opposition to the thumb. Furthermore, from the diagrams published the various configurations of the apparatus did not appear to be particularly lifelike in terms of their dimensions and no mention was made of any attempts to ensure that the apparatus were positioned at realistic heights (e.g. the tap appears to be at table height). One final drawback with this equipment was that it required a large 25-pin ‘D’ connector to transfer the force data which may also have detracted from the realism of the experiment. The use of a rotary dashpot in this work was however useful as it realistic added a dynamic element to the test.

A study which similarly included a dynamic aspect to its test equipment investigated the forces applied during plastic bottle opening (Carus et al., 2006). This equipment successfully concealed a 6 DoF force transducer inside a 500ml plastic water bottle which measured the forces applied by subjects when opening a real bottle lid, although it did not allow for the measurement of the individual finger loading components. On the other hand, Su et al. (2009) included two force transducers (one 6 DoF transducer to measure the loading on the thumb, and another single axis transducer to measure the total torque generated by the thumb and fingers combined) in their jar apparatus, however did not include any dynamic element to their test. Other studies that used single axis transducers to measure static maximal strengths in package opening include Berns (1981) who studied jars, bottles and cardboard washing powder boxes, and Yoxall et al. (2006a) who studied jars.

In other hand and finger force measuring experimental work, a maximal gripping device that measured the force on individual fingers was designed (Gislason et al., 2009). This used 5 separate 6 DoF transducers, with one digit placed on each, thus providing data to calculate the resultant forces and moments in each joint of each finger during static gripping. While this provided highly accurate data it would not be suitable for many other applications as it required that no digit be in contact with any other digit, which rarely happens during normal gripping. In work exploring the effect of torque direction and handle diameter, a split cylinder configuration was used to measure subjects total normal gripping force (which was then split into thumb and finger forces) using a force gauge (Seo et al., 2007). Both cylinder segments were fixed to a single axis torque cell, and a thin pressure measurement pad was wrapped around the split cylinder. This apparatus illustrates a helpful compromise as it allowed for the measurement of individual opposing grip components without compromising the subject's natural gripping posture.

Ideally in the design of force measuring equipment both accuracy and realism are highly desirable, although it appears that one is often achieved at the cost of the other.

2.3.5 Hand and Wrist Biomechanics – Implications for thesis

There was clearly a wealth of relevant data available on the functionality of the upper extremity, most of which had been collected within the research fields of ergonomics and medical science. There are a number of ways of measuring and classifying how well an individual's hands and arms are functioning. What may be of use, to the design community, is some supplementary information on how a deterioration of upper extremity function manifests itself when performing ADLs. A description of the compensatory strategies adopted by older adults when faced with such deterioration could provide valuable information to designers on what capabilities still remain. It should be acknowledged at this point that deterioration in upper extremity function can be experienced in people of all ages, but with age the likelihood increases. In relation to the available data on upper extremity functionality, it should also be highlighted that in only a small number of cases is this data currently accessible to designers.

Data on the functionality of the upper limb was not derived for the purpose of informing designers, but usually for a specific research or clinical audience. It is not surprising therefore that there appears to be little guidance as to how to apply any of this data directly to the design of a product.

Having discussed the literature on the biomechanics of the hand and wrist, the package opening research was then reviewed, with particular attention paid to studies which involved any older adults, biomechanical analysis or novel force sensing technologies.

2.4 Package Opening Research

Package opening has been identified as an activity that becomes progressively more difficult to accomplish with age. A series of government reports were commissioned to investigate the problem through the Department of Trade and Industry (DTi, 1999b, DTi, 1999a) showing that an estimated 67,000 people of all ages in the UK visit hospital casualty departments every year due to injuries associated with packaging opening. The same reports also estimated that a greater number of less serious injuries are treated at home or by GPs.

This section of the literature review will briefly describe the research that has been carried out to date on package opening activities, starting with a look at some of the broader key issues and then focussing specifically on the measurement of forces exerted by the hand during opening.

2.4.1 Key Package Opening Issues

While packaging related injuries are a major concern, it can be postulated that package opening will also cause a large amount of inconvenience, frustration and mild pain or discomfort which is not likely to show up on any government reports or national statistics. One report did investigate the improvised use of inappropriate everyday tools when package opening could not be achieved manually (DTi, 1999b). These inappropriate everyday tools included knives, scissors, pliers, screwdrivers, doorjambs and any other readily available object. Use of these tools poses risks to the user that would not occur if manual package opening was possible.

A study into the physical and personality characteristics of those most likely to injure themselves when opening packaging found that it was those who were left handed and those who scored low on a measure of personal control during decision-making that were most likely to have suffered injury. It also found that those who exhibited a decision-making style of social resistance (resisting asking for help) were most likely to suffer *serious* injury (Winder et al., 2002).

In addition to asking someone for help, package opening can be made easier through the use of specially designed package opening tools. While one study described the various opening tools available, and offered some quotes and generalisations about what design aspects of the tools were most desirable, it did not identify which specific tools were preferred by the test subjects involved (DTi, 1999b). A different study concluded that these tools were not effective because, on average, they made package opening more time consuming (Saha and Shehab, 2005). This conclusion was based on the assumption that speed was the most important criteria to the elderly subjects and no attempt was made to measure how levels of discomfort, or perceived level of difficulty affected decision making.

2.4.2 Opening Torques for Package Opening

It has been shown that difficulty in package opening is most commonly experienced with glass jars, plastic bottles and tins with ring pulls (Winder et al., 2002). Much subsequent research effort has been concentrated on further examining the nature of the ‘difficulty’ posed by these types of packaging, particularly with regards to measuring the forces and torques that have to be applied by the person to open the package.

In the case of the jar, one such study used a custom built torque measuring device to test 97 female (8-93 years) and 138 male (8-93 years) subjects’ peak static jar lid opening torque. Comparing this data against the torques required to remove a lid from real jars of similar dimensions, the authors estimated that 50% of females over the age of 75 years would be unable to open jars with a 75mm lid diameter (Yoxall et al., 2006a). The same authors also went on to generate a predictive equation for calculating the torque and subsequently the normal gripping force required of the person to remove a jar/bottle lid (Yoxall et al., 2006b, Fair et al., 2008).

In another study looking at maximal jar opening torques, comparing 123 mixed gender young subjects (20-30 years) against 627 mixed gender older subjects (50-80 years), a significant decline in opening torque was reported with age (Voorbij and Steenbekkers, 2002). The authors went on to prescribe that jar opening torques (for lids of 75mm diameter) should not exceed 2Nm, with the concession that this will still be too difficult to open for 2.4% of those people over 50 years old. As well as reporting an age related decrease in opening torque, a different study additionally investigated the effect of changing the dimensions and shape of a jar lid on opening torques (Crawford et al., 2002). This study found that the surface area of the test lids had a high positive correlation to the level of maximum torque generation as it provided greater contact area between the hand and lid. Furthermore, the authors found that square lids allowed for the exertion of more torque than round lids, and that the best predictors of torque strength were subject height, weight, hand length and hand breadth. While these findings were useful the study was limited by using a nylon material for the test lids, which was not representative of a standard jar lid material, and also by the fact that the torque measuring device seems to have been fixed in place. The earliest piece of research studying the forces applied during package opening appears to have been published as early as 1981, where the torques and forces applied during the opening of jars, a bottle and a cardboard soap powder box (Berns, 1981) were measured.

Finally, one last study which considered the forces applied during the opening of soft drinks bottles found that there were significant differences in the force/torque profiles exerted by older adults when compared with younger adults (Carus et al., 2006). The test procedure used a six degree of freedom transducer which measured all of the forces and moments applied by the subject onto the lid during opening. The authors concluded that the older adults tested exerted a great deal of unnecessary forces and moments on the lid, so while they removed the lid successfully, they lacked the level of control exhibited by younger adults.

2.4.3 Beyond Opening Torques

While much valuable research effort has been focussed on how much resultant torque can be generated by people when gripping lids of different size and shape in static scenarios, real life package opening is more complex as it is dynamic. In an ongoing study attempts have been made to investigate the dynamic nature of jar opening (Fair et al., 2008). Not only did this study have the advantage of studying the motions involved in opening real jars, but the testing included restrained and unrestrained postures for subjects. The test procedures also allowed for the fact that some subjects wrapped their supporting hand (the hand not placed on the lid) underneath the jar base rather than around the jar body. In this work the proposed analysis procedures also acknowledge that both hands contribute to jar opening, with the motion patterns of both being analysed. The published literature does however only describe work in progress, so full results were not available. It was also noted that a limited marker set (four per hand) was used. As no force measuring equipment was involved, only kinematic data would be generated.

Recent work has also been carried out to investigate the contributions to the resultant jar opening torque of the thumb and the grouping of four fingers by simultaneously measuring the force/torque contribution of each in isolation (Chang et al., 2008). This work marked a significant step forward in equipment design (Su et al., 2009) in that it allows for the splitting-up and measurement of the two main elements of hand grip. One slight limitation of the study was that it had a narrow subject group of 16 18-22 year old female subjects. More significantly, the test procedures were strict and may have caused unnatural jar opening postures; two different grip styles were imposed (opposed palmar grasp and disc grasp), two different jar positions were stipulated (standing vertically on a table and held neutral-diagonally), the subject's upper arm was strapped to their torso, and all tests were completed with the subject sitting in a chair.

2.4.4 Packaging Research – Implications for Thesis

While there has been much research carried out on the activity of package opening, many of the studies mentioned previously have looked at isolated aspects of the complete physical interaction that takes place between person and package.

The packaging research reviewed did go some way to highlighting how the decline in hand function mentioned in Section 2.3 directly affects an ADL. The age related decline in ability to generate forces to open packaging appeared to be closely related to decline in hand function, although this has not been explicitly tested. Carus et al. (2006) showed that there were distinct differences in the force profiles applied by a group of older adults while opening bottles, suggesting that they had less control than younger adults. What was lacking from the literature was information and data describing what people with diminished hand functionality did differently in terms of the grip styles they used and the associated body postures they adopted in applying forces and torques to packaging. It was assumed that such information would prove useful in describing the different strategies used which would then in turn allow conclusions about the remaining strengths of this group of people to be drawn.

2.5 Literature Summary

The literature on inclusive design, hand and wrist biomechanics and package opening has been discussed.

Inclusive design is important, and for it to become more prevalent appropriate data and tools are required. The upper limb is important for maintaining independence, and from a product design perspective, is the part of the body most likely to contact the product being designed. While there are a number of causes of age-related decline in hand function it is clear that more needs to be understood about the way older adults’ reduced hand functionality affects their ADLs. Using an appropriate biomechanical model of the upper limb, simultaneous motion analysis and force measurement was identified as offering a powerful technique for investigating how ADLs were affected by declining hand function. Package opening represented an appropriate activity through which to study such how hand function is affected.

In terms of the objectives outlined in Section 1.3, this literature review has established that biomechanical testing techniques can be employed to generate information on people's physical abilities as several studies have taken early steps towards this goal. What remains to be ascertained is whether this information can be made useful in an inclusive design context. Significant differences between young and older adults have been identified in terms of their ROM, strength and dexterity, however, outside of the empathic tools discussed in Section 2.2.4.2 no comprehensive descriptions of how these differences impinge on the everyday life of older adults were apparent in the literature. Previous attempts have been made to present biomechanical data to designers in the form of a design tool but these attempts did not appear to be underpinned by any detailed understanding of how designers work and what they might want from a design tool.

Chapter 3 Initial Designer Interviews

As discussed in the literature review (Chapter 2), there were a number of issues surrounding designers' use of ergonomic data as well as their motivations for practicing inclusive design. Before collecting data and presenting it to designers it was important to establish a clear picture of the context in which such information might be used. A series of interviews were conducted to generate rich qualitative data on designers and how they work. An appreciation of the additional design constraints they face, constraints that might detract from good ergonomic packaging design, was required. In addition to establishing the context in which data may be used by designers, an understanding of how, if at all, they include older adult's needs into their design process was necessary. This work was carried out to contribute towards objectives number 1 and partially towards objectives 4 and 5.

3.1 Methods

Structured face-to-face interviews were conducted with ten UK design companies involved in packaging design. One member of the design team was interviewed from each company, with interviews conducted on the company's premises and lasting approximately one hour. Participating companies ranged from small design consultancies through to large multinational manufacturers with the intention of involving a diverse range of organisational sizes and backgrounds. The companies that participated are detailed in Table 3.1.

Designers were initially contacted by telephone call and when the topic of the study had been introduced and an interest in participation established, a full description of the study was sent to the designer for their consideration. This was followed up with another telephone call to confirm participation and arrange a date and time for the interview.

Table 3.1 Description of ten companies involved in initial practicing designer interviews

Respondent No.	Location	Main Business	Size (number of employees)
R1	Glasgow	Product and industrial Design Consultancy	6
R2	Marlborough, Wiltshire	Design and innovation company specialising in structural packaging	16
R3	Stroud, Gloucestershire	Product design consultancy	2
R4	Walberton, West Sussex	Product development and structural packaging design	3.5
R5	London	Product design consultants	60
R6	Wrexham, Clywd	International food processing and packaging solutions	370 (plant) 25,000 (worldwide)
R7	East Kilbride	Corrugated box design and manufacture	290 (plant)
R8	Glasgow	Design and manufacture of moulded pulp packaging	120 (plant)
R9	Glasgow	Design, engineering and project management	4
R10	Port Sunlight, Merseyside	Multi-national corporation with food, beverage, personal care and cleaning agent brands	13 (packaging design technology team) >100,000 (worldwide)

One large multinational manufacturer insisted on a confidentiality agreement being signed prior to the interview. The structured interview investigated key issues including:

- The companies' current design process and practices i.e. common tools and techniques employed.
- Their awareness, understanding, and use of ergonomic, anthropometric and biomechanical data.
- Their understanding and use of inclusive design.
- How older adults are currently considered when designing new packaging.
- What design criteria were more important to them and where 'openability' ranks in importance relative to their other design criteria.
- What types of design data they currently use and why?

Each interview was recorded using a microcassette dictaphone and subsequently transcribed. Transcriptions were analysed to identify similarities, differences and patterns in the response from the companies. During this analysis quotations that were deemed pertinent to the keys issues listed above were extracted and grouped together according to which issue they were relevant to. Further to this grouping of quotations, a summary table of results was produced using a straightforward classification system for answers provided by designers. Answers were classified using the subjective judgement of one data analyst. While this clearly over simplified what were often extended and complex answers, it provided a clear and simple representation of the emerging patterns in responses. A sample of one fully transcribed interview is shown in Appendix C.

3.2 Results

Findings from the structured interviews are summarised below including selected quotes from the various respondents as labelled.

‘Openability’ was not a primary concern amongst the packaging designers interviewed. When asked to rank a number of design criteria in order of importance ‘openability’ was not amongst the top 3. Following discussion it became apparent that it was not a specific requirement of the companies or their clients to make the packaging ‘easy-to-open’. Ultimately, openability would be the decision of the individual designer.

“No, [openability] is not a criteria that has ever been specified by the customer, however it’s a criteria that we would probably set ourselves.” (R9)
“The motivation is personal. As a designer you should be doing it naturally – you should be trained to design for consumers” (R3)

Packaging appearance consistently ranked top. Designers generally believed that addressing openability issues would have an adverse effect on other ‘important’ design criteria.

“It will probably affect the cost because the closure is the most complex and therefore expensive part of a package” (R2)
“Yes, it will affect cost. The aesthetic appeal too” (R10)

Designers interviewed felt that if they had inadvertently designed difficult to open packaging, this would be identified early in the process through user groups.

“If we come up with a design concept which turns out to be difficult to open, the customer will point that out to them and they’ll rectify the design. There’s little chance that any ‘difficult-to-open’ packaging will make it through to the end user” (R7)

Packaging designers knew what inclusive design was, with 90% confidently offering an accurate definition. However, they appeared to have little or no knowledge of how to put it in to practice with very few having any experience of actually designing products inclusively. Some of the designers interviewed felt they intuitively designed products to be inclusive although there was little tangible evidence of this occurring. One company commented that they would start adopting inclusive design techniques if their clients demanded it.

“We tend to deal with mass products and the mass consumer, so [inclusive design] is not something we look at. We’ve done projects where the hub of the brief was to make sure that something was designed specifically to be used by the elderly, but we’ve never looked at a mass product and tried to increase it’s market breadth” (R5)
“It would definitely be customer led” (R7)

Most of the designers interviewed felt they included older adults in their design process intuitively, or through consumer testing or informal discussion.

"I would like to think I do it naturally in my way of thinking. I try to treat design as an inclusive process" (R3)
"Just go and speak to [older adults]. There's no better way to get good information. We try to involve prototypes, but even if we just use sketches then that's usually enough" (R1)

There was very little evidence of biomechanical data being used by packaging designers with only one of the ten companies regularly using it. Most felt this data was too generic and would rarely be suitable for their specific requirements. The preferred approach was to design then test products using end users through the adoption of user trials, focus groups, observation and ethnography. None of the designers interviewed had been encouraged by their management or clients to specifically use biomechanical data.

"We rely on the consumer testing. We find that observation is much more valid and useful than using any sort of data, which often tends to be too generic" (R5)
"Focus groups, observational studies, in-use trials and large scale in-use trials. We use them early on in the project, mainly qualitative work with 30-50 consumers, then later on they will use hundreds" (R10)

All designers interviewed had an awareness of biomechanics but only two out of ten could offer an accurate definition. Very few knew where they could access biomechanical data.

"Addressing mechanical issues in a natural way?" (R5)
"I assume [the data] would be available under some institution or research system, so I would probably have to pay some huge amount of money to use it" (R3)

Companies interviewed adopted user trials and focus groups, however, these did not always include older adults. Examples of practice included a small design consultancy regularly using a small, informal group comprising mainly of relatives and their friends through to a large international manufacturer on one occasion employing a focus group of older adults (although this was considered to be a one off as older adults were considered to be out with their target market).

“We prototype things as early as possible, get feedback and start to refine the ideas. We try to get the user involved from the word go, using people we know, including elderly relatives” (R9)
“We used the same design and consumer testing techniques as usual, but just changed the target group – 50-70 year olds instead of the normal 25-50 years olds. We used 3 or 4 new prototypes. We didn’t see it as being particularly successful” (R10)

Given that the observations and quotations above are somewhat difficult to compare and contrast, a summary table of results was created as shown in Table 3.2.

Table 3.2 Summary table of key simplified responses gathered during initial designer interviews

	Respondent's education level	Typical project timescales (months)	Encouraged to make package opening easy?	Encouraged to use ergonomic data?	Regularly use ergonomic data?	Familiar with inclusive design?	Tried to implement inclusive design?	Evidence of successful implementation?	Know what 'biomechanics' means.	Use biomechanical data?	Have access to biomechanical data?	Consider older adults in the design work?	Other testing techniques utilised?	Think packaging openability compromises design criteria?
R1	BA Product design	0.25-120	Yes	No	Yes	Yes	Yes	No	No	No	No	Yes	User trials	No
R2	BSc and MA Industrial design	8-36	No	No	No	Yes	Yes	No	No	No	No	Yes	Focus groups, user trials, ethnography	Yes
R3	BSc Product design	1-36	Yes	No	No	Yes	Yes	No	No	No	No	Yes	User trials, ethnography	Yes
R4	BA Product design	<3	No	No	No	Yes	No	No	No	No	No	No	User trials	Yes
R5	BA Consumer product design	3-24	No	No	No	Yes	No	No	No	No	No	Yes	Ethnography, user trials	No
R6	BSc Mechanical + electrical eng.	6-36	Yes	No	No	Yes	Yes	No	No	No	No	Yes	Focus groups, user trials	Yes
R7	Apprenticeship + experience	0.25-1	No	No	No	Yes	No	No	No	No	No	No	None	Yes
R8	BSc Mechanical design	0.5-2	No	No	No	No	No	No	No	No	No	No	Mechanical drop testing	Yes
R9	MEng Product design engineering	4-12	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	User trials, focus groups	Yes
R10	BSc Mechanical engineering	12-36	Yes	No	Yes	Yes	Yes	No	Yes	No	No	Yes	User trials, focus groups ethnography	Yes

3.3 Discussion

This initial study of practicing designers provided a broad overview of how packaging designers currently take older adults into account, as well as an understanding of what data they use. In terms of using data, it was apparent that designers did not use ergonomic data routinely and instead had strong preference towards focus groups and user trials despite the significant doubts over the validity of such methods, as discussed previously in Section 2.2.4.2.

With regard to inclusive design for older adults, it was also clear that designers did not consider older adults as standard in their design process. There was evidence of this happening occasionally but there was no success directly attributable to this use of inclusive design. Understandably on some occasions it might not be necessary to consider older adult. The general consensus was that there was not sufficient demand from any source to merit a concerted effort to achieve inclusive design.

Considering package openability, which is intrinsically linked to inclusive design, it was not expected that it would rank so low in designers' ordering of packaging design criteria. Packaging appearance was usually considered to be the most important design criteria. Appearance of packaging, price and content are what encourage sales of most consumer products, whereas package openability will be a secondary or tertiary consideration. If consumers are likely to buy the product regardless of how easy/difficult the packaging is to open it logically follows that openability should be a secondary consideration for designers. It makes business sense.

The methods described did have some limitations. Firstly, the sample size of design professionals was limited, so it was difficult to build an all-encompassing picture of how all designers practice. Secondly, as the participating designers worked in very different companies and had varied educational backgrounds (science, engineering and arts) comparisons between them could not be made. Finally, the method used to classify and compare the designers' response illustrated in Table 3.2 could be criticised for oversimplifying what were complex answers down to simple yes/no statements. Many of the original answers given were given with numerous caveats and described different scenarios where different answers might apply, so classification was difficult.

3.4 Implications for Thesis

Designers do not appear to routinely use ergonomic data; biomechanical or otherwise. This could be for any number of reasons – educational background, personal preference, limited access, perceived lack of validity, time pressure, or otherwise. The main challenge posed here was that the use of data was not habitual.

On investigation of the finding that package openability was not a primary design criteria it became apparent that packaging was not a straightforward 'product' as such. Consumers do not buy the packaging, they buy the product it contains. They generally buy the products that they want (packaging appearance can influence this) and assume that the packaging will perform its functional duties.

There was documented evidence of a genuine problem with older adults and package opening (DTi, 1999a, Yoxall et al., 2006a). Those who commissioned packaging design did not demand that designers provide inclusively designed packaging. This indicated a packaging-specific example of a bigger problem of lack of consumer demand for inclusive design (see Section 2.2.3).

Designers however did not acknowledge a significant problem with the status quo, and it appeared that as far as design commissioners were concerned there was no problem due to little or no direct consumer demand. The following stage of the research project was therefore designed to investigate, first hand, the attitudes of older adults towards consumer packaging, and whether or not they considered it to be problematic.

Chapter 4 Packaging Survey

Having established that there was little demand being placed on designers to implement inclusive design, the older adult consumer's perspective on the problem was required, so a packaging survey was designed. As well as aiming to directly answer objective 2 as listed in Section 1.3, this part of the project also served as a useful background study into the nature of the perceived package opening problem within the older adult population.

The specific micro-objectives of the study were to examine the issues of; which types of packaging were most difficult to open, which groups found packaging particularly difficult, how significant a problem was packaging openability, what alternative opening strategies were used, were older adults aware of the various assistive devices (ADs) that are available, who owned ADs and how did they really feel about them.

4.1 Methods

A subject group of 38 older adults was used, with a minimum of 5 from each gender in the following age categories; 60-69, 70-79 and 80+. The final subject group consisted of 23 females and 15 males, with the mean ages of 72.78 (±8.25) and 73.71 (±7.83) respectively. For comparison purposes a control group of young healthy adults was also included; 5 males and 5 females with mean ages of 23.8 (±0.84) and 28 (±2.83) respectively.

The older adult volunteers were recruited from a number of different sources to ensure a sample group with an even spread of socio-economic backgrounds, and who lived with varying degrees of independence. All subjects lived without any full-time carer. The sources used were; various lunch clubs (co-ordinated by the Social Work Services department of Glasgow City Council), the University of Strathclyde senior studies institute, sheltered housing complexes, and a bowling club, all within the Glasgow area.

4.1.1 Questionnaire Description

The subjects were asked to participate in a 20 minute face-to-face standardised questionnaire. The standardised interview technique was chosen to ensure higher response rates and to allow the opportunity to correct any misunderstandings that may have occured. Although this technique was time consuming to conduct and process, it did have the advantage of allowing the interviewer to probe the subjects for more detailed responses and to clarify any vague answers they might have given (Oppenheim and Oppenheim, 1992). The interview covered topics including; needing help to open packaging, what 'alternative opening strategies' they might use, if they use any ADs to help open packaging, rate how difficult they find opening different types of packaging, and their attitudes towards packaging design in general. Respondents were also asked if they suffered from any specific hand problems. A series of show cards, with photographs, were used in conjunction with questions to eliminate any ambiguity regarding packaging types and to show a series of ADs. A full copy of the questionnaire and sample show cards can be found in Appendix B.

In order to test their attitudes towards packaging design, a series of 24 attitude statements were used to establish respondent's feelings on the following six topics:

1. Level of anger/frustration/inconvenience caused by packaging (+ = Annoying)
2. Importance placed on independence, determination to be self-reliant (+ = High level of importance)
3. Packaging designers being inconsiderate of older adults' needs (+ = Inconsiderate)
4. Decline in hand function (+ = Noticeable decline)
5. Packaging could be designed to be easier to open (+ = Agree)
6. Finding packaging small and fiddly (+ = Agree)

Each individual attitude statement was measured using a Likert scale (strongly disagree=1, disagree=2, not sure=3, agree=4, strongly agree=5), although it should be noted that some of these scores had to be reversed when a negative statement was used.

For each respondent a 'total packaging score' was calculated as a measure of how difficult or easy they found it to open packaging in general, using a summation of the Likert ratings they provided for each individual packaging type (very easy=1, easy=2, OK=3, difficult=4, very difficult=5). The range of possible scores was from 16 (no difficulties at all) to 80 (found every type very difficult). A similar system was used to give each respondent an 'alternative score', a measure of how many different alternative strategies they use for packaging opening, and how frequently they use them. This scale ranged from 0 (never use any) to 24 (use all of them frequently). Finally, a Likert scale was used again to measure four AD related attitudes, as listed in Figure 4.3.

In order to establish statistical significance a number of non-parametric statistical tests were used; binomial distribution, 1-sample sign, Mann-Whitney and chi-square tests. These tests were carried out using Minitab v15 statistical software and a result was considered to be significant when $p<0.05$.

4.2 Results

The introductory questions of the questionnaire provided some interesting findings. Firstly, everybody in both the subject and control groups reported to having had some difficulty with packaging at some time. 29 of the 38 subject volunteers reported having had to ask someone to help them open packaging, which is statistically significant ($p<0.001$). Importantly, of these 29 subjects, 19 of them ($p<0.05$) had to occasionally rely on outside help from neighbours, relatives or visitors, when they are unable to open something themselves.

The most difficult types of packaging to open were identified, with the results ranked in order of difficulty in Table 4.1. The rankings were calculated using the means of the Likert ratings given by each respondent in the subject group only.

Table 4.1 Difficult/Easy Packaging, including gender and 'hand problem' differences

Packaging Type			**Gender**		**Reported Hand Problems**	
Rank	Description	Mean (SD)	**Male** Mean (SD)	**Female** Mean (SD)	**'Yes'** Mean (SD)	**'No'** Mean (SD)
1	Jars	4.03 (0.85) †	3.67 (0.98)	4.26 (0.69) *	3.58 (1.07)	2.95 (1.18)
2	Bleach Bottles	3.97 (0.99) †	3.57 (1.09)	4.22 (0.85) *	3.67 (0.84)	2.79 (1.13) *
3	Soft Drinks Bottles	3.54 (1.12) †	2.93 (1.21)	3.91 (0.90) *	3.05 (0.91)	2.63 (0.83) *
4	CRC Medicines	3.50 (1.13) †	2.73 (0.88)	4.00 (1.00) *	4.16 (0.96)	3.89 (0.74) *
5	Flexible Sealed Bags	3.46 (1.04) †	3.38 (1.19)	3.50 (0.96)	2.32 (0.75)	2.16 (0.76)
6	Shrink Wrapped	3.37 (0.79) †	3.27 (0.80)	3.43 (0.79)	3.61 (0.98)	3.29 (1.10)
7	Tins with Ring Pull	3.26 (1.16)	3.13 (1.13)	3.35 (1.19)	2.95 (1.03)	2.76 (1.03)
8	Drinks Cans	3.25 (1.08)	2.69 (1.11)	3.63 (0.90) *	3.32 (0.67)	3.42 (0.90) *
9	Biscuit Packets	3.22 (1.08)	3.07 (0.96)	3.32 (1.17)	3.21 (0.71)	2.95 (0.91) *
10	Trays with Film	3.08 (0.82)	2.80 (0.86)	3.26 (0.75)	3.89 (0.94)	3.17 (1.20)
11	Cartons	3.06 (0.86)	3.00 (1.00)	3.09 (0.79)	4.37 (0.90)	3.56 (0.92)
12	Milk Bottles	2.92 (0.97)	2.40 (0.83)	3.26 (0.92)	3.89 (1.15)	3.11 (0.99) *
13	Soup Pots	2.86 (1.02)	2.31 (0.95)	3.17 (0.94)	3.11 (0.81)	3.00 (0.94)
14	Normal Tins	2.84 (0.89)	2.60 (0.91)	3.00 (0.85)	3.32 (0.95)	2.53 (0.84)
15	Dessert Pots	2.75 (0.73) ‡	2.64 (0.93)	2.82 (0.59)	3.81 (0.98)	2.69 (0.87)
16	Margarine Tubs	2.24 (0.75) ‡	2.20 (0.86)	2.26 (0.69)	2.94 (0.64)	2.56 (0.78)

* Statistically significant difference with Mann-Whitney test ($p<0.05$)

† Significantly more DIFFICULT with 1-sample sign test ($p<0.05$)

‡ Significantly EASIER with 1-sample sign test ($p<0.05$)

The results showed that there were six packaging types that were considered significantly more difficult that the others, and two that were significantly easier. Both the difficult and easy types of packaging are highlighted in grey in Table 4.1. Table 4.1 also highlights any significant differences in results between the sexes, and furthermore between those who did and did not report any hand or wrist ailments.

From the same set of results a packaging score, as described previously, was calculated for each respondent. While age proved not to be a significant predictor of packaging score within the subject group, gender was, with males and females having mean scores of 45.7 (±9.3) and 53.48 (±6.19) respectively. The two groups were significantly different ($p<0.01$), with older women report more difficulties opening packaging than older men. The control group also had a significantly lower overall packaging score than the subject group, with a median of 32.5 compared to 50 ($p<0.0001$), so overall older adults reported more difficulties opening packaging than young healthy adults.

The next section of the questionnaire asked the subjects about which alternative strategies they might employ when they are having difficulty opening packaging. The most commonly used strategies are displayed in Figure 4.1a. The older adults in the subject group were significantly more likely to use alternative strategies more frequently than the control group ($p<0.01$), as shown in Figure 4.1b. Again, every respondent reported using some alternative strategy to get into packaging at some point or another.

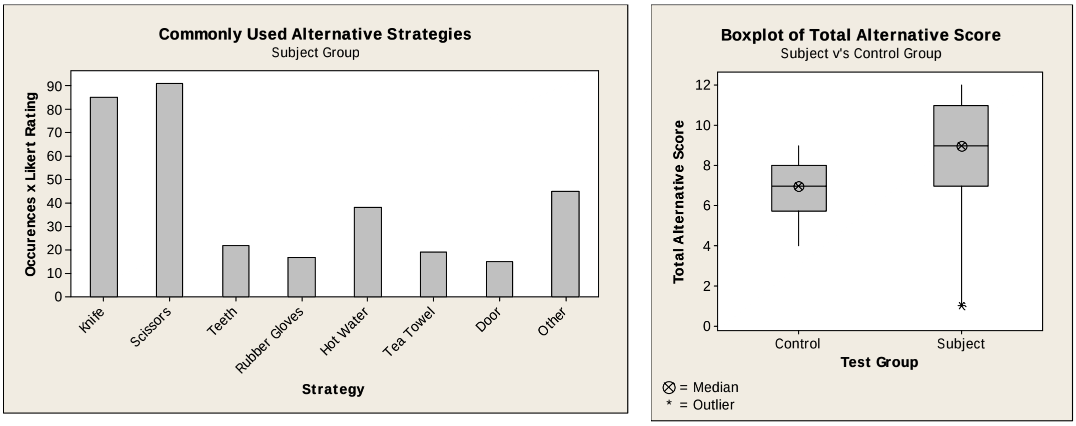


Figure 4.1 a) Most commonly used alternative strategies, and b) Comparison of control and subject groups total 'alternative score'

A comparison of the attitudes held by the subject and control groups is shown in Figure 4.2, demonstrating that the older adults generally reported positive scores for all of the attitudes tested apart from attitude 1 (see section 4.1.1 for full description of attitudes tested). There were significant differences between the attitude levels of the subject and control groups for attitudes 1, 4 and 6 ($p<0.05$; $p<0.001$; $p<0.001$ respectively). There were also significant gender differences for the same three attitudes within the subject group, with females reporting more positive responses ($p<0.05$; $p<0.01$; $p<0.001$ respectively).

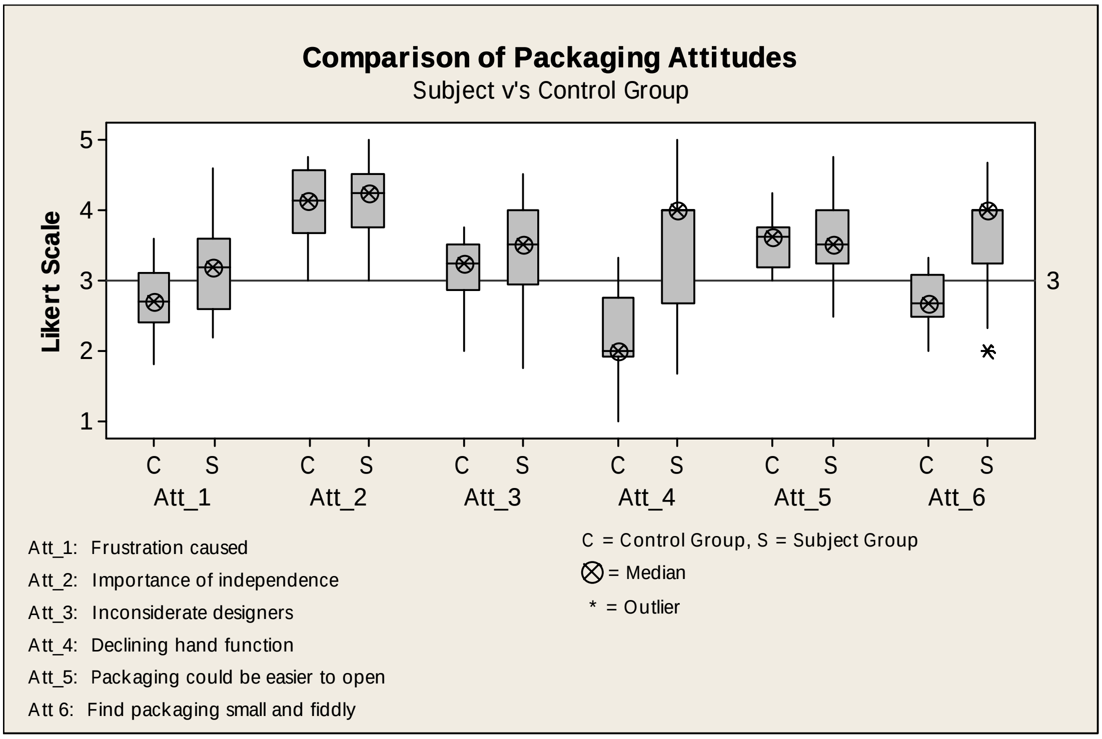


Figure 4.2 Comparison of subject and control group packaging attitudes

Respondents were asked a number of questions about ADs, mainly whether they owned any, and their attitudes towards them. The results showed that it is predominantly females who own assistive devices ($p<0.05$). The older adult group's responses to the four attitude statements are shown in Figure 4.3. The only significant gender difference was that females were more likely to agree with the statement "they make me feel old" ($p<0.05$). In comparing the responses of the subject and control groups there was just one significant difference in attitude, for question 3. The younger control group reported that they would "rather use which ever tools or utensils are to hand" rather than the assistive devices ($p<0.001$). When the results of statements 1, 2 and 4 were pooled together to give each respondent an overall positive/negative attitude score, the results showed that the control group had a significantly less positive attitude towards assistive devices ($p<0.05$) although it was still positive overall.

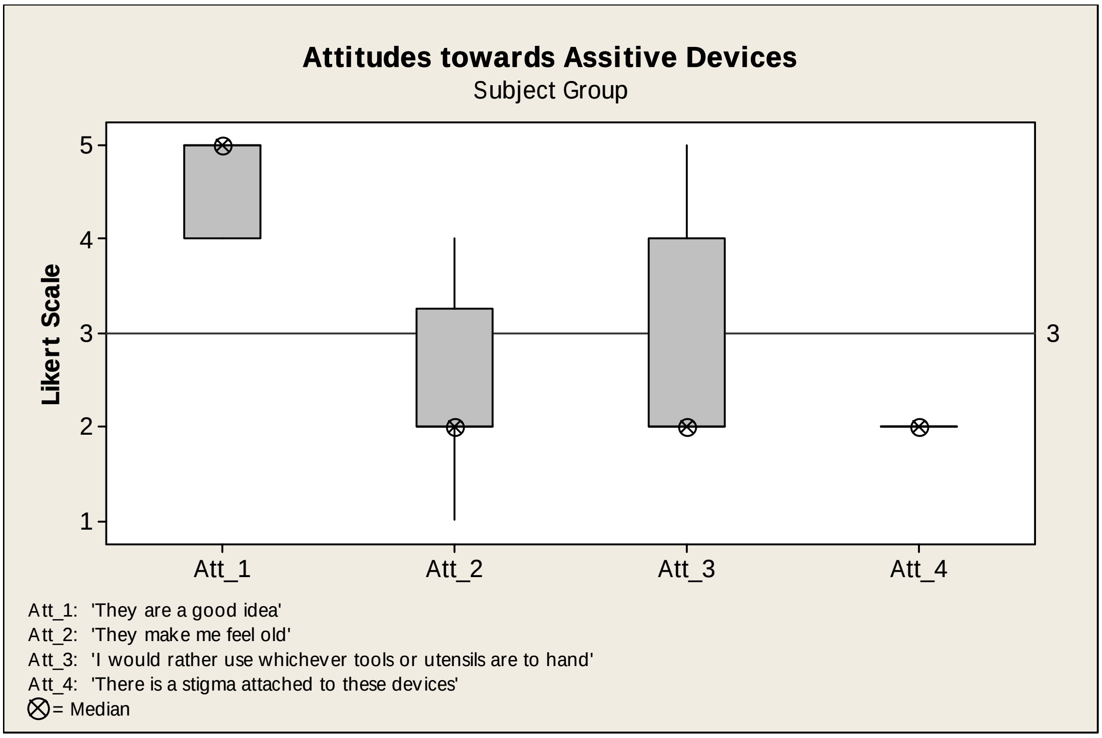


Figure 4.3 Older adult subject group attitudes towards assistive devices

An important result from the analysis of assistive device ownership was that it was not directly related to specific hand problems (p>0.1), suggesting there are a number of older adults with hand problems that do not use these devices, and similarly there are a number who have no hand problems that do use them.

4.3 Discussion

The results of the survey provided a number of both interesting and unexpected findings, many of which are important to both the packaging industry and the inclusive design community.

According to these results, the most difficult types of packaging predominantly seem to be those which involve the application of some torque through a twisting motion of the fingers and wrist. As highlighted in Table 4.1 these packaging types include jars, bleach bottles, soft drinks bottles and child resistant closure (CRC) medicine bottles. While previous studies have generated similar results (Winder et al., 2002), what was particularly apparent here was that it is principally female older adults who reported more difficulty with opening packaging across all varieties, although the differences were more pronounced for those requiring the application of torque. Given the prevalence of arthritis in females compared with males; 2.7:1 for rheumatoid arthritis (Symmons et al., 2002) and 2:1 (Flatt, 1995) for osteoarthritis, the reported difficulties are not surprising. This study agreed with these ratios, with the results showing that hand problems were more common for the women within the subject group ($p<0.05$). It was interesting that the packaging types considered to be the most difficult to open mainly relied on strength, whereas other types of packaging that relied more on dexterity and fine touch were described as being 'fiddly' or 'annoying' but not necessarily difficult.

The least difficult types of packaging, as highlighted in Table 4.1 appeared to be those which require only a small amount of force to be exerted by the user such as dessert pots and margarine tubs. These are characterised by the presence of a relatively stable base with a film on top which can be peeled off using a basic pinch grip, with no twisting action required. It was interesting that milk bottles (which do require a twisting action) were considered to be relatively easy to open, ranked in 12th position. It was thought that this is because when compared with the other packaging types that require a twisting motion, the torque required to open milk bottles is smaller.

In terms of the alternative strategies, every respondent reported using knives and scissors to open plastic packaging at some time or other, so although this is thought to be rather dangerous (DTi, 1999b), it can be regarded as commonplace. While there was nothing particularly remarkable about the alternative strategies listed in the questionnaire, some of the 'other' strategies mentioned were of interest mainly due to the higher levels of danger involved. Jars were most commonly involved with these strategies, with screwdrivers, teaspoons, worktops, kitchen knives and even tin openers being utilised to release their lids. One respondent reported using a claw hammer to open a can of beer, and another regularly carried a Swiss army-knife in preparation for any unforeseen packaging problems that may occur during the day. It was important to appreciate that these are some of the desperate measures that certain older adults will resort to when they become exacerbated with packaging. These may be the type of person that exhibit a decision-making style of social resistance (Winder et al., 2002) as mentioned in Section 2.4.1. Many people who needed help with packaging lived alone, so were forced to choose between using an alternative strategy, or being greatly inconvenienced and waiting for someone to help them.

The attitude statements provided results such that the following generalisations were drawn about the older adult subject group:

- They consider their independence to be of great importance
- They consider packaging designers to be inconsiderate towards their needs
- They have noticed a recent decline in their hand function
- They believe packaging could be designed to be easier to open
- They find packaging to be generally 'quite fiddly'

Few of these attitudinal results were strong enough such that they could be described as anything more than a disgruntled or dissatisfied attitude towards packaging. Some of the respondents commented that they appreciated the package's primary function is to protect its contents, and that making a package easier to open may compromise this. Furthermore, there was also a notable acceptance amongst the subject group that they will struggle with certain tasks as they get older, suggesting that they should be receptive to the idea of ADs.

It transpired that it was mainly female respondents who owned ADs which was understandable given that they generally find package opening more difficult than men, and are more likely to report specific hand problems. Although the subject group reported a generally positive attitude towards ADs, further analysis showed that the people who actually owned them were more likely to say that they made them feel old. This implies that although older adults are generally receptive to the concept of ADs, their attitudes change when they actually have to use them. It was noted during the interviews that a number of respondents, particularly men, adopted an almost disdainful attitude, commenting that "they're a good idea – for those who might need them" or words to that effect. It was initially hypothesised that AD ownership would be directly related to specific hand problems, such as arthritis, however this was certainly not the case as mentioned in Section 4.2. The group that suffered from hand or wrist ailments but did not own or use ADs all reported that they were aware of them being available, and none of them reported particularly negative attitudes towards them. It could be postulated that this group is either particularly self reliant, or that they do not know where to purchase these devices. The opposite group (who reported no specific hand problems but own ADs) will most likely be using them for convenience sake, and have no worries about how others may perceive them using these devices. One final noteworthy result related to ADs is the difference in attitudes towards them between the subject group and the control group. While the control group did have a positive attitude towards ADs, it was not as strong as that of the subject group, and they also reported that they would be much more likely to use standard kitchen utensils to open something, rather than an AD. This suggests that much of the supposed stigma surrounding these devices is only really apparent in the younger generations, whereas older adults mostly accept the fact that a decline in hand function is imminent, and they do not mind using these devices.

An important observation made during the analysis of the results was the distinct lack of statistically significant age related differences between the three sub groups of the older adults studied. It had been anticipated that the oldest members of the subject population would report more difficulty than their younger counterparts, given the expected age-related loss of hand function (see Section 2.3.2.2). One explanation for this is that the individual differences between older adults are most apparent in the physical functioning of the oldest older adults (Spirduso, 1995), so researchers are likely to find a high level of variation when testing with these groups. This would also presumably make it difficult for designers to design for a specific target age group. Furthermore a large number of research studies have proven that chronological age is not an accurate predictor of function or performance (Spirduso, 1995), so it may be more beneficial for designers and ergonomists to remain focussed on data describing physical ability.

The main limitation with this study was that it relied on subjective ratings whereby subjects were asked to rate terms like ‘difficulty’ using Likert scales. The survey also relied on them being able to accurately recall past package opening experiences. This meant they were often relaying a general impression of what they perceived to be difficult, rather than what they definitely knew from recent experience was difficult.

4.4 Summary

This study found that the most difficult to open packages were perceived to be, in order of difficulty; jars, bleach bottles, soft drinks bottles, CRC medicine bottles, flexible sealed bags and shrink wrapped packaging. It also was found that older and younger adults had complex attitudes towards ADs. As predicted it was older adults that reported more difficulties with package opening than young, with female older adults reporting most problems, mainly due to a higher prevalence of reported hand or wrist ailments. There were no significant differences found in the difficulty reported between the age groups of the older adults, reflecting the findings of others that as people age they become more diverse. Generally speaking, the strength of feeling towards the problem of package opening was not overwhelmingly high among older adults, with their attitude being summed up as dissatisfied.

4.5 Implications for Thesis

While this part of the project successfully confirmed which types of packaging were perceived to be difficult to open, which helped inform the following ethnographic study, it did have the limitation of relying on respondents’ perceptions and ability to recall package opening difficulties. It also raised the interesting point that although package opening difficulties were apparent, they often went unreported and thus possibly explained why design commissioners and manufacturers do not demand inclusive design be achieved by designers.

Given that difficulties did exist, it was decided that a more comprehensive analysis of the nature of the difficulties surveyed in this study would be advantageous. The alternative strategies mentioned by the older adults were of particular interest, as it was assumed they would contribute somewhat to the understanding of the differences in how older and young adults perform manual tasks (objective 3). In addition to studying the alternative strategies that involved various tools and ADs, an analysis of the hands during unaided package opening was deemed necessary.

Chapter 5 Ethnographic Packaging Study

5.1 Introduction

The main aim of this section of work was to conduct a comprehensive analysis of the difficulties faced by older adults during package opening, identified in Chapter 4, using video ethnography. This work focussed on contributing towards objective 3.

One of the micro-objectives was to develop a novel, structured approach to analysing video-based ethnographic studies with respect to how people move. The ethnography discussed previously in the inclusive design literature (Section 2.2) tended to focus on environmental factors, behaviours, habits and routines of the subjects. Similarly many ergonomic analysis techniques rely on checklists, and timings of activities (Stanton and Young, 1999). While these analysis methods are useful, they are more suited to the analysis of workplace tasks and do not attempt to offer the observer the ability to analyse how the person moves or the physical interaction between them and the object.

A novel, structured approach to analysing ethnographic video studies was needed to identify whether or not older adults used different opening strategies compared with younger adults. By introducing structure to the analysis procedure, it was anticipated that some of the doubts over the validity and reliability of user trials and focus groups (Green, 1999) would be addressed.

A secondary micro-objective of the study was to assess whether or not it was viable to conduct a detailed ergonomic analysis of an activity without using expensive equipment and lengthy test procedures. A third micro-objective was to ascertain what behaviours and strategies to expect for the following biomechanical testing phase, thus avoiding some of the limitations of previous work which imposed unnatural test conditions on the subjects (Fowler and Nicol, 1999a).

5.2 Methods and Materials

An observer-as-participant type of ethnographic study was employed, whereby the subjects were fully informed that they were being studied, and the observer acknowledged that they would interact with the subject at various points during the testing. While a covert (complete observer) style may have been useful for observing older adults in a more natural environment (i.e. their home), the level of control offered by the observer-as-participant style was preferred (Gill and Johnson, 1997).

A total of 40 subjects were studied opening six types of packaging. 10 subjects (5 male, 5 female) from each of the age groups 60-70, 70-80 and 80-90 years old were studied. Also a control group of young adults (20-35 years old) was studied. The young subjects were recruited by convenience from staff and students within the Bioengineering Unit of the University of Strathclyde. Older adults were recruited by writing to the participants of the packaging survey (Chapter 4) and from a database of older adult volunteers who had participated in previous studies. Subjects were fully informed of all procedures before giving informed consent in line with institution ethical procedures. Subjects were excluded from the study if they did not live independently or had any history of nervous system conditions. All testing documents are shown in Appendix D.

Six types of consumer packaging were chosen based on the packaging survey of older adults (Chapter 4):

1. Jar (Tesco own brand value Pasta Sauce, 440g) with a lid diameter of 73mm
2. Soft drinks bottle (Irn-Bru, Barr Ltd Scotland, UK, 500ml) with a lid diameter of 30mm.
3. CRC Medicine Bottle
4. Soup tin with ring pull (Heinz vegetable soup, 400g)
5. Soft drinks can (Irn-Bru, 330ml)

6. Child resistant bleach bottle (Domestos, 750ml)

A dimensional replica of a standard kitchen worktop was created. Subjects were video recorded opening each type of packaging using the method they would normally use in their home environment. A number of everyday kitchen tools and items (i.e. knives, scissors, dish cloth, etc.) were made available to all subjects and could be used freely to replicate everyday practice. Subjects were also given the option of using an assistive device (AD) if they regularly employed one in their home. Figure 5.1 shows the laboratory set up for the video study showing the standard kitchen worktop with typical kitchen implements provided and camera positions.

Figure 5.1 Laboratory set up for the ethnographic packaging study (camera's circled). Kitchen work bench in foreground (from subject's perspective).

The subjects were presented with each of the unopened packaging types in a random order. Initially subjects were asked about how they would normally open the packaging (i.e. sitting or standing, with their bare hands, using a typical kitchen tool or AD) and this was recorded on the testing sheet shown in Appendix Di. The subject was then asked to open the packaging adopting their normal approach. Each type of packaging was placed directly in front of the subject so as not to influence which hand the subject used. The number of attempts taken before successful opening occurred was recorded. Once the subject successfully opened each type of packaging they were asked to rate the level of difficulty they experienced using a visual-analogue scale (Appendix Dii). Similarly, if they experienced any pain and discomfort during the process they were asked to rate its severity together with a description, i.e. sharp, dull, aching, lingering and its location (Appendix Diii). It was thought this approach would provide more accurate information on package opening difficulty as they were questioned immediately after opening, whereas the previously described questionnaire relied on them remembering past difficulties.

Video recording of the subjects using two digital cameras (Prosilica EC 650C, Burnaby, Canada) opening the packaging (one capturing their hands, one capturing their whole body) and using a program written in Labview v7.0 (National Instruments, US) the two camera outputs were combined and written into one '.avi' file. This enabled convenient simultaneous characterisation of detailed hand postures and whole body posture during the opening tasks as shown in Figure 5.2. It was therefore possible to examine trends in opening strategy with age and in relation to perceived difficulty of the task and any pain or discomfort felt.

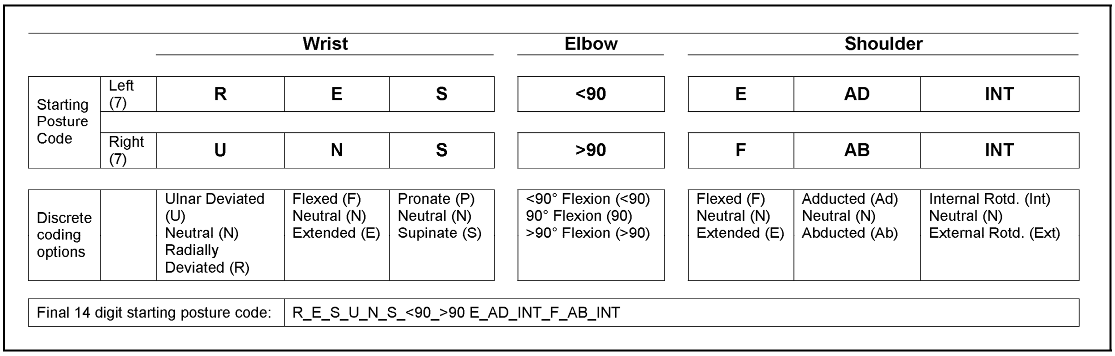
Figure 5.2 Example screenshot of package opening showing close-up view of hands and corresponding whole body posture.

The video study results were analysed to identify typical opening strategies. "Opening Strategy" was defined as consisting of three interrelated key components these being hand grip type, starting posture and opening motion:

Hand Grip Type referred to the way in which the subject grasped the lid of the packaging such that they could apply a torque by rotating their wrist/elbow/shoulder.

Starting Posture referred to a description of the static position of the wrist, elbow and shoulder joints immediately prior to the application of the force or torque to the packaging. Using the various degrees of freedom illustrated previously in Figure 2.8, the starting posture for each subject was then described by the code detailed in Figure 5.3, which was made up of 14 variables, each of which had 3 discrete alternatives.

Opening Motion referred to a description of the dynamics of each joint as the main opening force or torque was applied to the packaging. Again, a 14-varaible code similar to that used for starting posture was used to describe the opening motion.



		Wrist			Elbow	Shoulder		
Starting Posture Code	Left (7)	R	E	S	<90	E	AD	INT
	Right (7)	U	N	S	>90	F	AB	INT
Discrete coding options		Ulnar Deviated (U) Neutral (N) Radially Deviated (R)	Flexed (F) Neutral (N) Extended (E)	Pronate (P) Neutral (N) Supinate (S)	<90° Flexion (<90) 90° Flexion (90) >90° Flexion (>90)	Flexed (F) Neutral (N) Extended (E)	Adducted (Ad) Neutral (N) Abducted (Ab)	Internal Rotd. (Int) Neutral (N) External Rotd. (Ext)
Final 14 digit starting posture code:	R_E_S_U_N_S_<90_>90 E_AD_INT_F_AB_INT							

Figure 5.3 Example of a subject's 14-variable 'starting posture' code

The analyst of the video footage used their subjective judgement to classify the various hand grips exhibited, as well as the 14 DoF variables which described the starting postures and opening motions.

5.2.1 Statistical Analysis

Due to time constraints only two of the packaging types were selected for detailed analysis; the jar and the soft drinks bottle. These were chosen because they were previously identified as the two most difficult to open packaging type, so it was thought that their difficulty would highlight clear differences in opening strategy between the young and older adults.

All subjects were split into groups for comparison with respect to; control or subject group, hand or wrist ailments (HWA)(or none) and the level of difficulty they reported. 1-sample t-tests were used to split the subject group into 3 distinct categories of ‘Easy’, ‘Okay’ and ‘Difficult’ depending on the amount of difficulty they reported. Each of the 14 variables were analysed in isolation to identify commonly used starting postures and opening motions, using a One-Way Chi-Square test for statistical significance. Differences between opening strategies used by various subgroups were identified by tabulating them.

Mann-Whitney and cross tabulation chi-square tests were also used to test for various other relationships in the data. All tests were carried out using Minitab v15 statistical software and results were considered to be significant for $p<0.05$.

5.3 Results

It transpired that given the large number of variables involved, there were no combinations of grip style, starting posture and opening motion to give one ‘normal strategy’. It was therefore necessary to examine each individual variable in isolation, to identify any aspects of the complete opening strategy that were commonly found across the range of subjects.

Very few subjects chose to use ADs for their initial opening attempt (3 of 40 for the jar, 0 of 40 for the bottle) and they were excluded from the analysis of opening.

There was no clear trend between the hand placed on the lid and the handedness of the subject. A Mann-Whitney test was used to check whether or not placing one’s left or right hand on the lid was more likely to lead to a LOWER difficulty rating. The test did not prove any significant link. It was the case, however, that those who placed their left hand on the jar lid tended to conduct most of the twisting motion with either both hands or just their right hand, as shown in Table 5.1. This trend was not repeated in the case of the bottle.

Table 5.1 Comparison of hand placed on lid and hand which applies the twisting motion

		Hand(s) Appling Initial Twisting Motion		
		Left Hand	Both Hands	Right Hand
Jar	Left Hand on Lid	-	4	3
	Right Hand on Lid	1	3	18
Bottle	Left Hand on Lid	3	3	2
	Right Hand on Lid	3	13	16

5.3.1 Hand Grip Types

Six common grip types were identified for the bottle, as illustrated in Figure 5.4 with frequency of occurrence also indicated. Lateral Pinch Grip (Edwards and Buckland, 2002) using digits 1 and 2 was the most common.

A. Inverted Power Grip (2/40)

B. Lateral Pinch Grip (digits I and III) (6/40)

C. Lateral Pinch Grip (digits I and II) (22/40)

D. Other (1/40)

E. Power Grip (palm + digits III and IV) (7/40)

F. Normal Power Grip (2/40)

Figure 5.4 Grip types used for bottle opening (frequency of occurrence indicated)

Three main grip types (Edwards and Buckland, 2002, Yoxall et al., 2007) were identified for the jar. These grip types are illustrated in Figure 5.5 with the frequency of the occurrence of each grip type indicated in brackets.

A. Cylindrical Grip (1/37) B. Spherical Grip (19/37) C. Box Grip (17/37)

Figure 5.5 Grip types for Jar Opening (frequency of occurrence indicated)

Unlike for the bottle there was no clear favourite grip for the jar with the spherical and box grips being similarly popular.

There was no statistical relationship between the jar grip type used and the level of difficulty experienced. There was no particular grip style preferred by those reporting HWA.

5.3.2 Starting Posture and Opening Motion

Starting posture describes the static position of the wrist, elbow and shoulder joints immediately prior to the application of the force or torque to the packaging.

Table 5.2 shows the complete results for the common start postures and opening motions for both the jar and the bottle. It should be noted that in order to determine these ‘typical’ strategies the participants were split into two groups depending on which hand they placed on the lid (‘LH on Lid’ or ‘RH on Lid’). This was deemed necessary as during the analysis it became apparent that both the starting postures and opening motions were quite different depending on which hand was placed on the lid, and therefore not directly comparable. Refer back to Figure 5.3 for explanation of the 14-variable staring posture and opening motion codes used in Table 5.2.

Table 5.2 ‘Typical’ 14-variable Starting Postures and Opening Motions for the Jar and Bottle. ‘X’ denotes that there was no significant recurring pattern of posture/motion for that particular degree of freedom. Red= significant start posture, green = significant opening motion.

			L Wrist				R Wrist				L Elbow	R Elbow		L Shoulder				R Shoulder		
			Ulnar Deviated (U) Neutral (N) Radially Deviated ®	Flexed (F) Neutral (N) Extended (E)	Pronate (P) Neutral (N) Supinate (S)		Ulnar Deviated (U) Neutral (N) Radially Deviated ®	Flexed (F) Neutral (N) Extended (E)	Pronate (P) Neutral (N) Supinate (S)		<90° Flexion (<90) 90° Flexion (90) >90° Flexion (>90)	<90° Flexion (<90) 90° Flexion (90) >90° Flexion (>90)		Flexed (F) Neutral (N) Extended (E)	Adducted (Ad) Neutral (N) Abducted (Ab)	Internal Rotn. (Int) Neutral (N) External Rotn. (Ext)		Flexed (F) Neutral (N) Extended (E)	Adducted (Ad) Neutral (N) Abducted (Ab)	Internal Rotn. (Int) Neutral (N)
Start Posture	LH on Lid	Jar (7)	X	X	N		X	X	N		X	X		F	AB	INT		X	X	INT
		Bottle (8)	N	X	N		X	X	X		X	X		F	AB	INT		X	X	INT
	RH on Lid	Jar (30)	N	E	N		U	E	N		X	X		X	X	INT		X	AB	INT
		Bottle (32)	N	E	X		U	X	N		<90	X		X	N	INT		F	AB	INT
			Ulnar Deviation (U) No Movement (N) Radial Deviation	Flexion (F) No Movement (N) Extension (E)	Pronation (P) Neutral (N) Supination (S)		Ulnar Deviation (U) No Movement (N) Radial Deviation	Flexion (F) No Movement (N) Extension (E)	Pronation (P) No Movement (N) Supination (S)		Flexion (F) No Movement (N) Extension (E)	Flexion (F) No Movement (N) Extension (E)		Flexion (F) No Movement (N) Extension (E)	Adduction (Ad) No Movement (N) Abduction (Ab)	Internal Rotn. (Int) No Movement (N) External Rotn.		Flexion (F) No Movement (N) Extension (E)	Adduction (Ad) No Movement (N) Abduction (Ab)	Internal Rotn. (Int) No Movement
Opening Motion	LH on Lid	Jar (7)	N	N	X		X	X	X		X	X		X	AD	EXT		X	AD	EXT
		Bottle (8)	N	E	N		X	E	X		X	X		X	AD	X		X	AD	X
	RH on Lid	Jar (26)	U	F	N		R	N	N		X	X		N	X	X		X	AB	INT
		Bottle (32)	N	F	X		R	X	N		X	X		N	N	N		X	AB	X

It was possible to summarise starting positions and motions for both the jar, Figure 5.6, and bottle, Figure 5.7, as follows (for those who placed their RIGHT hand on the lid as they formed the vast majority (30 of 37 for jar, 32 of 40 for bottle)):

Jar Start Posture; Left wrist extended, right wrist extended and ulnar deviated, left shoulder internally rotated, right shoulder abducted and internally rotated.

Jar Opening Motion; Left wrist flexion, right wrist radial deviation, right shoulder abduction and internal rotation.

		LHS	RHS
Posture	Wrist	Extended	Extended + Ulnar deviated
	Elbow	-	-
	Shoulder	Internally Rotated	Abducted + Internally rotated
Motion	Wrist	Flexion	Radial deviation
	Elbow	-	-
	Shoulder	-	Abduction + Internal rotation

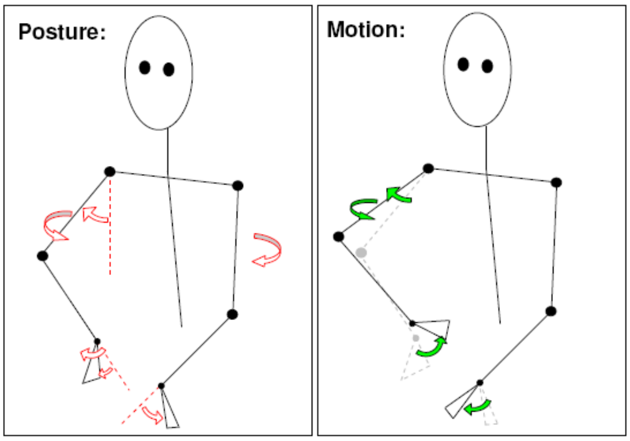


Figure 5.6 Starting postures (red) and motions (green) for JAR opening (for those who used right hand on lid)

Bottle Start Posture; Left wrist extended, right wrist ulnar deviated, left elbow flexed <90°, left shoulder internally rotated, right shoulder abducted and internally rotated.

Bottle Opening Motion; Left Wrist Flexion, right wrist radial deviation, left shoulder abduction.

Having established the typical starting postures and opening motions the results were analysed to check for any significant differences in the way that different groups opened the jar and the bottle.

		LHS	RHS
Posture	Wrist	Extended	Ulnar deviated
	Elbow	<90°	-
	Shoulder	Internally rotated	Abducted + Internally rotated
Motion	Wrist	Flexion	Radial deviation
	Elbow	-	-
	Shoulder	Abduction	-

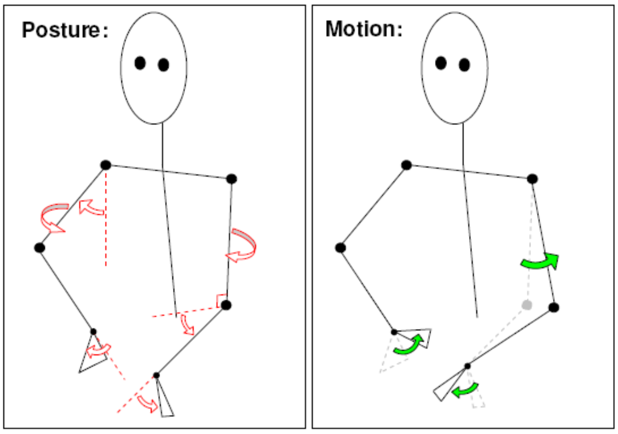


Figure 5.7 Starting postures (green) and motions (red) for BOTTLE opening (for those who used right hand on lid)

The first comparative test was between the older adults and young adults (subject group against control group) with the results shown in Table 5.3 There were no distinct differences between the subject and control groups, possibly due to insufficient data points for the control group (n=6).

Table 5.3 Differences between Control and Subject groups (RH on Lid only)

			L Wrist		R Wrist		L and R Elbows		L Shoulder		R Shoulder
Jar	Start Posture	Control (6)	X_**X**_**X**		U_E_**X**		X_X		X_X_INT		X_**X**_INT
		Subject (24)	X_**E**_**N**		U_E_**N**		X_X		X_X_INT		X_**AB**_INT
	Motion	Control (6)	N_**X**_X		R_X_X		X_X		**X**_X_X		X_**X**_**X**
		Subject (20)	N_**F**_X		R_N_N		X_X		**N**_X_X		X_**AB**_**INT**
Bottle	Start Posture	Control (6)	N_**X**_**N**		U_X_**X**		**X**_X		X_**X**_INT		**X**_**X**_INT
		Subject (26)	N_**E**_**X**		U_X_**N**		**<90**_X		X_**N**_INT		**F**_**AB**_INT
	Motion	Control (6)	N_F_X		**X**_X_N		X_X		**X**_**X**_**X**		X_AB_X
		Subject (26)	N_F_X		**R**_X_N		X_X		**N**_**N**_**N**		X_AB_X

In the case of difficulty levels reported, no statistically significant differences between age categories of the older adults were observed (all values p>0.05).

The second and third comparisons to be made were between those who found the opening activities significantly easier or significantly more difficult than the other subjects. Using the set of difficulty ratings gathered during testing, the complete group of subjects was split into 3 distinct categories according to how difficult they found each opening activity; ‘Easy’, ‘Okay’ or ‘Difficult’. The results of these comparisons are shown in Table 5.4 and Table 5.5 respectively.

Table 5.4 Differences (highlighted in bold) between ‘EASY’ and NORMAL groups (RH on Lid only)

			L Wrist		R Wrist		L and R Elbows		L Shoulder		R Shoulder
Jar	Start Posture	‘Easy’ (17)	**X**_E_N		U_E_N		X_X		X_X_INT		X_AB_INT
		Normal (30)	**N**_E_N		U_E_N		X_X		X_X_INT		X_AB_INT
	Motion	‘Easy’ (12)	**X**_**X**_X		R_**X**_N		X_X		**X**_X_X		X_AB_INT
		Normal (26)	**N**_**F**_N		R_**N**_N		X_X		**N**_X_X		X_AB_INT
Bottle	Start Posture	‘Easy’ (13)	N_E_X		U_X_N		<90_X		X_**X**_INT		**X_X**_INT
		Normal (32)	N_E_X		U_X_N		<90_X		X_**N**_INT		**F_AB**_INT
	Motion	‘Easy’ (13)	N_F_X		R_X_N		X_X		**X**_N_N		X_AB_X
		Normal (32)	N_F_X		R_X_N		X_X		**N**_N_N		X_AB_X

Table 5.5 Differences (highlighted in bold) between ‘DIFFICULT’ and NORMAL groups (RH on Lid only)

			L Wrist		R Wrist		L and R Elbows		L Shoulder		R Shoulder
Jar	Start Posture	‘Difficult’ (12)	**X_X_X**		U_**X**_N		X_X		X_X_INT		X_AB_INT
		Normal (30)	**N_E_N**		U_**E**_N		X_X		X_X_INT		X_AB_INT
	Motion	‘Difficult’ (8)	N_**X**_N		R_N_N		X_**E**		N_X_X		X_**X_X**
		Normal (26)	N_**F**_N		R_N_N		X_**X**		N_X_X		X_**AB_INT**
Bottle	Start Posture	‘Difficult’ (7)	**X**_E_X		**X**_X_**X**		**X**_X		X_**X**_INT		**X_X**_INT
		Normal (32)	**N**_E_X		**U**_X_**N**		**<90**_X		X_**N**_INT		**F_AB**_INT
	Motion	‘Difficult’ (7)	N_**X**_X		**X**_X_**X**		X_X		**X_X**_N		X_**X**_X
		Normal (32)	N_**F**_X		**R**_X_**N**		X_X		**N_N**_N		X_**AB**_X

Only 2 significant differences were recorded between the strategies adopted by those who found the packaging easier to open than the rest of the sample population (Table 5.4) and these were as follows:

JAR: Those in the 'Easy' group exhibited more variation in the left wrist (their jar body holding hand) in the ulnar-radial DoF, both in terms of their starting postures and their opening motions.
BOTTLE: The previously established norm (see Table 5.2) was for the right shoulder to have a flexed starting position, however the 'Easy' group exhibited a variety of different starting postures in this DoF.

There were 3 significant differences between the strategies adopted by those who found the packaging more difficult than the rest of the sample population (Table 5.5):

JAR: Those in the 'Difficult' group exhibited more variation in the left wrist in the ulnar-radial DoF when considering their starting posture.
JAR: Those in the 'Difficult' group showed more variation in the right wrist (their jar lid holding hand) in the flexion-extension plane when considering starting posture. The previously established norm was for the right wrist to be extended.
JAR: Those in the 'Difficult' group showed a preference towards extending their right elbow during the opening activity.

The final comparison to be made was between groups of those who reported HWA, and those who reported none.

Table 5.6 Differences (highlighted in bold) between subjects with and without reported hand or wrist ailments (RH on Lid only)

			L Wrist		R Wrist		L and R Elbows		L Shoulder		R Shoulder
Jar	Start Posture	None (16)	**N**_**X**_N		U_**E**_N		X_X		X_X_INT		X_AB_INT
		HWA(14)	**X**_**E**_N		U_**X**_N		X_X		X_X_INT		X_AB_INT
	Motion	None (15)	N_**X**_X		R_N_N		X_X		**X**_X_X		X_AB_INT
		HWA (11)	N_**F**_X		R_N_X		X_X		**N**_X_X		X_AB_INT
Bottle	Start Posture	None (16)	N_E_**N**		U_X_**N**		<90_X		X_**X**_INT		**X**_**AB**_INT
		HWA (16)	N_E_**X**		U_X_**X**		<90_X		X_**N**_INT		**F**_**X**_INT
	Motion	None (16)	N_F_X		**N**_**X**_N		**N**_X		N_**X**_N		X_AB_X
		HWA (16)	N_F_X		**X**_**X**_N		**X**_X		N_**N**_N		X_AB_X

The results in Table 5.6 show that there were only 4 significant differences in posture and motion between subjects who reported HWA and those who reported none. These four differences were as follows:

JAR: Those with HWA were more likely to start with their left wrist (left hand grasping main body of jar) extended.

JAR: Those with HWA were then more likely to display flexion of their left wrist during the opening motion. Those with no HWA tended to show more variability in this particular DoF of the left wrist.

JAR: Those with no HWA were more likely to start with their right wrist in an extended position.

BOTTLE: Those with HWA tended to adopt a start position with their right shoulder in the flexed position,

Tests were also carried out to confirm if those with HWA found opening more difficult. Chi-square table test confirmed this ($p<0.05$) for jars. Mann-Whitney test gave a strong confirmation ($p<0.001$) in the case of jars, but only a weak confirmation ($p=0.0603$) in the case of bottles. So it was concluded that there was a link, but it was more apparent with the jar than the bottle.

Further tests were applied to the data to test if holding the packaging at an angle while applying the opening torque made the opening task easier than holding it vertical. Mann-Whitney test provided a good confirmation that tilting the packaging at an angle did make it less difficult to open (Jars $p<0.05$, Bottle $p<0.05$).

5.4 Discussion

This study was primarily designed to elicit quantitative information on the opening strategies used by older adults to open difficult packaging, namely jars and bottles.

It has been demonstrated that older adults report greater levels of difficulty during package opening (Carse et al., 2007, Yoxall et al., 2006a), however, there is little evidence to suggest whether or not older adults adopted alternative strategies or coping strategies to compensate for a loss of hand function. By quantifying the opening strategies used by older adults in reference to a young adult population this study provided evidence that subtle differences do exist.

This study used a chronological age criteria to group subjects in the 60-90 years old age range and there were no clear differences in opening strategy used between the older adult age groups. There is evidence to suggest that there is considerable variation in the ability of people within any age group (Spirduso, 1995, Steenbekkers and Beijsterveldt, 1998). The use of physiological age rather than chronological age may have presented an alternative means of analysing the data. However, the use of simple pain and difficulty scales and a self assessed HWA indication allowed segregation of the older adult population into groups based on physical characteristics that may be considered to be loosely related to physiological age.

When subjects used ADs, it did not in lead to noticeably lower difficulty ratings, or speed it up, but it did usually reduce the amount of pain or discomfort experienced. Those using ADs did not appear to do so with a particularly high level of control.

The control group did report some high levels of difficulty, as well as pain and discomfort. Difficulty ratings were generally consistent with previous studies (Carse et al., 2007, Winder et al., 2002) with jars having the highest difficulty ratings and requiring the highest number of alternative strategies (note that a range of products were tested including a CRC medicine bottle, bleach bottle, soup tin and a soft drinks can, although only the results of the most difficult to open jar and bottle products are presented here).

The gripping strategies used not only involved application of force through the digits, but also through the palm (e.g. spherical grip (Figure 5.5b) and box grip (Figure 5.5c)). It might be hypothesised that these strategies allowed application of greater torque to the packaging whilst not requiring as much load to be transferred to the digits, thus reducing shearing effects at the base of the fingers and thumb; the metacarpophalangeal joints.

Subject and control group members quite often pressed the packaging down onto the work surface to provide them with extra grip. This strategy would have allowed the use of the weight of the upper body to provide a greater load perpendicular to the surface of the packaging lid to increase friction and therefore torque generation capacity.

Subjects and control group members often used a cup-shaped hand over the top of bottles and jars, grasping 2, 3 or 4 fingers together at once. This strategy provided additional 'lateral' support to the digits again allowing greater torque application and preventing overload of any one digit.

Handedness did not necessarily determine the way in which the subjects gripped the packaging. For example when a subject was right handed they did not necessarily use their right hand to grasp the lid of the packaging and support the base with their left. This was the case for both the subject and control groups. Previous research has found that most right-handed people preferred to have their left hand on the lid, and vice-versa (Voorbij and Steenbekkers, 2002). This would perhaps indicate that choice of which hand was placed on either the lid or product body was determined by factors other than relative strength or skill level in the hands.

There was only limited evidence to support the hypothesis that those with HWA adopt different package opening strategies, although for bottle opening those with HWA did tend to adopt a start position with their right shoulder in the flexed position (Table 5.6). It is possible that this strategy provided a better position in which to use full muscle strength or that it provided an additional safety/overload prevention mechanism to the opening strategy preventing the likelihood of development of pain. Another difference was that for jar opening those with HWA (RH on lid) were more likely to start with their left wrist in an extended position and then flex the left wrist during opening. This aspect of their strategy may have helped them to generate greater torque to open the lid, as previous studies have shown that not only is grasp strength greater when the wrist is slightly extended (Pryce, 1980), but greater force can be generated in flexion of the wrist than extension (Hallbeck, 1994). Adopting such strategies may represent a more efficient use of the diminished strength of this group.

In agreement with previous research (Chang et al., 2008) the results showed that holding both the jar and the bottle tilted at an angle made the opening task easier. Holding the jar tilted at an angle appeared to encourage the subject to supinate the forearm of the hand grasping the body of the jar or bottle. This supination combined with the flexion of the wrist will have provided an extra advantage as previous studies have shown that higher loading can be generated when the forearm is supinating than when it is pronating (O'Sullivan and Gallwey, 2005). There was however no evidence to suggest that those reporting HWA's were more likely to adopt this tilting strategy to make the opening task easier.

Opening strategies used by the subjects involved specific positioning of the whole arm in relation to the packaging and often involved the application of weight from the torso via the arm. The strategies described here provide quantitative insight into the way that adults open packaging. Although a number of subtle differences were observed between those reporting HWA and those who did not, these were mostly when studying the jar. One explanation for this might be that bottle opening was not a maximal task for the subjects, and they were therefore free to adopt any combination of grip style, starting posture and opening motion according to their individual preferences, which in turn resulted in greater variation in the results. Jar opening on the other hand presented more of a maximal task and required an optimal strategy whereby grip types, starting postures and opening motions were combined to generate the maximum torque to remove the lid. The optimal strategies used were more distinct and were therefore more straightforward to categorise. The results seem to indicate that the subjects would adopt an age independent, habit based strategy for relatively easier to open packaging, but would all adopt an optimal opening strategy with elements of self learnt modification (due to HWA) for the most difficult to open packaging.

By way of summarising the method developed by the work in this chapter, which can be used by designers and ergonomists alike to analyse video footage in a structured manner, the diagram in Figure 5.8 was produced. The complete method is described as follows.

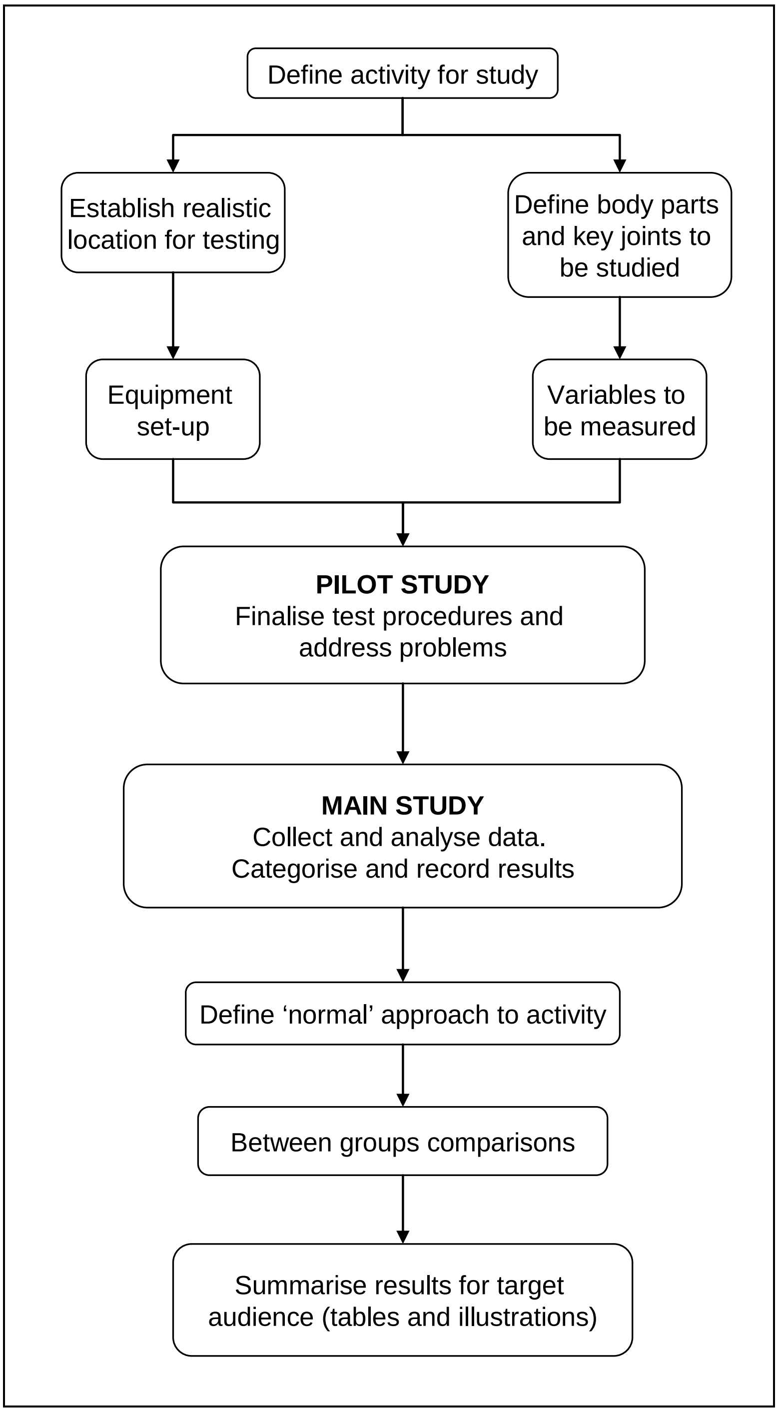


Figure 5.8 Flowchart of method for conducting and analysing a video-based ethnographic study.

Once the activity and product to be studied have been decided upon, the location(s) at which the activity would normally be used should be identified and efforts made to perform testing in such a location, or replicate it in laboratory. Every effort must be taken to ensure the testing environment is similar to that of where the product would usually be used. Recording equipment should be taken to the testing location and placed appropriately such that it records all the footage required for detailed analysis yet is not overly intrusive for the test subjects. Concurrently with location set-up, the key body parts of the subjects to be studied should be clearly identified, with particular attention being paid which joints are to be analysed. For each joint a classification system should be developed that allows the post-testing data analyst to measure each subject's postures and motions in a repeatable manner. Any additional variables to be measured during the testing should also be identified at this point, for example difficulty, pain/discomfort or presence of HWA.

The subsequent pilot study should consist of two main components; data collection and data analysis. During the data collection phase the tester will be identifying any technical issues with the cameras, problems with testing documents, the time required of subjects and any safety concerns that might arise. Close attention should also be paid to any unexpected behaviour or motion patterns that may not have been anticipated in the experiment design or positioning/angle of cameras. During the data analysis phase of the pilot study the analyst should assess whether or not the previously defined categorical variables are suitable and if not, revise them. They might also wish to suggest changes to the data collection procedures in light of any unclassifiable actions or behaviours observed. The time taken to complete a full analysis of one subject should be noted too, as this will provide an idea of how long the complete data analysis will take. Generally speaking a pilot study using up to 5 subjects should be sufficient.

Once the testing and analysis procedures have been finalised, the main study can take place with the results recorded and analysed. During the analysis of the results an attempt to identify a 'normal' approach should be done using statistical analysis techniques. Between groups comparisons can also be achieved by splitting the test subjects' results into the required groups and tabulating them (see Tables 5.3-5.6 for examples). Finally, every effort should be made to summarise the results and present them in a format that is understandable to the target audience (see Figures 5.6 and 5.7 for examples).

5.5 Summary

Using ethnographic video studies is popular with designers as it can provide a rich source of qualitative information, although it can also lend itself to a more focussed investigation and quantitative analysis of behaviours.

‘Opening strategies’ for bottles and jars have been identified, classified and described. Within this context an ‘opening strategy’ was defined as consisting of grip type, upper limb starting postures and motion patterns. This study has established that there is no statistically significant difference between young and old adults in terms of grip types, starting postures and motion patterns. There were, however, some adaptations of opening strategy for those suffering from HWA.

A method of quantitatively describing the interaction of people with packaging products has been presented. This method provides the basis for evaluating the interaction of people with products and may be used in a range of cases where people-product interactions are of interest. The ability to compare two groups of subjects offers potential to assess the inclusive nature of a design.

There is scope for this method to be applied to other products or activities, analysing any joints of the body, or indeed to generate more information on the design requirements of any other group, not just older adults.

5.6 Implications for Thesis

While the outlined approach to analysing ethnographic footage did not identify many statistically significant differences in package opening strategy, it did prove effective in providing a structured method of identifying and describing how people move during an interaction with a product. One important finding is that this sort of technique has to be accompanied by the simultaneous collection of other subject data such as difficulty and pain/discomfort ratings. The video footage in isolation was of limited use.

Important limitations of the method were that it lacked the facility to describe sequences of multi-joint movement as it implies they all happen at once which is not necessarily the case. It failed to account for multiple movements of single joint in any given degree of freedom. Furthermore, as it considered movement (caused by concentric and eccentric muscle contractions) and posture, it had no mechanism for indicating isometric muscle contraction.

The study successfully yielded a number of different types of data that could be presented to designers; video footage, still images, difficulty ratings, pain and discomfort charts, frequency of grip types used, starting postures and motion patterns. These sources of data would prove valuable when performing the second round of interviews with design professionals (Chapter 7).

Furthermore, the study proved to be highly useful in informing the subsequent biomechanical testing phase as it highlighted a number of package opening observations. Firstly, the grouping together of digits II-V observed in many subjects meant that load measurement of individual digits was not realistic. Secondly, the need for the subject to be able to pick up any jar or bottle and tilt it to their preferred angle was identified, so stipulating that the packaging be held on the table would not have been acceptable for realistic testing. Finally, the need to have a more comprehensive description of the various HWAs experienced by older adults was recognized. Given the variety and different severities of HWAs experienced by older adults, a nominal yes/no description was useful for splitting subjects into groups for comparison, but perhaps over simplified the situation. Biomechanical testing would allow for a closer examination of the effect of age and hand function on package opening tasks.

Chapter 6 Biomechanical Testing

6.1 Introduction

The ethnographic study successfully provided a number of insights into how people with hand and wrist ailments tackle package opening differently to young adults. As discussed previously in Section 2.3.5, using a motion analysis system and force sensing equipment can generate more detailed, objective data on the biomechanics of package opening activities. While this was clearly likely to require more equipment, time, and advanced data analysis techniques than the ethnographic study, it was thought that this level of detail was necessary to gain an in-depth understanding of package opening. This piece of work was concerned primarily with answering objective 3, but also provided findings for objective 4.

Given the analysis carried out during the ethnographic study, it followed logically that both the jar and soft drinks bottle should be activities analysed during the biomechanical testing phase. The specific micro-objectives of this part of the project were:

1. Make any test procedures as life-like as possible, without compromising accuracy levels.
2. Objectively quantify how older adults open packaging differently in terms of their grip style, starting posture and opening motion, identifying any clear compensatory strategies used.
3. Assess whether or not hand functionality is a more accurate predictor of ability/control than age.
4. Evaluate the viability of using biomechanical testing for product design assessment and for generating transferable ergonomic data.

The following chapter will describe in detail the methods used, the results that were generated, followed by a discussion of the results and their implications.

6.2 Methods

As there were a number of individual methods used for this part of the project, a diagram indicating the structure of this methods section (Figure 6.1) shows the methods used for capturing the data during subject testing as well as the methods used for the subsequent processing and analysis of the data.

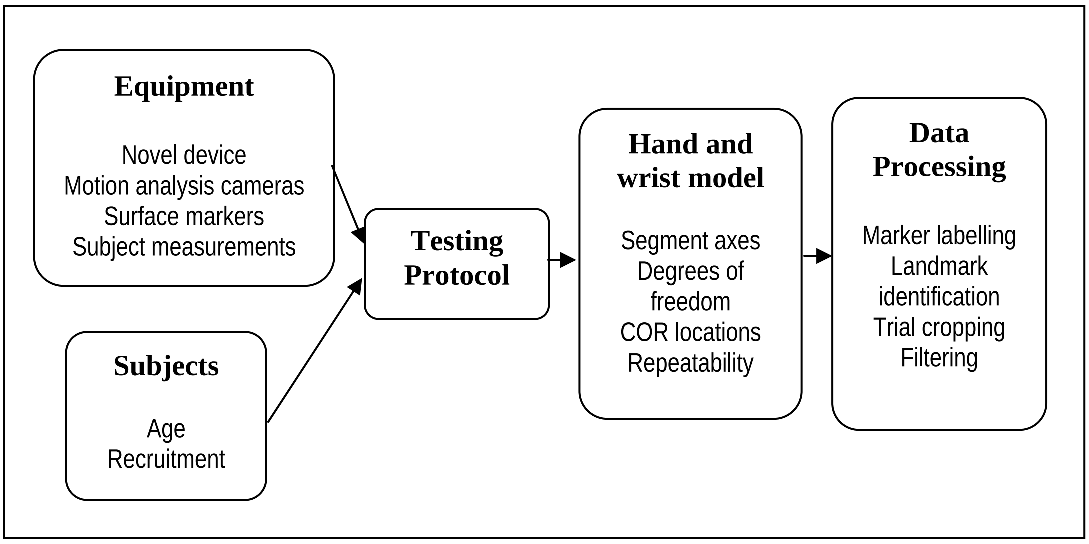


Figure 6.1 Outline diagram of 'Methods' section structure

6.2.1 Subjects

A control group of 10 young healthy adults was recruited along with a subject group of 18 older adults. The control group comprised of 5 males and 5 females with mean ages of 25.6 (±0.6) and 26.6 (±1.1) years respectively, while the subject group consisted of 8 and 10 females of 75.1 (±8.2) and 76.4 (±8.1) years respectively. The control group was made up of students from the Bioengineering Unit of the University of Strathclyde who had no history of nervous system conditions. The subject group was made up predominantly of older adults who had volunteered for the ethnographic study as well as one visiting lecturer from the University of

Strathclyde. All older adult subjects were screened to ensure they had no history of neurological conditions, and that they did live independently.

6.2.2 Equipment

There were a large number of pieces of equipment used during the biomechanical testing phase to measure hand functionality, track body segment motion, measure forces applied to the hand and also to process data. These will all be described in the following sub-section.

6.2.2.1 Preliminary Subject Measurements

Measurements of all subjects' hand functionality were taken before testing commenced. Power grip strength was measured using a standard Jamar® Hand Dynamometer (Lafayette Instruments, Lafayette, IN) with each subject completing three isometric maximal strength tests with each hand, alternating which hand was used. Subjects were invited to find the grip span setting they thought would provide the strongest gripping position and all chose to have the handle in the second position. The subjects were instructed to sit with their shoulder adducted and neutrally rotated, elbow flexed at 90°, forearm in neutral position and wrist between 0° and 30° extension and between 0° and 15° ulnar deviation (Mathiowetz et al., 1985). Results were recorded in kilograms force and were later converted into Newtons and mean measurements were calculated for each hand.

The manual dexterity of all subjects was measured using the Purdue Pegboard Test (Lafayette Instruments, Lafayette, IN). This test involved the subject picking up small metal pegs and placing them into a series of holes as quickly as they could within a specified time period. While there were number of commercially available manual dexterity tests available, the Purdue Pegboard Test was selected for this study because it was quickly administered (5 minutes), assessed both unilateral and bilateral hand co-ordination and measured finger, hand and arm function in addition to fingertip dexterity (Hardin, 2002). The guidelines provided with the testing kit were followed closely and four tests per subject were completed; left hand (30 seconds), right hand (30 seconds), both hands simultaneously (30 seconds) and an assembly task involving both hands (60 seconds). Subjects were invited to briefly practice each test before the timing began. They were also seated such that the board and pegs were within comfortable reach and instructed to keep their hands in a designated starting position until the 'go' command was given, thus ensuring no unfair advantage.

Anthropometric measurements were taken from all subjects, with the depths of 38 joints (19 right hand, 19 left hand) taken using standard digital callipers (Farnell, UK). Joint depths measured were the MCP, PIP and DIP joints of digits II-V on each hand, the MCP and DIP joints of digit I on each hand and the depth of the fingertips at approximately 5mm proximal to the end of the fingernail. All measurements were noted on a pre-prepared testing sheet, shown in Appendix Fiii.

6.2.2.2 Markers and Marker Placement

A series of reflective spherical markers of 4.5mm diameter were placed on nylon bases with the centre of the marker 10mm vertically above the underside of the base as shown in Figure 6.2. The reflective spheres were placed on stalks such that the motion analysis cameras would be able to pick up their locations more easily. The markers were attached to the subjects' hands using Clear™ toupée tape (3M, UK).

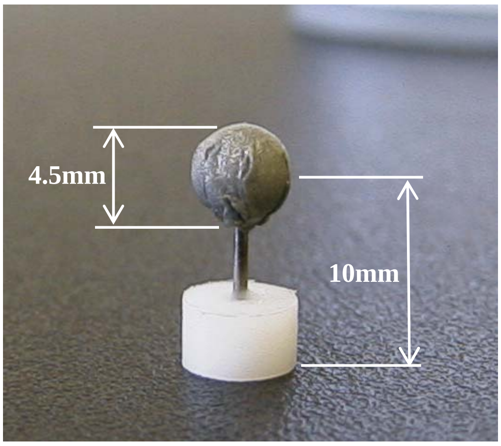


Figure 6.2 Dimensions of 26 x 4.5mm diameter markers used

The layout of the markers on one subject’s hand, along with the unique label assigned to each of the markers, is shown in Figure 6.3. A single marker method was adopted, similar to those in previous studies (Carpinella et al., 2006, Cerveri et al., 2007, Metcalf et al., 2008) with a total of 52 single markers (26 per hand) applied. Four markers were applied to digits II-V (MCP. PIP, DIP and fingernail), four to digit I (CMC, MCP, IP and fingernail), two to the dorsal aspect of metacarpals II and V and four to the forearm. One triad of markers was also each forearm. The exact anatomical position of each marker is described in Table 6.1. When markers were applied to a finger joint the subject was asked to flex the joint in question and the marker was placed on the resulting apex, thus ensuring it was placed directly over the joint’s centre of rotation as shown in Figure 6.4.

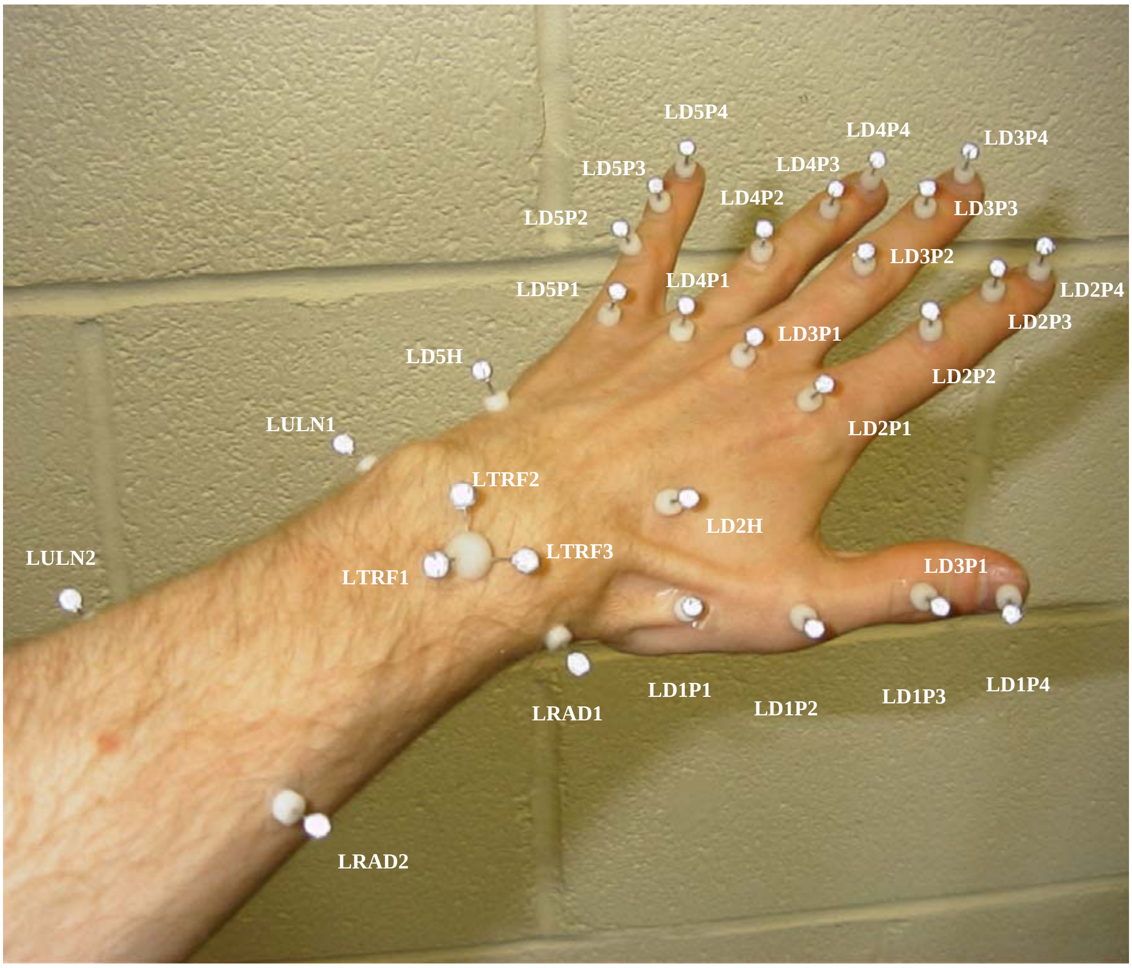


Figure 6.3 26 single markers and 1 triad of markers positioned on subject's hand. Unique marker labels indicated.

Table 6.1 Marker labels and anatomical position descriptions

Marker Label	Marker Position		Marker Label	Marker Position
LTRF1	Forearm triad marker one, pointing in the proximal direction		LD2P3	Apex of DIP joint, digit II
LTRF2	Forearm triad marker two, in clockwise direction from LTRF1		LD2P4	Fingernail, 5mm proximal from end of digit II
LTRF3	Forearm triad marker three, in clockwise direction from LTRF2		LD3P1	Apex of MCP joint, digit III
LRAD1	Most lateral point of radial styloid process		LD3P2	Apex of PIP joint, digit III
LRAD2			LD3P3	Apex of DIP joint, digit III
LULN1	Most medial point of ulnar styloid process		LD3P4	Fingernail, 5mm proximal from end of digit III
LULN2			LD4P1	Apex of MCP joint, digit IV
LD2H	Proximal head of metacarpal II		LD4P2	Apex of PIP joint, digit IV
LD5H	Proximal head of metacarpal V		LD4P3	Apex of DIP joint, digit IV
LD1P1	Apex of CMC joint, digit I		LD4P4	Fingernail, 5mm proximal from end of digit IV
LD1P2	Apex of MCP joint, digit I		LD5P1	Apex of MCP joint, digit V
LD1P3	Apex of IP joint, digit I		LD5P2	Apex of PIP joint, digit V
LD1P4	Fingernail, 5mm proximal from end of digit I		LD5P3	Apex of DIP joint, digit V
LD2P1	Apex of MCP joint, digit II		LD5P4	Fingernail, 5mm proximal from end of digit V
LD2P2	Apex of PIP joint, digit II			

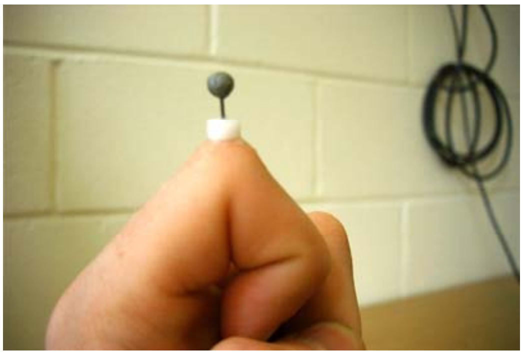


Figure 6.4 Marker placement on apex of flexed PIP joint

6.2.2.3 Motion Analysis Equipment

An eight camera Vicon 612 motion analysis system (Oxford Metrics, UK) with a capture rate of 120Hz was used to track the motion of the reflective markers on each subject's hands. Given the variety of opening strategies displayed by subjects during the ethnographic study (Section 5.3) the cameras were arranged such that they would capture the positions of as many markers as possible. The camera layout used is shown in Figure 6.5. Cameras were calibrated before each subject was tested with calibration residuals of 0.1-0.3mm obtained. In addition to tracking and recording the motion of the markers, the motion analysis system also simultaneously recorded 12 channels of analogue force and moment data from novel packaging device.

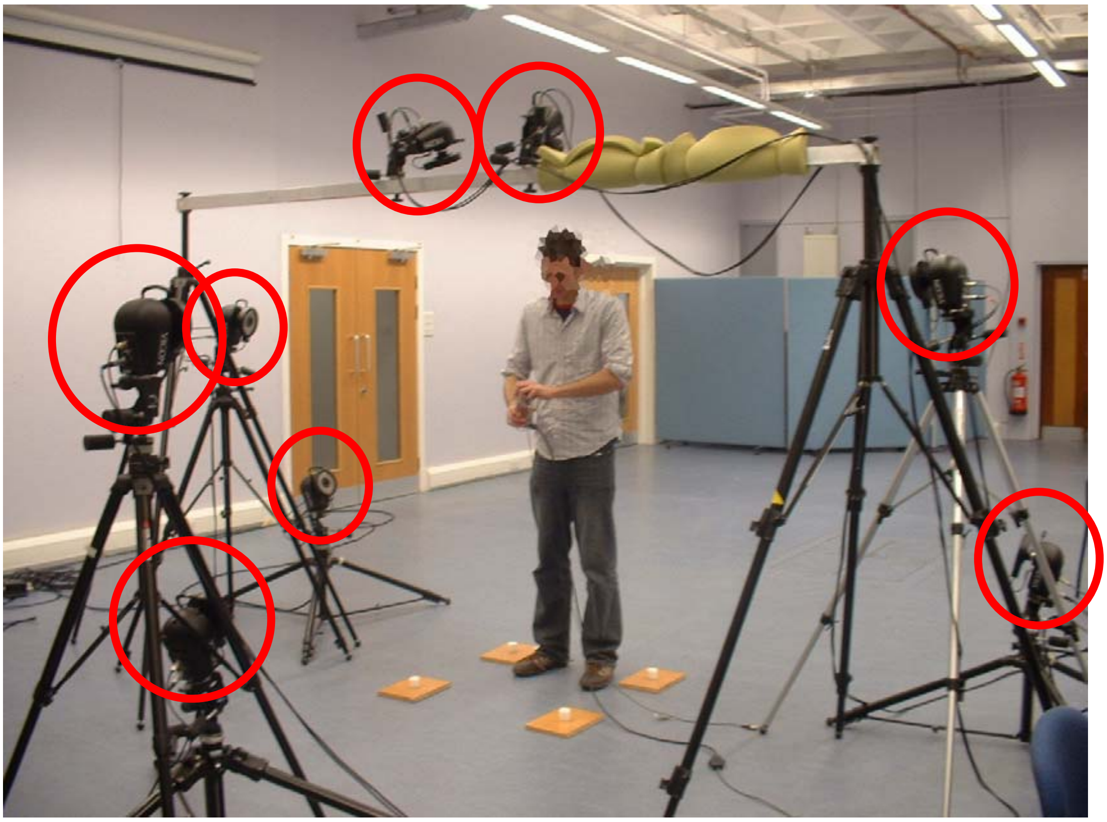


Figure 6.5 Eight motion analysis camera positions

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6.2.2.4 Jar/Bottle Force Measuring Device

As discussed previously in Section 2.4.2, the limitation of many studies that measured the forces and torques generated during package opening was that they were static (Voorbij and Steenbekkers, 2002, Yoxall et al., 2006a) with the exception of one (Carus et al., 2006). In order to gain insight into the dynamic nature of jar/bottle opening, a device was designed to serve four key functions:

1. Measure the forces and moments applied to each half of the lid, i.e. by opposing hand segments.

2. Mimic an everyday jar and bottle, both dimensionally and in the way the lid would rotate open once the required torque was generated by the subject.
3. Be interchangable from a jar to a bottle configuration, and vice-versa.
4. Allow a motion analysis system to track its position and the motion of its moving parts.

The device was designed with one central core which could have extra components added or removed to provide either a jar or soft drink bottle configuration as required. This central core included two rigidly mounted pre-calibrated ‘Nano 25’ six degree-of-freedom force/torque transducers (ATI Industrial Automation, Apex, NC) as shown in Figure 6.6. Full technical specifications for the Nano 25 transducers can be found in Appendix G.

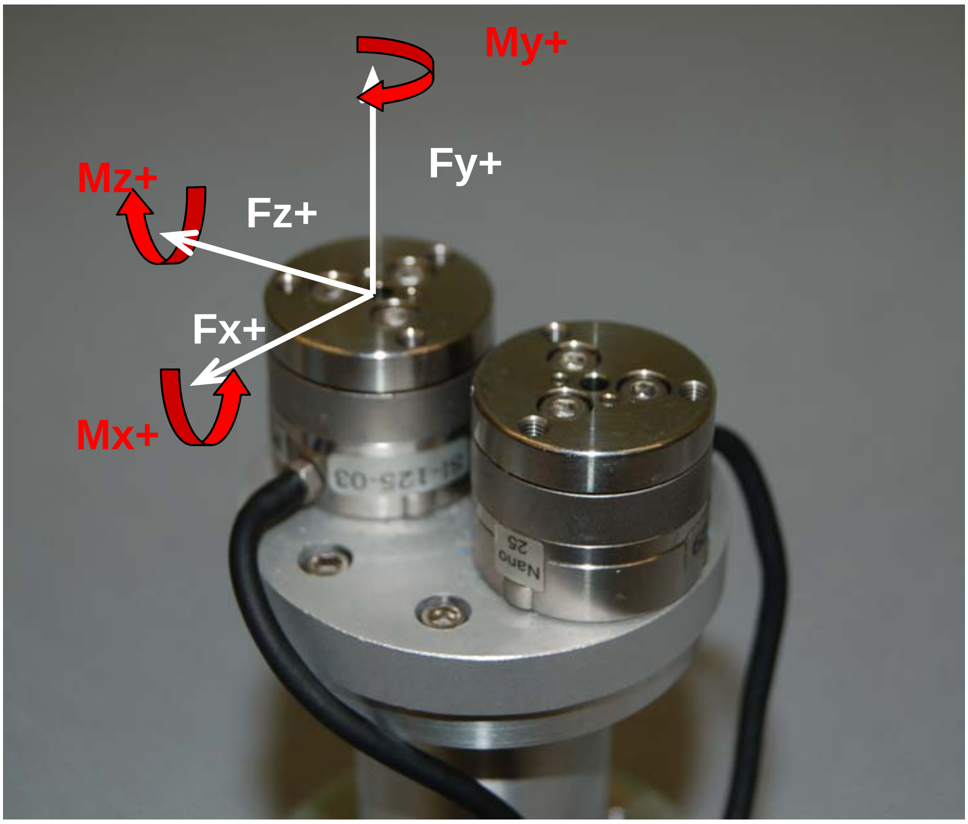


Figure 6.6 'Central core' of device, showing two Nano 25 transducers and an example 6 DoF axes system

Including two Nano 25 transducers allowed the measurement of two opposing grip components (discussed in Section 2.3.2.2) in isolation via a total of 12 analogue channels (6 for each transducer). Through fastening two rigid lid segments (adapted from real packaging) to these two transducers a realistic hand-lid interface was created for both the bottle and jar, as shown in Figure 6.7.

Figure 6.7 Segmented realistic hand-lid interfaces for a) jar, and b) bottle. Both mounted on the central core of the device

The design of the device's jar configuration (Figure 6.8a) was based on a 440g Tesco own brand value Pasta Sauce and the bottle configuration (Figure 6.8b) based on a Robinson's Orange Barley Water 1L bottle. While every attempt was made to exactly replicate the dimensions of the real packaging, some dimensional compromises had to be made in order to incorporate all of the required components and in the case of the bottle, the contours of the real packaging could not be replicated. The dimensional accuracy of both configurations is provided in Table 6.2.

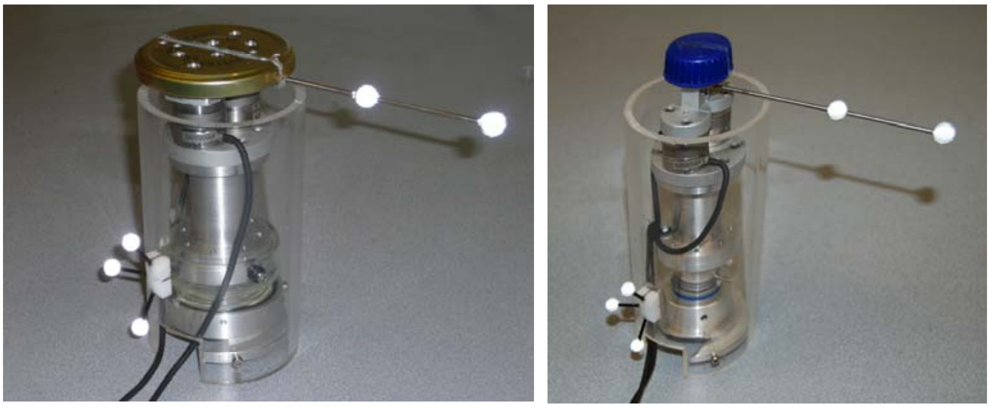


Figure 6.8 The final device in a) jar configuration, and b) bottle configuration. Device lid and body reflective markers shown.

Table 6.2 Dimensional accuracy of device's jar and bottle configurations

	Lid Diameter (mm)		Body Diameter (mm)		Body Height from base to underside of lid (mm)	
	Real Packaging	Device	Real Packaging	Device	Real Packaging	Device
Jar	73	73	76	80	130	144
Bottle	35	36	78	80	250	182

One of the most important design features of the device was that it provided a realistic dynamic opening resistance, which was achieved by incorporating real inverted jar and bottle lids. In the case of the jar configuration the sawn-off threaded neck of a jar was fastened to the rigid central core of the device (Figure 6.8a), which included the two Nano 25 transducers and the appropriate lid sections (see Figure 6.7). An internal lid was then tightened onto the neck by hand (Figure 6.8b) and the lid was then gripped in the base section using grub screws (Figure 6.8c).

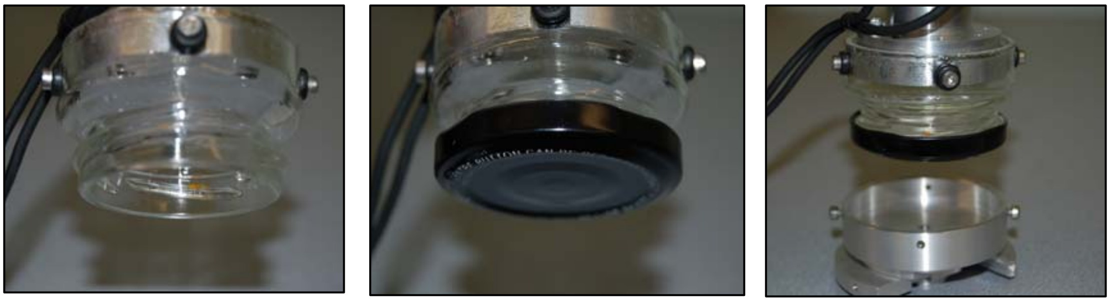


Figure 6.8 Realistic dynamic opening resistance for jar. a) Sawn-off threaded jar neck attached to central core, b) new 56mm jar lid tightened on by hand, c) jar lid gripped to base using grub screws

When the internal lid was fixed in place the subject would then pick up the complete device and in placing their hand on, gripping and twisting the segmented lid, they would build up a torque large enough that the resistance of the internal lid would be overcome. This resulted in the whole central core suddenly rotating in anti-clockwise direction similar to the way in which a normal jar lid ‘pops’ open.

The bottle configuration was designed using a similar concept only in this case due to the tamper-evident seal on the bottle lid it was impossible to remove the lid from the neck of the bottle without breaking this seal. A series of intact lid and sawn-off bottle neck combinations were obtained by draining the contents from full 500ml plastic bottles of Barr’s Irn-Bru, cutting them to size on a band saw and then drilling a 3mm hole laterally through the neck. This hole allowed the insertion of a pin to connect the inverted neck to the rigid central core, while the lid was gripped in the base section using grub screws (see Figure 6.9).

Figure 6.9 Realistic dynamic opening resistance for bottle.

Due to the plastic deformation that can occur during lid tightening, a new lid was used for each jar opening activity. Bottle opening also required a new bottle lid and neck combination for each activity, as the tamper-evident seal was broken during each activity.

Ideally the internal jar lid and the segmented lid at the top would have been identical, however the internal jar lid diameter had to be smaller than that of the segmented lid in order for it to fit inside the device. A suitably sized internal jar lid was identified (56mm diameter, 10mm depth from Crown Packaging UK) although it was immediately apparent that this lid did not provide enough torque resistance. A previous study measured the torque of intact jars (i.e. jar that had their vacuum seals intact) and found that jars of 75mm required an opening torque of 3Nm (±0.36) (Janson, 2007). Four small sections of duct tape were stuck over the four lugs of the internal jar lids to provide extra torque resistance. These lids were then tightened onto the jar neck as tightly as possible by hand and a Torqueleader 'ADS 12A' torque wrench (MHH Engineering Co. Ltd., UK) with a custom made lid gripping attachment was used to remove the lids. The opening torques were found to be 2.81Nm (±0.49) which, although less than the previously stated target 3Nm (±0.36) opening torque, was deemed suitable because all test subjects were required to successfully open each lid to make the tests dynamic. With the previous prediction that 50% of females over 75 years would struggle with 75mm diameter lids (Yoxall et al., 2006a), this lower mean value of opening torque meant that the female older adults would face less difficulty during the jar opening activity. The opening torque variability found in tightening the internal lids, complete with added duct tape, was no higher than that found in intact jars taken from the supermarket shelf, so again this was deemed to be acceptable.

The lid could be locked in position at any required angular displacement, allowing the reflective marker sets (shown in Figure 6.8) to be carefully positioned relative to one another such that they would be seen by the cameras, yet not impede the subject's natural favoured gripping style. Real jars and bottles were handed to the subject so their preferred starting posture and grip style could be assessed before testing. The lid was then positioned at the appropriate angular displacement and then locked in place.

6.2.3 Testing Protocol

Having designed, built and tested all of the equipment a standard subject testing protocol was required to ensure that testing was conducted in a structured and consistent manner. The protocol was as follows:

1. The subject was transported to the test laboratory.
2. The subject was welcomed and talked through the 'Information for Participants Sheet' (Appendix Fi).
3. The subject was shown where the toilets and emergency exits were located and then given the extension number to dial in the case of an emergency.
4. The subject signed the 'Informed Consent' form (Appendix Fii).
5. The subject's height and weight were measured.
6. A history of the subject's hand and wrist ailments was taken and noted on the 'Testing Sheet' (Appendix Fiii).

7. Hand functionality tests were conducted. These included a power grip strength test followed by a manual dexterity test. The results were noted on the 'Testing Sheet' (Appendix Fiii).
8. The subject's finger joint depths were measured. The results were recorded on the 'Testing Sheet' (Appendix Fiii).
9. Motion analysis markers were applied to the hand, wrist and forearm of the subject.
10. A static trial record of the subject was recorded.
11. The four forearm markers were removed before dynamic testing was performed.
12. The subject's preferred grip styles were established using non-instrumented packaging samples. The lid of the instrumented packaging was then oriented appropriately such that it was possible to record opposing hand segment grip forces without occlusion of markers.
13. The subject performed three jar opening trials. The device configuration was changed to that of the bottle (subjects were offered refreshments during this interval in testing).
14. The lid was aligned to allow preferred hand grip style without marker occlusion and three dynamic bottle opening trials were conducted.
15. Markers were removed from the subject. The subject was debriefed, thanked for their time and transported home.

The protocol and all supporting documentation were approved by the University Ethics Committee and were closely adhered to for the testing of all subjects. Subjects were only required to attend one testing session which lasted 90-120 minutes.

6.2.4 Model of the Hand and Wrist

In order to interpret the marker trajectories captured during the subject trials, a model of the hand and wrist was created such that joint forces, moments and angles could be calculated with respect to the anatomical planes of the hand and thumb as shown in Figure 6.10 and 6.11 respectively. These planes and directions will be referred to throughout the remainder of this thesis.

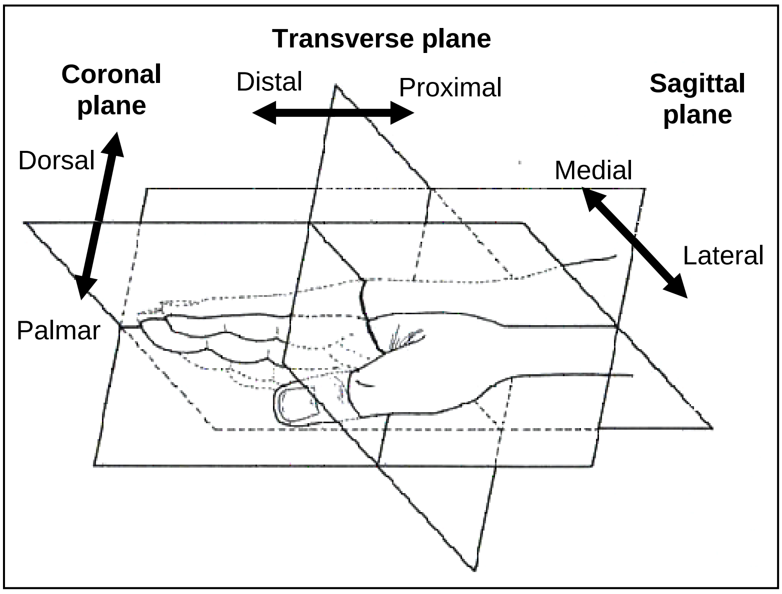


Figure 6.10 Anatomical planes of the hand including directional terms. Image adapted from Brand and Hollister (1999)

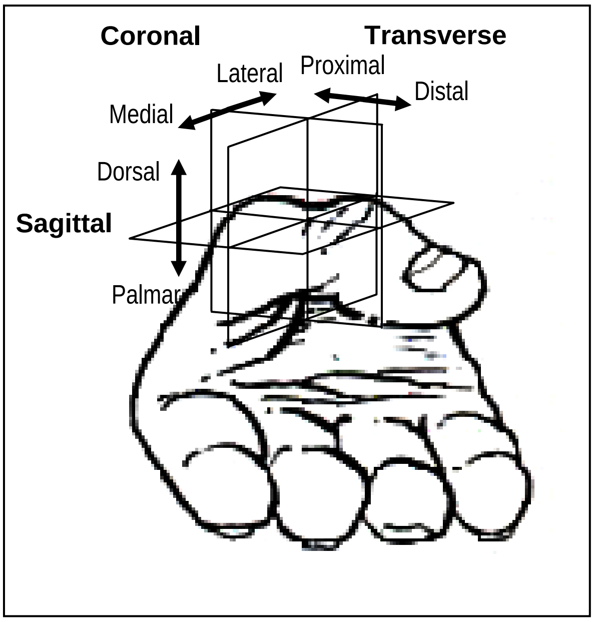


Figure 6.11 Anatomical planes of the thumb including directional terms. Image adapted from Nordin and Frankel (2001).

The model included 20 rigid segments per hand which meant that 20 corresponding axes systems were required. The axes systems were defined using the positions of the surface markers. An example of a series of final axes systems is illustrated for digit III of the right hand in Figure 6.12. This was repeated for digits II-V on both hands. The thumb axes systems for the left hand are shown in Figure 6.13. The origin of each segment axes systems was located at the segment's distal centre of rotation (COR) and took into account the height of the marker and the depth, or thickness, of each individual joint. A full explanation of how these axes systems were defined from the positions of the surface markers will be provided in this sub-section.

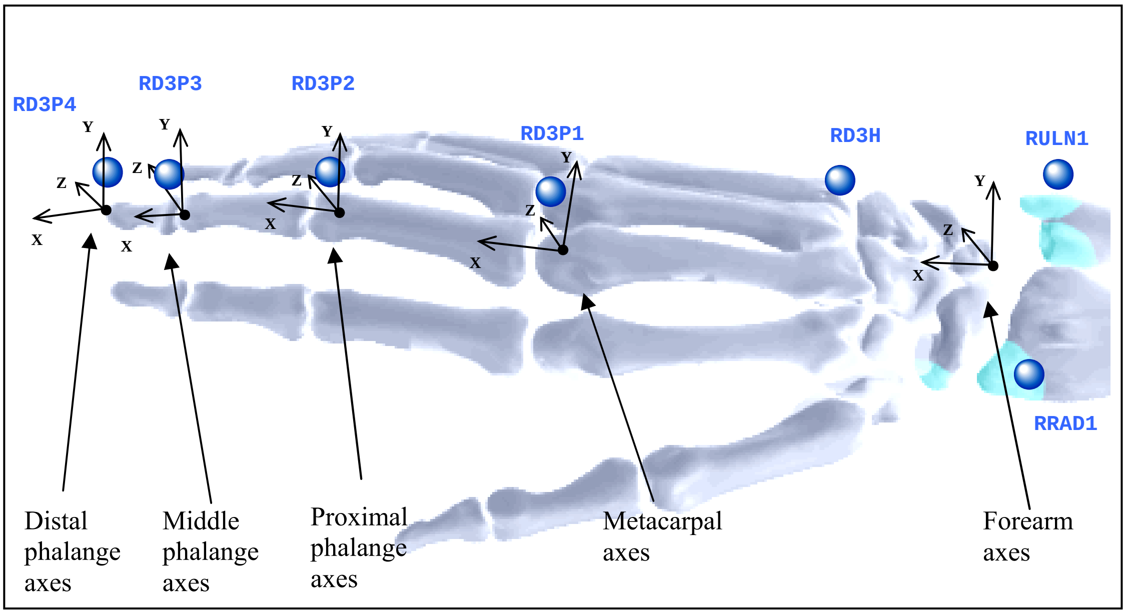


Figure 6.12 Medial view (sagittal plane) of right hand showing surface markers and final axes systems of the forearm, proximal, middle and distal phalanges of digit III. Segment axes have origins located at COR of each segment's distal joint.

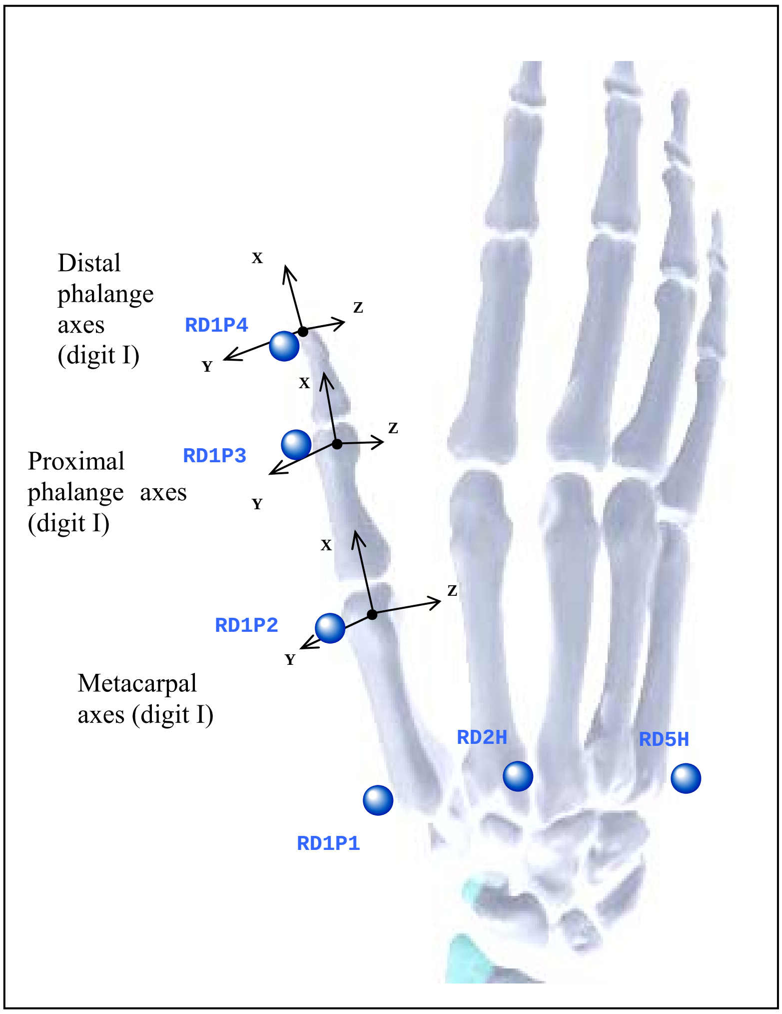


Figure 6.13 Dorsal view of right thumb (digit I) showing surface markers and metacarpal, proximal and distal phalange final axes systems.

The joints of each hand and wrist were considered to have a combined total of 22 degrees of freedom (Figure 6.14), with the wrist, the finger MCPs, the thumb CMC having two, and all others having one. It is acknowledged that this is a simplified model of the anatomical function of the hand and wrist, however the degrees of freedom deemed most important to this project were included.

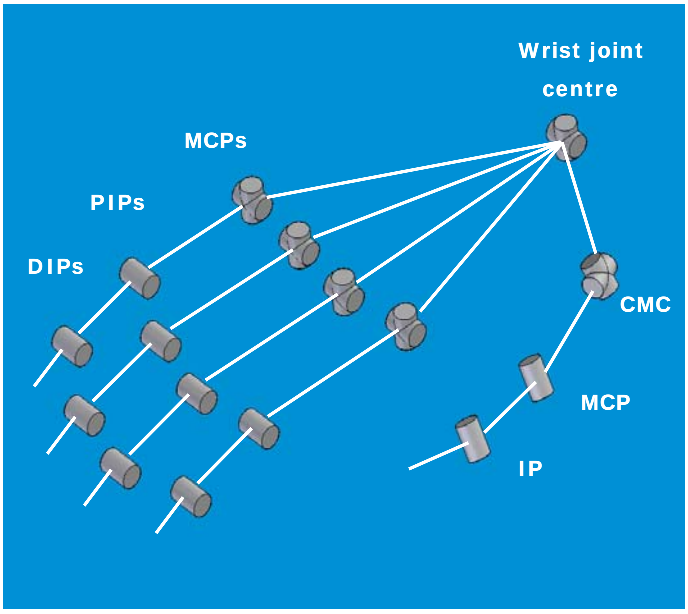


Figure 6.14 Degrees of freedom of the complete right hand model. 22 degrees of freedom in total.

The biomechanical model of the hand and wrist was implemented by running static and dynamic customised codes written in Vicon BodyBuilder v3.55 (Oxford Metrics, UK). These interpreted the marker trajectories, established the various axes systems described above and thereafter calculated the kinematic and kinetic variables in each trial. The following sub-sub sections will discuss in more detail how the specific joint centres of rotation (CORs) were calculated.

6.2.4.1 Forearm Axes and Locating the Wrist Joint Centre

Despite there being a number of different marker sets and hand models proposed in the literature (Cerveri et al., 2007, Metcalf et al., 2008), neither describe in detail the precise method of establishing segment axes and joint CORs. In order to find the wrist joint centre (WJC) and establish a forearm axes system experimental work was conducted with the aim of identifying the WJC and how to locate it using anatomical bony landmarks.

Previous research has shown that the centre of rotation of the wrist joint changes position as the hand moves due to the movement of the complex series of carpal bones within the wrist joint. A consensus was reached that the effective wrist joint centre can be assumed to be the proximal head of the capitate bone (Youm and Yoon, 1979) and it was this point that was used as the WJC in this study.

With the four forearm markers described in section 6.2.2.2 and the position of the wrist joint centre known (Figure 6.15), a preliminary forearm axes system was established with its origin at the midpoint between the radial and ulnar styloid processes. The position of the WJC relative to this forearm axes system was then calculated.

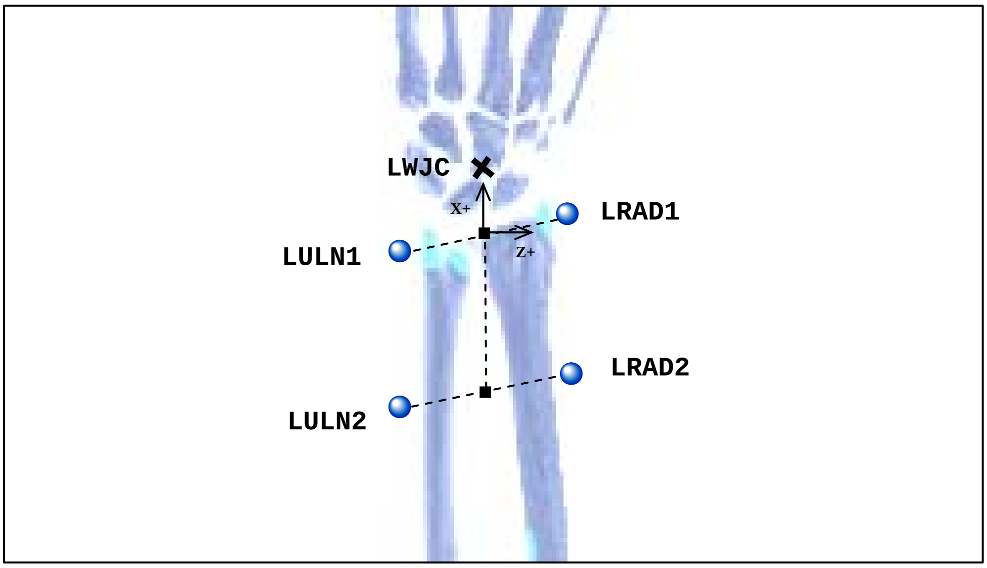


Figure 6.15 Dorsal view of left carpal and forearm bones, showing forearm markers and WJC relative to the preliminary forearm axes system.

The position of the WJC, relative to the preliminary forearm axes system, was calculated by taking the dimensions from one set of MRI scans of a hand and wrist (‘Interactive Hand – Anatomy’ v1.0.0, 1997, Primal Pictures Ltd.) as shown in Figure 6.16.

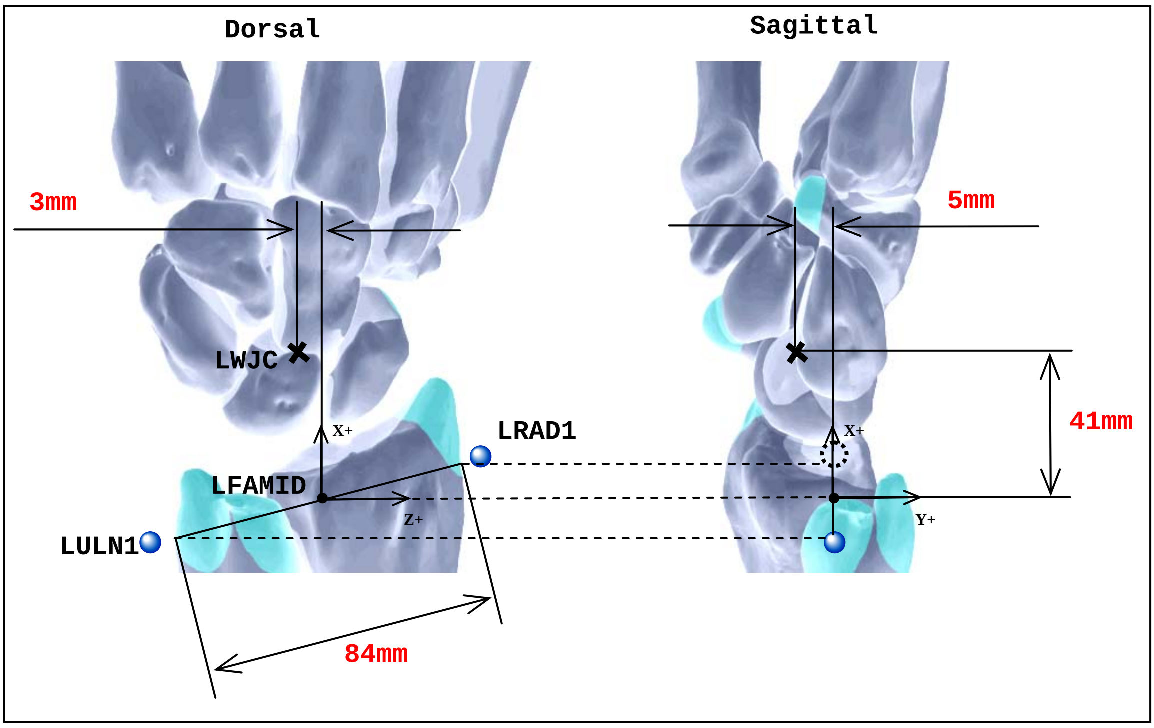


Figure 6.16 Dorsal and sagittal views of the left carpal bones. Location of WJC relative to the preliminary forearm axes system shown in mm.

The x,y and z components of the vector from point LFAMID1 to LWJC (shown in Figure 6.16) were measured by hand in millimetres and were specific to just one subject's MRI scan. Assuming that the geometry of this single MRI scan was representative of the whole population, the dimensions were made transferable to any subject by calculating them as proportions of the subject's wrist width as shown in Table 6.3.

Table 6.3 Components of vector from midpoint of radial and unlar styloid process to WJC

Vector Component	Measurement (mm)	% of Wrist Width (=84mm)
X	+41	49
Y	-5	-6.9
Z	-3	-3.6

These proportions were then incorporated into the static code which calculated the location of each subject's WJC relative to the four forearm markers and then transferred this point into a local coordinate system create using the triad of markers placed on the dorsal aspect of the forearm (see markers LTRF1, LTFR2 and LTRF3 in Figure 6.3). Thus the four forearm markers were not required during the dynamic testing as the WJC could be located using just the triad of forearm markers.

6.2.4.2 Metacarpal Axes and the Proximal Transverse Metacarpal Arch

Instead of defining one single hand segment, four individual segment axes systems were defined for each of the four hand metacarpal bones (II-V). This was done using just two markers on the proximal heads of metacarpals II and V and calculating the positions of two virtual markers for metacarpals III and IV. This offered the advantage of using fewer markers during testing.

Using a temporary axes system, as shown in Figure 6.17, the positions of the markers at the proximal heads of metacarpals III and IV were calculated using the geometry of a single MRI scan (‘Interactive Hand – Anatomy’ v1.0.0, 1997, Primal Pictures Ltd.), with the slice of the MRI scan taken 5-10mm distal from the proximal head of metacarpal III. The positions of the markers were initially calculated in millimetres by hand and were then converted into proportions of the subject’s hand width, which was taken as the distance between the two physical markers on metacarpals II and V. As with the calculation of the WJC it was assumed that the geometry of this single MRI scan was representative of the whole population and therefore that these proportions were transferable.

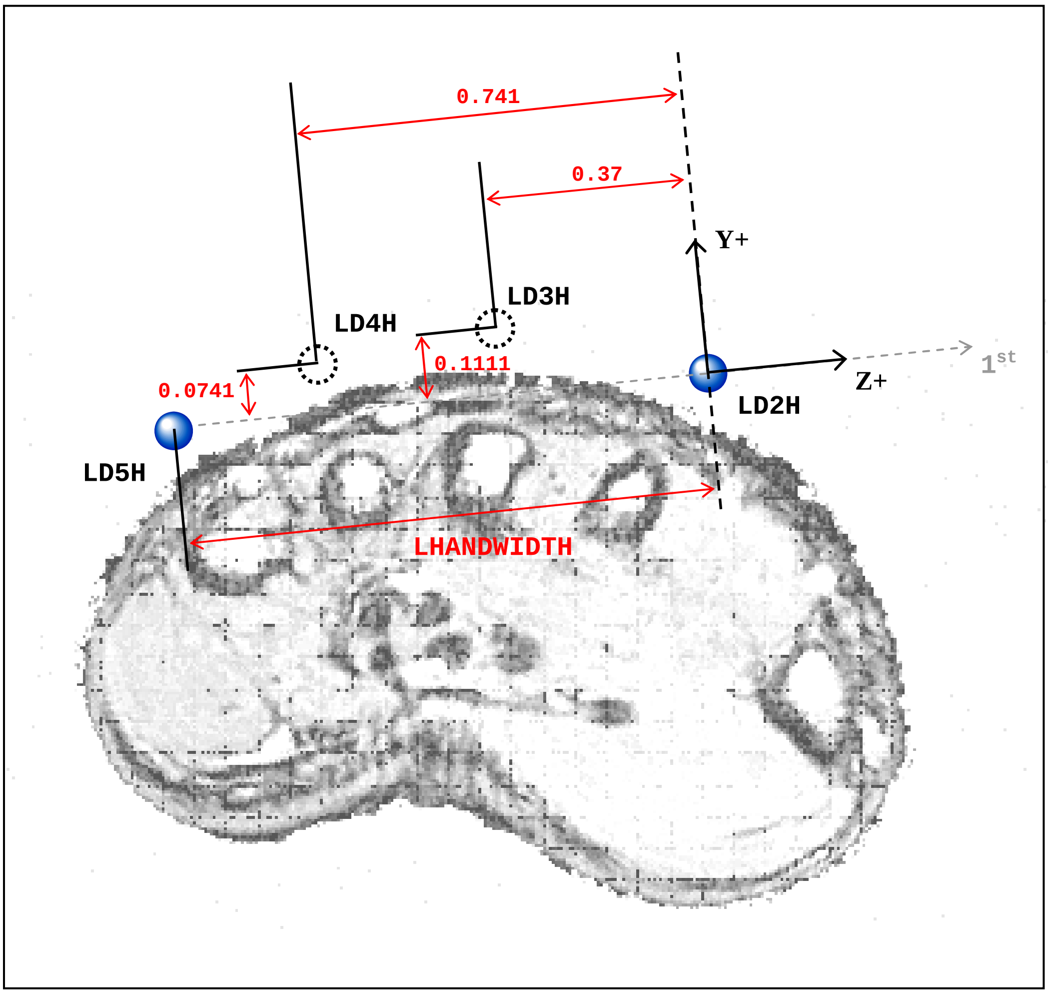


Figure 6.17 MRI scan in the transverse plane of left metacarpal bones taken 5-10mm distal from the proximal head of metacarpal III. The positions of virtual metacarpal markers relative to physical surface markers is shown. Distances are given as proportion of hand width

To avoid assuming that the centres of the metacarpal bones lay directly beneath the surface markers the same MRI scan geometry was used to calculate the position of the centres of metacarpal bones II-V relative to the surface markers (Figure 6.18). Once again, these dimensions were measured by hand and recorded as a proportion of the subject's hand width.

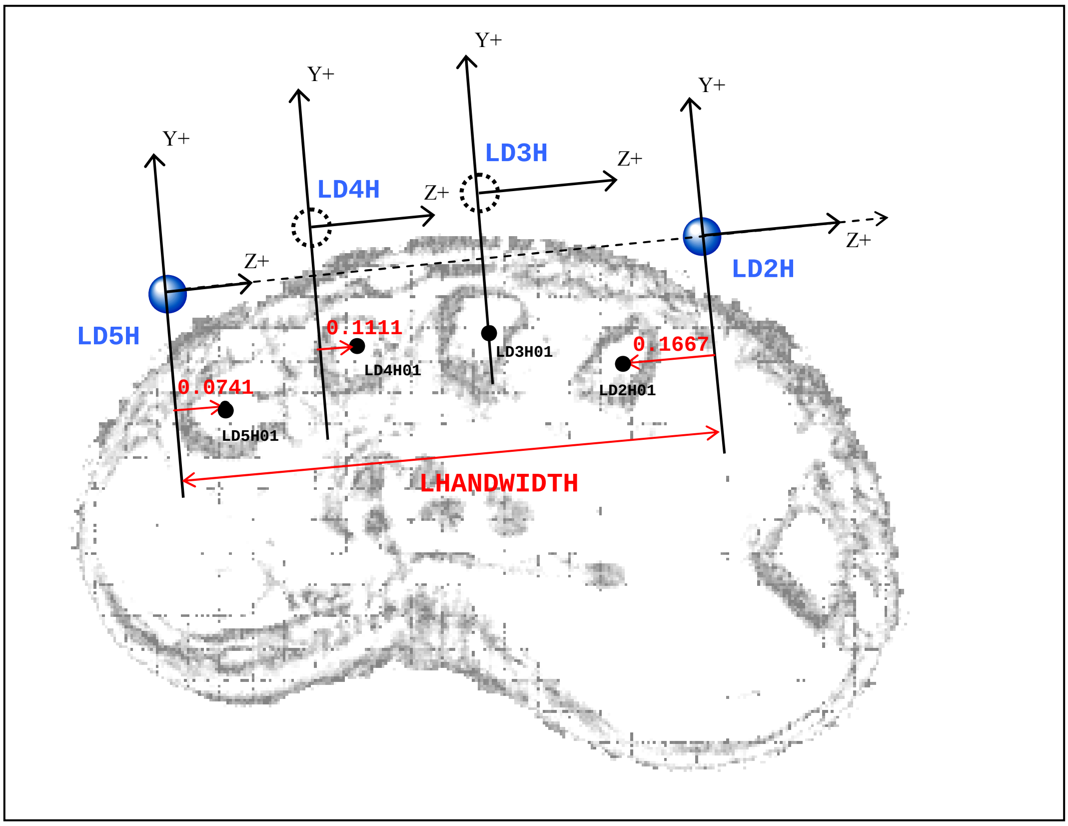


Figure 6.18 MRI scan in the transverse plane of left metacarpal bones taken 5-10mm distal from the proximal head of metacarpal III. Locations of metacarpal centres relative to surface markers are shown, with distances given as proportions of hand width.

The final stage in this process was to transfer the origins of the four axes systems to the metacarpal centres and to reorient them such that the palmar-dorsal axis (the y-axis) followed the line from the metacarpal centre through the corresponding surface marker (e.g. LD5H01 through LD5H). The final axes systems which reflect the proximal transverse metacarpal arch are shown in Figure 6.19.

6.2.4.3 *Finger Segment Axes*

Having rotated the metacarpal axes for each individual digit such that the proximal transverse metacarpal arch was represented, the finger segment axes systems were defined. The definition process for one digit is described, and the process was repeated for each digit.

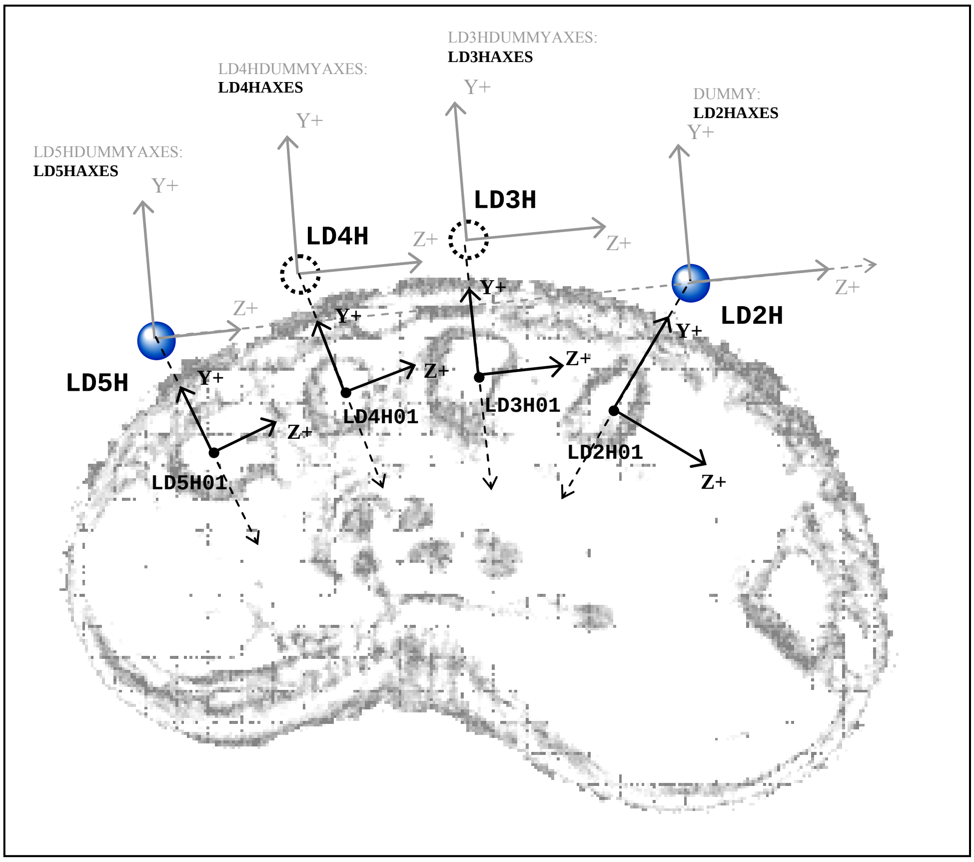


Figure 6.19 MRI scan in the transverse plane of left metacarpal bones taken 5-10mm distal from the proximal head of metacarpal III. Final reorientation of axes to represent proxiaml transverse metacarpal arch.

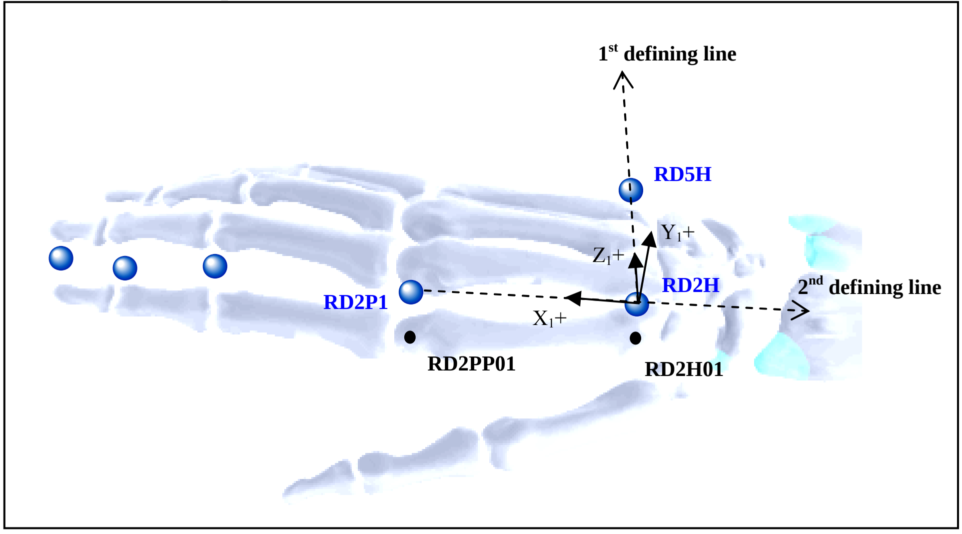


Figure 6.20 Defining lines used for temporary hand axes system

As shown in Figure 6.20 a temporary axes system was set up for locating the CORs of proximal metacarpal head (RD2H01) and MCP joint (RD2PP01). The Z_1 axis followed the 1st defining line in a lateral direction. The Y_1 axis was perpendicular to the plane formed by the 1st and 2nd defining lines, pointing dorsally. The X_1 axis was perpendicular to the planed formed by Y_1 and Z_1 in a distal direction.

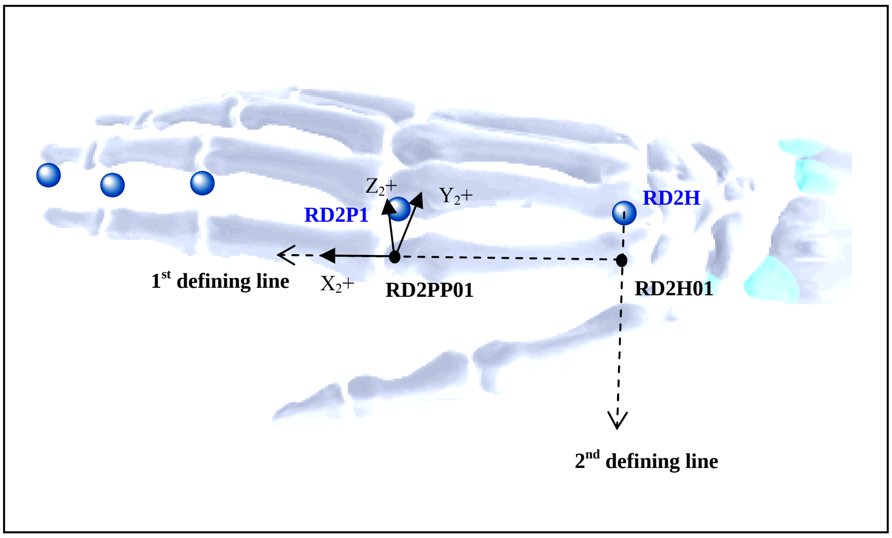


Figure 6.21 Defining lines used for right digit II metacarpal axes system

The second step was to define the right digit II metacarpal axes, as shown in Figure 6.21. The X_2 axis followed the 1st defining line distally. The Z_2 axis was perpendicular to the plane between the 1st and 2nd defining lines (lateral). The Y_2 axis was perpendicular to the plane between X_2 and Z_2 in a dorsal direction.

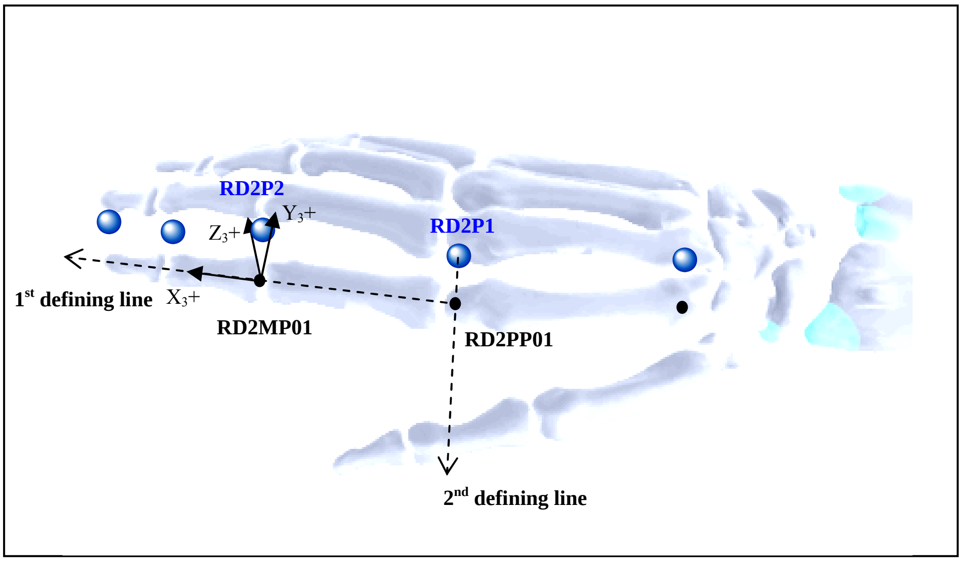


Figure 6.22 Defining lines used for right digit II proximal phalange axes system

The following step was to define the proximal phalange axes, as shown in Figure 6.22. The X_3 axis followed the 1st defining line distally. The Z_3 axis was perpendicular to the plane between the 1st and 2nd defining lines (lateral). The Y_3 axis was perpendicular to the plane between X_3 and Z_3 in a dorsal direction.

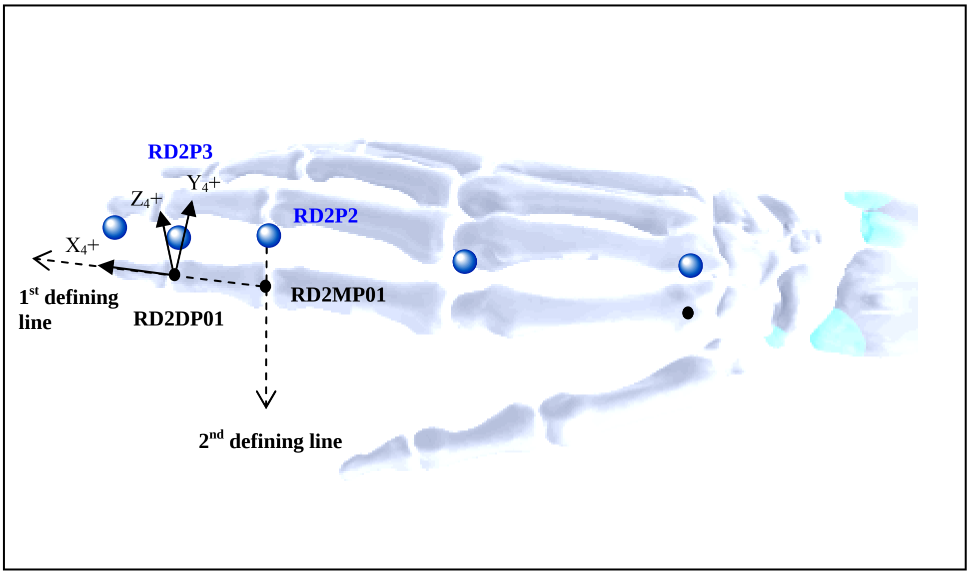


Figure 6.23 Defining lines used for right digit II middle phalange axes system

The final step was to define the middle phalange axes (Figure 6.23). The X_4 axis followed the 1st defining line distally. The Z_4 axis was perpendicular to the plane between the 1st and 2nd defining lines (lateral). The Y_4 axis was perpendicular to the plane between X_4 and Z_4 in a dorsal direction. Due to problem with marker occlusion of the distal markers on the fingertips of the subjects, the distal phalange axes were not defined.

6.2.4.4 Joint Angle Calculations

As the surface markers moved relative to the COR of any given joint during flexion and extension, it was important that the model of the hand account for this.

The CORs for the MCP, PIP and DIP in the joints were established by calculating their positions in the sagittal plane in two different axes systems as shown in Figure 6.24. Using the marker height and the depth of the joint in question, two CORs

(RD2PP01i and PD2PP01ii) for the MCP joint were calculated in the axes systems of the proximal and distal segments respectively. The proximal segment axes are represented by x_1' and y_1' and the distal axes by x_2' and y_2' in Figure 6.24. When the joint is fully extended these two points should be coincident, however as the angle of flexion increases they move further apart. The true centre of rotation of the MCP (RD2PP01) was located at the midpoint between these two points.

With all CORs and segment axes systems defined, joint angles were calculated using the Cole joint co-ordinate system (Cole et al., 1993) which used a Cardan angle sequence of flexion-extension (z-axis), ad-abduction (y-axis) then internal-external rotation (x-axis) to give an ordered rotation of axes.

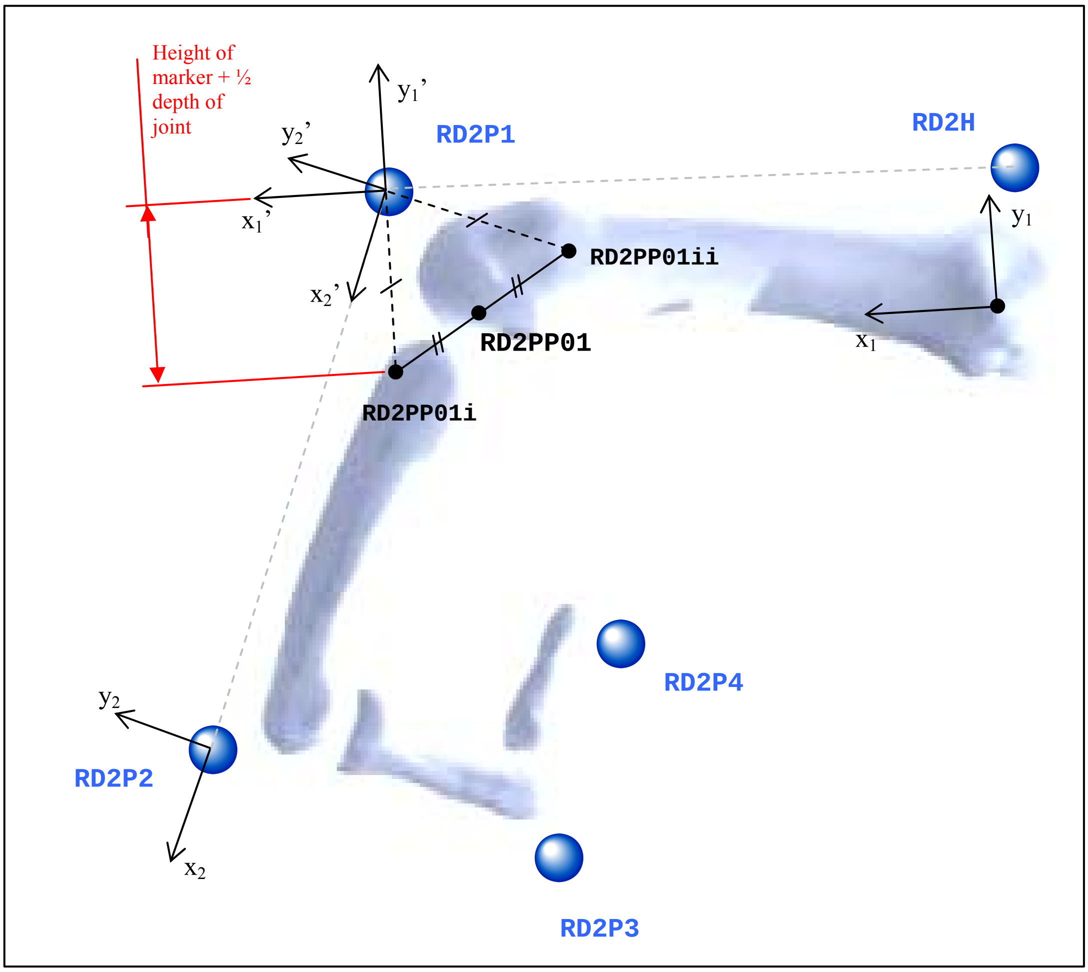


Figure 6.24 Medial view of right digit II in flexion. Proximal and distal axes systems are used to define two separate CORs for the MCP joint. The resulting midpoint (RD2PP01) between COR$_1$ (RD2PP01i) and COR$_2$ (RD2PP01ii) was taken as the true COR.

6.2.4.5 Marker Placement Repeatability

Given that the model of the hand and wrist employed in this study utilised a novel marker arrangement it was considered necessary to perform a series of tests to examine the repeatability of placing selected markers on the bony landmarks described previously in Table 6.1.

In order to ensure the intra-rater marker placement repeatability of the four forearm markers was within acceptable limits, data was gathered to test this. A forearm marker triad was attached to a subject's forearm and remained in place for all five trials. Four forearm markers were then attached for the trial, then removed and reattached for the following trial. The aim was to ensure that the WJC was being calculated accurately (relative to the constant forearm triad) each time the forearm markers were applied. 15 trials were captured in total with the wrist in different positions; 5 neutral, 5 fully flexed and 5 fully supinate.

Table 6.4 Individual components of WJC location calculated based on attached forearm markers relative to the origin of the constant forearm triad. Intra-rater repeatability for forearm marker placement.

	Co-ordinate	Trial 1 (mm)	Trial 2 (mm)	Trial 3 (mm)	Trial 4 (mm)	Trial 5 (mm)	Mean (mm)	St. Dev. (mm)	**Mean St. Dev. (mm)**
Neutral	x	41.96	45.49	45.51	48.48	46.66	45.62	2.38	
	y	-23.30	-30.09	-20.32	-26.67	-26.17	-25.31	3.69	
	z	-13.63	-15.55	-16.24	-17.10	-16.38	-15.78	1.32	**2.46**
Flexed	x	33.26	40.30	38.46	44.85	39.94	39.36	4.16	
	y	-28.96	-36.85	-28.25	-33.27	-32.18	-31.90	3.48	
	z	-20.08	-19.92	-18.36	-17.42	-18.17	-18.79	1.16	**2.93**
Supinate	x	36.63	39.59	38.86	45.90	40.23	40.24	3.44	
	y	-26.07	-28.94	-22.49	-21.10	-27.67	-25.25	3.35	
	z	-16.43	-17.96	-19.30	-24.11	-20.78	-19.72	2.94	**3.24**

The values shown in Table 6.4 show that the WJC position was repeatedly calculated with standard deviations ranging from 1.16-4.16mm.

To test the repeatability of metacarpal marker placement it was first necessary to verify that maximal wrist excursion angles for any one subject were consistent and repeatable. So, the WJC was located relative to the constant forearm triad of markers, two metacarpal markers and one on MCP III (thus establishing the metacarpal axes system for digit III) were attached and left in place for all trials. In each trial the subject was asked to repeatedly move their wrist to one extreme, return it to a neutral position and repeat ten times. This was done for wrist flexion, radial deviation and ulnar deviation. The small standard deviations (Table 6.5) recorded during these repetitions showed that the maximum excursions of the wrist joint in these three directions were sufficiently repeatable within one subject.

Table 6.5 Within-subject maximum wrist excursion angle repeatability

	Wrist Angle (degrees)												
	Excursion 1	Excursion 2	Excursion 3	Excursion 4	Excursion 5	Excursion 6	Excursion 7	Excursion 8	Excursion 9	Excursion 10		Mean Angle	St. Dev.
Flexion	-89.50	-92.88	-	-88.30	-91.57	-93.04	-92.74	-87.21	-88.33	-85.20		-89.86	2.83
Radial Dev.	13.60	15.90	15.75	16.56	15.98	15.69	14.90	12.32	15.66	12.97		14.93	1.45
Ulnar Dev.	-46.55	-48.75	-48.69	-47.85	-44.63	-47.44	-45.02	-46.07	-49.30	-47.84		-47.21	1.60

The intra-rater repeatability of placing markers on the proximal head of metacarpals II and V was then assessed using maximum wrist excursions as a metric. 15 trials were captured in total; 5 fully flexed, 5 fully radially deviated and 5 fully ulnar deviated. The same markers as described in the previous test were used only in this test the two metacarpal markers were removed and replaced between each trial.

Table 6.6 Intra-rater repeatability for metacarpal marker placement

	Wrist Angle (degrees)							
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5		Mean Angle	St. Dev.
Fully Flexed	-86.57	-86.05	-83.69	-83.49	-85.73		-85.11	1.42
Full Radial Deviation	7.76	7.90	12.65	8.25	14.08		10.13	3.00
Full Ulnar Deviation	-48.00	-47.63	-45.06	-45.76	-46.71		-46.63	1.23

The findings in Table 6.6 show that the repeatability of placing markers on the proximal heads was acceptable for calculating wrist angles (standard deviations ranging from 1.23-3°).

6.2.4.6 Joint Angle Calculation Accuracy

In order to verify the intra-rater repeatability of placing markers on the finger joints, a triad of forearm markers and two metacarpal markers were kept constant, while MCP, PIP and DIP markers (on digit III) were removed and replaced. During each trial the joint being measured was held still at a known flexion angle (80° MCP joint, 90° PIP joint) for 10 seconds. The predetermined joint angles were measured using a basic finger goniometer (Homecraft Rolyan, Nottingham, UK). As the overall standard deviation values in Table 6.7 show, intra-rater marker placement on the fingers was acceptable with only small amounts of variation between trials.

Table 6.7 Intra-rater repeatability for MCP, PIP and DIP marker placement and flexion angle calculation accuracy

		Joint Angle (degrees)							
		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5		Overall Mean	Overall St. Dev.
MCP Joint (80°)	Mean Angle (within trial)	-78.40	-79.68	-77.76	-81.29	-79.90		-79.28	1.56
	St Dev (within trial)	0.21	0.35	0.38	0.73	0.71			
PIP Joint (90°)	Mean Angle (within trial)	-90.45	-85.67	-85.29	-91.30	-91.92		-88.93	3.19
	St Dev (within trial)	0.26	0.34	0.14	0.12	0.16			

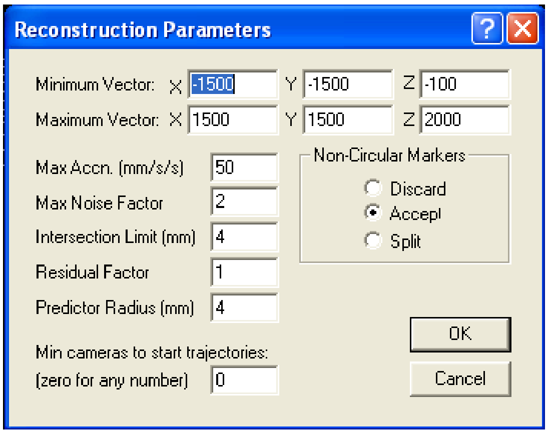
This test also proved that the method of calculating finger joint flexion/extension angles described previously in Section 6.2.4.4 was valid as the calculated angles were consistently close to the actual angles of 80° and 90° for the MCP and PIP. Considering the values of standard deviation (within trial) shown in Table 6.7 it is clear that there was slight marker movement during the static trial. It was difficult to ascertain whether or not this was caused by subject movement or by measurement error, however the errors were low (standard deviations ranging from 0.12-0.73°) such that they could be considered negligible.

6.2.5 Data Processing

Having defined and verified the model of the hand and wrist, and captured all the subject trials, the raw data had to go through a number of processing stages before usable results were generated for analysis.

While three trials were taken for each subject with both the jar and the bottle, only one trial per subject was used for the analysis. In most cases the third trial was used as by this point the subjects were most likely to have honed their technique, and be more comfortable with the markers on their hands and having the motion analysis cameras trained on them.

The first stage of data processing was to perform a visual inspection of the selected trial to ensure that all markers were visible. If there were any problems at this stage the trial was reconstructed using the parameters shown in Figure 6.25 within the Vicon Workstation v4.4 (Oxford Metrics, UK) software. These parameters were determined by trial and error to produce the best reconstruction of markers for the jar and bottle opening tasks, within the specific volume used for the specific camera positions.



Minimum Vector: X -1500 Y -1500 Z -100
Maximum Vector: X 1500 Y 1500 Z 2000
Max Accn. (mm/s/s) 50
Max Noise Factor 2
Intersection Limit (mm) 4
Residual Factor 1
Predictor Radius (mm) 4
Non-Circular Markers
○ Discard
● Accept
○ Split
Min cameras to start trajectories:
(zero for any number) 0

Figure 6.25 Vicon Workstation reconstruction parameters used for processing subject trials.

The static trial was then labelled and processed, with the subjects finger joint dimensions entered into ‘subject parameters’. All analogue channels were then zeroed. This was necessary to remove offsets on some of the channels due to attachment of the various components as mentioned previously in Section 6.2.2.4.

Using the labelling system described in Section 6.2.2.2 (Table 6.1 and Figure 6.3) markers were labelled using Vicon Workstation v4.4 (Oxford Metrics, UK). Some of the trials were of long duration (20-30 s) with a large number of markers (53). To make the process of labelling the markers more efficient a two stage process was used. During preliminary labelling key markers on the body of the device were labelled which, after running a shortened version of the dynamic code, allowed the identification of key landmark events in each trial. These landmarks were then used to crop trials in a repeatable and consistent manner, after which comprehensive labelling of markers was carried out.

After preliminary labelling, the first of the landmark events to be identified was the point at which the peak lid twisting torque occurred. The aim was not only to capture the magnitude of the peak torque required to remove the lid, given by T_{lid} as shown in Figure 6.26, but also to identify the point in the trial at which this peak torque occurred.

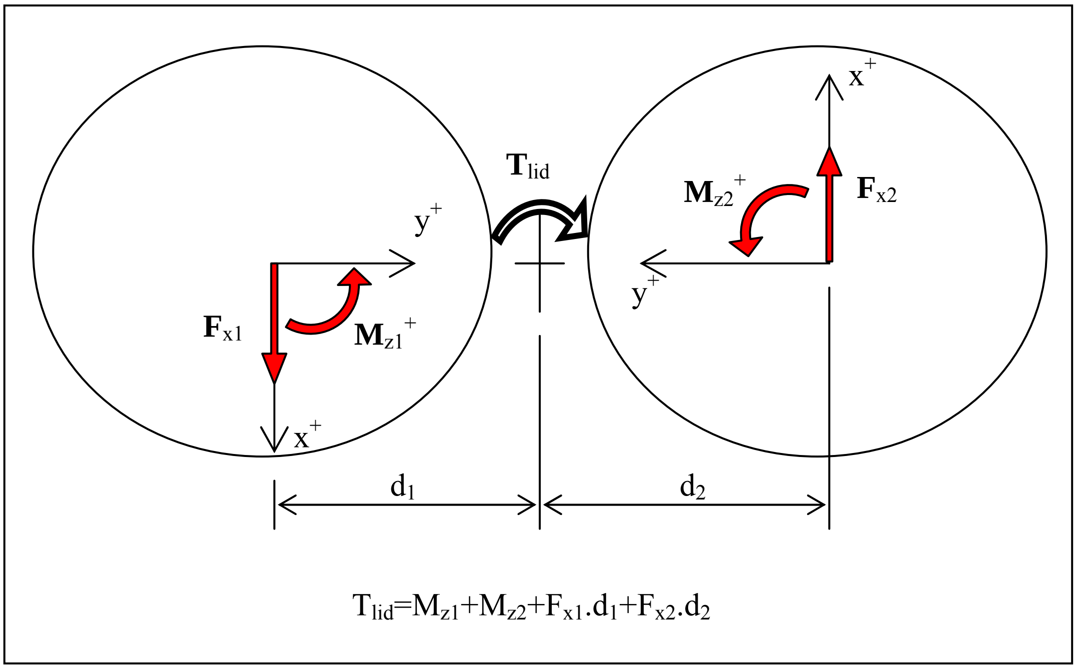


Figure 6.26 Schematic view of two Nano 25 transducers showing how measured force and moments (M_{Z1}, M_{Z2}, F_{X1} and F_{X2}) were used to calculate the lid torque resistance (T_{lid}).

Using programming code written in MATLAB (The MathWorks Inc., Natick, MA), T_{lid} and the time (t_1) at which it occurred were identified as illustrated in Figure 6.27. This point (t_1) would then be considered to be the ‘main analysis point’ for the analysis of kinetic and kinematic variables as it was assumed that at this point the forces and moments experienced at the subject’s thumb, hand and wrist would be close to maximal. It also provided a consistently identifiable point for between-subject comparisons.

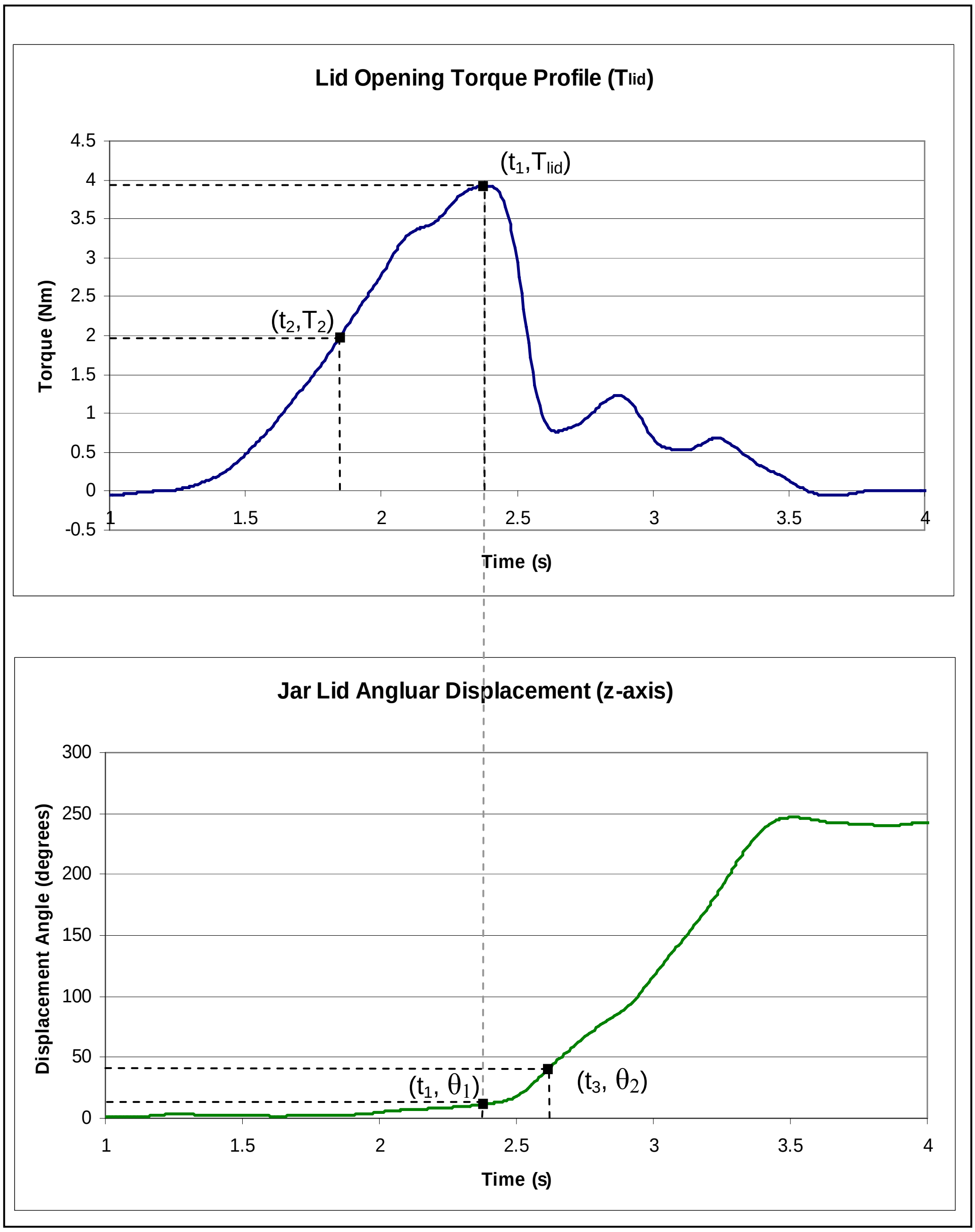


Figure 6.27 Graphs showing how three landmarks; peak opening torque, 50% of peak torque and 30° lid angular rotation, were identified.

Using the peak torque point identified (t_1), the MATLAB code then calculated the point (t_2) at which 50% of the peak torque (T_2) occurred. The point t_2 was used as the initial cropping point for the trial. In order to calculate the end cropping point, the jar lid displacement angle was then considered. As shown in Figure 6.27, starting at t_1, the angular displacement θ_1 was defined with θ_2 was then defined as θ_1+30°.

The frame t_3 where θ_2 occurred was used as the end cropping point. An angular rotational displacement of 30° was determined to be a sufficient amount of movement to successfully open a jar lid.

Using this method three distinct landmarks were identified; initial and end cropping points for subject trials and one which gave a standard analysis point, allowing for the realistic comparison of kinematic and kinetic data between subjects: the main analysis point.

The next stage was to carry out the comprehensive labelling, where all markers were labelled and any gaps in the marker trajectories were identified and filled using the 'copy pattern' function which copied the pattern of a similar adjacent trajectory into the gap in question. This was selected over the standard cubic spline interpolator. Also, each trajectory was inspected manually for any apparently abnormal trajectories jumping or shaking. Some subjects used gripping postures that were unpredictable and did not follow those used in the set up trials. This meant that certain trials had to be discarded due to occlusion of key markers, hence occasionally the second trial of the three captured was used. Once one trial for each subject had been fully labelled, and there were no breaks in the trajectories, the full dynamic code (see Appendix H) was then run to generate all of the variables required for analysis. The various stages of labelling markers, calculating the cropping points and inspecting and editing the trajectories took between 3-5 hours per person per trial. This large amount of processing time was another reason for electing to use just one trial per subject.

In order to reduce noise in the signal a low-pass double Butterworth filter was used on both the trajectories and the analogue signals. As shown in Figure 6.28a, a number of different frequencies were experimented with to find the optimum filtering frequency which appeared to have optimal performance, smoothing the data without affecting the peak values or causing any phase shift.

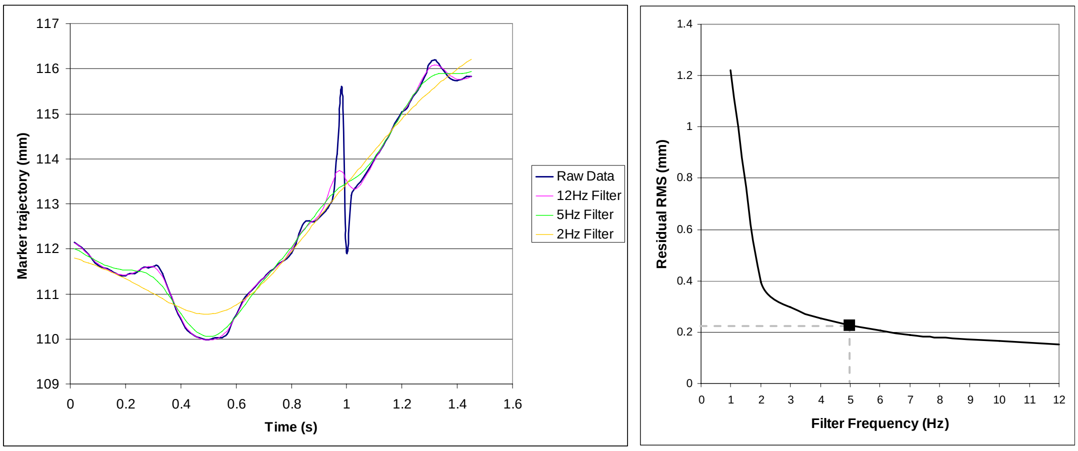


Figure 6.28 Trajectory filtering with low-pass double Butterworth filter; a) Comparison of filtering cut-off frequencies, b) Effect of frequency on residual RMS value, 5Hz highlighted.

Figure 6.28a suggests that a cut-off frequency of 5Hz is ideal as it appears to adequately smooth the spike in the signal without having any adverse effect on the magnitude of any genuine peaks in the data. On closer inspection of the residual values between the various filter frequencies and the raw data, Figure 6.28b shows that a 5Hz cut-off frequency offers a mean RMS residual of just 0.225mm which was deemed suitable for this project. It is generally recommended that a cut-off frequency of around 6Hz is used for motion capture recorded at 60Hz (Winter, 2004). As the trajectories captured in the package opening trials were moving small distances so relatively small spikes could cause large inaccuracies in joint angle calculations, hence the slighter stronger 5Hz filter was chosen.

6.3 Results

The biomechanical analysis performed had the scope to produce an immense volume of data concerning the tasks of jar and bottle opening. The presentation of a comprehensive data set was considered well beyond the scope of this thesis. To provide focus for this thesis, only selected results are presented. To provide evidence of the data that can be derived using the methods outlined a set of kinetic and kinematic results from the jar opening task are presented. It has not been possible to include the same level of detail for the bottle analysis within the constraints of this thesis. Only kinetic results of bottle opening will be presented.

The focus of this work was to explore the use of biomechanical data by designers, particularly to inform the consideration of older adults' requirements in the inclusive design process. Therefore, the presentation of results concentrates on those elements that might be of use in this context.

The results of the biomechanical testing were analysed to address the following objectives:

1. To identify the kinetic and kinematic differences between the younger and older groups.
2. To identify the kinetic and kinematic differences between male and female subjects.
3. To investigate the relative importance of age and gender as compared to hand size, power grip strength and dexterity in determining kinematics and kinetics.
4. To explore any links between kinematic variables and kinetic variables.
5. To determine if the kinematic data could be used to objectively classify hand postures which were subjectively classified previously in Section 5.3.1. If this was possible to establish which postures were associated with 'better/worse' jar opening characteristics.

6. To establish the main kinetic differences between placing the right or left hand on the jar lid.
7. To establish the main kinetic differences between jar and bottle opening.

Unless otherwise stated, the values discussed here were all take from the 'main analysis point' (identified in Section 6.2.5), so were not necessarily the maximum forces/moments/angles experienced by the subject during the jar opening cycle. The graphs shown in this section as thumbnail images can be found in full scale in Appendix I, showing all data for all subjects. Corresponding data tables can similarly be found in Appendix I which lists all variables taken for each subject at the main analysis point.

In the calculation of wrist, hand and thumb kinetics, body segment inertial forces were not included as there was insufficient mass, centre of mass and radius of gyration data available on the individual segments of the hand. Additionally, the accelerations involved in the jar and bottle opening activities were typically in the region of 0-2m/s^2 which would result in minimal inertial forces given the small masses involved. It was assumed that the weight of the device was fully supported by the hand which was not placed on the lid and would therefore have no effect on the forces and moments experienced by the hand that was on the lid.

6.3.1 Summary of Subject Data

Table 6.8 shows a summary of subjects' descriptive data (age, gender, height, weight, grip strength, dexterity, hand on jar lid).

Using the 2-sample t-tests it was found that there were significant differences in hand functionality between young and old subjects both for power grip strength ($p<0.05$) and dexterity ($p<0.005$). Male subjects had greater power grip strength than female subjects ($p<0.001$), however there were no significant gender based differences in dexterity score.

Table 6.8 Basic descriptive data for all subjects

Subject No	Gender	Control/Subject Group (C/S)	Hand on jar lid	Age (years)	Power Grip Strength (N)	Dexterity score	Hand Length (mm)	Height (m)	Weight (kg)
1	M	C	R	26	431.64	43	202	1.83	89.6
2	M	C	R	26	369.54	42	191.5	1.74	89.5
3	F	C	L	25	245.25	53	169.5	1.64	46
4	M	C	R	25	336.78	35	195	1.75	74
5	M	C	R	25	392.40	43	201.5	1.88	77
6	M	C	R	26	438.21	44	200	1.81	86
7	F	C	R	28	269.78	49	170	1.65	57
8	F	C	R	27	310.68	47	165.5	1.61	55
9	F	C	R	26	320.49	46	175.5	1.62	62.8
10	F	C	R	27	274.7	50	182	1.74	68
11	F	S	R	80	176.58	40	172.5	1.59	66.5
12	F	S	R	83	166.77	25	175	1.63	78
13	F	S	L	68	232.50	30	179	1.65	75
14	M	S	R	70	330.30	36	188	1.68	69
15	M	S	R	65	320.49	33	182.5	1.74	67
16	F	S	L	62	267.81	32	183	1.64	54.5
17	M	S	R	80	225.63	35	166.5	1.57	69
18	M	S	R	76	372.78	34	193	1.72	79
19	F	S	R	76	137.34	24	162	1.53	74
20	F	S	R	86	98.10	24	168	1.48	59
21	M	S	R	69	454.50	37	205	1.69	78
22	F	S	L	75	186.39	31	184	1.71	87
23	M	S	R	93	219.06	21	192.5	1.71	75
24	M	S	L	76	418.89	44	186	1.68	83
25	F	S	R	88	186.39	27	185	1.62	72
26	F	S	R	75	120.66	35	168.5	1.47	64
27	F	S	R	71	176.58	45	166	1.53	58
28	M	S	R	70	405.45	38	203.5	1.87	105
29	M	S	R	77	261.9	34	180.5	1.70	65

Due to technical difficulties some of the trials captured were done so using only five or six cameras, causing an unacceptable amount of marker occlusion. For this reason the jar opening trials for subjects 3, 10 and 29 were not used and likewise bottle opening trials 3, 10, 11, 24 and 28 were not used. With these trials discarded, the main analysis focussed on those who chose to place their right hand (8 young and 14 older adults) on the lid when opening the jar as they were more abundant than those who chose to use their left hand (4 older adults). When analysing the bottle, only subjects who placed their right hand on the lid were included for comparison against jar opening (8 young and 12 older adults).

6.3.2 Jar Opening Kinetic Data

Kinetic data at the wrist, hand and thumb were calculated through the jar opening cycle using the axes systems shown in Figure 6.29. The hand segment axes were based on the axes of metacarpal III with the x-axis following the longitudinal axis of the metacarpal, the y axis pointing in the dorsal direction the z-axis towards MCP V and the origin located at the midpoint between the CORs of MCP II and IV. The thumb axes system had it's origin at the COR of the MCP joint, x-axis following the longitudinal axis of metacarpal I, the y-axis pointing in the dorsal direction and the z-axis pointing medially. The forearm axes were described previously in Section 6.2.4.

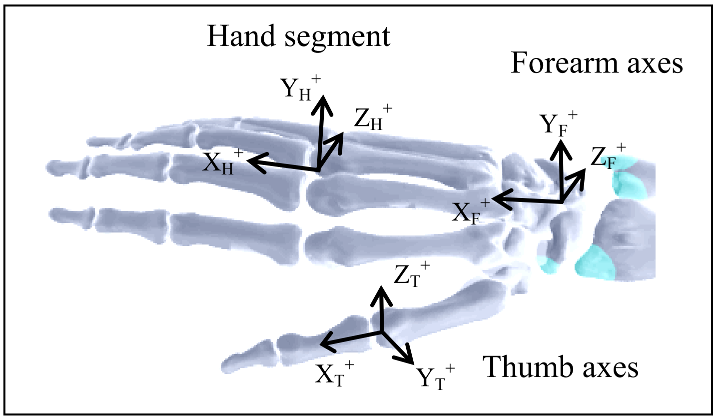


Figure 6.29 Axes systems used for kinetic calculations; thumb, hand segment and forearm

A free body diagram of the equipment in its jar configuration is shown in figure x, showing the forces and torques applied to the jar lid by the right hand, and to the jar body by the left hand. The reaction force applied by the left hand was a vector primarily counteracted the compressive force, $|F_{z1}+F_{z2}|$, as well as supported the weight of the jar, W_{jar}, thus providing equilibrium in the case of a static jar.

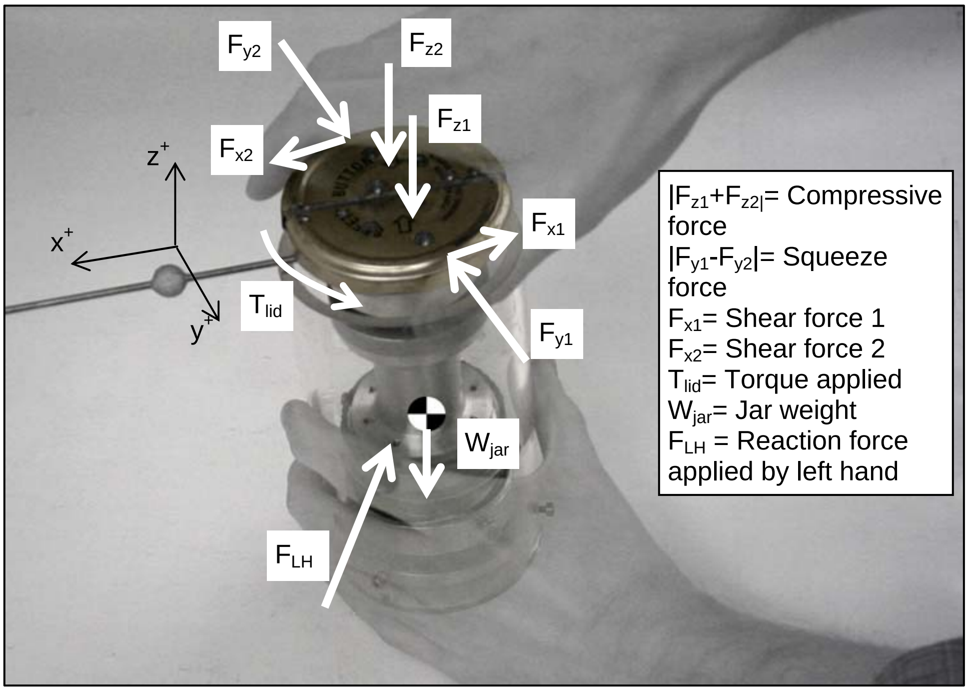


Figure 6.30 Free body diagram of jar, with forces applied by both hands of subject. Right hand on lid.

Full size graphs showing the raw data for each individual subject throughout the jar opening cycle can be found in Appendix I. Thumbnail images of these raw data graphs and key summary data (captured at the main analysis point) will be shown in the tables of results throughout this section. A general description of these results will be followed by between group comparisons.

Table 6.9 shows the different maximum levels of torque required by each individual subject to remove the jar lid (2.81Nm (±0.49)). To account for the variation in maximum opening torque between subjects and trials, data was multiplied by a scaling factor calculated as follows:

Scaling factor = 1/(maximum opening torque for trial/mean opening torque for all trials of all subjects)

All of the following kinetic results were scaled using this factor calculated for each individual trial.

Table 6.9 Jar kinetics and kinematics (* Forces x (1/(maximum opening torque for trial/mean opening torque for all trials of all subjects)))

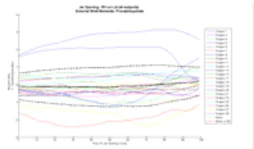
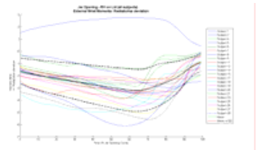
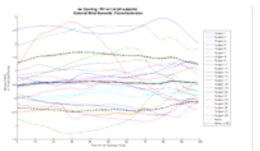
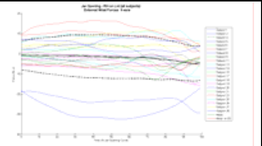
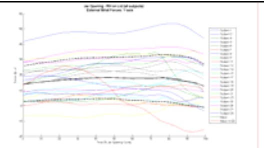
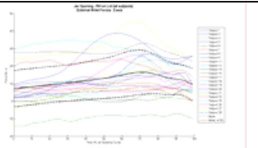
	Jar Kinetics				Jar Kinematics
Subject No.	Max. lid torque (Nm)	Lateral squeeze force (N)*	Downward compressive lid force (N)*	Lid torque profile gradient (N/s)	Lid w (rads/s)
1	-2.98	81.54	-20.80	-0.076	1.85
2	-3.19	114.34	-8.91	-0.033	0.95
4	-2.48	73.38	-17.07	-0.027	1.50
5	-2.74	93.62	-24.59	-0.045	1.85
6	-3.09	82.71	-50.41	-0.047	2.09
7	-2.35	133.59	-10.88	-0.032	1.01
8	-2.80	100.30	-21.10	-0.037	1.26
9	-3.07	81.50	-40.94	-0.057	2.24
11	-2.92	90.82	-56.93	-0.021	0.46
12	-1.77	183.17	-3.85	-0.035	0.59
14	-2.75	59.99	-1.16	-0.030	0.30
15	-3.26	106.48	-37.25	-0.097	2.24
17	-2.97	102.30	-3.93	-0.018	0.95
18	-3.92	84.30	-26.19	-0.043	1.08
19	-2.41	93.86	-11.97	-0.025	0.59
20	-2.15	71.55	-36.37	-0.039	0.57
21	-2.98	52.57	-1.98	-0.041	0.29
23	-2.44	124.50	-25.86	-0.032	1.26
25	-3.13	74.52	-28.64	-0.015	1.08
26	-2.29	75.62	-39.72	-0.021	0.32
27	-2.62	73.30	-22.90	-0.091	0.46
28	-3.58	83.32	-45.09	-0.020	1.37
13	-2.78	46.88	-4.47	-0.027	0.65
16	-3.35	53.00	-19.09	-0.053	1.26
22	-2.79	58.72	-29.19	-0.017	0.42
24	-3.83	83.60	-54.80	-0.037	0.85

6.3.2.1 External Wrist Moments

As Table 6.10 shows, the largest moment experienced by the wrist tended to cause ulnar deviation (-3.38Nm (±1.56)). It was anticipated that this would be the largest moment due to the way subjects naturally preferred to place the palm of their hand over the jar lid, grasp and radially deviate their wrist to rotate the lid anti-clockwise.

On average the wrist experienced a moment tending to cause extension, however there was a lot of variation in the results. The wrist experienced small moments tending either to pronate or supinate. However, the magnitudes of both of these moments were small when compared with the moments tending to ulnar deviate.

Table 6.10 External wrist moments and forces during jar opening (* Scaled mean values taken from main analysis point)

			Moment/Force Axis		
			x	y	z
Wrist (n=22)	Moments (Nm)	Raw data graph			
		Mean (SD)*	-0.09 (1.17)	-3.38 (1.56)	0.74 (1.18)
	Forces (N)	Raw data graph			
		Mean (SD)*	-2.17 (10.7)	19.98 (15.76)	15.91 (13.94)

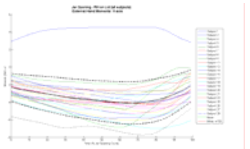
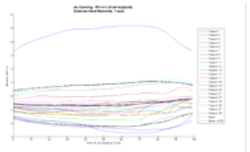
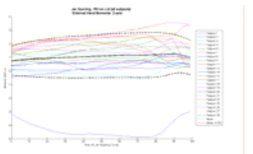
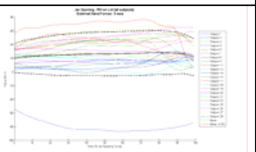
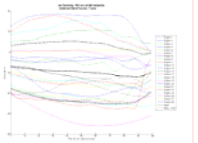
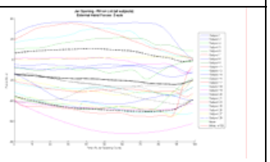
6.3.2.2 External wrist forces

The external forces acting on the wrist during jar opening included a relatively small (-2.17N (±10.7)) yet variable component acting alone the longitudinal axis (x-axis) of the forearm, as detailed in Table 6.10. Larger forces were found to act in a dorsal direction (19.98N (±15.76)) along the y-axis, with forces along the z-axis tending to act in an ulnar (or medial) direction, again with a large amount of variation (15.91N (±13.94)).

6.3.2.3 External Hand Moments

Table 6.11 shows that the external moments experienced at the hand were greater than those experienced at the wrist, with a moment of -4.17 Nm (±2.28) tending to internally rotate, or pronate, the hand segment. Moments about the other axes were present, however they were small and variable in nature.

Table 6.11 External hand segment moments and forces during jar opening (* Scaled mean values taken from main analysis point)

			Moment/Force Axis		
			x	y	z
Hand Segment (n=22)	Moments (Nm)	Raw data graph			
		Mean (SD)*	-4.17 (2.28)	-0.74 (1.63)	1.19 (1.67)
	Forces (N)	Raw data graph			
		Mean (SD)*	29.05 (35)	-19.57 (31.84)	83.87 (34.19)

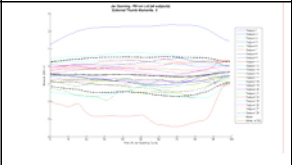
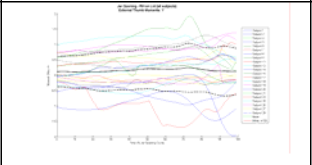
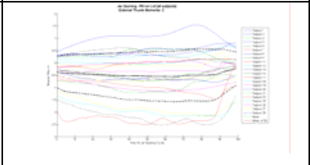
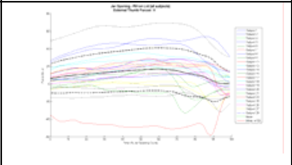
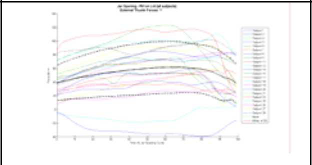
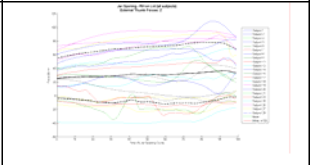
6.3.2.4 External Hand Forces

Table 6.11 shows that the largest component of the lateral squeezing reaction force exerted by the lid occurred along the z-axis of the hand segment (83.87N (±34.19)) pushing it towards the MCP V. The other main component of the reaction force occurred in the distal direction along the longitudinal x-axis. A component of the reaction force occurred along the y-axis of the hand in a palmar direction, suggesting that many subjects used this part of their hand to lift the lid, rather than press downwards.

6.3.2.5 External Thumb Moments

External thumb moments, taken about the MCP of digit I, were all fairly small in magnitude with a relatively large amount of variability within the data (Table 6.12). These moments of small magnitude were associated with close proximity of the origin of the thumb segment axes to the lid segment, and reaction force passing almost directly through the axes origin.

Table 6.12 External thumb moments and forces during jar opening (* Scaled mean values taken from main analysis point)

			Moment/Force Axis		
			x	y	z
Thumb (n=22)	Moments (Nm)	Raw data graph			
		Mean (SD)*	-0.56 (1.20)	0.18 (0.74)	-0.63 (1.15)
	Forces (N)	Raw data graph			
		Mean (SD)*	14.89 (25.46)	63.53 (42.23)	26.90 (44.72)

6.3.2.6 External Thumb Forces

The components of the reaction force at the thumb were of a similar magnitude to those experienced at the hand segment, as detailed in Table 6.12. Forces of 14.89N (±25.46) were experienced distally along the longitudinal axis of the segment representing the shear force between the skin and the lid as the thumb attempts to drag the lid in a proximal direction. The largest component of the reaction force was generally encountered along the y-axis of the thumb segment (63.53N (±42.23)), tending to push it in a dorsal direction. Due to a downward force being applied to the lid, and the positioning of the thumb, a mostly positive reaction force in the z-axis was calculated (26.90N (±44.72)).

6.3.2.7 Age and Gender Related Kinetic Differences

A series of descriptive boxplots were used to give a visual representation of whether or not any clear kinetic differences existed between the young control group and the older adult subject group. External forces are shown in Figure 6.31, external moments in Figure 6.32 and the forces applied to the jar lid in Figure 6.33. All variables were tested for normality using both the Anderson-Darling and Kolmogorov-Smirnov tests, both of which confirmed that all data was normally distributed. Where there did appear to be a significant difference between the groups, a 2-sample t-test for significance was employed to verify significance.

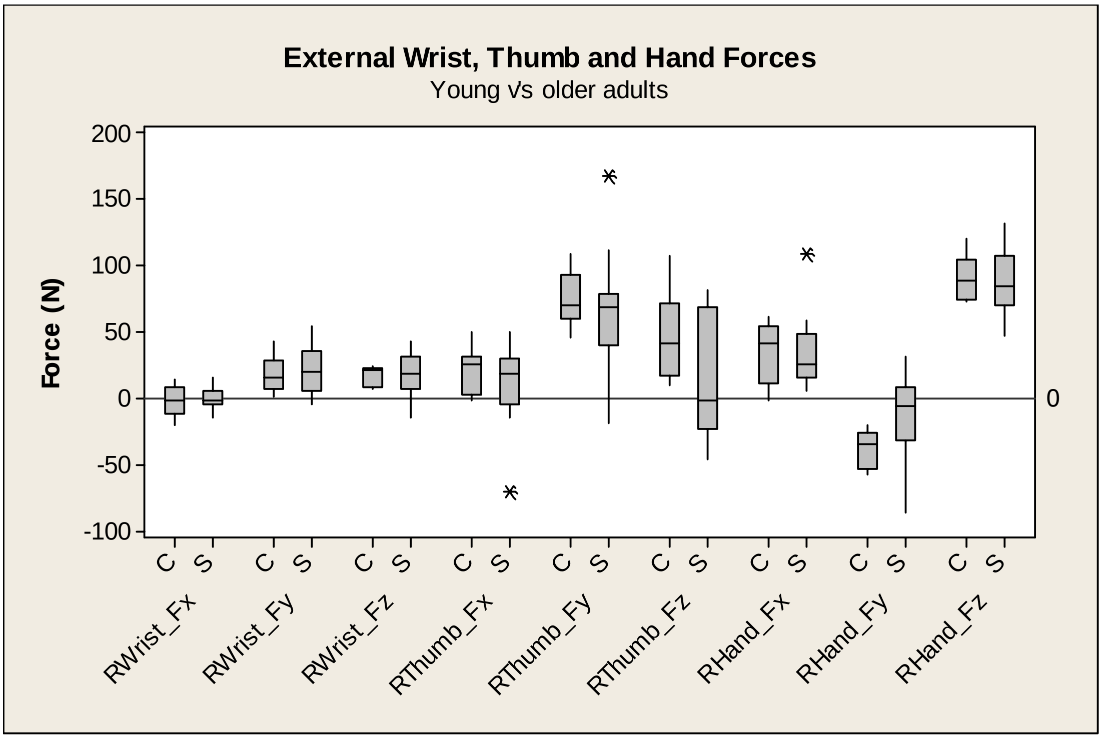


Figure 6.31 External wrist, thumb and hand forces. Comparison of young (C) and older adult (S) groups

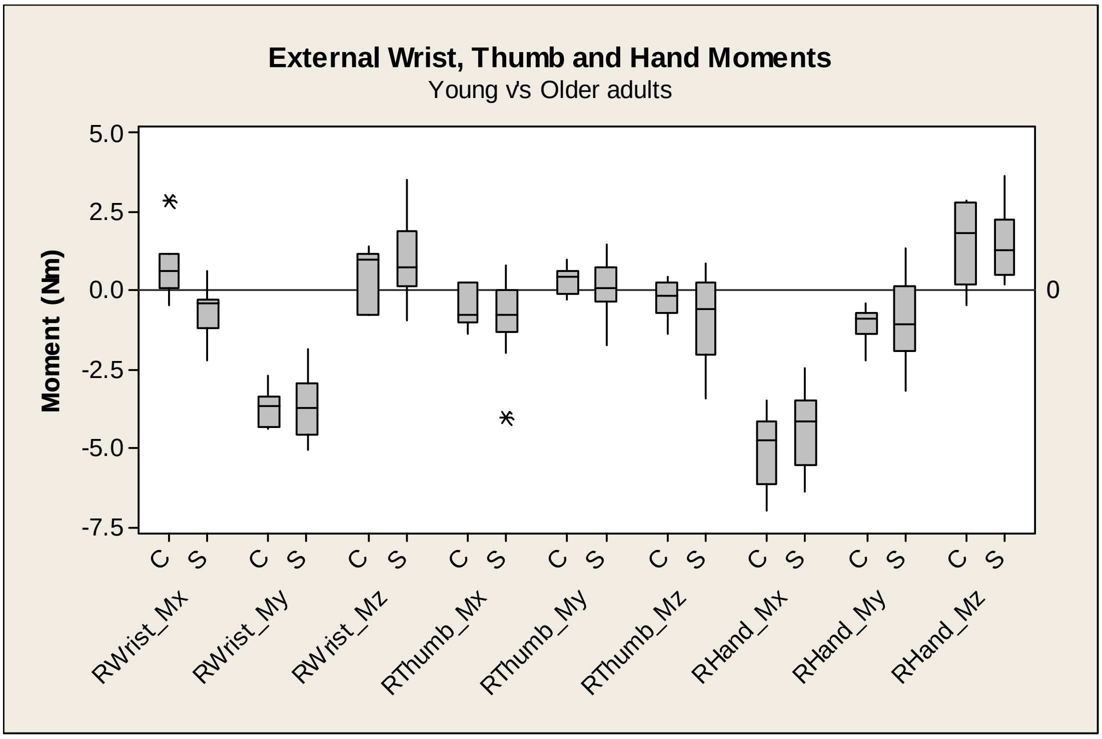


Figure 6.32 External wrist, thumb and hand moments. Comparison of young (C) and older adult (S) groups.

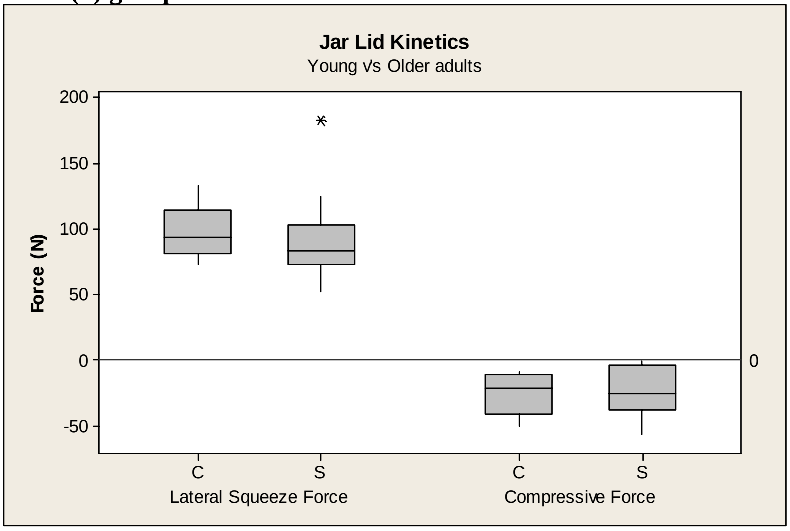


Figure 6.33 Jar lid kinetics. Comparison of young (C) and older adult (S) groups.

The only significant kinetic difference observed between the young and older adult groups was found when considering the moments about the x-axis of the wrist ($p<0.005$). As Figure 6.32 shows, older adults tended to experience a small moment tending to pronate the forearm, whereas young subjects experienced a moment tending to supinate the forearm.

The boxplots in Figure 6.31, 6.32 and 6.33 effectively highlight the amount of variability measured in the various kinetic factors which was particularly apparent in the older adult group.

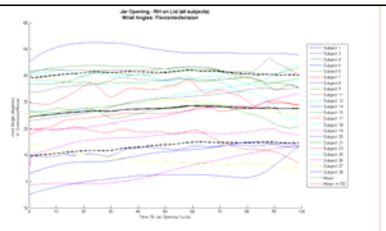
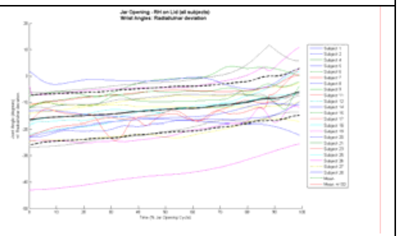
Despite there being significant differences in the power grip strengths between male and female subjects, there were no significant gender differences in any of the kinetic variables that were measured.

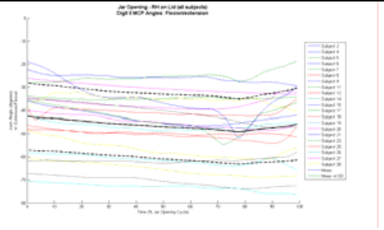
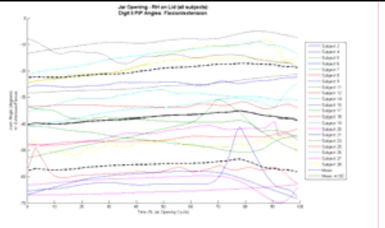
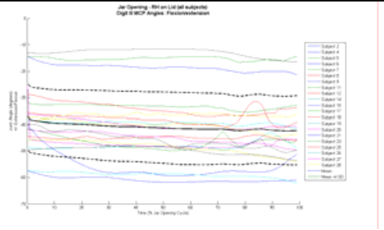
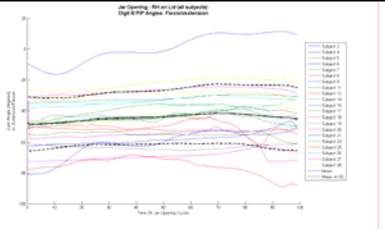
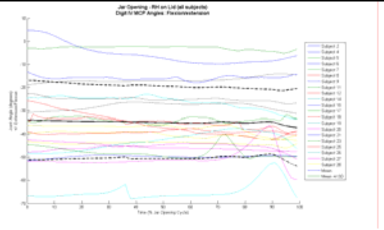
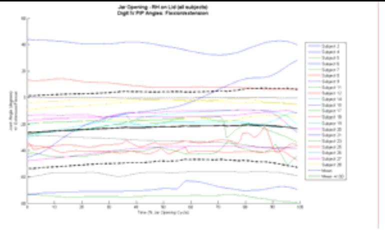
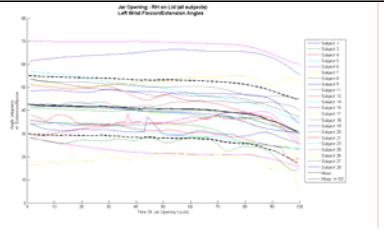
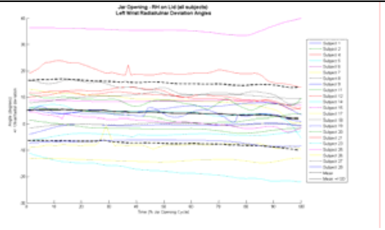
The variability in kinetic results suggested that there were a number of strategies adopted to open the packages. The different strategies could not be fully described using kinetic data alone.

6.3.3 Jar Opening KINEMATIC Data

Kinematic data on the joint angles used by the subjects during the jar opening cycle were calculated. Table 6.13 shows thumbnail images of the joint angle raw data graphs, and includes key summary data for each joint angle which was extracted from each trial at the main analysis point.

Table 6.13 Joint kinematics during jar opening. Mean values taken from main analysis point.

	Right Wrist	
	Flexion(-)/extension(+)	Radial(+)/ulnar(-) deviation
Raw data graph		
Mean (SD)	29.45° (12.48)	-11.30° (7.99)
	Right Digit II	
	MCP: Flexion(-)/extension(+)	PIP: Flexion(-)/extension(+)

Raw data graph		
Mean (SD)	-48.18° (14.22)	-35.99° (17.93)
	Right Digit III	
	MCP: Flexion(-)/extension(+)	PIP: Flexion(-)/extension(+)
Raw data graph		
Mean (SD)	-41.72° (13.54)	-43.07° (19.17)
	Right Digit IV	
	R4MCP: Flexion(-)/extension(+)	R4PIP: Flexion(-)/extension(+)
Raw data graph		
Mean (SD)	-35.05° (15.63)	-20.53° (26.86)
	Left Wrist	
	Flexion(-)/extension(+)	Radial(-)/ulnar(+) deviation
Raw data graph		
Mean (SD)	39.07° (11.55)	3.66° (11.41)

Other than the wrist joints, few of the other angles showed a great deal of rotational displacement through the opening cycle. There was a slight flexion of MCPs II and

III before the point of lid opening associated with increasing torque application. At the right wrist there was slight tendency to extend during the cycle, however the most pronounced movements of all joints were the right wrist, starting in an ulnar deviated position (-11.3° (±7.99)) followed by radial deviation, and also the left wrist, which started in an extended position (39.07° (±11.55)) followed by flexion. The flexion of the left wrist predominantly occurred towards the end of the opening cycle.

6.3.3.1 Age and Gender Related Kinematic Differences

Figure 6.34 and Figure 6.35 show a comparison between the wrist joint and MCP/PIP joint angles respectively, comparing the young control group against the older adult subject group.

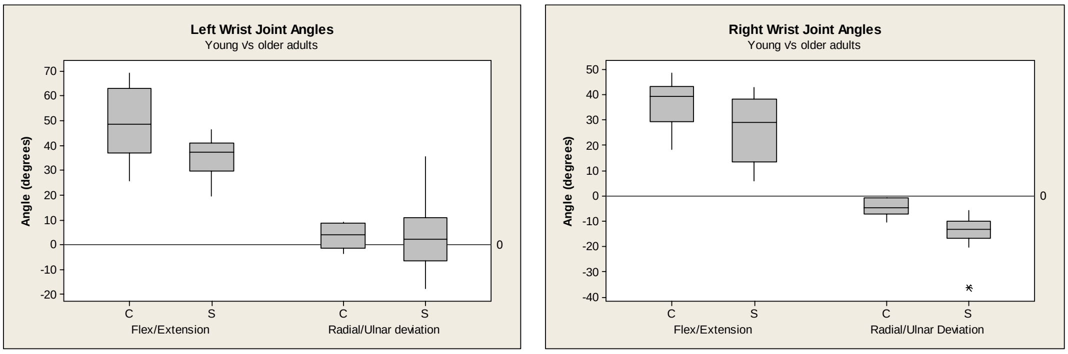


Figure 6.34 Wrist joint angles for jar opening at main analysis frame. Comparison of young (C) and older adult (S) groups; a) left wrist, and b) right wrist.

While there were no significant age related differences in the flexion angles of the MCP and PIP joints of the fingers (Figure 6.35), there was a significant difference in the radial/ulnar deviation angle of the right wrist, with the older adult group tending to initiate the opening process with their wrist more ulnar deviated than the young adult group ($p<0.01$), as shown in Figure 6.34a. There was also a significant difference in the angle of flexion of the left wrist as shown in Figure 6.34b, with the younger subjects starting with their wrist extended more than the older adults ($p<0.005$).

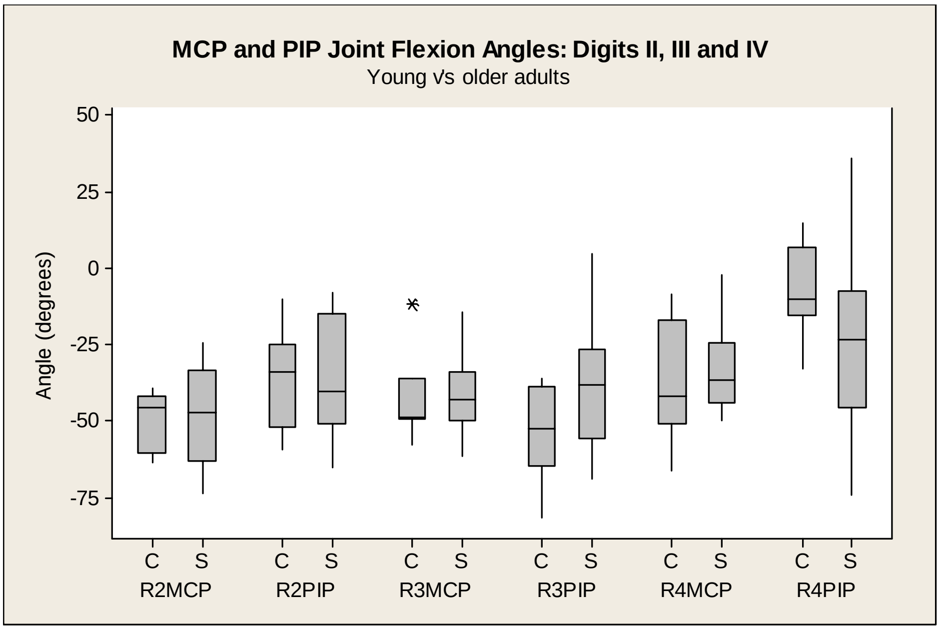


Figure 6.35 Right MCP and PIP joint flexion angles for digits 2, 3 qnd 4 during jar opening at main analysis point. Comparison of young (C) and older adult (S) groups

Figure 6.36 highlights the fact that older adults tended to open the jar with a lower rotational velocity than young adults (p<0.005).

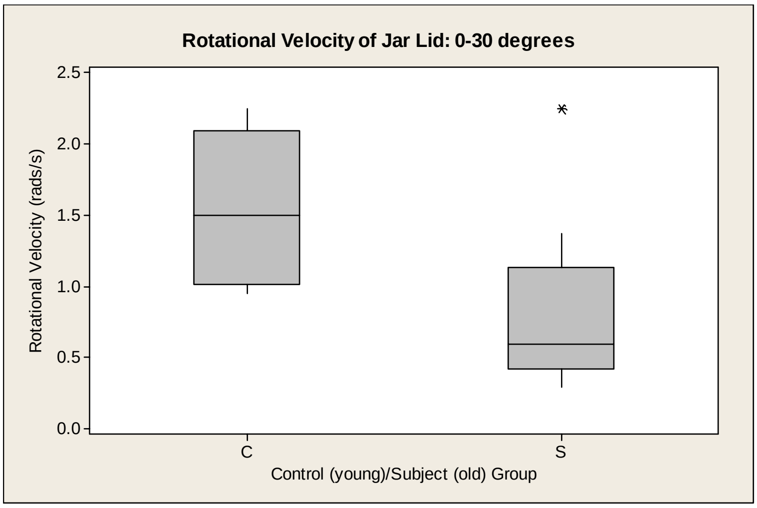


Figure 6.36 Jar lid rotational velocity. Comparison of young (C) and older adult (S) groups.

As was the case with the kinetic data, there were no significant gender-based differences within the kinematic data.

6.3.4 Relationships between Kinetics and Kinematics

The analysis of results began with the identification of kinetic differences between young and older adults. While a significant between-groups difference was found in the moment tending to pronate/supinate the forearm, it was necessary to investigate if this variable was exclusively age related or if there were additional contributing factors. A correlation matrix, using Pearson's correlation statistic, was employed to test for correlations between the forearm rotation moment and both the joint angles and basic descriptive data. The variables that showed fair-to-good correlations with forearm rotation moment were as follows:

- Age, $r=-0.599$ ($p<0.005$)
- Left wrist extension angle, $r=0.524$ ($p<0.05$)
- Lid rotational velocity, $r=0.668$ ($p<0.001$)

Age, left wrist extension angle and lid rotational opening velocity were significantly related to forearm rotation moment.

The kinematic variables which showed differences between young and older adults were also investigated in terms of their correlations with other variables to ascertain whether or not these differences were attributable to age alone. The variables that showed fair-to-good correlation to right wrist radial/ulnar deviation angle were:

- Age, $r=-.435$ ($p<0.05$)
- Right wrist extension angle, $r=0.612$ ($p<0.005$)

So although there were significant between-group differences for this variable, it only had slight correlation with age and was more strongly correlated to the angle of right wrist extension. The further extended the subjects had their right wrist, the smaller the amount of ulnar deviation it exhibited.

The variables that showed fair-to-good correlations with left wrist extension angle were as follows:

- Age, r=-0.493 (p<0.05)
- Power grip, r=0.523 (p<0.05)
- Dexterity score, r=0.572 (p<0.01)
- Right forearm supination moment, r=0.524 (p<0.05)

The results show that it was a subject's level of dexterity and power grip rather than their age which had the strongest correlation with left wrist extension angle.

6.3.5 Level of control

There were no joint angles that were correlated with the rotational velocity of the lid, or the gradient at which the torque was applied to the lid which were both taken to be indicators of a subject's level of control.

6.3.6 Classification of hand postures

Using all of the kinematic joint angle data (see Table I3 in Appendix Iii) a hierarchical cluster analysis was carried out to establish if the varied hand postures employed by the subjects could be arranged into distinct groups using similarities in the joint angle patterns. This provided an objective method of classifying hand and wrist postures, in contrast to the subjective methods used previously in the ethnographic study (Section 5.3.1). Figure 6.37 shows the dendrogram of how the subjects were grouped together during the cluster analysis. The analysis showed that although the subjects can be grouped together, there was no obvious 'clustering effect' occurring whereby subjects might fall into say 2, 3 or 4 distinct groups. When subjects were grouped together the similarity level was low, suggesting that this was not identifying clear patterns.

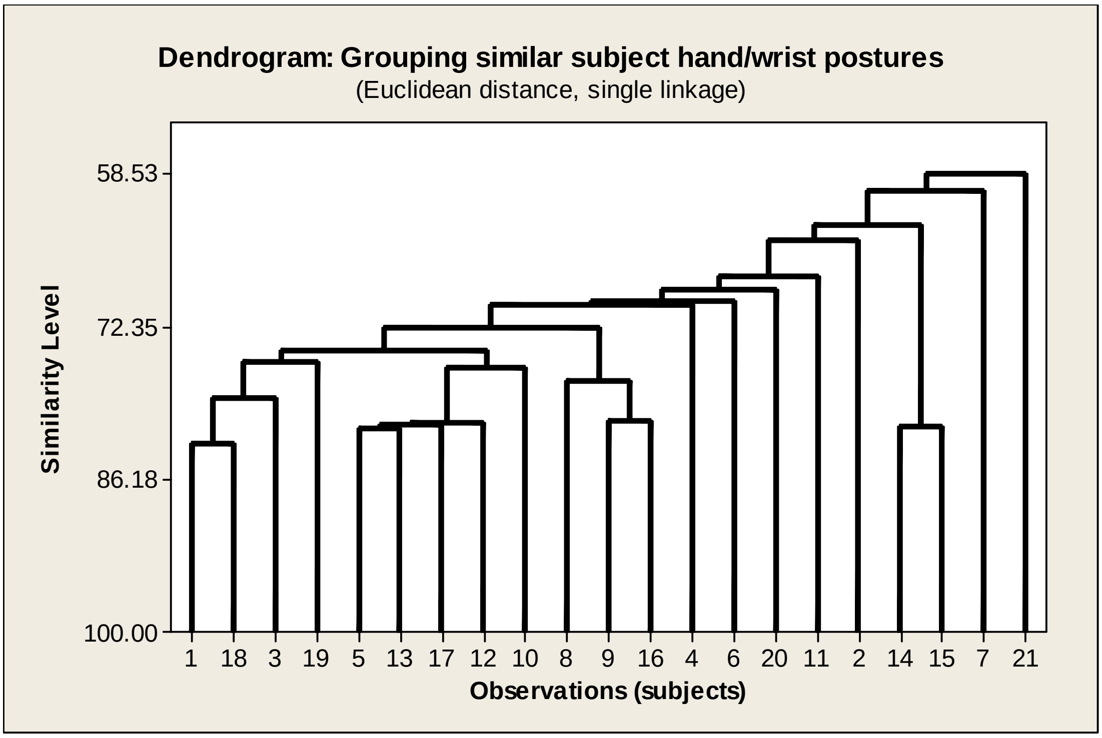


Figure 6.37 Grouping similar hand postures. Dendrogram of hierarchical cluster analysis showing little similarity between groups of subjects.

6.3.7 Left v's Right Hand on Lid

The graph shown in Figure 6.38 highlights the main kinetic differences that occurred when users placed their left hand on the lid (n=4) rather than their right (n=22). The most significant kinetic difference occurred at the wrist, with subjects experiencing an external moment tending to radially deviate the left wrist. This was the reverse of the moment that occurred at the right wrist when the right hand was placed on the lid, which is understandable given the direction of lid opening remained constant.

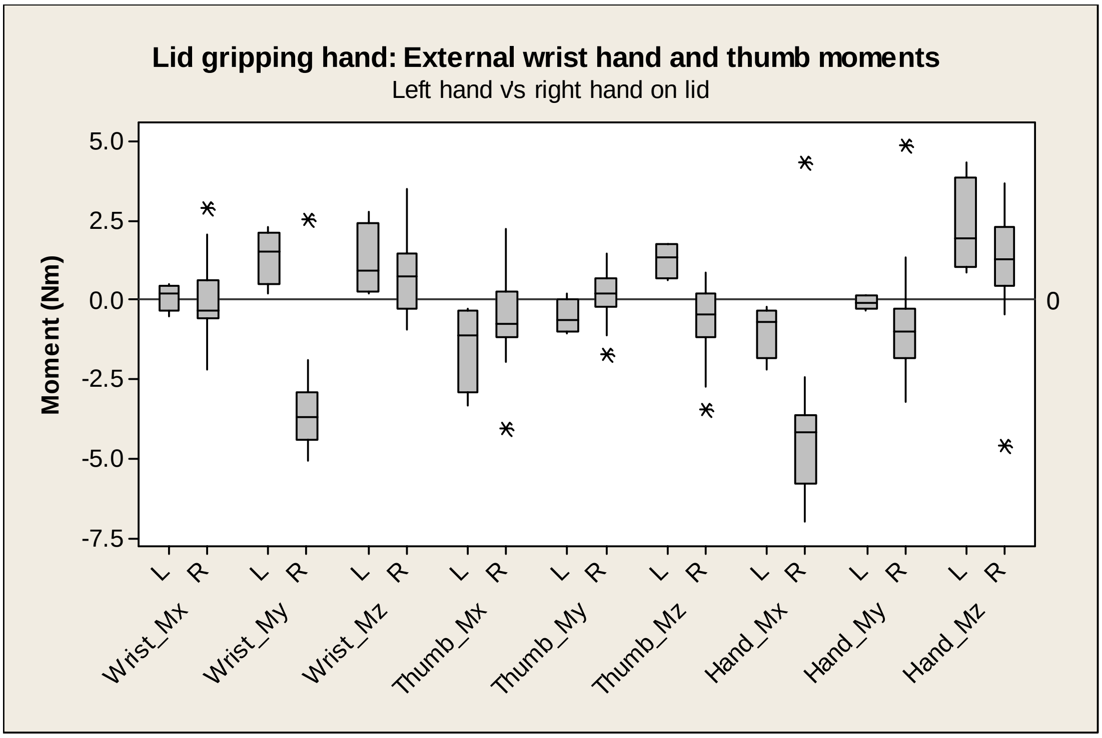


Figure 6.38 Comparison of external moments experienced during jar opening between subjects placing left hand (L) on lid (n=4) and right hand (R) on lid (n=22).

6.3.8 Bottle v's Jar Opening – Kinetic Differences

Figure 6.39 compares the jar and bottle kinetics at the thumb, hand and wrist and shows that the main differences between the activities are experienced at the right wrist. Through conducting paired t-tests on data from 8 young and 10 older adults, bottle opening appeared to generate greater moments at the wrist about two of the axes; M_x ($p<0.0001$) and M_z ($p<0.0001$) were both greater, while M_y was smaller ($p<0.05$). This was an unexpected result as the mean bottle opening torque was -1.88Nm (±0.24) which was considerably less than that of the jar (-2.81Nm (±0.49)). As illustrated in Figure 6.40, there was also a marked difference in the amount of compressive force applied downward onto the bottle and jar lids, with a greater force applied to the bottle lid ($p<0.005$). However, with a mean lateral squeeze force of 89.99N (±21.33), the bottle required a similar magnitude to that of the jar 92.6N (±28.19).

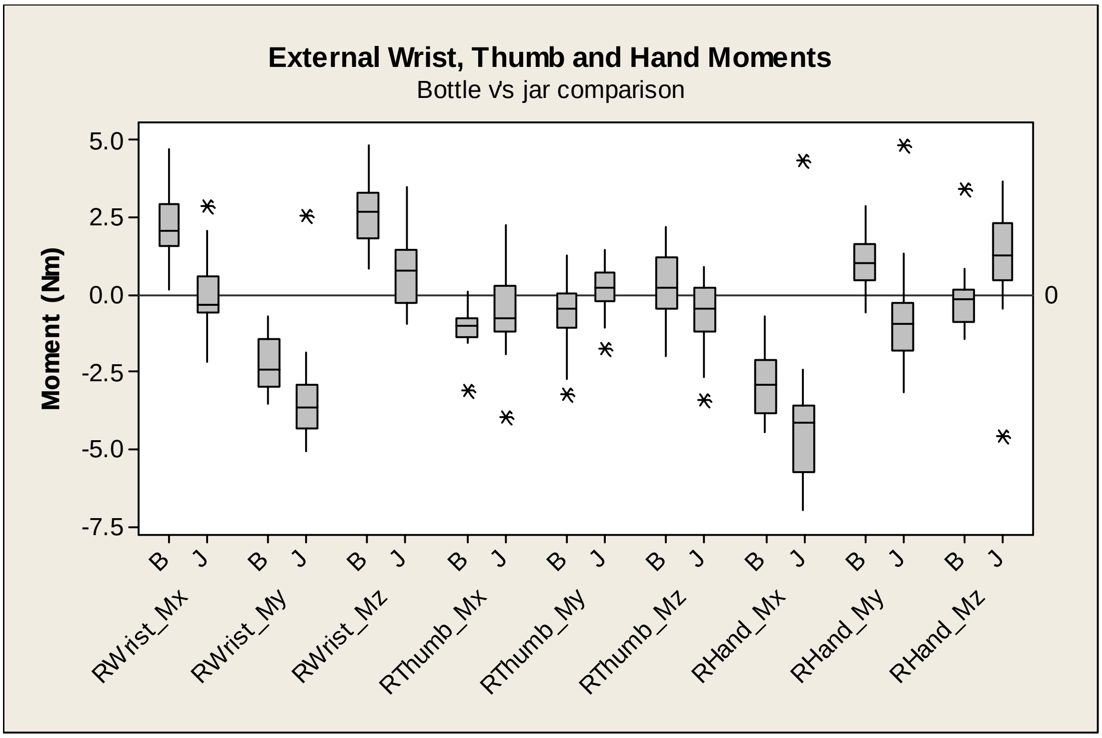


Figure 6.39 Comparison of external moments experienced during jar (J) opening (n=22) and bottle (B) opening (n=20). Subjects placing right hand on lid only.

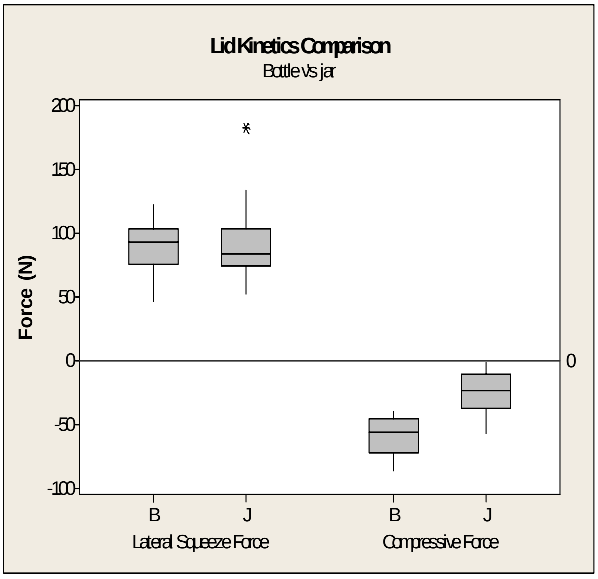


Figure 6.40 Comparison of jar (J) and bottle (B) lid kinetics. Subjects placing right hand on lid only.

6.4 Discussion

The following section will start by considering the various experimental errors present this chapter of the study, will then go on to discuss the significance of the various kinetic and kinematic results described in the previous section and will finish with an appraisal of the overall experimental design. During the discussion reference will be made to different muscle groups of the upper limb and their actions, taken from the tables and figures presented in Appendix A.

6.4.1 Experimental Errors

There were a number of sources of error within the experiments that may have influenced the results described previously in Section 6.3. The following subsection will describe these errors individually, commenting on their magnitude and relevance where appropriate.

6.4.1.1 Motion Analysis – Kinematics

Cameras misinterpreting surface marker locations

Residual values of 0.1-0.3 mm were obtained when calibrating the motion analysis cameras for all test sessions. The residual is a parameter calculated by the motion analysis system software and provides an indication of the accuracy in locating a point in space. This is a global average and cannot be considered to apply to any individual marker location. Given the small distances between surface markers this error in predicting their locations could have caused errors of several degrees in joint angle calculations. For example, when calculating a joint angle with two segments of 30mm length and the joint flexed at 90°, a worst case scenario for marker prediction was considered and the maximum conceivable error was calculated at ±3.2°.

Erratic marker movement

When capturing the trials a trajectory ‘predictor radius’ of 4mm was set, so if a marker appeared to move more than 4mm in the space of one frame (0.0167s) it would no longer be considered to be part of that trajectory, i.e. not the same marker. Effectively this meant that any erratic marker movements were no more than 4mm per frame. Again, given the small scale of the body segments being considered and thus the proximity of the markers, a discrepancy of 4mm could have caused a large jump in output values. While a 5Hz double-pass Butterworth filter was used (described in Section 6.2.5) to smooth the trajectories, if a prolonged spike occurred over a period of >0.2s it was rounded by the filter, but its peak was not completely flattened.

Using a stronger filter would have lead to genuine trajectory peaks being lost, so that was not an ideal solution. Similarly, if the predictor radius were decreased it would have lead to fragmented trajectories and subsequently much more time spent performing post-capture corrections.

Skin movement artefact

The skin mounted markers were used to track the movement of the hand and forearm. All analysis implicitly assumed that the markers did not move relative to underlying bones during the dynamic trials. However, the skin would have moved over the underlying bones and therefore so would the markers attached to the skin. This skin movement artefact would have introduced errors in the identification of the exact location of the bone embedded axes systems. It was difficult to ascertain how significant this error was. The markers were placed on the apex of the flexed joints in an attempt to minimise skin movement artefact at the digit joints.

Measurement of joint depths

The joint centres were defined to be at half the external dimension from the dorsal surface of the hand. This assumption was made as no images of internal structures were available. It is possible that variation in soft tissue over the joints caused errors in location of the true joint centre.

Calculation of joint CORs.

There was a potential source of error in the calculation of the location of the joint CORs as they were assumed to lie on the midline between the dorsal and palmar aspects of the thickest part of each joint. It is known that as a joint articulates, its COR moves slightly too. There was no representation of this in the biomechanical model of the hand and wrist used in this study.

Error due to hierarchical nature of segment definitions

Another source of error was the cumulative effect of the transference of errors from one segment to another. The model of the hand and wrist used was particularly prone to this given that each segment relied on the preceding proximal segment's axis system to define its own axis system.

Combined error in joint angle calculation

Concerns over the multiple sources of error were allayed somewhat by the accuracy of the results when calculating joint angles during the repeatability tests described in Table 6.7. Although the test was carried out statically it did prove that despite all the individual potential errors, MCP and PIP joint angles were calculated to a high degree of accuracy (within ±5°). This testing could have been carried out in a more comprehensive manner using dynamic fluoroscopy techniques, analysing more joints in multiple planes, however this was deemed to be beyond the scope of this research.

6.4.1.2 Motion Analysis – Kinetics

Similarly to the calculation of joint angles, the calculation of joint kinetics may have been affected by any inaccuracies in the cameras predicting marker locations. As the two force transducers were mobile they relied on markers attached to the body and lid of the jar/bottle to establish their respective axes systems in the global co-ordinate system. As the triad of markers on the body was quite small (~45mm between markers) it was sensitive to any spikes in trajectories. These trajectories were subject to post-capture correction and filtered to minimise the effect of any erratic marker movement, thus minimising this error source.

6.4.2 Jar Opening Kinetics

6.4.2.1 External Wrist Moments

As anticipated the largest external moments at the right wrist were found about the y-axis, tending to radially deviate it, and as shown in Figure I.3 in Appendix Ii, the moment profile followed a consistent trend for the vast majority of subjects. The external moments tending to flex/extend and pronate/supinate were both generally lower in magnitude and exhibited much variation. So although the main group of muscles acting in the forearm were the radial deviators (flexor carpi radialis, and extensor carpi radialis longus and brevis) there were a variety of other muscles used in conjunction with these.

Prior to scaling, all external moment values calculated were comfortably within the limits of the quoted maximal wrist strengths, described previously in Table 2.2. These maximal wrist strengths were collected with the wrist isolated and therefore allowed no contribution from the elbow and shoulder to generate the stated moments. In this experiment the shoulder and elbow were unrestrained, therefore likely allowing greater moments to be generated at the wrist.

The age-related differences observed in the external moments tending to supinate the forearm of the young and pronate the forearm of the older adults (M_x), indicated a difference in technique during the jar opening activity. It is known from previous research (Askew et al., 1987) that the pronating muscle groups favoured by the young (pronator teres and pronator quadratus) are not as strong as the supinating muscle groups favoured by the older adults (supinator and brachioradialis). So the older adults were recruiting their strongest muscle groups to aid the radial deviators in removing the jar lid.

When looking at the correlations between M_x at the right wrist and a number of predictor variables, there were none that provided a robust correlation. The strongest correlation found was between M_x at the right wrist and the extension angle of the left wrist; the greater the left wrist extension the more positive the right wrist moment (tending to supinate). The reason for this correlation was not clear.

Although there is no clear explanation of this observed kinetic difference between young and older adults, it remains important that difference was identified. It was anticipated that while age group may highlight important kinetic differences, ultimately other variables such as hand size, power grip or dexterity would prove to be stronger predictors of these differences. This was not the case, as no strong correlations were found.

6.4.2.2 External Wrist Forces

The external forces calculated at the wrist did not provide any evidence of kinetic differences between young and older adults, although they did help describe the nature and magnitude of the forces experienced at the wrist joint during jar opening. The first observation was that they were not as large as those experienced at the thumb and hand segment. As the thumb and hand segment forces were opposing one another to grip the lid, the resultant external force experienced at the wrist was relatively small as these two components tended to cancel one another out. The resultant force would generally act in the dorsal and lateral directions, with a smaller and variable component acting along the longitudinal axis of the forearm in either a proximal or distal direction.

6.4.2.3 External Hand Moments and Forces

The largest external moment applied to the hand segment occurred about its x-axis and tended to internally rotate it. This large moment (-4.17Nm (±2.28)) was most likely caused by the large component of the lateral squeeze force passing palmar to the hand segment origin and parallel to the line from MCP II to MCP V.

The external forces confirmed that the lateral squeeze force component did indeed act along the line of the MCP joints, as F_z was calculated at 83.87N (±34.19) which was the largest individual component of the resultant force experienced at the hand.

The direction of F_y was not expected, as it acted in a palmar direction, suggesting instead of the fingers pushing down on the lid, they were actually pulling the lid upwards slightly, although again there was such variability about this mean value of F_y that some subjects were pushing downwards as anticipated. The upwards pulling force can be accounted for in that many subjects will hook their fingers underneath the lid to grip it, thus pulling inward towards the centre and upwards as the flexor muscles contract.

6.4.2.4 External Thumb Moments and Forces

The external moments at the thumb were small in magnitude and variable in nature about all axes, so they did not provide much insight into the contribution of the thumb to jar opening. The fact that the thumb did not experience large moments when the subject uses their preferred grip suggested that subjects naturally manage to position their thumb such that the lateral squeeze force passes through it, thus avoiding potentially large external moments.

The largest component of the external force experienced at the thumb occurred in the dorsal and medial directions. Given the orientation of the thumb on the lid, the medially directed component occured as a result of the thumb pressing downwards onto the lid as the muscles contract. This downward force, combined with the slight upward pulling force exerted by the fingers (mentioned previously) created a levering action on the lid. So while there was net downward compressive force exerted on the jar lid, it appears to have been composed of the fingers pulling upwards on one side and the thumb pressing downwards on the other.

6.4.3 Kinematics During Jar Opening

6.4.3.1 Kinematics of the Jar

The rotational velocity of the jar lid was greater for young adults when compared with that of older adults, suggesting that older adults performed the task in a more controlled manner. However, contrary to this there was no significant between-group difference when considering the gradient of the torque profile as the torque was applied to the lid, so the torque was applied in the same manner and the difference occurred after the required lid removal torque had been exceeded. This may be as a result of older adults recruiting their antagonist muscles (ulnar deviators) to a greater extent than the younger adults, thus slowing the lid as they felt it starting to move.

Finding that older adults exhibited greater levels of control was not anticipated for two reasons. Firstly, they exhibited poorer hand functionality both in power grip and dexterity, therefore it was inferred that they had less control over their hands. Secondly, previous research (Carus et al., 2006) showed that older adults applied many unnecessary forces and moments to the lid when opening an instrumented bottle, suggesting that although they completed the task, they did so with less control than the younger subjects. This difference in opening torque could be attributable to past experiences, with more older adults having spilled the contents of a jar, therefore choosing to complete the task more carefully. The subjects were not explicitly informed that their ‘level of control’ was being measured so had no reason to deliberately open the jar more carefully. It is also conceivable that this was an injury avoidance strategy as too rapid a change of joint orientation could potentially cause soft tissue damage.

From the results it cannot be assumed that older adults have more control as such, rather that they exhibited more control than younger adults during this experiment. It perhaps suggests more about their approach and attitude towards tasks than their physical ability.

6.4.3.2 Right Wrist Angles

All subjects held their right wrist in an extended and ulnar deviated position at the point of opening the lid (the main analysis point). Analysis showed that older adult subjects tended to hold their wrist in a significantly more ulnar deviated position than the younger adults. This initially suggested that perhaps the older adults tend to lock their wrist in the extreme of one degree of freedom and use the shoulder and elbow, rather than the wrist, to provide the rotation required to turn the jar lid. On closer inspection, it transpired that there was no difference in the amount of subsequent radial deviation of the wrist between groups, so neither locked their wrist in position.

It may have been the case that the older adults anticipated having to turn the lid further than the required 30°. Regardless of the reasons for positioning their wrist so, they were in fact holding their wrist in a slightly weaker position than the younger adults, as previous work has shown that power grip (Li, 2002) and various pinch grip strengths (Imrhan, 1991) decrease as ulnar deviation increases beyond ~5°. Delp et al. (1996) similarly showed that the radial deviation moment generated by the wrist decreases as ulnar deviation increases.

6.4.3.3 Right MCP and PIP Angles: Digits II-IV

The higher level of flexion exhibited in the MCP and PIP joints of both digits II and III (when compared with digit IV) implied that these may be the main contributors to the gripping force applied to the lid in opposition to that of the thumb.

The flexion angles of these digits did not yield many differences between young and older adults. It was anticipated that these variables might have had some correlation to hand length, with larger hands exhibiting great flexion angles (due to the constant lid size), but this was not the case. One finding was that they did not move much during the opening cycle, and were therefore assumed to be locked in position throughout. Given the erratic appearance of many of the 'MCP/PIP flexion angle v's time' graphs shown in Appendix Iii, it would appear that the surface markers involved in calculating these angles were subject to much unwanted movement rendering the calculated values somewhat erroneous.

6.4.3.4 Left Wrist Angles

Younger adults tended to have their left wrist extended further than the older adults. This initially suggested that they would involve their left wrist more in the lid opening cycle, but on closer inspection it transpired that they displayed the same amount of flexion as the older adults, the only difference being that they started from a more extended position. Previous work (Odriscoll et al., 1992) found that power grip was strongest when the wrist is extended to approximately 35° in normal healthy subjects. Delp et al. (1996) also found that the more extended the wrist, the smaller the flexion moment exerted. In this experiment older adults had their wrists extended at 35.3° (±8.3) whereas the young adults had their wrist extended at 48.9° (±14.7), which would appear to be a slightly weaker position.

It would appear that older adults favoured a strong left wrist position while the young adults preferred a strong right wrist position.

6.4.4 Left or Right Hand on Lid - Kinetic Differences

The main kinetic difference involved in placing the left hand on the lid, instead of the right, was the moment experienced at the wrist. With the left hand placed on the lid, the left wrist experienced the largest moment tending to radially deviate it, so the ulnar deviators were active (flexor carpi ulnaris, and extensor carpi ulnaris and brevis) whereas with the right hand on the lid the radial deviators were active. Delp et al. (1996) showed that the wrist is slightly stronger in radial deviation than it is in ulnar deviation, so those placing their right hand on the lid were using their strongest muscle groups, unless they had any ailments in their right hand/wrist, or for any other reason had a stronger left hand.

6.4.5 Bottle and Jar Lid Opening – Kinetic Differences

The largest external moments at the wrist during bottle opening, for all subjects, tended to supinate and extend the wrist. The external moment tending to supinate the forearm (M_x), with the pronator muscles (pronator teres and pronator quadratus) active, was larger in magnitude and more consistent than the corresponding moment during jar opening. The external moment tending to extend the wrist (M_z) of all subjects, with the flexors muscles (flexor carpi ulnaris and flexor carpi radialis) active, was also larger in magnitude and more consistent than with jar opening. There was a less pronounced moment tending to ulnar deviate the wrist (M_y) in comparison with jar opening.

The decrease in M_y and the change in M_z between jar and bottle opening, can be explained as follows. During jar opening the hand was placed over the top of the flat surface at the top of the lid requiring the main torque component to be applied via wrist radial deviation. Bottle opening however required that the forearm was instead supinated slightly such that digits I and II were wrapped around the rim of the lid or used to form a lateral pinch grip. This hand and wrist posture meant that the main contributors to the application of torque to the lid were wrist flexion and forearm pronation. Overall, during bottle opening there was a greater contribution from muscle groups generating moments around all axes of the wrist.

The magnitude of the external moments at the right wrist were greater during bottle opening than jar opening, which was not anticipated as the torque required to remove the bottle lid (-1.88Nm (±0.24)) was significantly less than the torque required for the jar lid (-2.81Nm (±0.49)). One reasonable explanation for this is that the bottle lid is usually gripped between digits I and II, therefore subjects tended to hold the COR of the lid a greater distance from their wrist joint centre than they would do during jar opening. This would give the resultant reaction force a longer lever arm.

6.4.6 Experimental Design Appraisal

While the experiment described in the present chapter represented a novel biomechanical model of the hand and use of small scale force transducers in a unique, dynamic packaging device, it also had a number of limitations. Both the limitations and the advantages of the experimental design will be discussed.

The motion analysis cameras and/or their set-up were not originally designed to capture such a high number (50) of small (4.5mm diameter) markers in such a small volume (300x300x300mm) and therefore experienced difficulty in accurately and reliably tracking markers during this experiment. This was evident in the amount of time spent on post-capture corrections; reconstructing trials, filling gaps and deleting split or overlapping trajectories. The sheer number of small markers in this confined space meant the image analysis algorithms were not always able to correctly track markers.

The use of varying opening torques from trial to trial represented a compromise in order to achieve a dynamic torque opening profile for both the bottle and jar lids. Ideally the torque profiles would have been identical throughout the experiment. Although the variation in lid torque between trials was not great, and scaling factors were applied to all kinetic variables, there was the possibility that those attempting to open the most difficult lids adopted different hand and wrist postures related to that increased difficulty.

With the experiment not acting as a maximal strength test, it had the advantage of allowing investigation of the dynamic aspect of package opening, adding the anticipatory aspect of the lid opening suddenly enhancing the realism of the experiment. It may, however, also have been useful to establish which hand and wrist postures allowed subjects to achieve their maximum lid opening torques during a static maximal trial.

Other minor limitations of the experimental design included the surface markers possibly inhibiting the manner in which subjects handled the jar/bottle device, combined with the presence of cameras and the laboratory setting detracting from the realism of the test. Also, due to the nature of the tasks and freedom to choose their preferred postures, subjects occasionally chose postures which were unforeseen, and subsequently the cameras were not positioned appropriately and marker occlusion occurred, rendering some trials unusable. Unfortunately this was the drawback of allowing subjects such freedom, although given the comments of designers in Chapter 7, this was preferable to prescribing strict opening postures to the subjects.

While there were significant kinetic and kinematic differences between the older and younger adults, data on the position of the hand relative to the device, the hands relative to one another and the position of the device in the global co-ordinate system may have added useful results for analysis. These variables may have explained the differences in opening torque gradients and rotational velocities during jar lid opening.

The statistical analysis of the results was limited slightly by the fact that the control and subject groups were of different sizes, as this meant two-way ANOVA tests could not be carried out. These would have provided a deeper insight into the interaction between the different variables, however individual t-tests and simple

Pearson correlations provided an adequate method of analysing between-group differences and basic correlations. The lack of comparative data in the literature also made it difficult to determine whether the variation observed in the results was attributable to experimental error or due to genuine variations in the way the human subjects perform the package opening tasks.

6.5 Summary

The preceding sections have described how the biomechanical testing of young and older adults opening jar and bottles was conducted. Novel packaging equipment was designed which mimicked the dynamic nature of jar and bottle opening while simultaneously measuring the forces and moments applied by the two components of the subject's grip. Jar and bottle opening tasks were recorded using a motion analysis system. Adapted from previous work, a biomechanical model of the hand and wrist was developed which included a representation of the proximal transverse metacarpal arch, calculation of the location of the wrist joint centre, and individual axes for the each metacarpal bone. Limited marker placement repeatability and joint angle calculations proved that the model was viable. The various data processing steps from data capture through to usable results were described in detail.

Only a small fraction of the total number of variables measured are reported in this thesis. Those variables presented have been chosen to provide insight into differences in opening strategies adopted and demonstrate the feasibility of the methods implemented.

The only significant kinetic difference between young and older adults during jar opening was found in the external moment M_x which tended to pronate the forearm of the older adults and supinate that of the young adults. There were no strong correlations between this external moment and any kinematic predictor variables.

Kinematic differences between young and older adults during jar opening were found in both the left and right wrists in extension and ulnar deviation respectively. Older adults tended to position their right wrist more ulnarly deviated and their left wrist less extended. There was also a significant difference in the velocity with which the jar lids were removed, with older adults opening the lid more slowly. Hand grip styles could not be objectively grouped together based on similarities in the joint angle data calculated.

While there were distinct between-groups kinetic and kinematic differences, the data was not sufficient to provide a detailed description of the interaction between the variables.

There were significant kinetic differences between subjects who chose to place their left or right hands on the lid, with external moments tending to radially and ulnarly deviate the respective wrists. There were also significant kinetic differences between jar and bottle opening activities. External moments at the right wrist showed the largest difference, with substantial moments experienced about all axes of the wrist during bottle opening, whereas with jar opening the only consistently large moment tended to ulnarly deviate the wrist.

There were a number of experimental errors that may have affected both the kinetic and kinematic results, mainly concerned with the accuracy of measurement of the surface marker positions. It remains unclear whether the large amount of variation observed in the variables was caused by experimental error or by genuine variation in the subject movements. More extensive verification of the biomechanical model of the hand and the marker system would clarify which caused the variation.

6.6 Implications for Thesis

This chapter represented a scientific and objective approach to the study of package opening. Clear kinetic and kinematic differences in the way young and older adults performed a dynamic jar opening activity were identified. These differences were not strongly correlated to hand functionality, as was originally hypothesised. This implies that the information generated here can only be used for drawing broad conclusions about how two groups of people perform a particular activity, and that more expansive extrapolations would be unwise given the sample sizes used.

This chapter also served to highlight the limitations of performing a detailed biomechanical analysis of an individual task to generate data for inclusive design. The expertise, time and expensive equipment required are prohibitive to such an application. There is also the further problem of ongoing debates within the rapidly changing biomechanics research field, whereby there are not yet established standard approaches to generating data on the hand and wrist. This will make between-study data comparisons impossible, so there is little chance of building up a 'bank' of transferable data.

Regardless of the lengths required to generate the data, the subtle kinetic and kinematic differences identified here for the package opening activities, which would not have been observed using video ethnography, can be interpreted in a number of ways and could conceivably be presented to designers.

Chapter 7 Follow-up Designer Interviews

7.1 Introduction

The initial study of practicing designers (Chapter 3) provided a broad overview of how packaging designers currently take older adults into account including an understanding of what data they currently use and how they apply it. Instead of asking them about hypothetical data it was thought that there would be more value in showing them real data in various formats, and discussing how and when they might use it.

Previous chapters have detailed the collection of various types of real data pertaining to a particular task (package opening) that could be presented to designers. In light of objective 5, this chapter represents an investigation into the opportunities for and barriers against designers using such data.

7.2 Methods

A semi-structured face-to-face interview was developed in order to establish the most useful way to present older adult biomechanical requirement data to designers and to investigate what other information they might need to complement this data. A semi-structured interview approach was chosen to allow a free flowing, relaxed discussion that would allow the collection of rich qualitative data. Eight of the ten packaging design companies who participated in the initial study of practicing designers (see Table 7.1 for details) took part in these structured interviews, with respondents R8 and R10 unable to participate.

Table 7.1 Description of eight companies involved in initial follow-up designer interviews

Respondent No.	Location	Main Business	Size (number of employees)
R1	Glasgow	Product and industrial Design Consultancy	6
R2	Marlborough, Wiltshire	Design and innovation company specialising in structural packaging	16
R3	Stroud, Gloucestershire	Product design consultancy	2
R4	Walberton, West Sussex	Product development and structural packaging design	3.5
R5	London	Product design consultants	60
R6	Wrexham, Clywd	International food processing and packaging solutions	370 (plant) 25,000 (worldwide)
R7	East Kilbride	Corrugated box design and manufacture	290 (plant)
R9	Glasgow	Design, engineering and project management	4

The semi-structured interview allowed the various data formats to be discussed with each of the designers. Data produced from the ethnographic packaging study (Chapter 5) and previous motion and force studies (unrelated to package opening) were presented. A range of different data formats were used for presentation to the designers, including:

- Still screenshots/photos of handgrips whilst opening packaging. These were close ups of subjects at specific points in the package opening process. (e.g. Figure 5.2)
- Video clips of subjects interacting with packaging. These were generated from two views; one showing a close up of the subject's hands and another showing their whole upper body. (e.g. Figure 5.2)
- Motion and force measurement system outputs showing joint angles and ground reaction forces during normal walking and stair climbing activities. 3D motion of the tasks being performed was also presented in 'stick figure' format.
- Motion and force measurement system output alongside simultaneously captured standard video of a weight-lifting activity.

- Data relating to pain and discomfort experienced whilst opening packaging.

The structured interview also provided an opportunity to obtain designers' opinions on various 'novel' approaches of presenting and manipulating biomechanical information within the design process, specifically:

- Virtual biomechanical testing
- Information on which muscle groups are being used at different points while interacting with packaging
- 3D motion and force system output with normal video footage synchronised on top
- The ability to assess the effects of changing various design variables
- A database of videos of users with various hand impairments interacting with packaging

The various data presentation formats were shown to the designers at strategic points during the interview using a slide show on a laptop. The results were recorded using a digital voice recorder and were subsequently transcribed and analysed, with an example interview transcription shown in Appendix E. During the analysis significant quotations were extracted and grouped together according to similar or directly contrasting viewpoints and attitudes towards the data presented to them. Once the quotations had been grouped a summary table of results was generated that allows the reader to establish a quick impression of which data sources and presentation techniques were understood easily and were considered to be useful by designers. This method of summarising results relied on a very straightforward classification system for answers provided by designers. The answers were classified using the subjective judgement of one data analyst.

7.3 Results and Discussion

The results of the interviews are summarised below, with example quotes from the various designers who participated. Similar to the method used for analysing the results in Chapter 3, See for Table 7.1 descriptions of each of the respondent's organisations.

The prevailing feedback from this series of interviews was that despite the high levels of precision offered by biomechanical testing, designers harbour a strong preference towards traditional ethnographic video data. Designers feel that the lifelike reality of 3D motion and force data is compromised by the fact that it is generated in a laboratory environment.

"Our whole remit as a business is to get our testing as real as possible and this feels just like measuring to a high level of accuracy something which is hugely inaccurate" (R2)
"Sometimes being too specific in research is wrong, and the picture becomes too complex" (R3)
"I would only be looking for very crude results. Everything in design is crude, it's not science, it's just thumb in the air" (R1)
"The drawback to lab-based ethnographic and biomechanical studies, is the lab effectively acts like zoo and I cannot interact with the person and see how they react to new things" (R2)

Another concern raised related to transferability of biomechanical data. Designers' understanding is that biomechanical tests and data are very specific to a task and therefore do not lend themselves well to transferability.

"The problem is that if you are trying to design something [completely] new there will be no way of having such footage. It's limited to existing designs" (R7)
"It is limited to existing designs - it would have to be constantly updated with new products." (R4)

"I don't see how you could ever have accurate "generic data" like this that would be comprehensive enough to be useful– it would have to be very product specific" (R3)

Another concern voiced, related to transferability, was that the data collected does not provide any means for predicting how a person might behave when presented with a new product.

"It might help to show what the problem is but it doesn't help me to generate any new solutions" (R6)
"I want to know what effect my potential design changes might have" (R4)

Designers found the 3D motion output screen too clinical, whilst they commented that seeing a true 3D image useful, they also found it dehumanising. Finding out more than physical parameters and abilities was a recurring theme throughout the series of interviews. Simply considering how an individual physically interacts with a product in isolation was thought unrealistic. Designers wanted more information about the person; where they lived, their socio-economic status, what products they used and liked, their previous occupations, who they lived with, their aspirations, where they shopped, etc.

"It looks very primitive if you compare it to most modern-day graphics" (R6)
"It would be a bit more life-like if there were the ability to add some flesh onto the stick figure somehow" (R3)
"It's important to have more information about the person in the picture or video, such as their age and more importantly their socio-economic group" (R6)

Biomechanical results were thought to be easier to interpret when they had some video complementing them, either overlaid or playing alongside. It seemed that capturing video data and presenting this with biomechanical data would make it clearer to designers. It was also discussed that some sort of introduction to biomechanics, what it means and its basic principles would be vital to allow any designer to interpret the data and most importantly to understand why it was important and how it could be used to improve design.

"[Synchronised video] is useful to be able to visualise what is really going on with the vicon output….. I would want the ability to go into the vicon output screen and watch it from different angles and play around with it" (R2)

A number of designers mentioned that they would only want the conclusions from such testing, without having to understand what they meant or how they were derived. One mentioned that access to the raw data in tabular or graph format would be useful once their biomechanics knowledge grew and they were able to interpret the results themselves. They would also need to have a clear explanation of how the test was carried out, what variables were controlled and various other details.

"There's no clear conclusions to seeing those images, so it's not that useful" (R5)
"I would like to see some pictures alongside the graphs and table so I can see what's happening at different points in the cycle" (R6)

It appeared established that biomechanical testing techniques would not be used as standard on a packaging design project. Many of the designers said they would only go into that level of detail if it had been requested specifically by their client, and obviously they would have to get some external help with this. It was highlighted that the levels of precision and detail produced by biomechanical tests are not necessary in the case of packaging design.

"This approach would represent an unprecedented level of detail [for packaging design]" (R3)
"If it's testing or research we can't carry out ourselves, we will involve some external expertise" (R5)

The test subject's natural environment, the people they'd be with, their state of mind could never be accurately reproduced in a laboratory. This was the main reason for the designers citing video footage as a richer source of information than pure biomechanical data. Ethnographic video footage of subjects in their own home was cited as being preferable to the more controlled laboratory-based data presented to them in this study.

"Video's really, really powerful and we use it on every project" (R2)
"The person should be on their own, in their own environment, unaware of being filmed would be ideal too" (R5)
"One thing that is missing form this sort of data is the person's environment, and what 'rituals' they perform when using the product. We want to know information about their daily routine" (R5)

Although it was considered difficult to compare and contrast the response of designers from such a variety of educational backgrounds and working in fairly diverse environments, a summary of their responses is offered in Table 7.2

Table 7.2 Summary table of simplified responses to data types gathered during follow-up designer interviews

	Video clips		Still screen shots		Motion analysis stick figure output		Motion analysis + standard video		Pain and discomfort charts		Joint angle data graphs		Moment data graphs	
	Understand	Useful?	Understand	Useful?	Understand	Useful?	Understand	Useful?	Understand	Useful?	Understand	Useful?	Understand	Useful?
R1	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Maybe	Yes	Maybe
R2	Yes	Yes	Yes	Yes	Yes	No	Yes	Maybe	Yes	No	No	No	No	No
R3	Yes	Yes	Yes	Yes	Yes	Maybe	Yes	Maybe	Yes	Yes	Yes	No	Yes	No
R4	Yes	Yes	Yes	Yes	Yes	No	Yes	Maybe	Yes	Yes	No	No	No	No
R5	Yes	Yes	Yes	Yes	Yes	Maybe	Yes	Yes	Yes	Yes	Yes	Maybe	Yes	Maybe
R6	Yes	Yes	Yes	Yes	Yes	No	Yes	Maybe	Yes	Maybe	Yes	Maybe	Yes	Yes
R7	Yes	No	Yes	Maybe	No	No	No	No	Yes	Maybe	Yes	No	No	No
R9	Yes	Yes	Yes	Yes	Yes	Maybe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

The results from both the quotations and summary table suggest that the best way to present biomechanical data is with an introduction to biomechanics, clear conclusions from the tests, a full explanation of the results and test procedures used, and preferably alongside some synchronised video data. This would all be done in conjunction with additional information about the end user of a product, giving the designer a more comprehensive view of the ‘bigger picture’. It was not within the scope of this project to go to such lengths.

7.4 Summary

Although limited by its small number of participants, this part of the project provided vital information for establishing how best to present biomechanical data to designers. The designers questioned did not dismiss the use of biomechanical data out of hand, but felt that there was no clear remit for them to use biomechanical data extensively due to resource pressures. Also there was an indication that unless the data can be demonstrated to have a wider applicability it would only be useable on specific design projects. They did not recognise the potential use as a means for quantifying design exclusion (Keates and Clarkson, 2003), which could be influential in convincing design commissioners of the financial benefits of investing time and resources on inclusive design.

The designers demonstrated a clear preference for video based evidence of product use as compared to quantitative motion and force data. Designers expressed concerns regarding the use of biomechanical data due to its laboratory based nature and preferred using ‘real life’ focus groups in their design process. Designers may need to see comprehensive case studies illustrating exactly how this type of data can be applied to the redesign of a product, with empirical validation to show the benefit to the end user, before they will consider utilising it.

7.5 Implications for Thesis

When biomechanical data is being collected, significant time and effort should be spent investigating appropriate ways of summarising and presenting this data to designers. An appreciation of the fact that such data will rarely be used in isolation is also important. The data would often be used alongside other information on the target consumer and within additional economic and scheduling requirement constraints of the particular design project.

There are a number of important challenges that have to be overcome before biomechanical data is used by designers. Their scepticism towards ergonomic data collected in a laboratory has to be addressed through empirical evidence that such data can contribute to improved design. At present there is not a strong, documented argument in support of the use of ergonomic data of any sort. There also needs to be more direct consumer demand for inclusive design before designers will look towards data as a means through which to achieve it.

Chapter 8 Overall Project Discussion

Although each of the separate chapters of this thesis have been discussed individually throughout, this chapter will discuss the project as a whole, making direct reference to the five main objectives identified at the outset.

Objective 1: Explore the working practices of designers involved in packaging design paying particular attention to their use of ergonomic data and their attitudes towards inclusive design.

The findings of the initial designer interviews (Chapter 3) showed that designers were aware of existing ergonomic data but generally only considered it useful for very specific design projects, not including packaging design. It could have been the case that they were not taught how to use it properly, did not understand it or that it was genuinely not applicable to any of their design work.

The same interviews showed that designers do not currently consider inclusive design to be a pressing issue. While they understood the concept of inclusive design and acknowledged its importance, they did not appear to have any structured approach to achieving it, nor any perceptible evidence of it being successful. Some mentioned that inclusive design is second nature to them and is something they do naturally, which may be the case, however there was little evidence to support such claims. The overriding reason for the lack of emphasis placed on inclusive design was the absence of pressure from the clients commissioning the design work.

These findings related to the use data of ergonomic data and inclusive design showed that there were a number of challenges, namely that complex biomechanical data would have to be presented to designers not conversant with data, and that inclusive design is not viewed as a vehicle for design or commercial success.

Objective 2: Investigate the attitudes and opinions of older adults towards the problem of package opening.

The findings of the packaging survey with older adults (Chapter 4) showed that older adults had complex attitudes towards the problem of package opening. While they reported difficulties (on asking) with package opening and regularly used assistive devices, compensatory strategies and asked friends/relatives for help, they rarely complained to manufacturers or altered their purchasing habits. This went some way to explaining why design commissioners do not demand that designers strive for inclusive design. With no direct consumer demand from older adults traditional market-driven organisations are unlikely to invest extra money to ensure their product is inclusively designed. There also remains the problem of accurately attributing the success of any given product to inclusive design.

So although there is no great direct demand for it at present, it was assumed that as the population ages further consumer demand for inclusive design will increase. There are other forces that could escalate demand, such as government legislation (insisting on inclusive design), or the catalyst may be the advent of a particularly successful, high-profile, inclusively designed product. When inclusive design is more frequently demanded, designers will have to meet that demand.

Objective 3: Establish if there are significant differences in the way that young and older adults perform package opening tasks.

As was illustrated in Chapters 5 and 6, biomechanics can be used to characterise differences in the way young and older adults use their hands when opening packaging.

Despite the previously described limitations of classifying people by chronological age, the use of other criteria, such as hand functionality, did not reveal large differences. Poor dexterity scores or power grip strengths can be indicative of a number of different ailments, affecting a number of different joints of the upper limb in a number of different ways, so classifying subjects using these measures did not provide any further insights into compensatory strategies. This finding, combined with the previous argument about the drawbacks of considering biomechanical variables in isolation, suggests that designers may gain more from being presented biomechanical information in a form that focuses on individual subjects.

Problems with gathering biomechanical data on the hand and upper limb were that due to the size and large number of moving segments, motion analysis was difficult. There was a further problem in the lack of comparative data in the literature on the external forces and moments experienced by the hand and wrist during everyday activities, nor was there a consensus on a biomechanical model of the hand and wrist (and corresponding marker set) that should be use as standard. The model developed during this project (Section 6.2.4) appeared to be an improvement on the previous models although it would need further verification studies to be completed on it before publication. Biomechanics is a relatively new and rapidly evolving research field, there are many new technological and methodological advances. This causes difficulties in relaying results from this field to the field of design, as many of the outputs are still under debate at a time when the receiving field requires definitive answers.

An alternative method of analysing human movement, through the biomechanical analysis of ethnographic video footage was also proposed (Chapter 5). This provides designers with a method of identifying differences in how people manipulate products without expensive motion analysis equipment and without complex statistical analysis. It also represents a logical methodological step for those designing a biomechanical test, as it allows the researcher to observe the natural behaviour of a number of subjects completing a certain activity, rather than designing a test around how they anticipate subjects will behave. This could potentially help to make biomechanical testing more realistic, going some way to addressing the concerns raised by designers during Chapter 7.

There are significant differences apparent in the way young and older adults manipulate products with their hands and these can be measured and characterised using biomechanical testing. These age-related differences were not apparent during the ethnographic study which relied on a degree of subjectivity when classify observed movements.

Objective 4: Assess whether or not it is realistic to use biomechanical testing techniques and/or biomechanical data in the product design process.

It is possible to use biomechanical testing to gather data to aid product design. The data generated from biomechanical testing not only allows a deeper understanding of the physical interaction between the person and the product, but it also allows for differences in groups to be measured (in this case young and old). There are however two important caveats to this statement; certain conditions have to be in place to merit biomechanical testing, and there also needs to be the motivation on the part of the designer to use it (and other ergonomic data).

It is unlikely that specific biomechanical research would be commissioned for one design project unless there was sufficient investment in the research and development phase or the team had access to and experience of using motion analysis equipment. The main reasons for this are likely to be the time and cost involved in such testing.

Investment in such specific testing may only be feasible for research into a product that will be used frequently and repetitively, such as a manual tool or manually operated machinery. Testing is also more suited to the design of products which are associated with high levels of impact or strain being applied to the body, such as heavy manual tools (e.g. shovels, pneumatic drills or sledgehammers), or where impact and accuracy of movement are required simultaneously, such as in sports equipment. It could also have a positive impact on the design of elements of automobile interiors, computer workstations and public transport systems, as these represent other highly important activities in our daily lives.

Whatever the product being considered for biomechanical testing, another key criterion is that it be something which is open to and accepting of design changes. While a jar or bottle acts as an important part of the ADL of feeding oneself, they are both fairly cheap and relatively simple to make as they rely on established technology and manufacturing processes, and would not appear to be receptive to design improvements. There are other criteria mentioned above that the jar and bottle do not fulfil; no high impacts on the body are involved, no great accuracy of movement is required and they are not used particularly frequently or repetitively. Furthermore, the impact of a negative experience with these products generally is fairly minor compared to, say, repetitive strain injury suffered from years of using a badly designed computer workstation, or an injury sustained by a runner wearing badly designed shoes.

Biomechanics can still play an important role in the design of products that do not merit dedicated testing, as people will still move and interact with these products. A basic understanding of the principles of biomechanics on the part of the designer may be sufficient to inform the design of a new product without the need for lengthy and expensive testing, and without necessarily introducing numerical data. A series of illustrated design case studies where biomechanical principles and/or data is used showing how to apply them to design may also be of use. These various potential methods for incorporating biomechanics into the designer's toolkit will be discussed in **Error! Reference source not found.**.

Another key prerequisite for the use of biomechanical (or any other type of ergonomic) testing or information in the design process, is the motivation of the design team to do so. This motivation generally stems from the need to solve a particular problem. In this case the problem is that of achieving inclusive design although, while the argument for inclusive design remains strong, it is not necessarily perceived as being a significant problem by all stakeholders in the design process. Chapters 3 and 4 described parts of this project which took into account the perspectives of the designers who deliver products and some of the end users (older adults) who use those products. These studies proved that, in the context of packaging design, designers did not place inclusive design high on their priority list. In short, at the time of writing there was little demand for and therefore little supply of inclusive design.

It is speculated that the infrequent use of biomechanical data and testing techniques by designers is due to the lack of a well publicised and compelling supporting argument. The argument would have to show a clear commercial benefit to using such techniques, not to mention a direct and measureable benefit to the end user in terms of their comfort and safety. Many of the sceptical attitudes towards ergonomics identified in Chapter 7 appear to be related to this lack of a strong supporting argument, although may also be compounded by a lack of emphasis on teaching the subject to design students at university level. The challenge is for researchers and practicing designers to incrementally build up a robust and convincing argument for using biomechanical principals.

Yet there are a number of smaller challenges regarding the formulation of such an argument. For example, in Section 6.3 due to the imbalanced sample sizes used many of the measured biomechanical variables had to be analysed in isolation. The complexity of the human body is such that considering these variables in isolation fails to describe the combined effects of the many degrees of freedom of the upper limb, the coupling of certain movements and muscle activation causing moments about more than one axis. This is similar to the problem found with anthropometric data as discussed previously in Section 2.2.4.2 – looking at variables in isolation, and the process of averaging values and trying to extrapolate general rules removes the individual measurements from their original context and a great deal of the meaning is lost. Another smaller challenge is that a better knowledge of designers' working practices is required. While the interviews with designers in Chapters 3 and 7 provided many valuable insights into their attitudes towards and preferences for certain types of data and user testing, they relied heavily on the integrity of the participants and their ability to recall past experiences, and also their ability to think of hypothetical design scenarios. A greater insight into how designers work could be achieved through an ethnographic study of designers.

Should the design project in question meet the criteria above, and the correct levels of motivation be apparent, then biomechanical testing can be used to encourage better product design through the implementation of inclusive design.

Objective 5: Determine the most effective way of presenting biomechanical data to designers.

When characterising kinetic and kinematic differences in a manner that might be useful when presented to designers, the limitation of biomechanics is that at present it can only measure these differences with existing products and therefore has no predictive capabilities as such. For example, when redesigning a jar a designer is likely to want to investigate what effect changing the shape or diameter of the lid might have. The ability to experiment with the different design variables is something that designers would value but biomechanical testing cannot offer at present. The fact that biomechanics cannot yet offer this predictive ability suggests that biomechanical data, presented in novel formats, is the most promising method of using data for inclusive design.

According to the findings of Chapter 7, attempts should also be made to present the biomechanical information in a visual manner. It would also be advantageous if, in addition to summarised data, complete sample data sets for individuals suffering from particular ailments were presented. Such an approach would not involve stipulating general rules to the designer, instead allowing them to observe the differences between asymptomatic subjects and those with certain hand or wrist ailments and draw their own conclusions.

The unique mixed-methods methodology adopted to fulfil this project has allowed the investigation of the problem from a number of different perspectives. It has allowed the generation of different types of biomechanical data that can be used to inform inclusive design and has suggested a number of approaches to integrating such data into the design process. However, the challenge remains to truly prove in the context of a real design project that this can be achieved.

The project as a whole has produced a number of important contributions to knowledge. Before discussing the contribution of each individual chapter the overall contribution of the project and its unique methodology should be described. Through approaching the problem using mixed methods a thorough understanding of the needs of the various stakeholders was developed thus avoiding, as far as possible, making assumptions about them. The project did not solely rely on producing quantitative empirical data as much previous biomechanics research has done, so the data capture here was conducted with a very specific target audience in mind. The approach led to a measured set of conclusions being drawn about the considerable challenges that lay ahead for inclusive design, and also the sizable barriers that prevent ergonomic data (biomechanical or otherwise) becoming an integral part of a designer's toolkit.

The key contribution of the initial designer interviews (chapter 3) was that while the vast majority of designers interviewed knew what inclusive design was, few practiced it regularly, and those who did were unable to offer tangible evidence of its success. This series of interviews also revealed that most designers did not use ergonomic data regularly, for a number of valid reasons.

The most important contribution of the packaging survey with older adults (chapter 4) was the finding that older adults, while reporting several problems with package opening during the survey, did not report their dissatisfaction to the manufacturers. The result was an effective lack of direct demand for inclusive design being passed on by the consumer to those who commission design work.

Ethnography, in the form of a package opening study with older adults (chapter 5) had two key contributions to knowledge. The first was the proposal of a method for conducting and analysing ethnographic studies in structured way that would allow quantitative statistical analysis, and also between-group comparisons. Directly related to the problem of package opening, this study also contributed the identification of a number subtle differences in opening strategy between subjects with and without hand and wrist ailments.

Biomechanical testing (chapter 6) offered an opportunity to accurately measure and quantify the differences between young and older adults in the context of jar and bottle opening. The first key contribution was the design and production of novel dynamic force sensing equipment, which reproduced real-life jar opening while simultaneously measuring the forces applied by the subject's hand. The second was the proposal of a new biomechanical model of the hand and wrist for use with a motion analysis system. Collection and analysis of the motion and force data provided a third contribution, with distinct kinetic and kinematic differences identified between young and older adults during package opening.

A final series of interviews with designers (chapter 7) in which they were presented with various types of ergonomic data in a number of different formats also provided valuable contributions to knowledge. The first was the finding that designers have a strong preference for data to be presented in a visual format, preferably with accompanying video footage of subjects, ideally in their natural environment. The second was the development of a set of criteria for when biomechanical testing would be suitable for use in design.

The key contributions to knowledge of the entire project are summarised in diagram form in Figure 8.1 in relation to the overall methodology and each of the individual chapters.

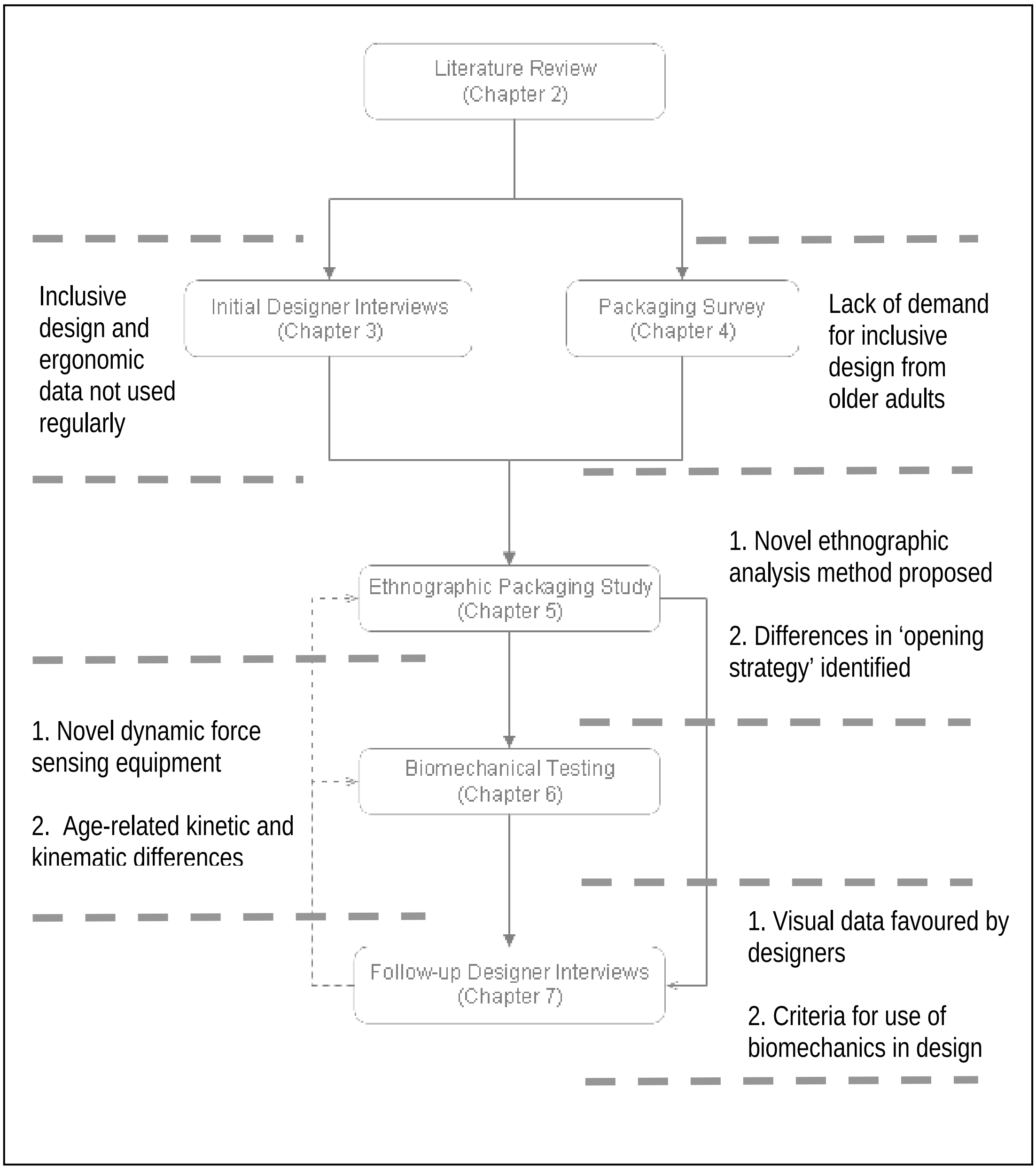


Figure 8.1 Key contributions to knowledge of whole project

The overall aim of the project was: "To investigate how biomechanical data on the hands and wrists of older adults can be used by packaging design professionals in the inclusive design process". This aim was achieved the derivation of five clear research objectives. These involved identifying the most important issues involved in providing data to design professionals and the subsequent generation of several types of ergonomic data, including biomechanical data. The answer to the aim is that biomechanical data can be presented to packaging designers, however there are a number of reasons describing why this is not likely to become common practice for a number of years.

Chapter 9 Conclusions and Future Work

9.1 Conclusions

A multi-method approach was taken to investigate the use of biomechanical data in an inclusive design context. The methods used were a packaging survey with older adults, two series of interviews with design professionals, an ethnographic study of package opening activities, and finally a biomechanical study of the hand and wrist during jar and bottle opening.

During the packaging survey it was older female adults that reported the most problems with package opening. The impact that package opening difficulties have on individual's lives was not great enough to merit them making a formal complaint to the manufacturers.

There was not an overwhelming demand for inclusive design from consumers at present, even though there is evidence that older adults genuinely struggle when completing tasks that involve mainstream products. Designers have a number of other important design criteria to consider when designing packaging and inclusive design did not rank highly amongst them. Designers did not routinely use ergonomic data in the course of their design work.

A new system for analysing ethnographic study footage has been proposed, analysing it in a manner that focuses on the movements of the subject. It can be used to describe the complex combination of movements that occur when a particular task is being performed with a product and can establish subtle differences in technique between groups. It provides a variety of types of data on any chosen activity that are useful to the design community, such as; opening strategy, pain/discomfort, difficulty experienced and frequency of grip type used. Additionally, it can offer biomechanists a technique for informing the design of realistic biomechanical testing.

Design professionals have reservations about data generated in a laboratory environment, as they feel it is devoid of context, whereas they have strong preference for data presented in a visual format. A convincing, evidence-based argument for the use of biomechanical data is required.

A new biomechanical model of the hand and wrist was developed. It included a novel technique for locating the wrist joint centre, a representation of the proximal metacarpal arch and a separate system of axes for each metacarpal bone. More robust validation work is required before the model can be recommended to the wider biomechanics community.

A novel piece of force sensing equipment was designed and built which dynamically replicated both jar and bottle opening, incorporating two small force/torque transducers, one to measure each opposing component of the subject's grasp.

Using the novel force sensing equipment and a motion analysis system, significant kinetic and kinematic differences were observed in the way that young and older adults performed a jar opening task. This proved that there were significant age related differences in jar opening technique.

There are certain key criteria that have to be met by a design project before the use of specific, dedicated biomechanical testing can be justified to enhance the design of that product. This does not, however, mean that basic biomechanical principles and data cannot be of use to the design community.

9.2 Future Work

Throughout the course of this thesis there have been a number of findings that are recommended for the basis of future research studies:

Understanding the design process

With the aim of better understanding the design process an ethnographic study of designers and the practicalities of how they work would be of great value. This work would allow for a more realistic outline of when ergonomic data should be used and more detail about what the most effective forms of presentation are.

Static maximal jar and bottle opening strength tests

Motion analysis tests should be performed using static jar and bottle lids to test maximal opening torques and the hand, wrist and arm postures used to achieve them. The tests should include analysis of the elbow and shoulder joints. This would provide designers with information on the strongest hand postures, allowing them to reshape the packaging to encourage the user to intuitively adopt the strongest grip posture.

Ethnography based inclusive design

Given designers strong preference for visual data which has been collected in a realistic environment, a database of short video clips showing older adults performing various basic ADLs in their own homes could provide designers with a valuable inclusive design resource. The footage would include additional information about each older adult such as their age, dexterity level, grip strength and medical conditions, thus allowing designers to see how diminished physical abilities affected their daily lives.

Design case studies using ergonomic and biomechanical data

The development of a series of illustrated biomechanical case studies may prove effective in educating design professionals in the use of ergonomic data. An initial series of case studies would analyse existing products from a biomechanical point of view, using just basic principles (no data) and explaining how certain products were biomechanically sound, and how others were not and how they might be improved. The second series of case studies would start to introduce data and show how it can be applied directly to improve various physical characteristics (dimensions, geometry, weight and surface finish) of a product.

Biomechanical hand and wrist model

A comprehensive verification of the biomechanical model of the hand and wrist is required. Work should be done to establish the exact locations of all joint CORs in all planes relative to surface markers, which would require the use of dynamic fluoroscopy techniques. If necessary, further work should then be done to improve the marker placement and joint angle calculation algorithm. Repeatability studies on the errors inherent in inter-rater marker placement will also be needed. Finally, work to quantify how much error is caused by movement of the skin with respect to underlying structures will be necessary. Once the model has been completely verified it could be published and a standard model and surface marker layout agreed upon by the biomechanics community. Future studies using this standard would then be directly comparable and would allow the build-up of biomechanical data on the hand and wrist.

9.3 Publications

Journal articles:

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Conference proceedings:

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Appendices

Appendix A: Muscles of the hand and upper limb

Appendix A Figures:

Appendix A Tables:

Table A.1 Muscles of the upper extremity and their actions. Adapted from Nordin and Frankel (2001)

Muscles of the Wrist and Hand	
Muscles of the Wrist	
Muscle	**Action**
Flexors	
Flexor carpi ulnaris	Flexion of wrist; ulnar deviation of hand
Flexor carpi radialis	Flexion of wrist; radial deviation of hand
Palmaris longus	Tension of the palmar fascia
Extensors	
Extensor carpi radialis longus and brevis	Extension of wrist; radial deviation of hand
Extensor carpi ulnaris and brevis	Extension of wrist; ulnar deviation of hand
Pronators-Supinators	
Pronator teres	Forearm pronation
Pronator quadratus	Forearm pronation
Supinator	Forearm supination
Brachioradialis	Pronation or supination, depending on position of forearm
Extrinsic Muscles of the Hand	
Muscle	**Action**
Flexors	
Flexor digitorum superficialis	Flexion of PIP and MCP joints
Flexor digitorum profundus	Flexion of DIP, PIP and MCP joints
Flexor pollicis longus	Flexion of IP and MCP joints of thumb (digit I)
Extensors	
Extensor pollicis longus	Extension of IP and MCP joints of thumb; secondary adduction of the thumb
Extensor pollicis brevis	Extension of MCP joint of thumb
Abductor pollicis longus	Abduction of the thumb
Extensor indicis proprius	Extension of index finger (digit II)
Extensor digitorum communis	Extension of fingers
Extensor digiti quinti proprius	Extension of digit V
Intrinsic Muscles of the Hand	
Muscle	**Action**
Interossei (all)	Extension of PIP and DIP joints and flexion of MCP joints
Dorsal Interossei	Spread of index and ring fingers away from long finger
Palmar Interossei	Adduction of index (digit II), ring (digit IV), and little fingers (digit V) toward long finger (digit III)
Lumbricals	Extension of PIP and DID joints and flexion of MCP 2-5 finger
Thenar Muscles	
Abductor pollicis brevis	Abduction of thumb
Flexor pollicis brevis	Flexion and rotation of thumb
Opponens pollicis	Rotation of first metacarpal toward palm
Hypothenal Muscles	
Abductor digiti quinti	Abduction of little finger (digit V) and extension of PIP and DIP joints
Flexor digiti quinti brevis	Flexion of proximal phalanx of little finger and forward rotation of fifth metacarpal
Adductor pollicis	Adduction of thumb

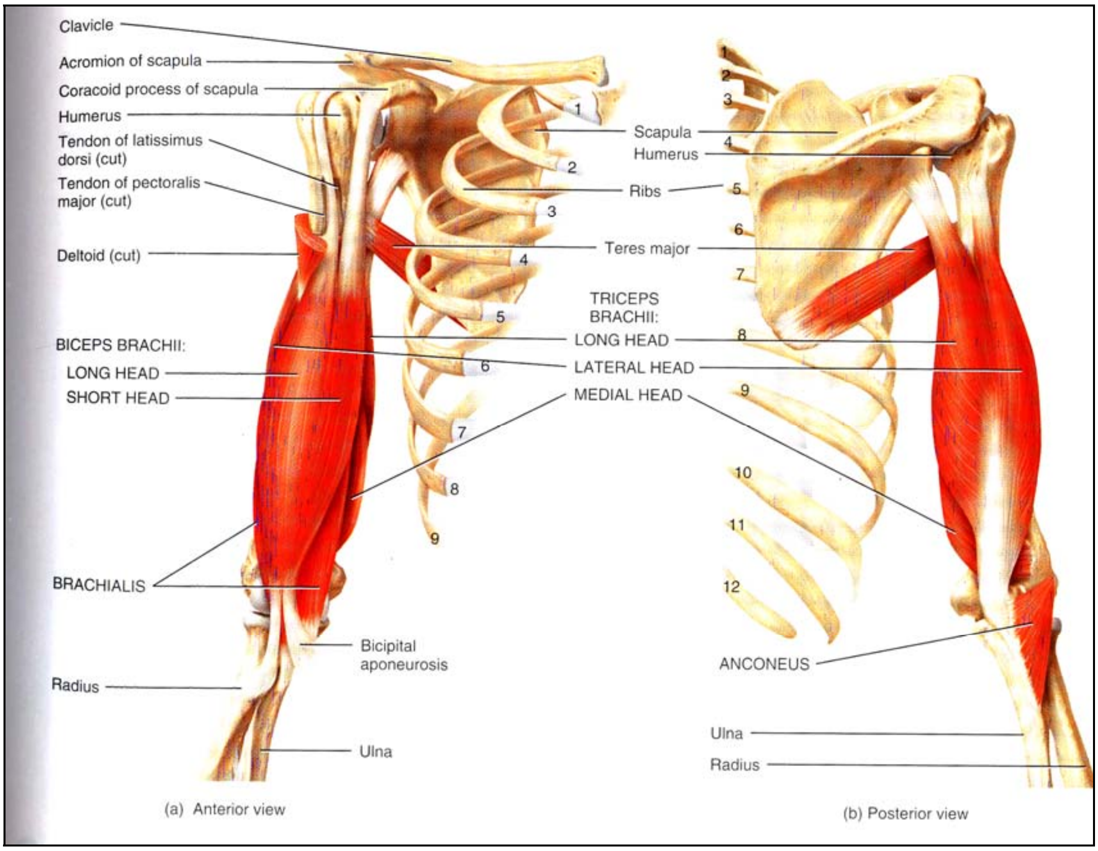


Figure A.1 Muscles of the upper arm that move the radius and ulna. Anterior and posterior views. Tortora (2009)

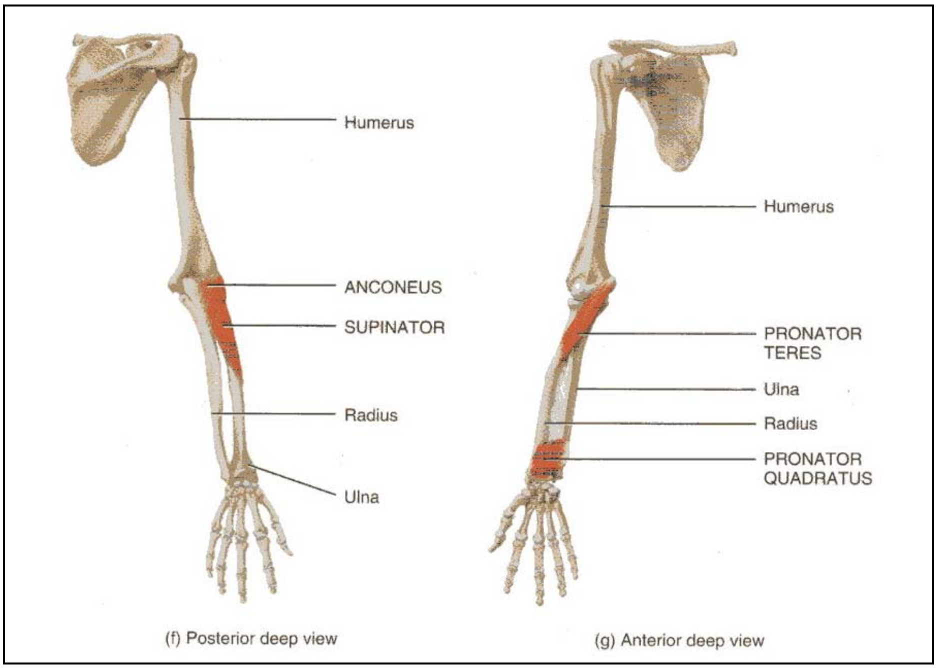


Figure A.2 Muscles of the forearm that move the radius and ulna. Anterior and posterior deep views. Tortora (2009).

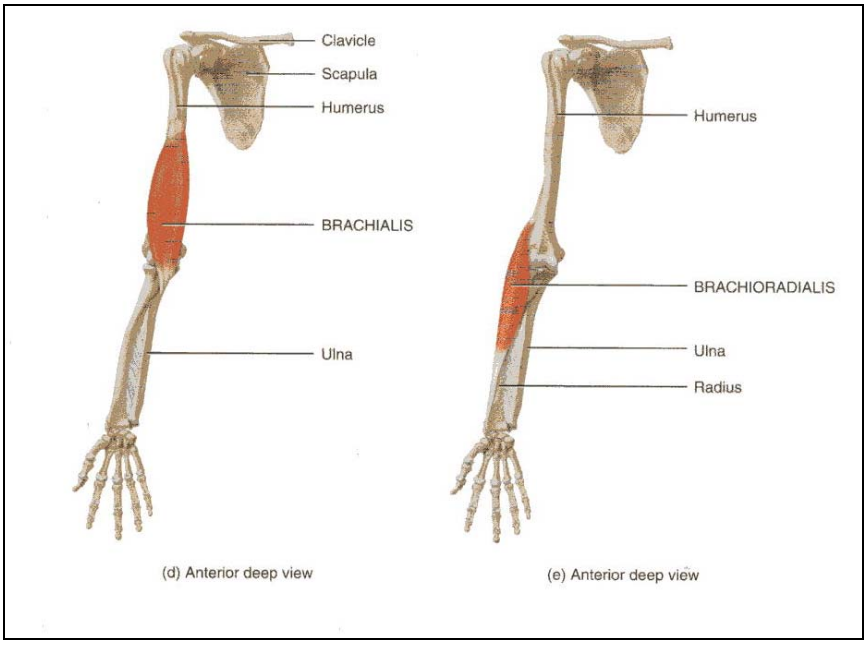


Figure A.3 Muscles of the forearm that move the radius and ulna. Anterior deep views. Tortora (2009).

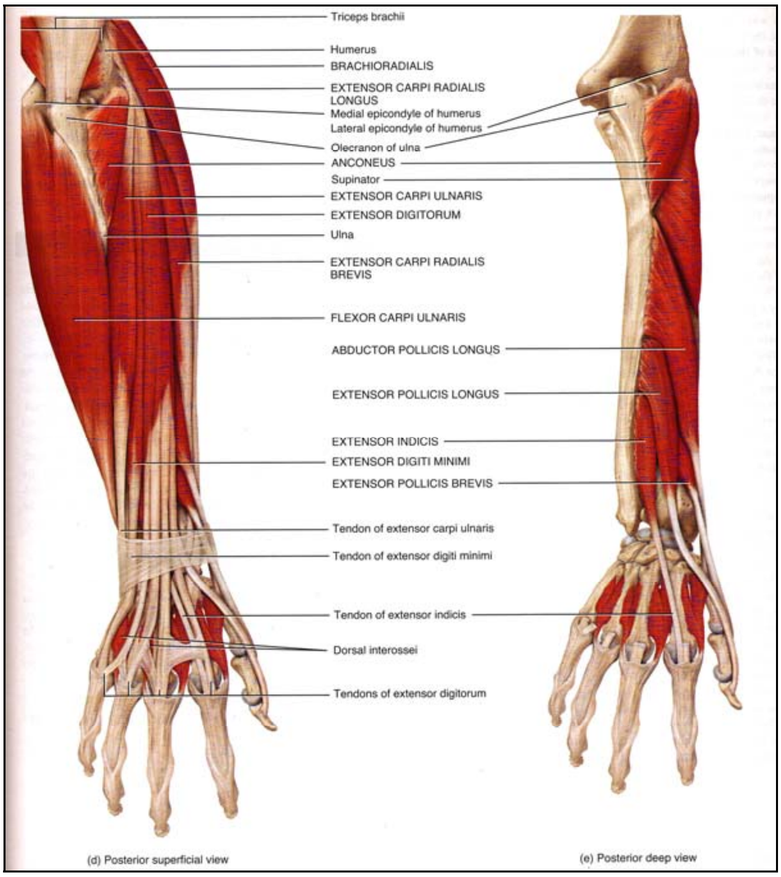


Figure A.4 Muscles of the forearm that move the wrist, hand and digits. Posterior superficial and deep views. Tortora (2009).

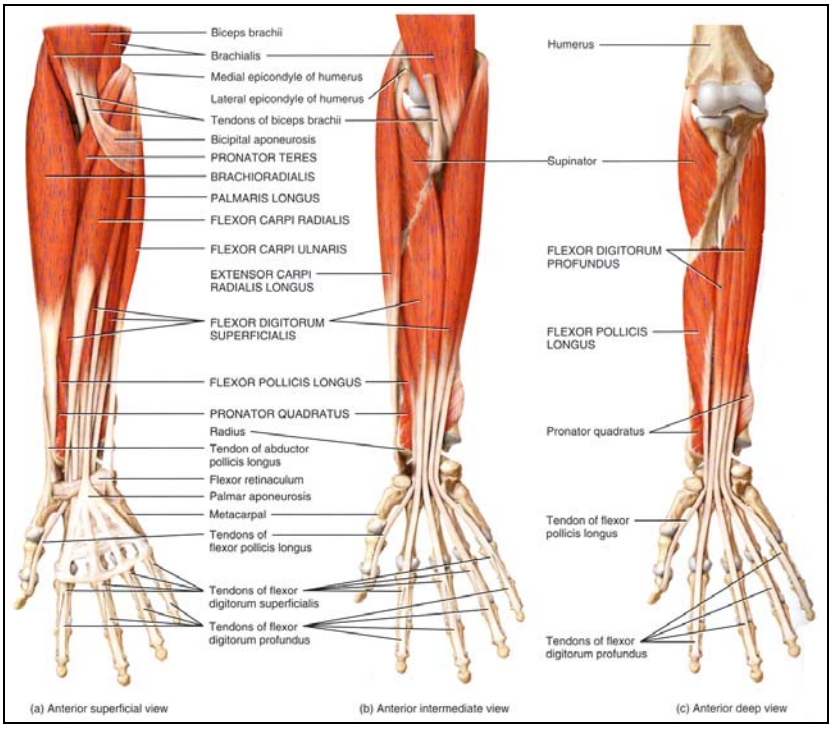


Figure A.5 Muscles of the forearm that move the wrist, hand and digits. Anterior superficial, intermediate and deep views. Tortora (2009).

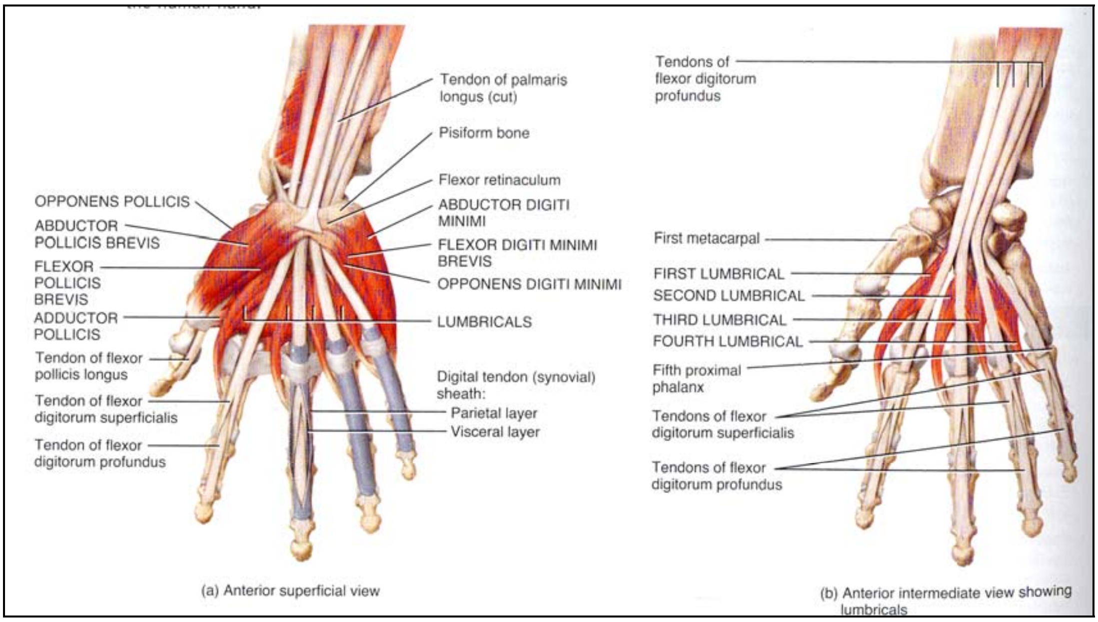


Figure A.6 Intrinsic muscles of the hand – muscles of the palm that move the digits. Anterior superficial and intermediate views. Tortora (2009)

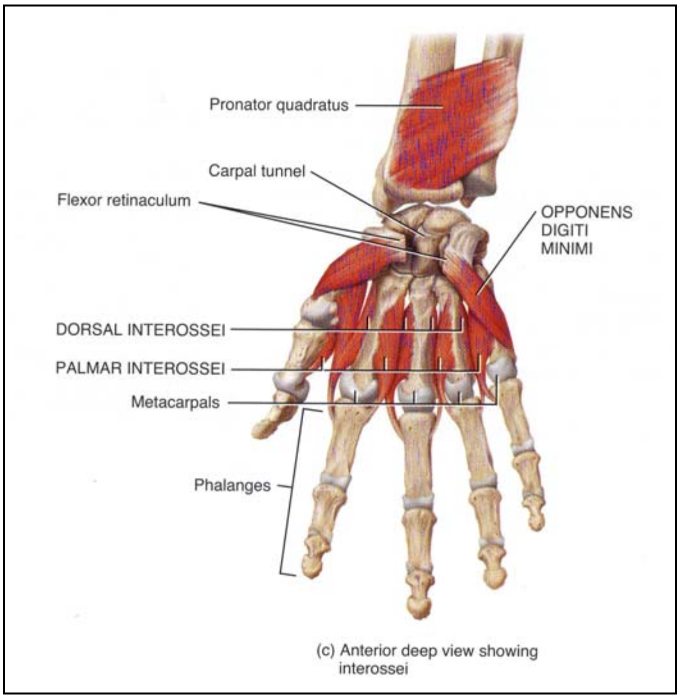


Figure A.7 Intrinsic muscles of the hand – muscles of the palm that move the digits. Anterior deep view. Tortora (2009)

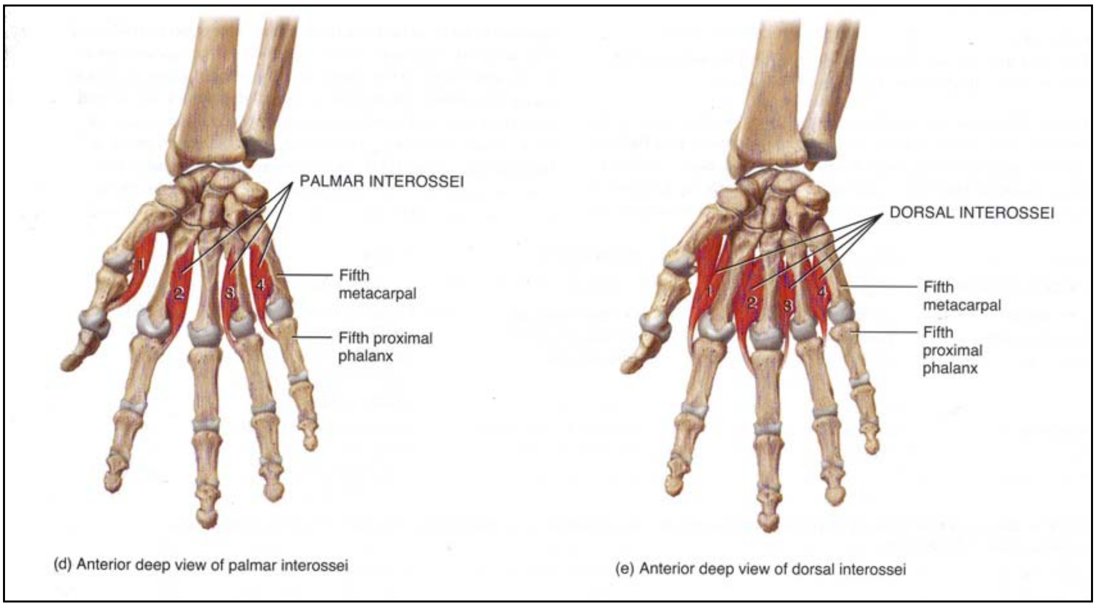


Figure A.8 Intrinsic muscles of the hand – muscles of the palm that move the digits. Anterior deep views of palmar and dorsal interossei. Tortora (2009)

Appendix B: Packaging Questionnaire and Sample Show Cards

Packaging Design for the Older Adult: Stage 1

PACKAGING SURVEY

During the course of our everyday lives, whether at work or at home, to varying extents we all come across different types of packaging.

The following questionnaire is concerned with the way in which people interact with everyday consumer packaging.

The questions are designed to find out how *you* use different types of packaging used for food, drinks, cleaning products and medicines. They also want to find out more about how well *you* think packaging is designed and how straightforward *you* think it is to open. Additionally, there will be a set of attitude statements to find out how you feel about a variety of packaging related topics, as listed on the information for participants sheet.

1. ASKING FOR HELP

In general, would you say that you have ever had any difficulty in opening any type of packaging?

Yes No Not sure

Have you ever asked someone to help you open any type of packaging?

Yes No Not sure

If yes, what types of packaging have you asked for help with?

____
____

Can you remember which specific brands?

____

And who did you ask for help?

Husband/Wife Friend Neighbour Other relative

Flatmate Other____________________

Do you live with this person?

Yes No Not sure

2. ALTERNATIVE STRATEGIES

Sometimes people don’t always open packaging in the way that the designer had originally intended, maybe because the package is designed badly, or the consumer has difficulty opening it, or they don’t know how they are *supposed* to open it. These alternative strategies can involve a certain amount of improvisation, often involving some utensils or tools that might be close to hand.

Off the top of your head, can you think of any alternative strategies that you use, or have used in the past?

No

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________

Below is a list of alternative strategies that we have found are quite often used. Can you tell me if you have ever used any of them?

	Regularly	**Sometimes**	**Rarely**	**Never**
Used a knife to cut open plastic packaging	☐	☐	☐	☐
Used scissors to cut open plastic packaging	☐	☐	☐	☐
Used your teeth to open a screw-on bottle top	☐	☐	☐	☐
Used your teeth to pierce and tear some plastic packaging	☐	☐	☐	☐
Used rubber gloves to open a jar	☐	☐	☐	☐
Held a jar with a metal lid under hot water to loosen it	☐	☐	☐	☐
Any others you might use?				
______________________	☐	☐	☐	☐
______________________	☐	☐	☐	☐
______________________	☐	☐	☐	☐

* It is likely that a number of new strategies might be added to this list once the pilot study has been completed

If you do use any alternative opening strategies, generally what would you say are your reasons for doing so?

3. ASSISTIVE DEVICES

Have you ever seen/noticed any specially designed devices available to help you open difficult packaging?

Yes No Not Sure

Have you ever used any of these specially designed devices?

[Assistive Devices Show Card]

DEVICE	**'I own one'**	**'I have used One'**	**'I've seen before'**	**'I've never seen one'**
Jar Key	☐	☐	☐	☐
Magi-Pull	☐	☐	☐	☐
Get to Grips	☐	☐	☐	☐
Unknown	☐	☐	☐	☐
Baby Boa	☐	☐	☐	☐
CapGrippa	☐	☐	☐	☐

Used or Own at least 1
Seen but never used
Never seen them

What are your attitudes towards the devices that I have just shown you?

	Strongly Agree	**Agree**	**Not sure**	**Disagree**	**Strongly Disagree**
They are a good idea					
They make me feel old					
I'd rather use whichever tools or utensils are to-hand					
There is a stigma attached to these devices					

Any other comments:

4. SPECIFIC TYPES OF PACKAGING

Now I would like to ask you in a little bit more detail about some specific types of packaging that you may or may not be familiar with. What I would like to find out is the nature of the different problems you might face with different types of packaging.

For each card that I show you, can you identify which types of packaging, if any, that you find particularly difficult. Any additional comments that you might have will can be noted.

[Packaging Types Show Card]

CATEGORY	**Very Difficult**	**Difficult**	**OK**	**Easy**	**Very Easy**	**Don't Use**
1. Tinned goods with ring-pull Comments	☐	☐	☐	☐	☐	☐
2. Biscuit Packets Comments	☐	☐	☐	☐	☐	☐
3. Regular tinned goods Comments	☐	☐	☐	☐	☐	☐
4. Glass jars Comments	☐	☐	☐	☐	☐	☐
5. Margarine Tubs Comments	☐	☐	☐	☐	☐	☐
6. Flexible sealed bags Comments	☐	☐	☐	☐	☐	☐
7. Soup pot and tubs Comments	☐	☐	☐	☐	☐	☐
8. Shrink-wrapped goods Comments	☐	☐	☐	☐	☐	☐
9. Trays with Plastic Film Tops Comments	☐	☐	☐	☐	☐	☐
10. Soft Drinks Bottles (including 'sports caps) Comments	☐	☐	☐	☐	☐	☐
11. Bleach and other household cleaning products Comments	☐	☐	☐	☐	☐	☐
12. Child Resistant Medicine Bottles Comments	☐	☐	☐	☐	☐	☐

13. Cardboard cartons Comments	☐	☐	☐	☐	☐	☐
14. Milk bottles Comments	☐	☐	☐	☐	☐	☐
15. Soft drinks cans Comments	☐	☐	☐	☐	☐	☐
16. Dessert pots Comments	☐	☐	☐	☐	☐	☐

Importantly, are there any other types of packaging which I haven't mentioned that you find particularly annoying?

____

____

Are there any of these types of packaging that you think require a high level of dexterity? By dexterity, I mean the use of fine (nimble) finger control, as opposed to basic strength. Feel free to have a look back through the show cards.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Have you ever avoided buying something because the packaging is difficult to open?

Yes No Don't know

If yes, what was it?

____

____

When you come across new type of packaging, do you read the instructions first?

Yes No Sometimes Never

Other______________________________

5. ATTITUDE STATEMENTS

Now I would like to read out a series of statements to you and for each one you should give one of five answers; strongly agree, agree, not sure, disagree or strongly disagree. There are no right or wrong answers – all these statements are designed to do is test your own personal feelings.

	Strongly Agree	Agree	Not sure	Disagree	Strongly Disagree
Packaging could be designed to be easier to open (5)					
Poorly designed packaging causes me annoyance (1)					
I dislike having to ask for help (2)					
I am proud of my independence (2)					
When I can't open packaging at the first attempt, I feel useless (1)					
Packaging designers do not consider the needs of people like me (3)					
I prefer to be able to open things with my bare hands (2)					
The way packaging is designed on the whole is OK (5)					
I enjoy the challenge of opening packaging (5)					
If I'm not sure how to open something, I won't buy it x()					
Most things are designed specifically for the young (3)					
I accept that I will struggle with certain tasks as I get older (x)					
Difficult packaging has no real impact on my life (1)					
I don't like things that are small and fiddly (4)					
Over the last 10 years, I have noticed that my fingers are not as nimble as they once were (4)					
Packaging is designed for young people by young people (3)					
Being able to prepare my own food is important to me (2)					
Packaging design doesn't bother me (1)					
I get angry when I can't open something (1)					
Things are not designed with older people in mind (3)					
I find packaging to generally be a bit of a fiddle (4)					
I am aware of packaging becoming more fiddly as I age (4)					
Having spent my money on a product, I think that the packaging should be easy for me to get into (1)					
I manage to get things open, but I do have the same level of control of my hands that I used to (4)					

6. DEXTERITY QUESTIONS

Firstly, do you suffer from any HAND problems which make it difficult for you to open consumer packaging?

Yes No

____

____

____

____

Do you suffer from any OTHER problems which make it difficult for you to open consumer packaging?

Yes No

____

____

____

Next I would like to ask you about whether or not you can perform certain tasks which related to your dexterity. All you have to do is answer each question either ‘yes’ or ‘no’. If you are unsure about any question, please stop me and ask.

Dexterity

Cannot pick up and hold a mug of coffee with either hand	10.5
Cannot turn a tap or control knobs on a cooker with either hand	9.5
Cannot pick up and carry a pint of milk or squeeze the water from sponge with either hand	8.0
Cannot pick up a small object such as a safety pin with either hand	7.0
Has difficulty picking up and pouring from a full kettle or serving food from a pan using a spoon or ladle	6.5
Has difficulty unscrewing the lid of a coffee jar or using a pen or pencil	5.5
Cannot pick up and carry a 5lb bag of potatoes with either hand	4.0
Has difficulty wringing out light washing or using a pair of scissors	3.0
Can pick up and hold a mug of coffee with one hand but not the other	2.0
Can turn a tap or control knob with one hand but not with the other/Can squeeze the water from a sponge with one hand but not the other	1.5
Can pick up a small object such as a safety pin with one hand but not with the other/ Can pick up and carry a pint of milk with one hand but not the other/ Has difficulty tying a bow in laces or strings	0.5

8. CLOSING QUESTIONS

Gender: Male Female

Age Group: 60-69, 70-79, 80-89, 90+

Would you be interested in participating in the next stage of this research project? What we want to do is observe and record you opening a few different types of packaging – the type that you would open during your everyday life. It would help us to gain a better understanding of the precise movement patterns used when opening different packages.

It would involve just one hour of your time, transport to and from the University of Strathclyde can be provided.

Name:

Address:

Phone Number:

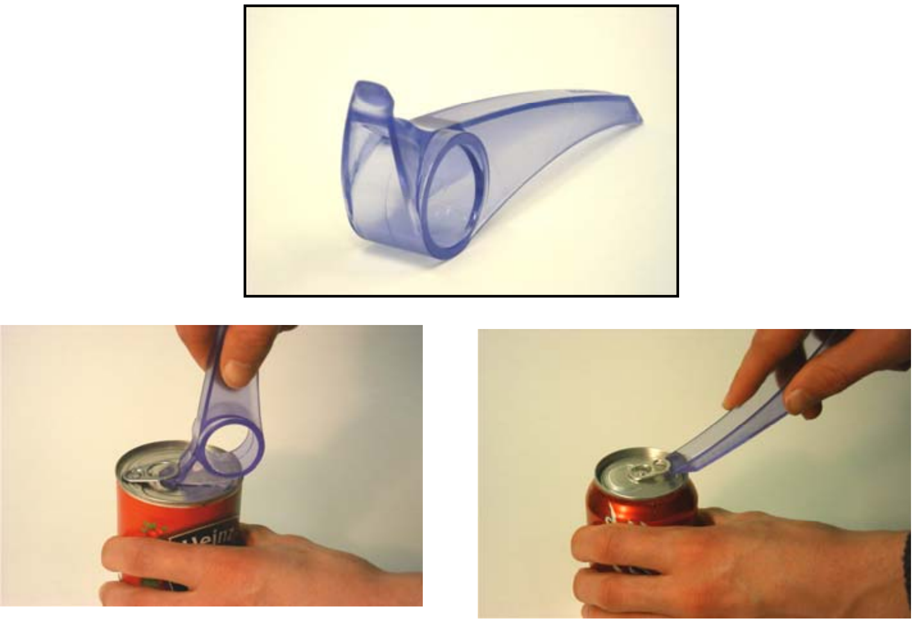
Packaging show cards:

1. Tinned Goods with Ring-Pull

8. Shrink-wrapped goods

Assistive device show cards:

1. ‘JarKey’ – Opening jars



2. ‘MagiPull’ – Opening ring pulls on tinned goods and soft drinks

Appendix C: Example of Fully Transcribed Initial Designer Interview

Packaging Designer Interview

Company Name: **XXXXXXXXXX** - Multi-national corporation with food, beverage, personal care and cleaning agent brands **(R10)**

Types of packaging designed: Home Care (laundry, household cleaning, dish washing), Personal Care (shampoos, shower gel, body lotion), Oral Care (toothbrush and toothpaste) and Deodorants.

Respondent's Name: Paulo Seresini – Packaging Prototyping Manager

Education Level + No. years in industry: BA, 15 years.

Company Size (number of employees): Globally, hundreds of thousands. Port Sunlight Research Centre 1000-1500. Packaging Design Technology Centre 13

Main area of business:

Initial questions:

1. How often are they asked to design new packaging – how many projects per year?

4 or 5 large projects (per category (deodorants, shampoos, etc.)) so roughly 30 in total.

2. What sort of timescales do their design projects typically follow?

Significant structural changes can take 2-3 years. Simpler restyling project are less than 1 year.

3. What sort of CAD packages, if any do they use?

Unigraphics NX

Mouldflow and CAE is done on software by Altair

4. What are the channels of feedback from the end user, if any? If someone had a complaint about the openability of something, would it come to you directly? If not, then who receives the complaint?

They test any new designs extensively with the consumers to avoid any complaints arising early on in the design process. They test high quality physical samples with the consumers BEFORE the tooling stage.

If there are any complaints, the consumer phones the customer care line number on the back of the packaging.

Complaints are split into 2 categories by the customer care team; those which suggest how the product could be made even better, and those which suggest they should be addressing a technical weakness of the product.

At least once a year the packaging design teams will have a review of the key complaints, and then plan their future development work to address these.

5. What is the main source of complaints or praise?

Praise comes in the form of re-purchase. 2 types of complaint – the first is the product delivering something different from what they had expected, the second is that the product has failed such that it doesn't deliver the minimum expected functionality.

6. How do you typically respond to complaints? Can you give any examples?

Firstly, take the complaint and learn from it – how can they use it to improve the design of the product? Secondly they offer the consumer some compensation.

20-30% of the complaints will be about the openability, however the majority will be about how the cap closes.

Sometimes they will restart the whole design process from the beginning to address a complaint however when this is too expensive or time consuming, they prefer to concentrate on improving other aspects of the 'product mix' in order to drawn attention away from any shortcomings with the design which might have lead to the complaint. It depends on how strong and frequent the complaints are.

Basically they respond to and try to avoid complaints

Design Process:

7. Can you describe your company's design process for a new type of packaging (or for a packaging update)?

Innovation Process at [R10]:

‘Charter Document’ (what are the objectives, what is the expected business result, what resources should be allocated to this project)

Management approve the document

Feasibility phase – do some real design work, making prototypes and testing with the consumer, to establish if it’s worth going ahead. Are they actually going to be able to make the product.

Contract Document – a contract between the team and the company. They have evidence that this product can work for the consumer, so are requesting the funds. The biggest investments are in the factories.

Capability/Implementation Phase – the design is now fixed. What they have to do is ensure that the design (one CAD file) will be reproduced accurately at all of their global manufacturing plants.

Production and Product Launch – launch in a pilot market

Specifically within the packaging department:

‘Idea Space’ (before it’s a project as such) you need to do 2 things…prepare a document broadly and generically state what kind of product they want to make. Initial sketches which will then be documented. After the initial scoping work you produce a scoping document – what different forms could the product be presented in? This can be presented to the board.

They also produce a ‘Concept Design Log’. Decide on the product form (for shampoo it would be a foam, a liquid, a mousse or a gel) then investigate what sort of bottle shape and type of cap will be best for it. Here they have to do some consumer testing, to provide real evidence to support and back up their final design decision.

Initial Manufacturing Evaluation. Large scale consumer test with prototypes. Use manufacturing simulation software to check that technically everything is OK with the design. All of this is presented to the marketing department who then pitch the idea to the board.

8. **a)** Are the designers restricted in your organisation by the processes and materials that you have available? Yes or No.

   b) Please expand.

Yes there are restrictions, as with any design work.

The main restriction is that [R10] do not sell the product direct to the consumer as they prepare the products which are then sold by the retailers. This is a restriction because the retailers tend to only sell the things that they like. They know how to please the consumers, but are restricted by the retailer's rules, restrictions and requirements.

Blow moulding for bottles and injection moulding for caps. These are all manufactured by external suppliers and assembled by themselves.

9. Are these restrictions more apparent when attempting to achieve high levels of openability, more so than any other design criteria?

Yes, if they are completely redesigning some packaging, as they need to change suppliers.

No, not if it is just an iterative step in the design development.

10. **a)** Are you encouraged to design packaging to be easy-to-open?

Yes.

b) YES, what is the source of this encouragement? (e.g. end users, manufacturers, retailers, design If journals)

They listen to what the consumer wants, and they do this is two ways; listening to the consumer complaints, and also developing techniques to understand how 'silent' consumers react to their products without relying on them to contact the company directly. Using ethnography is an example of this.

The source of encouragement is from the marketing department, which represents the consumer's voice and opinion.

c) If NO, do you think that it should be encourage

11. Have you ever been encouraged by the (senior) management team to use ergonomic data?

No, but it's something that the packaging design team are trying to promote more and more within the company. They do use it under their own initiative.

12. **a)** What is your understanding of the term Inclusive Design? - if NONE then give them the **definition**.

He's trying to make inclusive design as a principle more familiar to other people within the company.

It's an area that is not seen as being of great importance in an industry like theirs mainly because it is only addressing one aspect of the product mix.

He considers it to be a philosophical concept, where you need to address a broader range of users at the beginning, which may make the project more difficult, but ultimately increases the number of people who can use your product. It doesn't tell you *how* to do it though.

b) Have you, or anyone else in your organisation, taken steps to start using/implementing ID?

Yes, they tried to redesign laundry liquid bottles in a more inclusive way. This was just a small experimental project and ultimately the product was not launched. They didn't see it as being particularly successful. They used the same design and consumer testing techniques as usual, but just changed the target group – 50-70 year olds instead of the normal 25-50 years olds. Used 3 or 4 new prototypes.

They got the ideas from consumer observation of older users (<10) and developed a design brief from the results. The testing was carried out in their mock kitchen facilities at their testing lab, and the group was mainly women, on the assumption that it is them that will usually be doing the laundry.

13. **a)** Do you include older adults in any of their design considerations? YES or NO

In general, from their sales tables, they reckon that the vast majority of their customers are in the 15-60 age bracket (depending on the product) so apart from the project mentioned above, they have never tried to address the specific needs of older adults.

b) If so, who tells them to do this, or do they just do it naturally anyway?

c) What tools/techniques do they use to include older users?

Observational study in their testing lab (see above)

They have used video ethnographic studies on their target aged consumers, using 20-30 subjects here in the UK, and 50-60 in the US. It was a generic study of the usage of their products and their packaging.

d) At what point in the design process are older adults considered?

At the moment they do not specifically include them. If they were then they would include them early on in the process, at the feasibility stage – the concept design log.

14. In your opinion, do you consider openability to be a relevant issue for your packaging? – do they see that there is a clear NEED for change (e.g. using more ergonomic data or user trials)?

Yes, but it's not a massive issue. Their consumers are more concerned about the closing of the packaging. Sees openability to be more relevant to the food production side of the business.

15. How important do they consider package openability to be in comparison with the other design criteria? **Rank these in order of importance – separate sheet**

16. **a)** Do you think improving openability will have an adverse affect on these other criteria?

Yes, it will affect cost. The aesthetic appeal.

b) Which ones in particular?

Technical Section:

17. In general what ergonomic data, if any, do the designers use?

They don't have access to this. They rely on their design partners to do this.

Focus groups, observational studies, in-use trials and large scale in-use trials. Early on in the project it is mainly qualitative work with 30-50 consumers, then later on they will use hundreds.

YES

a) What type do you use?

b) What do you use it for?

c) At which point in the design process?

d) Can you give me examples of how you've used it?

e) Have you ever tried to use the traditional anthropometric data? How difficult/easy/useful did they find it?

f) Can you give any examples of success stories, or failures?

g) Have you ever used any of the strength data, as opposed to just the standard anthropometrics?

h) Do you use ergonomic data in isolation, or do you conduct user trials?

NO

i) Why don't you use any? What puts you off? Do you think it is relevant to you and your design work?

j) Do you use something else instead?

k) Do they conduct user trials?

l) Are they aware of the different types of ergonomic data available?

18. Have you ever heard of the term ‘Biomechanics’?

Yes

19. What is your understanding of this term?

Collecting measurements about the different parts of the body and the movements they make in relation to the product or object they are using

20. Have you ever used any biomechanical data?

No

21. Are you aware of any of your competitors using biomechanical data?

He is quite sure that some of them use this technique, but has no proof.

22. Also, would you know where to find it, and if you did, would you have access to it?

Their group is a part of the Faraday Packaging Partnership, and he can use his academic contacts through this to gain access to these studies.

23. **a)** Have they ever tried to use the traditional anthropometric data?

They rely on the external design consultancies to do this, or to come up with similar evidence from other sources such as observational studies

b) How difficult/easy/useful did they find it?

24. Can they give any examples of success stories, or failures?

They have found big success in their use of video ethnography in the last 2 or 3 years. It has given them important insights that they could not get from just speaking to the users.

Found out that when users are washing their hair they are effectively blind so could not distinguish between the shampoo and conditioner bottles. They have changed the design so that they include a tactile distinction between the two. They had never heard about any of this through their questionnaires or complaints line.

Quickfire closing questions:

Have you ever read the Dti Reports on packaging accidents? – if YES, probe them for more information (are they useful, how often do they use them, etc.)

Specific anthropometric and strength data for people with limited dexterity ability (URN 02/743)

Strength data for design safety: phase 1 + phase 2 (URN 00/1070 and 02/744)

Assessment of broad age-related issues for packaging (URN 99/621)

Use and misuse of packaging opening tools (URN 99/619)

What about the following Inclusive Design resources:

Steenbekkers, Design-relevant characteristics of ageing users: backgrounds and guidelines for product innovation

Older adultdata

IDEO methods cards

Notes:

There are certain products where about 80% of the success comes from the closure. This means that it is both the openability and closability that are both important.

They do recognise that there is a type of ‘silent consumer’ who won’t phone the customer care line, or write a letter, they’ll just buy something different the next time.

Packaging Design Criteria

Considering a packaging design project, please choose what you consider to be the 3 MOST important criteria and rank them 1, 2 and 3 accordingly.

Then could you please choose what you consider to be the 2 LEAST important criteria, and rank them 11 and 12 accordingly.

Providing a unique selling point (or novelty)	
Containment of the product	
Protection of the product	
Appealing appearance	1
Openability	
Tamper-evident features	
Package strength/integrity	
Recyclability	
Process/material restrictions	12

Dispensing/measuring the product	2
Time pressure	11
Overall Costing	3

DEFINITIONS

“**Ergonomics** (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance (definition adopted by the International Ergonomics Association in 2000)”

Anthropometry literally means ‘the measurement of humans’.

Biomechanics…..is the field of study which makes use of the laws of physics and engineering principles to describe the motion of body segments and the forces which act upon them during activity.

Inclusive Design….. is a general approach to designing in which designers ensure that their products and services address the needs of the widest possible audience, irrespective of age or ability.

Inclusive Design…. means that products and services should be designed to be easily usable by as many people as possible. In particular inclusive design aims to meet the needs of people who have been unable to use mainstream products because of age or disability

Appendix D: Testing Documents for the Ethnographic Study

Appendix D Contents:

D.i Main testing document

Subject No	
Subject Name	
Consent Form Signed?	
Permission to use footage?	
Do you have any ailments affecting your hands or wrists?	
Do you have any other ailments that might affect your ability to open packaging?	

Today we want to observe you opening a number of different types of consumer packaging. It is important that during the course of this experiment that you only do what you would normally do at home.

Stand with your feet either side of the line and I will place items of packaging directly in front of you. Please wait until I say so before you attempt to open them.

On the table there are a number of standard kitchen utensils alongside some specially designed devices to help you open consumer packaging. Again, please do not use any of these that you would not normally use at home. Take care with these, as some of them are very sharp, particularly the kitchen knife and kitchen scissors.

After each attempt I will ask you to rate the level of difficulty you experienced during the activity, as well as if you experienced any pain or discomfort.

Try to just ignore the cameras – nobody else will see the footage of this test. We are looking for our subjects to be relaxed and to act as naturally as possible.

Please let me know if at any point you would like a rest.

Do not worry if you cannot open any type of packaging. We are equally interested in observing both successful and unsuccessful attempts at opening these packages.

Package 1:				
Would you normally sit or stand for this task?		Stand	Sit	
When faced with this type of packaging, do you normally attempt to open it with your bare hands first?		Yes	No	
		Succeed	Fail	Spillage
		Pain	Discomfort	None
Have you ever been unable to open this type of packaging with your bare hands? If so, what would you normally do next?		Yes	No	
Alternative Strategy 1		Pain	Discomfort	None
Alternative Strategy 2		Pain	Discomfort	None
Alternative Strategy 3		Pain	Discomfort	None
Reason(s) for not using bare hands:				
*Complete HAND form if pain or discomfort is being described				
Package 2:				
Would you normally sit or stand for this task?		Stand	Sit	
When faced with this type of packaging, do you normally attempt to open it with your bare hands first?		Yes	No	
		Succeed	Fail	Spillage
		Pain	Discomfort	None
Have you ever been unable to open this type of packaging with your bare hands? If so, what would you normally do next?		Yes	No	
Alternative Strategy 1		Pain	Discomfort	None
Alternative Strategy 2		Pain	Discomfort	None
Alternative Strategy 3		Pain	Discomfort	None
Reason(s) for not using bare hands:				

*Complete form if pain or discomfort is being described

Package 3:				
Would you normally sit or stand for this task?		Stand	Sit	
When faced with this type of packaging, do you normally attempt to open it with your bare hands first?		Yes	No	
		Succeed	Fail	Spillage
		Pain	Discomfort	None
Have you ever been unable to open this type of packaging with your bare hands? If so, what would you normally do next?		Yes	No	
Alternative Strategy 1		Pain	Discomfort	None
Alternative Strategy 2		Pain	Discomfort	None
Alternative Strategy 3		Pain	Discomfort	None
Reason(s) for not using bare hands:				

*Complete HAND form if pain or discomfort is being described

Package 4:				
Would you normally sit or stand for this task?		Stand	Sit	
When faced with this type of packaging, do you normally attempt to open it with your bare hands first?		Yes	No	
		Succeed	Fail	Spillage
		Pain	Discomfort	None
Have you ever been unable to open this type of packaging with your bare hands? If so, what would you normally do next?		Yes	No	
Alternative Strategy 1		Pain	Discomfort	None
Alternative Strategy 2		Pain	Discomfort	None
Alternative Strategy 3		Pain	Discomfort	None
Reason(s) for not using bare hands:				

*Complete form if pain or discomfort is being described

Package 5:				
Would you normally sit or stand for this task?		Stand	Sit	
When faced with this type of packaging, do you normally attempt to open it with your bare hands first?		Yes	No	
		Succeed	Fail	Spillage
		Pain	Discomfort	None
Have you ever been unable to open this type of packaging with your bare hands? If so, what would you normally do next?		Yes	No	
Alternative Strategy 1		Pain	Discomfort	None
Alternative Strategy 2		Pain	Discomfort	None
Alternative Strategy 3		Pain	Discomfort	None
Reason(s) for not using bare hands:				

*Complete HAND form if pain or discomfort is being described

Package 6:				
Would you normally sit or stand for this task?		Stand	Sit	
When faced with this type of packaging, do you normally attempt to open it with your bare hands first?		Yes	No	
		Succeed	Fail	Spillage
		Pain	Discomfort	None
Have you ever been unable to open this type of packaging with your bare hands? If so, what would you normally do next?		Yes	No	
Alternative Strategy 1		Pain	Discomfort	None
Alternative Strategy 2		Pain	Discomfort	None
Alternative Strategy 3		Pain	Discomfort	None
Reason(s) for not using bare hands:				

*Complete form if pain or discomfort is being described

Are you right or left handed? Right Left

What age are you?

Can I contact you again to let you know the outcomes of this part of the study, and to let you know of any future work?

Yes No

Thank you very much for your help.

Would you like to take away any of the packages you opened today?

D.ii Package difficulty ratings

Subject No:

1. Jar

Very EASY — Very DIFFICULT

2nd Attempt

3rd Attempt

2. **CRC Medicine Bottle**

Very EASY — Very DIFFICULT

2nd Attempt

3rd Attempt

3. Bleach

Very EASY — Very DIFFICULT

2nd Attempt

3rd Attempt

4. Soft Drink Can Very EASY ______________________________ Very DIFFICULT

2nd Attempt ______________________________

3rd Attempt ______________________________

5. Tin Very EASY ______________________________ Very DIFFICULT

2nd Attempt ______________________________

3rd Attempt ______________________________

6. Soft drinks bottle Very EASY ______________________________ Very DIFFICULT

2nd Attempt ______________________________

3rd Attempt ______________________________

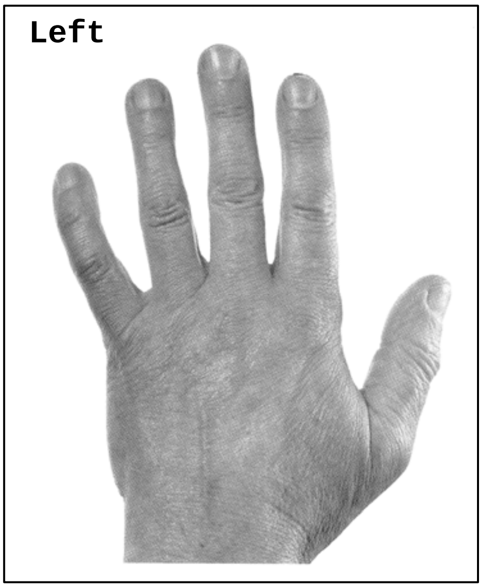
D.iii Pain and discomfort charts

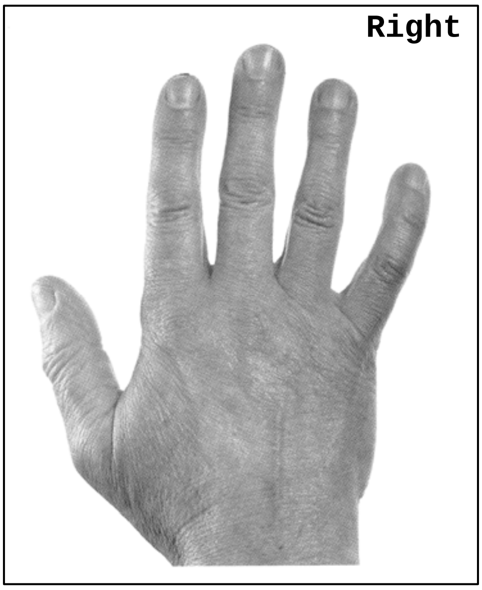
Subject No	
Package Type	Jar Bleach IB Bottle CRC Soup IB Can
Attempt	Hands AS1 AS2 AS3

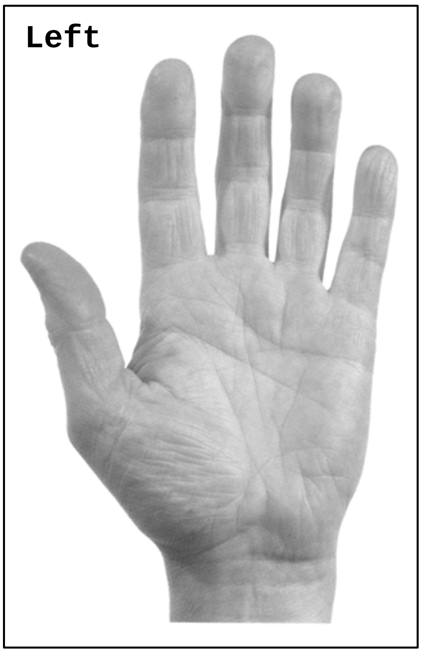
Hand and Wrist DISCOMFORT

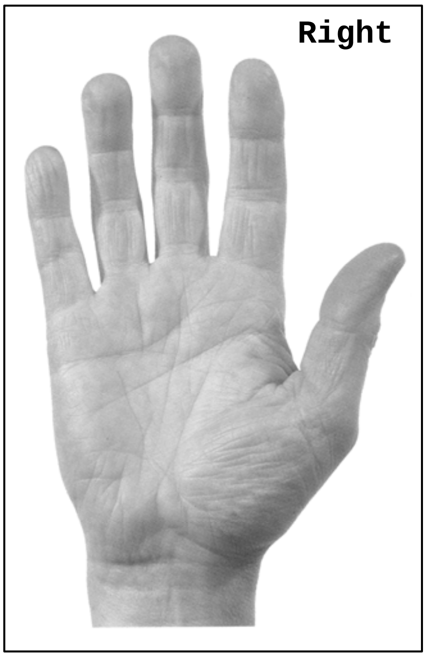
No
discomfort
at all

Worst
possible
discomfort





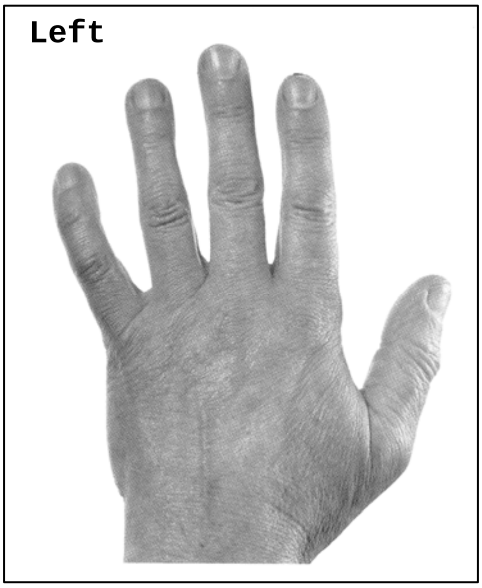


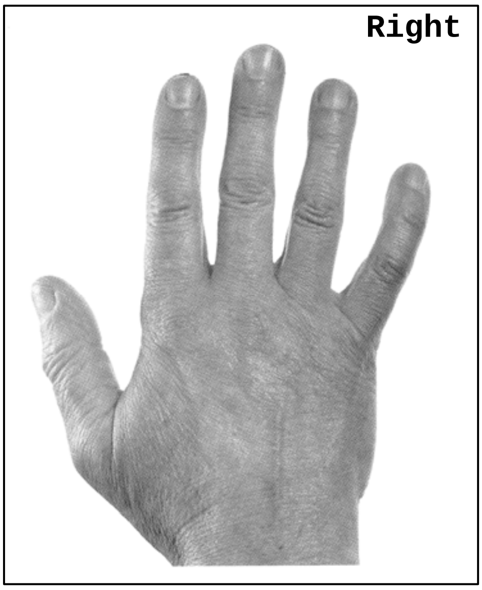


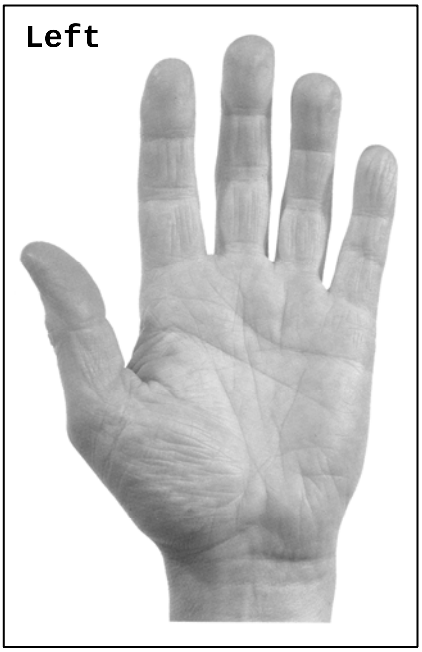
Hand and Wrist PAIN

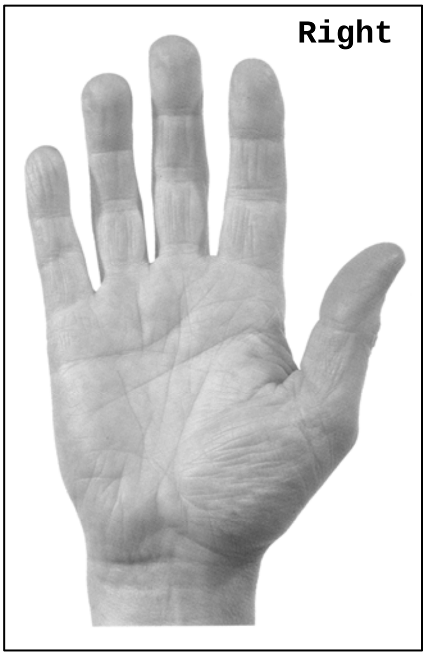
No pain
at all

Worst
possible
pain









Appendix E: Example of Fully Transcribed Follow-up Designer Interview

Packaging Designer Interview II

Company: XXXXXXX - Design and innovation company specialising in structural packaging (R2)
Respondents name: Pete Booth
Job Title: Director (involved in hands-on design work)
Years in Industry: 18
Types of packaging designed: Pharmaceuticals, DIY products, foods, confectionary, nutrition, personal care, alcoholic drinks.

INTRODUCTION

Briefly discuss their results from the previous interview.

Biomechanics…..is the field of study which makes use of the laws of physics and engineering principles to describe the motion of body segments and the forces which act upon them during activity……..therefore we can say that biomechanics is an *aspect* of ergonomics/human factors.

Inclusive Design….. is a general approach to designing in which designers ensure that their products and services address the needs of the widest possible audience, irrespective of age or ability

The ultimate aim of the interview is to establish the best way to present biomechanical data to designers to help them practise inclusive design.

MAIN INTERVIEW

What I would like to do is present to you a number of different possible ways of presenting information and data on how users interact with products, ranging from pictorial information, raw data in tabular and graphical format, video clips and motion analysis capture clips. After I have briefly introduced each I will ask you a series of questions about it's suitability and potential uses.

We're talking in general terms here, but at points use the work that I've been doing, on consumer packaging as an example to highlight a point. Please remember to try and give a general answer, or if you want to relate it to something which you've designed recently, please feel free to do so.

INITIAL DESIGN AIDS

1. Video clips of subjects manipulating an existing product, or perhaps a prototype, with a close-up of their hands.

They already do their own video-based observational work and they have a database of different opening and closings and fixings and they do that in each project they work on.

The main thing that they are looking for when they analyse the results are “the practises that are inherent in the opening/interaction”, but those practices are not just an observational piece. It’s a relationship between the object, the competencies of the person, and the images of what they expect to happen.

Mismatches occur between the object and the person’s skill, but between the object and your expectation, or your expectation and your skill.

They couldn’t just passively digest the visual information.

Just watching the video doesn’t tell him enough, he needs to be able to find out what their expectations were. If they were doing a video they would ask the person how they went about doing a certain activity, e.g. when they ask someone how they close a paint tin they would say they used their feet, and they would be laughing about this because it seems ridiculous for them to have to do that.

They keep and archive of all of their videos.

It shows the veracity of what you’re saying and allows you to internally manage a project. It acts as evidence of the investigative lengths which they have gone to.

They would not verify a new design against old video footage.

He would like to know the exact context of where the footage was taken, which is important to them. It’s not just the demographic information they’d want, it would be info on what attitudinal set; one might favour freshness of the product over another person who is looking for value. Someone might be willing to compromise their usage strategies for something that is half the price of their normal choice.

Not only do they want to know about the person, but they need to know about the context of their expectation.

They use the information two-fold. Firstly it helps them to generate insight, and highlight any problems with an existing design. They also use it to help with the internal management of a project within a business. It justifies and supports the project work.

Video’s really, really powerful and they use it on every project. He realises that because it was not he who had editorial control he doesn’t know if he’s being told the full story behind what is happening there.

He see drawback to both observational studies, in which the lab effectively acts like zoo, as well as ethnography, whereby he is unable to interact with the person and see how they react to new things. It won’t help with innovation, but it might throw up some general insights.

2. Still screenshots of their hand grip style as they handle/operate existing products or prototypes.

This type of study only focuses on the physical interaction, whereas he would need to know more about the surrounding environment, and the jestures involved in the opening activity. So this information is rather limited.

They would look into using this sort of information, but combined with other info too. They would probably look at this within a video, as that allows them to see more of how the subject prepares themselves, how you’ve had to organise the parts and what the person does afterwards. They might stop it at certain bits and edit the image in order to make a certain point, but they wouldn’t use still images in isolation

Any packaging is a form of 5 different types of control; distribution, functions, communication, emotion, through to the build-up of habits and practices which are above and beyond the intended use. This example is only focussing solely on the functionality, so is a limited look at how engagement with packaging occurs.

It does however tell him what the different type of opening styles are, and he would then look to try and design something which covered all of them.

What this represents is a look at just one aspect of a pack design.

When analysing this sort of information they will look for patterns in the way people do things and the time it takes them to do it, but they won't necessarily try to involve using numbers.

He would be more interested in looking at the practises that people use to compensate, rather than the specific hand grip styles.

They employ the tactic of making the activity they are analysing seem strange therefore forcing them to really think about what they're doing and why. An example of this would be getting their designers to wear a pair of the gloves which simulate having arthritis. Again, this only tells you so much.

They find that they are able to design things that work better, but they find that is not necessarily linked with whether or not somebody will buy more of, or pay more for a certain product.

3. Vicon video output, with forces and a basic graphical representation of the product (or prototype) being handled. Explain that we will eventually have a visual representation of the product AND force/moment indicators.

"Our whole remit as a business is to get it as real as possible and this feels just like measuring to a high level of accuracy something which is hugely inaccurate"

I think you would get some confused faces if we introduced this into the studio, as designers wouldn't really know what they would do with it.

He worries that going down this sort of route that you would be pre-supposing what would happen, so you not trying to find any new way of doing something. They might want to radically change the way they do something and this sort of thing wouldn’t really support this.

The look of it is far too clinical.

He can see that someone involved in designing closures might be interested in this sort of thing when trying to refine the fine detail of a particular design – rather than the ‘bigger picture’ thinking that they tend to look at. A closure manufacturer might want to look at this to determine how they might change the variables of the thread in a screw cap, and see how that affect the way that the person interacts with it.

4. Vicon video output alongside standard digital video

It’s useful to be able to visualise what is really going on with the vicon output. The problem that he has with it is that it’s in a laboratory environment which is not representative of what that person might normally do.

The combination of the 2 moving images is far more interesting to him.

He would want the ability to go into the vicon output screen and watch it from different angles and play around with it.

5. Levels of pain or discomfort experienced – plus locations and descriptions of the pain/discomfort

He can see that this is useful for evaluating a design, it provides him with all of that subject’s details background data, which one is right or wrong.

He still feels that it doesn’t tell him anything about their attitudes towards the object or the meanings that are buzzing around too.

People looking for a reliable seal on something would have the EXPECTATION that the closure will be difficult to open, so he would want to know what they were expecting.

It’s the persons expectation that will define whether or not they are disappointed by the way something opens – they might have to squeeze or twist the lid a bit harder than normal, but this might make them happy as it reassures them that the product inside is fresh.

It’s not about making something easier to open, it’s about mating peoples expectations with their interaction with the product.

6. Joint angles used ……..namely the angles at point of greatest force exertion (e.g. the lid ‘popping’ when you open a jar).

“It’s swimming in front of my eyes at the moment. I couldn’t use that at all”

It’s the difference between analytic and generative information for design – this is analytic.

This would let me compare two things that are already existing, it’s not going to help me to generate any new ideas. It might set up a set of thoughts that might conclude that one type of heel might be advantageous to another, therefore I could use the summary of that information

Somebody else can do the precise measurements accurately – he just needs to know the end result.

Definitely prefers looking at graphs to looking at tables. He finds them much easier to understand.

It’s really hard to go from that [graph of data] to some sort of design parameter

7. Resultant moments generated at various joints – in biomechanics we consider the resultant moments acting at the various joint centres as they indicate how much demand will be placed on the muscles acting around each joint. In terms of inclusive design, moments are particularly important as they can indicate the level of pain that a user might experience while interacting with a product

To him, this is just background information and not foreground information. They might expect some of this information to be in the back pages of the detailed project brief that was provided by the client. It would maybe help to set up some ruling guidelines that they could take into account OR for setting up some clear evaluation criteria for the final design.

8. Accuracy of force/moment application

If you wanted to investigate why something wasn't working properly, or being used properly, then you might use this type of test, along with video footage and getting the person to script their interaction with the object to find out more about what's going wrong.

They could also find out more about how people tend to apply forces and use that information to design the object such that it makes it easier for them to do this.

There would have to be some obvious problem with the existing design before meriting such an investigation.

VIABLE FUTURE DESIGN AIDS

9. Virtual Biomechanical Testing – the ability to design something in CAD and then import it into some software to run some basic biomechanical tests, then play around with the design such that, thus allowing you to assess the biomechanical effects of changing variables such as; geometry, material, weight distribution, surface finish, etc.

He cannot imagine doing the tests without actually having the person there. Again hae wants to know what their expectations and understanding of what they're trying to do.

He is interested in seeing what happens when someone experiences something new, and doesn't know what to do (or how to open it, in this case).

When people have worked out how to open something there are the physical mechanics of the opening, but they cannot the persons conceptual understanding of what is happening.

Most user centred design seems to be the least subject-oriented system, because it treats users as data or abstract information and does not treat them as individuals who should be talked to on an individual basis.

It seems to strip out ‘the person’ from the design process. It’s talking about an abstract set of information at a point of interface, in an imaginary context. So with any sort of test like this you absolutely have to have the person there.

10. Which muscle groups are being used at different points during the user’s interaction with the product or prototype.

He can’t imagine he would be able to make sense of it.

11. Vicon video footage with normal video footage synchronised on top of it.

He wants to be able to see the 2 and be able to control it. He would like to have this alongside the information the summary of the finding from the tables.

But again he needs to know more about the context. I have to see it for real, in the right location. Wants to see the user put back into ‘user information’ – then he’ll start to have more faith in it.

12. The ability to assess the effects of changing various design variables such as; geometry, material, weight distribution, surface finish, etc.

If the site of the virtual testing can be context specific.

13. A database of videos of users with various hand impairments manipulating a variety of different products or prototypes, supplemented by information on their hand impairments.

They have toyed with the idea of doing this themselves. He would want to see the context, information about the person (as in the pain experienced slide), and use data tagging so that he can then search through the catalogue of clips at a later date.

OTHER QUESTIONS:

14. In general, what do you think are the main barriers to inclusive design?

Need to beware that in making something that appeals to everyone you don’t make the design banal. It might end up being equally unappealing to everybody, rather than appealing to just a few.

It’s also not just about the physicality of engagement, it’s about the mental aspiration or attitudinal engagement as well.

With the 50+ group there is the whole attitudinal side that needs to be addressed.

You need to put the person back into ‘user centred’ design. Sometimes its about giving something to people and letting them do with it exactly what they want – rather than prescribing it to them.

17. If you could choose just one of the ideas we’ve just discussed, which one do you think would be of most use to you? QUICKLY RUN THROUGH OPTIONS AGAIN

It would have to be combination – he doesn’t think he could use any of them in isolation.

Design is a generative approach, rather than an analytic or differentiating system.

He wants to pull things together and see what will happen in a series of complex constraints, rather than just what happens in one isolated constraint.

Something which allows him to drill down to which ever level he wants and draw his own conclusions.

Appendix F: Testing documents for biomechanical testing

Appendix F Contents:

F.i Information for participants sheet

Packaging Design for the Older Adult (Stage 3)

You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Please ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

Purpose of the study:

Opening different types of consumer packaging is an activity that is carried out frequently throughout everyday life. The ability to do this safely and comfortably becomes more difficult as our muscle strength declines and our manual dexterity is reduced. Previous studies have shown that older adults have more difficulty opening various types of packaging due to physical changes that occur due to ageing, as well as the way in which packaging is designed.

This project will measure in detail the forces that are applied to the body as the older adult goes about a normal package opening activity. The purpose of the study is to examine exactly how older adult's movement and force patterns differ from those exhibited by younger adults, when performing this everyday activity. The results will then be taken and presented to designers so that they can use that information to improve their future designs, making them more suitable for the older adult population.

There is no financial reward associated with your participation in this experiment. The Bioengineering Unit will either provide free transport for all subjects or alternatively will reimburse any travel expenses incurred.

Who should volunteer?

This study requires the participation of any young and older adults who live independently (i.e. live in their own home with no full-time carers) and have no history of nervous system conditions.

You should not volunteer if you are:

- Ill for any reason
- Known to have previously received treatment for any neurological condition (i.e. condition affecting your nervous system).
- Known to have a diagnosed skin condition
- Known to have any infectious disease
- Taking medication that makes you drowsy or influences your balance

The experiment:

Hand Function Tests

The experiment requires that you complete three standard hand function tests; power grip strength, lateral pinch grip strength and a manual dexterity test. These tests are designed to give the researchers an indication of your individual level of hand function. In this part of the experiment your MAXIMAL strength will be tested, however it is important that you do not over-exert yourself, nor cause yourself any pain or discomfort.

Package Opening Activity

The experiment requires that you have a set of small reflective markers placed on your hands and arms (see picture below), and then in front of a series of motion analysis cameras, open some different types of packaging.

Each of these types of the three types of packaging will resemble the kind that you would encounter on a day-to-day basis however, they will contain a device that can measure the amount of force that you exert with different parts of your hand as you open the package. We will also use a conventional video camera to record the experiments.

Examples of the types of packaging you may be asked to open are as follows:

- Glass Jar
- Soft drinks bottle
- Tin can

The packaging opening experiment does NOT seek to test your maximal strengths. It is vitally important that you do not exert yourself more than you would do normally when opening packaging.

The experiments should take no longer than 3 hours in total.

If at any point you feel that you do not wish to attempt to open any of the items of packaging you are free to do so. Also, if at any point you wish to take a break simply alert the tester and the experiment can be resumed whenever you are ready.

Procedure	**Risk**
Manoeuvring around test area	Studies on opening packaging may result in a situation where a fall could occur. The probability of falling increases with age but the experimental design will minimize this risk by allowing you to stop at any time of the experiment for a break. Due to the instrumentation required, leg supports and cables, there is a risk of tripping. The tester will highlight the potential hazards and make you aware of the risks.
Hand Function Tests	These tests could result in over exertion. Please take care to only apply you maximal COMFORTABLE grips while doing these tests. This will be reemphasised to you immediately prior to the testing.

It is up to you to decide whether or not to take part. If you do decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason. A decision to withdraw at any time, or a decision not to take part, will not affect the standard of any other care or medical services you receive.

Will my taking part in this study be kept confidential?

All information collected about you throughout the course of this study will be kept strictly confidential.

If you give consent for them to do so, the researchers may use some of the still and video images of yourself opening different types of packaging during various presentations, lectures, conferences and in subsequent journal papers. Should you give consent for this, all possible measures will be taken to preserve your anonymity and you will never be referred to by name.

It is important to note that should you not wish to give consent to your image being used, you can still participate fully in this study.

During the course of the research the video footage will be stored on an external hard drive and a personal computer, both of which will only be accessible to the researchers named at the end of this form. The external hard drive will be stored securely in a locked cupboard when not in use. When the whole project is complete (August 2010) all of the video files will be destroyed appropriately.

What will happen to the results of this study?

The results from this study will form part of a Ph.D. programme which will be published for use in the University of Strathclyde library. Some of the results may also be used in conferences, presentations and journal papers, although the images captured will only be used if the appropriate consent is provided (as mentioned above). If you would like to see results from this study, please contact the researchers. You will not be identified in any way in the published results.

Who is organising and funding the research?

This research project is being conducted by the Bioengineering Unit (and the department of Design, Manufacture and Engineering Management) of the University of Strathclyde, and is funded by the Strategic Promotion of Ageing Research Capacity (SPARC).

Contact for further information:

If you require any further information regarding this study, please feel free to contact the following, who are directly involved in the project:

Mr Bruce Carse
PhD Student
Bioengineering unit
University of Strathclyde
106 Rottenrow East
Glasgow
G4 0NW

Phone: 0141-548 3228
Mobile: 07804 977 655

Email: bruce.carse@strath.ac.uk

Dr Ben Stansfield
Senior Lecturer
Room A256 Govan Mbeki Building
School of Health and Social Care
Glasgow Caledonian University
Glasgow
G4 0BA

Phone: 0141-273 1551

Email: ben.stansfield@gcal.ac.uk

Alternatively, if you require information and wish to speak to someone who is INDEPENDENT from the project, please contact the following:

Mrs Gwen McArthur

Head of Court Office
University of Strathclyde
McCance Building
16 Richmond Street
Glasgow
G1 1XQ

Tel: 0141 548 2472   Email: g.mcarthur@strath.ac.uk

F.ii Declaration of consent

Project Title: Packaging Design for the Older Adult (Stage 3)

To be completed by the subject

Please initial box

I have read and understood the form ‘Information for Participants’, and I have had the opportunity to discuss this study. ☐

I have spoken to a researcher regarding any questions I have about this study and I have received satisfactory answers. ☐

I do not suffer from any of the medical conditions listed on the participant information sheet. ☐

I am aware that I am free to withdraw from this study at any time, and I agree to participate in this study. ☐

OPTIONAL:

I give my consent to having parts of the video footage of myself used during various presentations, lectures, conferences and journal articles. ☐

Name (please print):………………………………………………………………
Signature:…………………………………………………………………………
Date:…………………………….
Witness signature:…………………………………
Date:…………………………….

F.iii Main testing sheet

Subject Number:	
Name:	
Age:	
DoB:	
Height:	
Weight:	
Handed:	
Description of Hand or Wrist Ailments:	

Notes from previous trial:

	Hand on Lid	Grip Type	Difficulty Rating	
Jar				
Bottle				

1. Power Grip Strength:

	Attempt 1(kg)	Attempt 2(kg)	Attempt 3(kg)
Right Hand			
Left Hand			

2. Dexterity Test:

	Score
Right Hand (30s)	
Left Hand (30s)	
Both together (30s)	
Sum of Scores	
Assembly (60s)	
TOTAL	

3. Measure Subject Finger Joints and Hand Length

Left Hand Length	
Right Hand Length	

4. Subject Toilet Break?

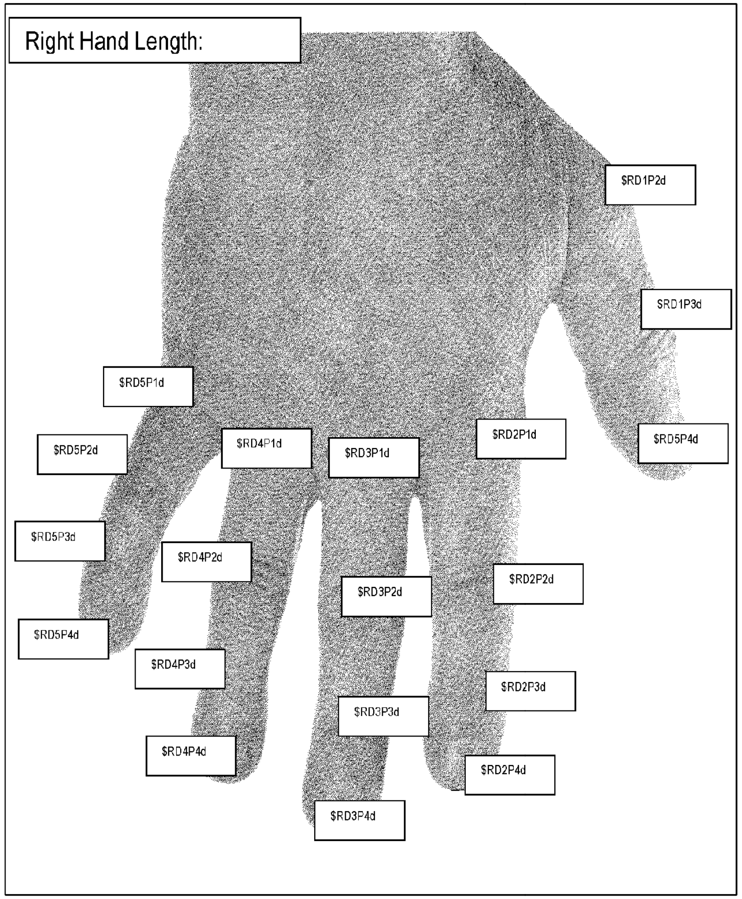
5. JEWELLERY OFF.

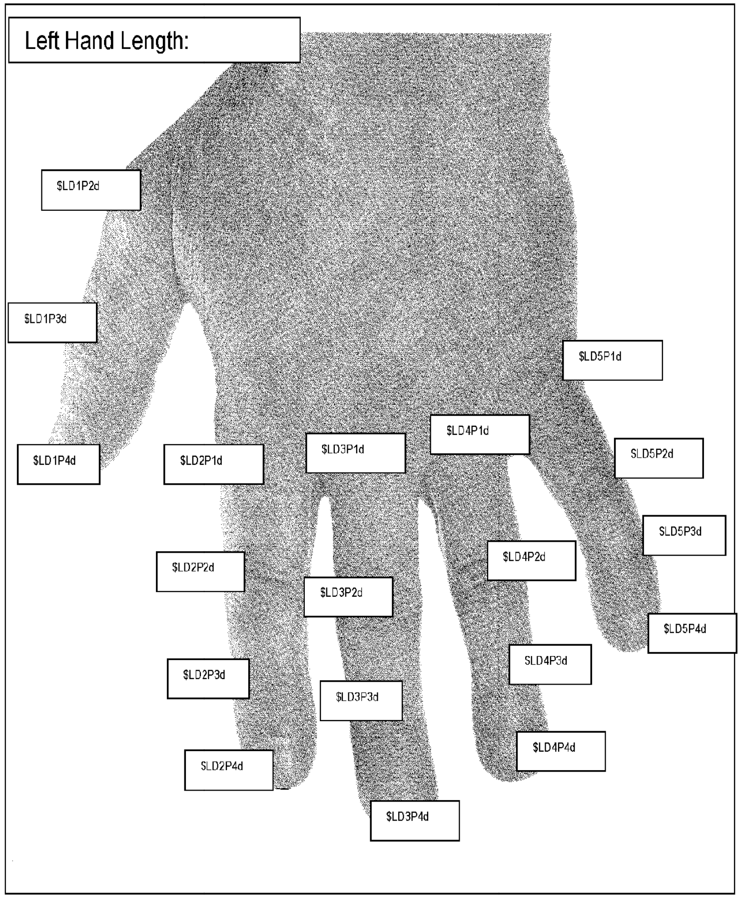
6. Attach Markers – explain not to worry if any markers get knocked off in the process.

7. Motion Analysis:

Static Trial		
Remove Forearm Markers		
Jar 1	Right / Left Hand on Lid	Normal / Reversed
Jar 2		
Jar 3		
Model File:		
Bottle 1	Right / Left Hand on Lid	Normal / Reversed
Bottle 2		
Bottle 3		
Model File:		

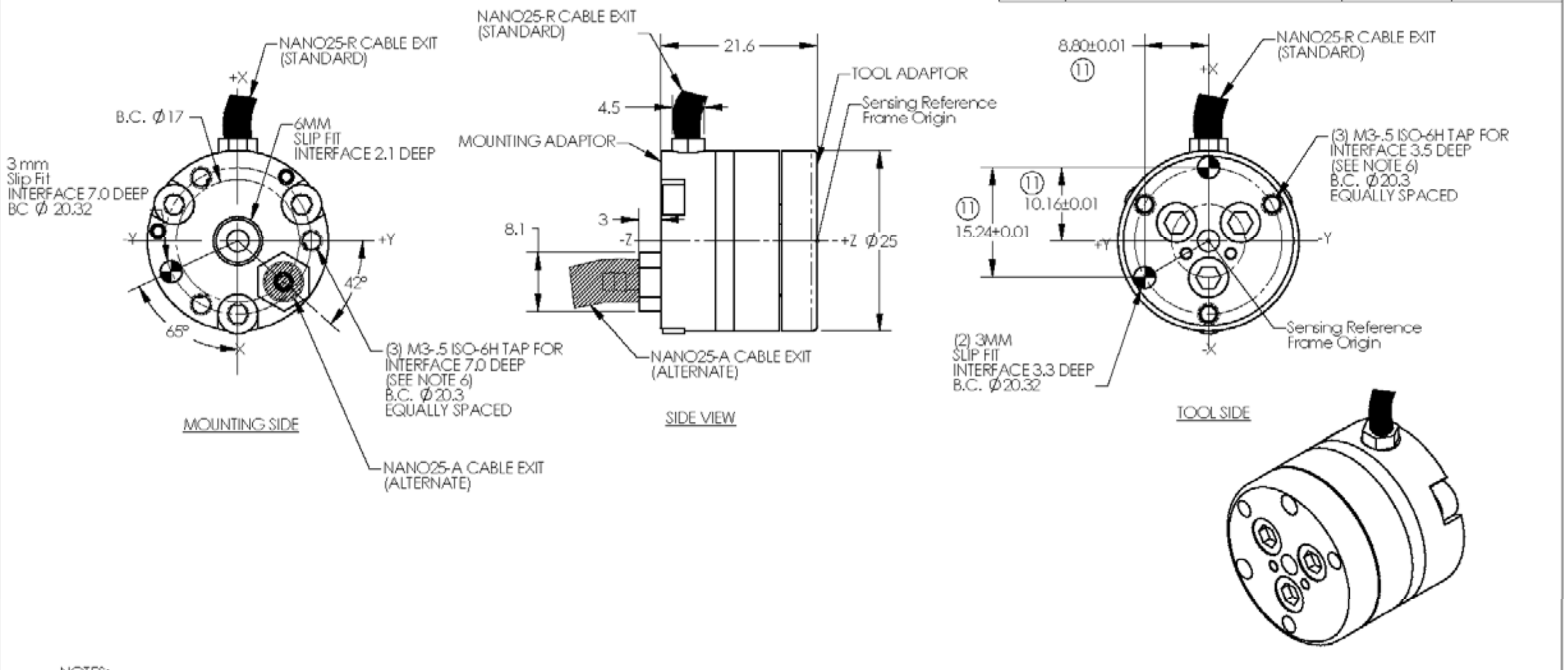
HAND JOINT DIMENSIONS





Appendix G: Technical specifications for Nano 25 transducers

Rev.	Description	Initiator	Date
09	Corrected B.C. callout on mounting side.	PS	8/17/2005
10	Eco 4338; Corrected M3 Barb part number.	LJH	11/23/2005
11	Eco 4104; DP dims were radial	LJH	2/27/2006



ISOMETRIC VIEW

NOTES:
1. MATERIAL: ALL MADE OF STAINLESS STEEL.
2. TOOL AND MOUNTING ADAPTOR HAVE M3 TAPS FOR INTERFACING.
3. CABLE CAN BE FACTORY INSTALLED ON SIDE OR THE TOP.
4. CONNECTOR (NOT SHOWN) HAS 17MM DIAMETER AND IS 67.5MM LONG.
5. WARNING-- DO NOT LOOSEN OR REMOVE INTERFACE PLATES DUE TO POTENTIAL DAMAGE
6. DO NOT EXCEED INTERFACE DEPTH MAY CAUSE DAMAGE

NOTES: UNLESS OTHERWISE SPECIFIED
DO NOT SCALE. DRAWN IN SOLID WORKS.98 .
ALL DIMENSIONS ARE IN MILLIMETERS.

ATI INDUSTRIAL AUTOMATION

1031 Goodworth Drive, Apex, NC 27539, USA
Tel: +1.919.772.0115 Email: info@ati-ia.com
Fax: +1.919.772.8259 www.ati-ia.com
ISO 9001 Registered Company

DR. BY: BDIGESO 3-8-00
CKD. BY:
ENG. APPR.
MFG. APPR:
ASSEMBLY REF.

TITLE NANO25 TRANSDUCER
SCALE 2:1
SIZE B-11X17
DRAWING NUMBER 9230-05-1083-11
PD
SHEET 1 OF 1

Technical specification for Nano 25

Single-Axis Overload	
Fxy	±2300 N
Fz	±7300 N
Txy	±43 N-m
Tz	±63 N-m
Stiffness (Calculated)	
X-axis & Y-axis forces (Kx, Ky)	5.3x10^{7} N/m
Z-axis force (Kz)	1.1x10^{8} N/m
X-axis & Y-axis torque (Ktx, Kty)	6.5x10^{3} Nm/rad
Z-axis torque (Ktz)	9.2x10^{3} Nm/rad
Resonant Frequency (Measured)	
Fx, Fy, Tz	3600 Hz
Fz, Tx, Ty	3800 Hz
Physical Specifications	
Weight*	0.064 kg
Diameter*	25 mm
Height*	22 mm

Metric Calibrations (SI)

Calibration	**Fx,Fy**	**Fz**	**Tx,Ty**	**Tz**	**Fx,Fy**	**Fz**	**Tx,Ty**	**Tz**
SI-125-3	125 N	500 N	3 N-m	3 N-m	1/192 N	1/64 N	1/5280 N-m	1/10560 N-m
	SENSING RANGES				**RESOLUTION**			

Appendix H: Dynamic BodyBuilder Code for Interpreting Jar Opening Motion Analysis Data

```
{*Start of macro section*}
{*======================*}

macro SUBSTITUTE4(p1,p2,p3,p4)
{*Replaces any point missing from set of four fixed in a segment*}

s234 = [p3,p2-p3,p3-p4]
p1V = Average(p1/s234)*s234
s341 = [p4,p3-p4,p4-p1]
p2V = Average(p2/s341)*s341
s412 = [p1,p4-p1,p1-p2]
p3V = Average(p3/s412)*s412
s123 = [p2,p1-p2,p2-p3]
p4V = Average(p4/s123)*s123

p1 = p1 ? p1V
p2 = p2 ? p2V
p3 = p3 ? p3V
p4 = p4 ? p4V
endmacro

macro SEGVIS(Segment)
{*outputs a visual representaion of the segment to be viewed in the Workspace*}
{*0(Segment) is the origin of the segment*}

ORIGIN#Segment=0(Segment)
XAXIS#Segment=0(Segment)+(1(Segment)*10)
YAXIS#Segment=0(Segment)+(2(Segment)*10)
ZAXIS#Segment=0(Segment)+(3(Segment)*10)
OUTPUT(ORIGIN#Segment,XAXIS#Segment,YAXIS#Segment,ZAXIS#Segment)
endmacro

macro POINTER(Anatomy,Segment)

{*Calculates the position of the end of the pointer for calibration in the technical frame it belongs to*}
{*1st determine the "point" in the Global system and outputs it as point#Calib. Then converts the point into*}
{*the appropriate technical reference frame and stores it as parameter $%#point#Calib*}

unitPointer=((POI1-POI2)/DIST(POI1,POI2))
Anatomy#Calib=POI1+123*unitPointer
OUTPUT(Anatomy#Calib)
PARAM(Anatomy#Calib)
%#Anatomy#Calib=Anatomy#Calib/Segment
PARAM(%#Anatomy#Calib)
endmacro

macro ColeJCS(seg1,seg2,joint)
{*  Procedure to calculate the rotations about defined embedded axes using the joint
co-ordinate system.

References:          Cole,G.K. et al (1993).  Application of the Joint Co-ordinate System
                     to Three-dimensional Joint Attitude and Movement Representation : A
                     Standardization Proposal.  Journal of Biomechanical Engineering.
                     November 1993 : Vol 112 : pp 344-349

aEone,aEtwo,aEthree =unit vector describing the attitude of the 1st,2nd and 3rd axis of
the joint co-ordinate system between the reference segment (seg1) and the target segment
(seg2), relative to an inertial reference system.

If the axes of a body segment co-ordinate system are identified as an axis of Flexion, a
Longitudinal axis and a Third axis, then Fone, Lone, Tone are unit vectors that describe
the attitude of the Flexion, Longitudinal and Third axes respectively, in an inertial
reference system.
```

```
Input:    'seg1', 'seg2' describing the axes of the co-ordinate systems embedded in each segment.
          Fone, Lone, Tone describe the flexion, longitudinal and third co-ordinate
          axes of the proximal segment.
          Ftwo, Ltwo, Ttwo describe the flexion, longitudinal and third co-ordinate
          axes of the distal segment.
          'joint' is the name given to the joint at which the specified segments interact.

Output:   Angles of rotation about axes aEone,aEtwo,aEthree, flexion, abduction and rotation
          respectively. Counterclockwise rotations are chosen as positive*}

Fone=3(seg1)
Lone=2(seg1)        {*** Swap '1' and '2' around here? *}
Tone=1(seg1)
Ftwo=3(seg2)
Ltwo=2(seg2)   {*** Swap '1' and '2' around here? *}
Ttwo=1(seg2)

{*Defines e1 and e3*}
aEone=Fone
aEthree=Ltwo

{*Calculate the Vector or Cross Product between the Vectors*}
Va={2(aEthree)*3(aEone)-3(aEthree)*2(aEone),3(aEthree)*1(aEone)-1(aEthree)*3(aEone),1(aEthree)*2(aEone)-
2(aEthree)*1(aEone)}
Vb=DIST({2(aEone)*3(aEthree)-3(aEone)*2(aEthree),3(aEone)*1(aEthree)-1(aEone)*3(aEthree),1(aEone)*2(aEthree)-
2(aEone)*1(aEthree)},{0,0,0})
Vc={2(Va)*3(aEthree)-3(Va)*2(aEthree),3(Va)*1(aEthree)-1(Va)*3(aEthree),1(Va)*2(aEthree)-2(Va)*1(aEthree)}

{*Calculate the Scalar or Dot Product between the Vectors*}
DPone=(1(Va)*1(Ttwo))+(2(Va)*2(Ttwo))+(3(Va)*3(Ttwo))
DPtwo=(1(Vc)*1(Ftwo))+(2(Vc)*2(Ftwo))+(3(Vc)*3(Ftwo))

{*Calculates A (AA) and then e2*}
IF DPone < 0 AND DPtwo > 0 THEN AA=-1 ELSE AA=1 ENDIF
aEtwo=(Va/Vb)*AA

{*Calculate the value of r.*}
Rone={2(Fone)*3(aEtwo)-3(Fone)*2(aEtwo),3(Fone)*1(aEtwo)-1(Fone)*3(aEtwo),1(Fone)*2(aEtwo)-2(Fone)*1(aEtwo)}
Rtwo=DIST(Rone,{0,0,0})
r=Rone/Rtwo

{*Calculate the Scalar or Dot Product between the Vectors.*}
aEtwoTonedp=(1(aEtwo)*1(Tone))+(2(aEtwo)*2(Tone))+(3(aEtwo)*3(Tone))
aEtwoLonedp=(1(aEtwo)*1(Lone))+(2(aEtwo)*2(Lone))+(3(aEtwo)*3(Lone))
rLtwodp=(1(r)*1(Ltwo))+(2(r)*2(Ltwo))+(3(r)*3(Ltwo))
FoneLtwodp=(1(Fone)*1(Ltwo))+(2(Fone)*2(Ltwo))+(3(Fone)*3(Ltwo))
aEtwoTtwodp=(1(aEtwo)*1(Ttwo))+(2(aEtwo)*2(Ttwo))+(3(aEtwo)*3(Ttwo))
aEtwoFtwodp=(1(aEtwo)*1(Ftwo))+(2(aEtwo)*2(Ftwo))+(3(aEtwo)*3(Ftwo))

IF aEtwoLonedp >= 0 THEN aEtwoLonesign=1 ENDIF
IF aEtwoLonedp < 0 THEN aEtwoLonesign=-1 ENDIF
IF FoneLtwodp >= 0 THEN FoneLtwosign=1 ENDIF
IF FoneLtwodp < 0 THEN FoneLtwosign=-1 ENDIF
IF aEtwoFtwodp >= 0 THEN aEtwoFtwosign=1 ENDIF
IF aEtwoFtwodp < 0 THEN aEtwoFtwosign=-1 ENDIF

joint#Flex=(acos(aEtwoTonedp))*(aEtwoLonesign)
joint#Abd=(acos(rLtwodp))*(FoneLtwosign)
joint#Rot=(acos(aEtwoTtwodp))*(aEtwoFtwosign)
joint#JCSAngles=<joint#Flex,joint#Abd,joint#Rot>

{*For later calculations of moments*}
{*x axis will be the floating axis*}
joint#JCS=[0(Seg1),aEtwo,aEone,xyz]
```

```
XAXISjcs#joint=aEtwo

ENDMACRO

macro PROJECTION(line,segment,joint)
{* Calculates flexion/extension and abduction/adduction angles using technique of:
Cheng P.L., Pearcy M. (1998) A 3D Definition for the Flexion/Extension  and Abduction/Adduction Angles.
Proc. 4th International Symposium on the 3D Analysis of Human Movement, July2nd-2th, Chattanooga, USA.*}
{* input is the unit vector of the distal segment as "line" *}

%line=(line+0(segment))/segment
RotZ=acos(SQRT((2(%line)*2(%line))+(3(%line)*3(%line))))
RotX=acos(SQRT((1(%line)*1(%line))+(2(%line)*2(%line))))
If 1(%line) > 0 Then RotZ=-RotZ Else RotZ=RotZ EndIf
If 3(%line) > 0 Then RotX=-RotX Else RotX=RotX EndIf

RotZ2=acos(SQRT(1-1(%line)*1(%line)))
RotX2=acos(SQRT(1-3(%line)*3(%line)))

joint#ProjAngles=<RotX,0,RotZ>
joint#ProjAngles2=<RotX2,0,RotZ2>
output(joint#ProjAngles)
endmacro

{*Macro for Dot Product*}
MACRO DotProduct (One,Two,DotProd)
        DotProd = (1(One)*1(Two)+2(One)*2(Two)+3(One)*3(Two))
ENDMACRO

{* Macro to do a cross product *}
MACRO CrossProduct ( First, Second, Result )
        Result = { First(2)*Second(3)-First(3)*Second(2),
        First(3)*Second(1)-First(1)*Second(3),
        First(1)*Second(2)-First(2)*Second(1)}
ENDMACRO

{*End of macro section*}


{*Optional points are points which may not be present in every trial*}
{*=====================================================================================*}

{*   All points always present
OptionalPoints(THO1,THO2,THO3,THO4) *}


{*Substitutes missing markers based on clusters of 4 markers*}
{*===========================================================================*}
{*    No clusters of 4
SUBSTITUTE4(C7,T8,XYPH,JUG)

                *}


{*Defines technical axis systems for the segments from the clusters*}
{*====================================================================================*}

{*Note how the four Trunk technical axis frames are defined and how this
relates to the anatomical calibration in the section below*}

{* Example RightForeArm=[RFA1,RFA1-RFA3,RFA2-RFA3,yxz]  *}


{*Anatomical calibration from static/pointer trials*}
{*===============================================================*}
```

```
{*  No static trials   If $Static==1  *}

{*Dynamic trials*}
{*==============*}
{*If $Static==0*}

{*Anatomical frame definition*}


{*New Left forearm system*}
{*====================*}


{* DYNAMIC Trials *}


        LTRFMID=(LTRF2+LTRF3)/2
        LTRIPODAXES=[LTRFMID,LTRFMID-LTRF1,LTRF3-LTRF2,xyz]

        RTRFMID=(RTRF2+RTRF3)/2
        RTRIPODAXES=[RTRFMID,RTRFMID-RTRF1,RTRF3-RTRF2,xyz]

        SEGVIS(LTRIPODAXES)
        SEGVIS(RTRIPODAXES)

        {*New Left Forearm System*}
        {*=================*}

        {* Import points defined in Static Trial and define FOREARM axes *}

        LFAMID1=$%LFAMID1*LTRIPODAXES
        LFAMID2=$%LFAMID2*LTRIPODAXES
        LWJC=$%LWJCTRIPOD*LTRIPODAXES
        LRAD1=$%LRAD1*LTRIPODAXES
        LULN1=$%LULN1*LTRIPODAXES

        OUTPUT(LFAMID1,LFAMID2,LWJC,LRAD1,LULN1)

        LForearm=[LWJC,LFAMID1-LFAMID2,LRAD1-LULN1,xyz]
        SEGVIS(LForearm)




{* Right forearm system*}
{*====================*}

        {* Import points defined in Static Trial and define FOREARM axes *}

        RFAMID1=$%RFAMID1*RTRIPODAXES
        RFAMID2=$%RFAMID2*RTRIPODAXES
        RWJC=$%RWJCTRIPOD*RTRIPODAXES
        RRAD1=$%RRAD1*RTRIPODAXES
        RULN1=$%RULN1*RTRIPODAXES
        OUTPUT(RFAMID1,RFAMID2,RWJC,RRAD1,RULN1)

        RForearm=[RWJC,RFAMID1-RFAMID2,RULN1-RRAD1,xyz]
        SEGVIS(RForearm)

{* LEFT Finger System *}
{*=========================*}
```

```
{*DIGIT 1*}

LD1HAXES=[LD1P1,LD1P2-LD1P1,LD1P2-LD1P3,xzy,LD2P1-LD5P1]  {*FIRST vDIGIT METACARPAL axes*}{*LD2H-LD5H
USED AS AN ANTIFLIP LINE*}

LD1P101=LD1P1-((0.5*$LD1P1d)+$MARKDEP)*LD1HAXES(2)                  {*LOCATION OF JOINT CENTRE*}
LD1HAXES=[LD1P101,LD1P2-LD1P1,LD1P2-LD1P3,xzy,LD2P1-LD5P1]                    {*SHIFT TO ORIGIN AT JOINT
CENTRE*}

LD1P201i=LD1P2-((0.5*$LD1P2d)+$MARKDEP)*LD1HAXES(2)                  {*LOCATION OF JOINT CENTRE*}
LD1PPAXES=[LD1P201i,LD1P3-LD1P2,LD1P1-LD1P2,xzy,LD2P1-LD5P1]                  {*FIRST DIGIT PROXIMAL
PHALANX axes*}

LD1P201ii=LD1P2-((0.5*$LD1P2d)+$MARKDEP)*LD1PPAXES(2)
LD1P201=(LD1P201i+LD1P201ii)/2

LD1P301=LD1P3-((0.5*$LD1P3d)+$MARKDEP)*LD1PPAXES(2)                  {*LOCATION OF JOINT CENTRE*}

        {* Make axes distal*}

        LD1HAXES=[LD1P201,LD1P201-LD1P101,LD1P201-LD1P301,xzy,LD2P1-LD5P1]
        LD1PPAXES=[LD1P201,LD1P301-LD1P201,LD1P101-LD1P201,xzy,LD2P1-LD5P1]


        OUTPUT(LD1P101,LD1P201,LD1P301)
        SEGVIS(LD1HAXES)
        SEGVIS(LD1PPAXES)

        {*DIGIT 2*}

        DUMMY=[LD2H,LD2H-LD5H,LD2H-LD2P1,zyx]  {*wrongly defined second metatarsal axes based on surface
markers*}
        SEGVIS(DUMMY)

        {*Imaginary Hand Markers for digits 3 and 4*}

        LHANDWIDTH=DIST(LD2H,LD5H)

        LD3H=LD2H+LHANDWIDTH*0.1111*DUMMY(2)-LHANDWIDTH*0.37*DUMMY(3)
        LD4H=LD2H+LHANDWIDTH*0.0741*DUMMY(2)-LHANDWIDTH*0.741*DUMMY(3)
        OUTPUT(LD3H,LD4H)

{*DIGIT 2*}

LD2H01=LD2H-((0.5*$LD2Hd)+$MARKDEP)*DUMMY(2)-LHANDWIDTH*0.1667*DUMMY(3)       {*LOCATION   OF   JOINT
CENTRE*}

LD2HAXES=[LD2H01,LD2P1-LD2H,LD2H01-LD2H,xzy] {*SHIFT TO ORIGIN AT JOINT CENTRE*}


LD2PP01i=LD2P1-((0.5*$LD2P1d)+$MARKDEP)*LD2HAXES(2)   {*Initial definition of CENTRE OF PROXIMAL PHALANX
JOINT*}

LD2PPAXES=[LD2PP01i,LD2P2-LD2P1,LD2PP01i-LD2P1,xzy] {*second PROXIMAL PHALANX axes*}

LD2PP01ii=LD2P2-((0.5*$LD2P2d)+$MARKDEP)*LD2PPAXES(2)              {*2nd definition*}

LD2PP01=(LD2PP01i+LD2PP01ii)/2

LD2MP01i=LD2P2-((0.5*$LD2P2d)+$MARKDEP)*LD2PPAXES(2)  {*Initial definition of CENTRE OF MID PHALANX JOINT*}
LD2MPAXES=[LD2MP01i,LD2P3-LD2P2,LD2MP01i-LD2P2,xzy] {*second MID PHALANX axes*}

LD2MP01ii=LD2P2-((0.5*$LD2P2d)+$MARKDEP)*LD2MPAXES(2)

LD2MP01=(LD2MP01i+LD2MP01ii)/2
```

```
LD2DP01=LD2P3-((0.5*$LD2P3d)+$MARKDEP)*LD2MPAXES(2)  {*CENTRE OF DISTAL PHALANX JOINT*}


{* MAKE AXES DISTAL, NOT PROXIMAL *}

LD2HAXES=[LD2PP01,LD2PP01-LD2H01,LD2H01-LD2H,xzy]
LD2PPAXES=[LD2MP01,LD2MP01-LD2PP01,LD2PP01-LD2P1,xzy]
LD2MPAXES=[LD2DP01,LD2DP01-LD2MP01,LD2MP01-LD2P2,xzy]


        OUTPUT(LD2H01,LD2PP01,LD2MP01,LD2DP01)
        SEGVIS(LD2HAXES)
        SEGVIS(LD2PPAXES)
        SEGVIS(LD2MPAXES)



{*DIGIT 3*}

LD3HDUMMYAXES=[LD3H,LD3P1-LD3H,LD2H-LD5H,xyz]  {*wrongly defined third metatarsal axes based on surface
markers*}
LD3H01=LD3H-((0.5*$LD3Hd)+$MARKDEP)*LD3HDUMMYAXES(2)  {*LOCATION OF JOINT CENTRE*}

LD3HAXES=[LD3H01,LD3P1-LD3H,LD3H01-LD3H,xzy] {*SHIFT TO ORIGIN AT JOINT CENTRE*}

LD3PP01i=LD3P1-((0.5*$LD3P1d)+$MARKDEP)*LD3HAXES(2)   {* Initial definition of CENTRE OF PROXIMAL PHALANX
JOINT*}
{LD3PPAXES=[LD3PP01i,LD3P2-LD3P1,LD3PP01i-LD3P1,xzy] {*third PROXIMAL PHALANX axes*}

LD3PP01ii=LD3P1-((0.5*$LD3P1d)+$MARKDEP)*LD3PPAXES(2)  {*2nd definition*}

LD3PP01=(LD3PP01i+LD3PP01ii)/2

LD3MP01i=LD3P2-((0.5*$LD3P2d)+$MARKDEP)*LD3PPAXES(2)    {* Initial definition of CENTRE OF MID PHALANX
JOINT*}
LD3MPAXES=[LD3MP01i,LD3P3-LD3P2,LD3MP01i-LD3P2,xzy] {*third MID PHALANX axes*}

LD3MP01ii=LD3P2-((0.5*$LD3P2d)+$MARKDEP)*LD3MPAXES(2)   {*2nd definition*}

LD3MP01=(LD3MP01i+LD3MP01ii)/2

LD3DP01=LD3P3-((0.5*$LD3P3d)+$MARKDEP)*LD3MPAXES(2)  {*CENTRE OF DISTAL PHALANX JOINT*}



{* MAKE AXES DISTAL, NOT PROXIMAL *}

LD3HAXES=[LD3PP01,LD3PP01-LD3H01,LD3H01-LD3H,xzy]
LD3PPAXES=[LD3MP01,LD3MP01-LD3PP01,LD3PP01-LD3P1,xzy]
LD3MPAXES=[LD3DP01,LD3DP01-LD3MP01,LD3MP01-LD3P2,xzy]


OUTPUT(LD3H01,LD3PP01,LD3MP01,LD3DP01,LD3H)
SEGVIS(LD3HAXES)
SEGVIS(LD3PPAXES)
SEGVIS(LD3MPAXES)

{*DIGIT 4*}

LD4HDUMMYAXES=[LD4H,LD4P1-LD4H,LD2H-LD5H,xyz] {*wrongly defined FOURTH metatarsal axes based on surface
markers*}
LD4H01=LD4H-((0.5*$LD4Hd)+$MARKDEP)*LD4HDUMMYAXES(2)+LHANDWIDTH*0.1111*LD4HDUMMYAXES(3)

{*LOCATION OF JOINT CENTRE*}
```

```
LD4HAXES=[LD4H01,LD4P1-LD4H,LD4H01-LD4H,xzy]            {*SHIFT TO ORIGIN AT JOINT CENTRE*}

LD4PP01i=LD4P1-((0.5*$LD4P1d)+$MARKDEP)*LD4HAXES(2)  {* Initial definition of CENTRE OF PROXIMAL PHALANX
JOINT*}
LD4PPAXES=[LD4PP01i,LD4P2-LD4P1,LD4PP01i-LD4P1,xzy]

{*FOURTH PROXIMAL PHALANX axes*}

LD4PP01ii=LD4P1-((0.5*$LD4P1d)+$MARKDEP)*LD4PPAXES(2)

LD4PP01=(LD4PP01i+LD4PP01ii)/2          {*2nd definition*}

LD4MP01i=LD4P2-((0.5*$LD4P2d)+$MARKDEP)*LD4PPAXES(2)            {*Initial definition of CENTRE OF MID
PHALANX JOINT*}
LD4MPAXES=[LD4MP01i,LD4P3-LD4P2,LD4MP01i-LD4P2,xzy]             {*FOURTH MID PHALANX axes*}

LD4MP01ii=LD4P2-((0.5*$LD4P2d)+$MARKDEP)*LD4MPAXES(2)

LD4MP01=(LD4MP01i+LD4MP01ii)/2                          {*2nd definition*}

LD4DP01=LD4P3-((0.5*$LD4P3d)+$MARKDEP)*LD4MPAXES(2)                         {*CENTRE OF DISTAL PHALANX
JOINT*}


{* MAKE AXES DISTAL, NOT PROXIMAL *}

LD4HAXES=[LD4PP01,LD4PP01-LD4H01,LD4H01-LD4H,xzy]
LD4PPAXES=[LD4MP01,LD4MP01-LD4PP01,LD4PP01-LD4P1,xzy]
LD4MPAXES=[LD4DP01,LD4P3-LD4MP01,LD4MP01-LD4P2,xzy]

OUTPUT(LD4H01,LD4PP01,LD4MP01,LD4DP01,LD4H)
SEGVIS(LD4HAXES)
SEGVIS(LD4PPAXES)
SEGVIS(LD4MPAXES)



{*DIGIT 5*}

LD5HDUMMYAXES=[LD5H,LD5P1-LD5H,LD2H-LD5H,xyz]         {*wrongly defined fifth metatarsal axes based on surface
markers*}
LD5H01=LD5H-((0.5*$LD5Hd)+$MARKDEP)*LD5HDUMMYAXES(2)+0.0741*LHANDWIDTH*LD5HDUMMYAXES(3)

{*LOCATION OF JOINT CENTRE*}

LD5HAXES=[LD5H01,LD5P1-LD5H,LD5H01-LD5H,xzy]                    {*SHIFT TO ORIGIN AT JOINT CENTRE*}

LD5PP01i=LD5P1-((0.5*$LD5P1d)+$MARKDEP)*LD5HAXES(2)              {*Initial definition of CENTRE OF PROXIMAL
PHALANX JOINT*}
LD5PPAXES=[LD5PP01i,LD5P2-LD5P1,LD5PP01i-LD5P1,xzy]    {*fifth PROXIMAL PHALANX axes*}

LD5PP01ii=LD5P1-((0.5*$LD5P1d)+$MARKDEP)*LD5PPAXES(2)                       {*2nd definition*}

LD5PP01=(LD5PP01i+LD5PP01ii)/2

LD5MP01i=LD5P2-((0.5*$LD5P2d)+$MARKDEP)*LD5PPAXES(2)            {*Initial definition of CENTRE OF MID
PHALANX JOINT*}
LD5MPAXES=[LD5MP01i,LD5P3-LD5P2,LD5MP01i-LD5P2,xzy]  {*fifth MID PHALANX axes*}

LD5MP01ii=LD5P2-((0.5*$LD5P2d)+$MARKDEP)*LD5MPAXES(2)                       {*2nd definition*}

LD5MP01=(LD5MP01i+LD5MP01ii)/2

LD5DP01=LD5P3-((0.5*$LD5P3d)+$MARKDEP)*LD5MPAXES(2)             {*CENTRE OF DISTAL PHALANX JOINT*}
```

```
{* MAKE AXES DISTAL, NOT PROXIMAL *}

LD5HAXES=[LD5PP01,LD5PP01-LD5H01,LD5H01-LD5H,xzy]
LD5PPAXES=[LD5MP01,LD5MP01-LD5PP01,LD5PP01-LD5P1,xzy]
LD5MPAXES=[LD5DP01,LD5DP01-LD5MP01,LD5MP01-LD5P2,xzy]

{*RIGHT Finger System*}
{*========================*}

{*DIGIT 1*}

RD1HAXES=[RD1P1,RD1P2-RD1P1,RD1P2-RD1P3,xzy,RD2P1-RD5P1]     {*FIRST DIGIT METACARPAL axes*}{*RD2H-RD5H USED AS AN ANTIFLIP LINE*}
RD1P101=RD1P1-((0.5*$RD1P1d)+$MARKDEP)*RD1HAXES(2)            {*LOCATION OF JOINT CENTRE*}
RD1HAXES=[RD1P101,RD1P2-RD1P1,RD1P2-RD1P3,xzy,RD2P1-RD5P1]      {*SHIFT TO ORIGIN AT JOINT CENTRE*}

RD1P201i=RD1P2-((0.5*$RD1P2d)+$MARKDEP)*RD1HAXES(2)            {*ROCATION OF JOINT CENTRE*}
RD1PPAXES=[RD1P201i,RD1P3-RD1P2,RD1P1-RD1P2,xzy,RD2P1-RD5P1]              {*FIRST DIGIT PROXIMAL PHALANX axes*}

RD1P201ii=RD1P2-((0.5*$RD1P2d)+$MARKDEP)*RD1PPAXES(2)
RD1P201=(RD1P201i+RD1P201ii)/2

RD1P301=RD1P3-((0.5*$RD1P3d)+$MARKDEP)*RD1PPAXES(2)            {*LOCATION OF JOINT CENTRE*}

RD1HAXES=[RD1P201,RD1P201-RD1P101,RD1P201-RD1P301,xzy,RD2P1-RD5P1]   {*Axes shifted to be DISTAL*}
RD1PPAXES=[RD1P301,RD1P301-RD1P201,RD1P101-RD1P201,xzy,RD2P1-RD5P1]


OUTPUT(RD1P101,RD1P201,RD1P301)
SEGVIS(RD1HAXES)
SEGVIS(RD1PPAXES)



{*DIGIT 2*}


RDUMMY=[RD2H,RD5H-RD2H,RD2H-RD2P1,zyx] {*wrongly defined second metatarsal axes based on surface markers*}

SEGVIS(RDUMMY)

{*Imaginary Hand Markers for digits 3 and 4*}

RHANDWIDTH=DIST(RD2H,RD5H)

RD3H=RD2H+RHANDWIDTH*0.1111*RDUMMY(2)+RHANDWIDTH*0.37*RDUMMY(3)
RD4H=RD2H+RHANDWIDTH*0.0741*RDUMMY(2)+RHANDWIDTH*0.741*RDUMMY(3)
OUTPUT(RD3H,RD4H)


{*DIGIT 2*}

RD2H01=RD2H-((0.5*$RD2Hd)+$MARKDEP)*RDUMMY(2)+RHANDWIDTH*0.1667*RDUMMY(3)  {*LOCATION OF JOINT CENTRE*}

RD2HAXES=[RD2H01,RD2P1-RD2H,RD2H01-RD2H,xzy] {*SHIFT TO ORIGIN AT JOINT CENTRE*}


RD2PP01i=RD2P1-((0.5*$RD2P1d)+$MARKDEP)*RD2HAXES(2)                                    {*CENTRE OF PROXIMAL PHALANX JOINT*}
```

```
RD2PPAXES=[RD2PP01i,RD2P2-RD2P1,RD2PP01i-RD2P1,xzy]                    {*second PROXIMAL
PHALANX axes*}

RD2PP01ii=RD2P1-((0.5*$RD2P1d)+$MARKDEP)*RD2PPAXES(2)

RD2PP01=(RD2PP01i+RD2PP01ii)/2

RD2MP01i=RD2P2-((0.5*$RD2P2d)+$MARKDEP)*RD2PPAXES(2)          {*CENTRE OF MID PHALANX JOINT*}
RD2MPAXES=[RD2MP01i,RD2P3-RD2P2,RD2MP01i-RD2P2,xzy]           {*second MID PHALANX axes*}

RD2MP01ii=RD2P2-((0.5*$RD2P2d)+$MARKDEP)*RD2MPAXES(2)

RD2MP01=(RD2MP01i+RD2MP01ii)/2

RD2DP01=RD2P3-((0.5*$RD2P3d)+$MARKDEP)*RD2MPAXES(2)           {*CENTRE OF DISTAL PHALANX JOINT*}

{* MAKE AXES DISTAL, NOT PROXIMAL *}

RD2HAXES=[RD2PP01,RD2PP01-RD2H01,RD2H01-RD2H,xzy]  {*Axes shifted to be DISTAL*}
RD2PPAXES=[RD2MP01,RD2MP01-RD2PP01,RD2PP01-RD2P1,xzy]
RD2MPAXES=[RD2DP01,RD2DP01-RD2MP01,RD2MP01-RD2P2,xzy]

OUTPUT(RD2H01,RD2PP01,RD2MP01,RD2DP01)
SEGVIS(RD2HAXES)
SEGVIS(RD2PPAXES)
SEGVIS(RD2MPAXES)

{*DIGIT 3*}


RD3HDUMMYAXES=[RD3H,RD3P1-RD3H,RD5H-RD2H,xyz] {*wrongly defined third metatarsal axes based on surface
markers*}
RD3H01=RD3H-((0.5*$RD3Hd)+$MARKDEP)*RD3HDUMMYAXES(2)  {*LOCATION OF JOINT CENTRE*}
RD3HAXES=[RD3H01,RD3P1-RD3H, RD3H01-RD3H,xzy]        {*SHIFT TO ORIGIN AT JOINT CENTRE*}

RD3PP01i=RD3P1-((0.5*$RD3P1d)+$MARKDEP)*RD3HAXES(2)                  {*CENTRE OF PROXIMAL
PHALANX JOINT*}
RD3PPAXES=[RD3PP01i,RD3P2-RD3P1,RD3PP01i-RD3P1,xzy]                  {*third PROXIMAL PHALANX axes*}

RD3PP01ii=RD3P1-((0.5*$RD3P1d)+$MARKDEP)*RD3PPAXES(2)

RD3PP01=(RD3PP01i+RD3PP01ii)/2

RD3MP01i=RD3P2-((0.5*$RD3P2d)+$MARKDEP)*RD3PPAXES(2)                 {*CENTRE OF MID PHALANX
JOINT*}
RD3MPAXES=[RD3MP01i,RD3P3-RD3P2,RD3MP01i-RD3P2,xzy]                  {*third MID PHALANX axes*}

RD3MP01ii=RD3P2-((0.5*$RD3P2d)+$MARKDEP)*RD3MPAXES(2)

RD3MP01=(RD3MP01i+RD3MP01ii)/2

RD3DP01=RD3P3-((0.5*$RD3P3d)+$MARKDEP)*RD3MPAXES(2)                  {*CENTRE OF DISTAL PHALANX
JOINT*}

{* MAKE AXES DISTAL, NOT PROXIMAL *}

RD3HAXES=[RD3PP01,RD3PP01-RD3H01,RD3H01-RD3H,xzy]
RD3PPAXES=[RD3MP01,RD3MP01-RD3PP01,RD3PP01-RD3P1,xzy]
RD3MPAXES=[RD3DP01,RD3DP01-RD3MP01,RD3MP01-RD3P2,xzy]

OUTPUT(RD3H01,RD3PP01,RD3MP01,RD3DP01,RD3H)
SEGVIS(RD3HAXES)
SEGVIS(RD3PPAXES)
SEGVIS(RD3MPAXES)
```

```
{*DIGIT 4*}


RD4HDUMMYAXES=[RD4H,RD4P1-RD4H,RD5H-RD2H,xyz] {*wrongly defined FOURTH metatarsal axes based on surface
markers*}
RD4H01=RD4H-((0.5*$RD4Hd)+$MARKDEP)*RD4HDUMMYAXES(2)-RHANDWIDTH*0.1111*RD4HDUMMYAXES(3)
{*LOCATION OF JOINT CENTRE*}
RD4HAXES=[RD4H01,RD4P1-RD4H, RD4H01-RD4H,xzy] {*SHIFT TO ORIGIN AT JOINT CENTRE*}

RD4PP01i=RD4P1-((0.5*$RD4P1d)+$MARKDEP)*RD4HAXES(2)  {*CENTRE OF PROXIMAL PHALANX JOINT*}
RD4PPAXES=[RD4PP01i,RD4P2-RD4P1,RD4PP01i-RD4P1,xzy] {*FOURTH PROXIMAL PHALANX axes*}

RD4PP01ii=RD4P1-((0.5*$RD4P1d)+$MARKDEP)*RD4PPAXES(2)

RD4PP01=(RD4PP01i+RD4PP01ii)/2

RD4MP01i=RD4P2-((0.5*$RD4P2d)+$MARKDEP)*RD4PPAXES(2)  {*CENTRE OF MID PHALANX JOINT*}
RD4MPAXES=[RD4MP01i,RD4P3-RD4P2,RD4MP01i-RD4P2,xzy] {*FOURTH MID PHALANX axes*}

RD4MP01ii=RD4P2-((0.5*$RD4P2d)+$MARKDEP)*RD4MPAXES(2)

RD4MP01=(RD4MP01i+RD4MP01ii)/2

RD4DP01=RD4P3-((0.5*$RD4P3d)+$MARKDEP)*RD4MPAXES(2)  {*CENTRE OF DISTAL PHALANX JOINT*}


{* MAKE AXES DISTAL, NOT PROXIMAL *}

RD4HAXES=[RD4PP01,RD4PP01-RD4H01,RD4H01-RD4H,xzy]
RD4PPAXES=[RD4MP01,RD4MP01-RD4PP01,RD4PP01-RD4P1,xzy]
RD4MPAXES=[RD4DP01,RD4DP01-RD4MP01,RD4MP01-RD4P2,xzy]


OUTPUT(RD4H01,RD4PP01,RD4MP01,RD4DP01,RD4H)
SEGVIS(RD4HAXES)
SEGVIS(RD4PPAXES)
SEGVIS(RD4MPAXES)




{*DIGIT 5*}

RD5HDUMMYAXES=[RD5H,RD5P1-RD5H,RD5H-RD2H,xyz]                              {*wrongly defined fifth
metatarsal axes based on surface markers*}
RD5H01=RD5H-((0.5*$RD5Hd)+$MARKDEP)*RD5HDUMMYAXES(2)-0.0741*RHANDWIDTH*RD5HDUMMYAXES(3)
        {*LOCATION OF JOINT CENTRE*}
RD5HAXES=[RD5H01,RD5P1-RD5H,RD5H01-RD5H,xzy]          {*SHIFT TO ORIGIN AT JOINT CENTRE*}

RD5PP01i=RD5P1-((0.5*$RD5P1d)+$MARKDEP)*RD5HAXES(2)            {*CENTRE OF PROXIMAL PHALANX JOINT*}
RD5PPAXES=[RD5PP01i,RD5P2-RD5P1,RD5PP01i-RD5P1,xzy]            {*fifth PROXIMAL PHALANX axes*}

RD5PP01ii=RD5P1-((0.5*$RD5P1d)+$MARKDEP)*RD5PPAXES(2)
RD5PP01=(RD5PP01i+RD5PP01ii)/2

RD5MP01i=RD5P2-((0.5*$RD5P2d)+$MARKDEP)*RD5PPAXES(2)           {*CENTRE OF MID PHALANX JOINT*}
RD5MPAXES=[RD5MP01i,RD5P3-RD5P2,RD5MP01i-RD5P2,xzy]                    {*fifth MID PHARANX axes*}

RD5MP01ii=RD5P2-((0.5*$RD5P2d)+$MARKDEP)*RD5MPAXES(2)

RD5MP01=(RD5MP01i+RD5MP01ii)/2

RD5DP01=RD5P3-((0.5*$RD5P3d)+$MARKDEP)*RD5MPAXES(2)            {*CENTRE OF DISTAR PHALANX JOINT*}

{* MAKE AXES DISTAL, NOT PROXIMAL *}
```

```
RD5HAXES=[RD5PP01,RD5PP01-RD5H01,RD5H01-RD5H,xzy]
RD5PPAXES=[RD5MP01,RD5MP01-RD5PP01,RD5PP01-RD5P1,xzy]
RD5MPAXES=[RD5DP01,RD5DP01-RD5MP01,RD5MP01-RD5P2,xzy]

OUTPUT(RD5H01,RD5PP01,RD5MP01,RD5DP01)
SEGVIS(RD5HAXES)
SEGVIS(RD5PPAXES)
SEGVIS(RD5MPAXES)

{* Calculate the Hand segment axes systems *}

RHMidpoint=(RD3PP01+RD4PP01)/2
LHMidpoint=(LD3PP01i+LD4PP01i)/2

RHandSeg=[RHMidpoint,RD2PP01-RD2H01,RD4P1-RD2P1,xyz]
SEGVIS(RHandSeg)

LHandSeg=[LHMidpoint,LD2PP01i-LD2H01,LD4P1-LD2P1,xyz]
SEGVIS(LHandSeg)



{********** Define device axes systems *********}

{* Jar Body Tripod Markers are JBMK1, JBMK2 and JBMK3, Lid Markers are JLIDMK1 and JLIDMK2*}

JBMKMID=(JBMK1+JBMK2)/2
JarBodyAxes=[JBMKMID,JBMK1-JBMK2,JBMK3-JBMKMID,yzx]

%JARBODYCENT={0,0,58}
JARBODYCENT=%JARBODYCENT*JarBodyAxes
OUTPUT(JARBODYCENT)
JarBodyAxes=[JARBODYCENT,JBMK1-JBMK2,JBMK3-JBMKMID,yzx]
SEGVIS(JarBodyAxes)

{*JAR - Forward Orientation*}

JarLidAxes=[JLIDMK1,JLIDMK2-JLIDMK1,JBMK2-JBMK1,xzy]     {*JARLIDCENT being the top of the middle of the jar lid*}
%JARLIDCENT={137,9.5,-5}
JARLIDCENT=%JARLIDCENT*JarLidAxes
JarLidAxes=[JARLIDCENT,JLIDMK2-JLIDMK1,JBMK1-JBMK2,xyz]


%NANOCENT={0,-14.5,-15}                                   {*Nano 1's position relative to JARLIDCENT*}
%PYLONCENT={0,14.5,-15}                                  {*Nano 2's position relative to JARLIDCENT*}

NANOCENT=%NANOCENT*JarLidAxes
PYLONCENT=%PYLONCENT*JarLidAxes

NanoAxes=[NANOCENT,JLIDMK2-JLIDMK1,JBMK1-JBMK2,xyz]
PylonAxes=[PYLONCENT,JLIDMK1-JLIDMK2,JBMK1-JBMK2,xyz]

OUTPUT(JARLIDCENT,NANOCENT,PYLONCENT)
SEGVIS(JarLidAxes,NanoAxes,PylonAxes)


{***** KINEMATIC CALCULATOR *****}

{*Cardan angles for output into computer programme*}


{*Angles calculated using the floating axis method*}
```

```
ColeJCS(JarLidAxes,JarBodyAxes,JarLid)                  {*Calculates the angle of the lid relative to the body*}
JarLidJCSAngles=<1(JarLidJCSAngles),2(JarLidJCSAngles),3(JarLidJCSAngles)>
Output(JarLidJCSAngles)




ColeJCS(LD5HAXES,LD5PPAXES,LD5PP)
ColeJCS(LD5PPAXES,LD5MPAXES,LD5MP)

ColeJCS(LD4HAXES,LD4PPAXES,LD4PP)
ColeJCS(LD4PPAXES,LD4MPAXES,LD4MP)

ColeJCS(LD3HAXES,LD3PPAXES,LD3PP)
ColeJCS(LD3PPAXES,LD3MPAXES,LD3MP)

ColeJCS(LD2HAXES,LD2PPAXES,LD2PP)
ColeJCS(LD2PPAXES,LD2MPAXES,LD2MP)

ColeJCS(LD1HAXES,LD1PPAXES,LD1PP)

ColeJCS(LForearm,LD3HAXES,LWrist)


ColeJCS(RD5HAXES,RD5PPAXES,RD5PP)
ColeJCS(RD5PPAXES,RD5MPAXES,RD5MP)

ColeJCS(RD4HAXES,RD4PPAXES,RD4PP)
ColeJCS(RD4PPAXES,RD4MPAXES,RD4MP)

ColeJCS(RD3HAXES,RD3PPAXES,RD3PP)
ColeJCS(RD3PPAXES,RD3MPAXES,RD3MP)

ColeJCS(RD2HAXES,RD2PPAXES,RD2PP)
ColeJCS(RD2PPAXES,RD2MPAXES,RD2MP)

ColeJCS(RD1HAXES,RD1PPAXES,RD1PP)

ColeJCS(RForearm,RD3HAXES,RWrist)

LWristJCSAngles=<1(LWristJCSAngles),2(LWristJCSAngles),3(LWristJCSAngles)>
Output(LWristJCSAngles)

LD1PPJCSAngles=<1(LD1PPJCSAngles),2(LD1PPJCSAngles),3(LD1PPJCSAngles)>
Output(LD1PPJCSAngles)

LD2PPJCSAngles=<1(LD2PPJCSAngles),2(LD2PPJCSAngles),3(LD2PPJCSAngles)>
LD2MPJCSAngles=<1(LD2MPJCSAngles),2(LD2MPJCSAngles),3(LD2MPJCSAngles)>
Output(LD2PPJCSAngles,LD2MPJCSAngles)

LD3PPJCSAngles=<1(LD3PPJCSAngles),2(LD3PPJCSAngles),3(LD3PPJCSAngles)>
LD3MPJCSAngles=<1(LD3MPJCSAngles),2(LD3MPJCSAngles),3(LD3MPJCSAngles)>
Output(LD3PPJCSAngles,LD3MPJCSAngles)

LD4PPJCSAngles=<1(LD4PPJCSAngles),2(LD4PPJCSAngles),3(LD4PPJCSAngles)>
LD4MPJCSAngles=<1(LD4MPJCSAngles),2(LD4MPJCSAngles),3(LD4MPJCSAngles)>
Output(LD4PPJCSAngles,LD4MPJCSAngles)

LD5PPJCSAngles=<1(LD5PPJCSAngles),2(LD5PPJCSAngles),3(LD5PPJCSAngles)>
LD5MPJCSAngles=<1(LD5MPJCSAngles),2(LD5MPJCSAngles),3(LD5MPJCSAngles)>
Output(LD5PPJCSAngles,LD5MPJCSAngles)

RWristJCSAngles=<1(RWristJCSAngles),2(RWristJCSAngles),3(RWristJCSAngles)>
Output(RWristJCSAngles)
```

```
RD1PPJCSAngles=<1(RD1PPJCSAngles),2(RD1PPJCSAngles),3(RD1PPJCSAngles)>
Output(RD1PPJCSAngles)

RD2PPJCSAngles=<1(RD2PPJCSAngles),2(RD2PPJCSAngles),3(RD2PPJCSAngles)>
RD2MPJCSAngles=<1(RD2MPJCSAngles),2(RD2MPJCSAngles),3(RD2MPJCSAngles)>
Output(RD2PPJCSAngles,RD2MPJCSAngles)

RD3PPJCSAngles=<1(RD3PPJCSAngles),2(RD3PPJCSAngles),3(RD3PPJCSAngles)>
RD3MPJCSAngles=<1(RD3MPJCSAngles),2(RD3MPJCSAngles),3(RD3MPJCSAngles)>
Output(RD3PPJCSAngles,RD3MPJCSAngles)

RD4PPJCSAngles=<1(RD4PPJCSAngles),2(RD4PPJCSAngles),3(RD4PPJCSAngles)>
RD4MPJCSAngles=<1(RD4MPJCSAngles),2(RD4MPJCSAngles),3(RD4MPJCSAngles)>
Output(RD4PPJCSAngles,RD4MPJCSAngles)

RD5PPJCSAngles=<1(RD5PPJCSAngles),2(RD5PPJCSAngles),3(RD5PPJCSAngles)>
RD5MPJCSAngles=<1(RD5MPJCSAngles),2(RD5MPJCSAngles),3(RD5MPJCSAngles)>
Output(RD5PPJCSAngles,RD5MPJCSAngles)



{*DEFINE NANO FORCE AND MOMENT COMPONENTS*}

{*1st Nano, named NANO - Updated to Nano 25 Ft05525*}

{******** F O R C E  P L A T E  5 **************}

        {* These lines extract the Force, Moment and Point vectors from Force Plate 5, as defined in Workstation*}

ForcePlate5F=ForcePlate5(1)
ForcePlate5M=ForcePlate5(2)
ForcePlate5P=ForcePlate5(3)


{*This line reverses the axes 'flip' which occurs when assigning an AMTI force plate*}

ForcePlate5F={-ForcePlate5F(2),ForcePlate5F(1),ForcePlate5F(3)}
ForcePlate5M={-ForcePlate5M(2),ForcePlate5M(1),ForcePlate5M(3)}


{* The following applies the calibration matrix to the FORCE input voltage signals, and makes them negative so from here on
we use REACTION forces*}

ForcePlate5FxCorrected=-(0.138586*ForcePlate5F(1)+ 0.039028*ForcePlate5F(2)+ 0.252436*ForcePlate5F(3)+
15.4762*ForcePlate5M(1)-0.38292*ForcePlate5M(2)-14.3811*ForcePlate5M(3))
ForcePlate5FyCorrected=-(-0.67857*ForcePlate5F(1)-14.5725*ForcePlate5F(2)+ 0.090886*ForcePlate5F(3)+
8.993498*ForcePlate5M(1)+0.514845*ForcePlate5M(2)+8.155606*ForcePlate5M(3))
ForcePlate5FzCorrected=-(31.09336*ForcePlate5F(1)-0.10648*ForcePlate5F(2)+32.49297*ForcePlate5F(3)-
0.04881*ForcePlate5M(1)+31.36974*ForcePlate5M(2)-1.17452*ForcePlate5M(3))


{* This line collates the forces, with Z pointing upwards, so no changes made to axes!*}

ForcePlate5FCorrected={ForcePlate5FxCorrected,ForcePlate5FyCorrected,ForcePlate5FzCorrected}


{* The following applies the calibration matrix to the MOMENT input voltage signals, and makes them negative so from here
on we use REACTION moments*}

ForcePlate5MxCorrected=-(-0.00368*ForcePlate5F(1)-
0.12431*ForcePlate5F(2)+0.316415*ForcePlate5F(3)+0.067822*ForcePlate5M(1)-
0.31593*ForcePlate5M(2)+0.087631*ForcePlate5M(3))
ForcePlate5MyCorrected=-(-0.35166*ForcePlate5F(1)+0.006377*ForcePlate5F(2)+0.177573*ForcePlate5F(3)-
0.13408*ForcePlate5M(1)+0.178177*ForcePlate5M(2)+0.111996*ForcePlate5M(3))
```

```
ForcePlate5MzCorrected=-(-0.00681*ForcePlate5F(1)-0.1162*ForcePlate5F(2)-0.01019*ForcePlate5F(3)-
0.14452*ForcePlate5M(1)+0.0033*ForcePlate5M(2)-0.13134*ForcePlate5M(3))


{* If we want the Moments to adhere to the definition of the NanoAxes (with Y pointing up) we need to rotate these forces.  If
not, then miss this bit out*}

{*ForcePlate5MxCorrected=ForcePlate5MxCorrected
ForcePlate5MyCorrected=ForcePlate5MzCorrected
ForcePlate5MzCorrected=-ForcePlate5MyCorrected *}

ForcePlate5MCorrected={ForcePlate5MxCorrected,ForcePlate5MyCorrected,ForcePlate5MzCorrected}

                {* Next we will define a new force plate so we can extract the APPLIED forces and moments as measured by the
Nano transducers*}

NewFP5=|-ForcePlate5FCorrected,-ForcePlate5MCorrected,NANOCENT|

AppliedForce5=NewFP5(1)
AppliedMoment5=NewFP5(2)


OUTPUT(AppliedForce5,AppliedMoment5)


{* This generates vectors from abs values calculated above and puts them in the direction of the axes of the force transducer
(LOCAL)*}

F5_x = ForcePlate5FxCorrected*NanoAxes(1)
F5_y = ForcePlate5FyCorrected*NanoAxes(2)
F5_z = ForcePlate5FzCorrected*NanoAxes(3)

M5_x = ForcePlate5MxCorrected*NanoAxes(1)
M5_y = ForcePlate5MyCorrected*NanoAxes(2)
M5_z = ForcePlate5MzCorrected*NanoAxes(3)

{* Vicon Coordinates *}

CoordXV = {1,0,0}
CoordYV = {0,1,0}
CoordZV = {0,0,1}




{* The following converts the AMTI force vectors from the AMTI/NanoAxes (local) coordinate system to the Vicon (global)
coordinate system *}

ForceXAV = COMP(F5_x,CoordXV) + COMP(F5_y,CoordXV) + COMP(F5_z,CoordXV)
ForceYAV = COMP(F5_x,CoordYV) + COMP(F5_y,CoordYV) + COMP(F5_z,CoordYV)
ForceZAV = COMP(F5_x,CoordZV) + COMP(F5_y,CoordZV) + COMP(F5_z,CoordZV)


MomentXAV = COMP(M5_x,CoordXV) + COMP(M5_y,CoordXV) + COMP(M5_z,CoordXV)
MomentYAV = COMP(M5_x,CoordYV) + COMP(M5_y,CoordYV) + COMP(M5_z,CoordYV)
MomentZAV = COMP(M5_x,CoordZV) + COMP(M5_y,CoordZV) + COMP(M5_z,CoordZV)


{* Calculates the x,y and z distances between the transducer centre and the joint centre RD1P201*}

X_5_Dist=(RWJC(1)-NANOCENT(1))/1000
Y_5_Dist=(RWJC(2)-NANOCENT(2))/1000
Z_5_Dist=(RWJC(3)-NANOCENT(3))/1000

{* Transfers and recalculates the forces and moments in the Global co-ordinate system at the point RD1P201*}
```

```
Fx2=ForceXAV
Fy2=ForceYAV
Fz2=ForceZAV

Mx2=MomentXAV+ForceYAV*(Z_5_Dist)-ForceZAV*(Y_5_Dist)
My2=MomentYAV+ForceZAV*(X_5_Dist)-ForceXAV*(Z_5_Dist)
Mz2=MomentZAV+ForceXAV*(Y_5_Dist)-ForceYAV*(X_5_Dist)


{* This generates vectors from abs values calculated above and puts them in the direction of the axes of the GLOBAL origin*}

FWrist5_x = Fx2*CoordXV
FWrist5_y = Fy2*CoordYV
FWrist5_z = Fz2*CoordZV


MWrist5_x = Mx2*CoordXV
MWrist5_y = My2*CoordYV
MWrist5_z = Mz2*CoordZV

{* The following converts these new force vectors from the GLOBAL coordinate system to the RForearm axis system
(LOCAL) coordinate system *}

RWRIST_5_FX=COMP(FWrist5_x,RForearm(1))+COMP(FWrist5_y,RForearm(1))+COMP(FWrist5_z,RForearm(1))
RWRIST_5_FY=COMP(FWrist5_x,RForearm(2))+COMP(FWrist5_y,RForearm(2))+COMP(FWrist5_z,RForearm(2))
RWRIST_5_FZ=COMP(FWrist5_x,RForearm(3))+COMP(FWrist5_y,RForearm(3))+COMP(FWrist5_z,RForearm(3))

RWRIST_5_MX=COMP(MWrist5_x,RForearm(1))+COMP(MWrist5_y,RForearm(1))+COMP(MWrist5_z,RForearm(1))
RWRIST_5_MY=COMP(MWrist5_x,RForearm(2))+COMP(MWrist5_y,RForearm(2))+COMP(MWrist5_z,RForearm(2))
RWRIST_5_MZ=COMP(MWrist5_x,RForearm(3))+COMP(MWrist5_y,RForearm(3))+COMP(MWrist5_z,RForearm(3))

RWrist5_F_Res={RWRIST_5_FX,RWRIST_5_FY,RWRIST_5_FZ}
RWrist5_M_Res={RWRIST_5_MX,RWRIST_5_MY,RWRIST_5_MZ}

OUTPUT(RWrist5_F_Res,RWrist5_M_Res)

Wrist5FP=|RWrist5_F_Res,RWrist5_M_Res,RWJC|

{*  That's the FP 5 component of the resultant wrist force calculated.  Now we need the FP 6 componemt so we can combine
the two *}


{******** F O R C E  P L A T E  6 **************}


{* These lines extract the Force, Moment and Point vectors from Force Plate 6, as defined in Workstation*}

ForcePlate6F=ForcePlate6(1)
ForcePlate6M=ForcePlate6(2)
ForcePlate6P=ForcePlate6(3)


{*This line reverses the axes 'flip' which occurs when assigning an AMTI force plate*}
ForcePlate6F={-ForcePlate6F(2),ForcePlate6F(1),ForcePlate6F(3)}
ForcePlate6M={-ForcePlate6M(2),ForcePlate6M(1),ForcePlate6M(3)}


{* The following applies the calibration matrix to the FORCE input voltage signals, and makes them negative so from here on
we use REACTION forces*}


ForcePlate6FxCorrected=-(0.420386*ForcePlate6F(1)+0.143792*ForcePlate6F(2)-
1.39963*ForcePlate6F(3)+13.65726*ForcePlate6M(1)+0.135648*ForcePlate6M(2)-15.5207*ForcePlate6M(3))
```

```
ForcePlate6FyCorrected=-(1.56751*ForcePlate6F(1)-
17.1858*ForcePlate6F(2)+0.169665*ForcePlate6F(3)+7.996557*ForcePlate6M(1)-
0.85671*ForcePlate6M(2)+8.734824*ForcePlate6M(3))
ForcePlate6FzCorrected=-(31.81899*ForcePlate6F(1)-2.03021*ForcePlate6F(2)+32.03014*ForcePlate6F(3)-
0.92818*ForcePlate6M(1)+32.78808*ForcePlate6M(2)-1.0826*ForcePlate6M(3))


{* This line collates the forces, with Z pointing upwards, so no changes made to axes!*}

ForcePlate6FCorrected={ForcePlate6FxCorrected,ForcePlate6FyCorrected,ForcePlate6FzCorrected}

{* The following applies the calibration matrix to the MOMENT input voltage signals, and makes them negative so from here
on we use REACTION moments*}

ForcePlate6MxCorrected=-(0.007785*ForcePlate6F(1)-
0.14403*ForcePlate6F(2)+0.322951*ForcePlate6F(3)+0.049604*ForcePlate6M(1)-
0.33379*ForcePlate6M(2)+0.091771*ForcePlate6M(3))
ForcePlate6MyCorrected=-(-0.35133*ForcePlate6F(1)+0.031303*ForcePlate6F(2)+0.195467*ForcePlate6F(3)-
0.12521*ForcePlate6M(1)+0.182706*ForcePlate6M(2)+0.119515*ForcePlate6M(3))
ForcePlate6MzCorrected=-(0.01384*ForcePlate6F(1)-0.13781*ForcePlate6F(2)+0.009272*ForcePlate6F(3)-
0.12814*ForcePlate6M(1)+0.002463*ForcePlate6M(2)-0.13887*ForcePlate6M(3))


{* If we want the Moments to adhere to the definition of the NanoAxes (with Y pointing up) we need to rotate these forces.  If
not, then miss this bit out*}

{*ForcePlate6MxCorrected=ForcePlate6MxCorrected
ForcePlate6MyCorrected=ForcePlate6MzCorrected
ForcePlate6MzCorrected=-ForcePlate6MyCorrected *}

ForcePlate6MCorrected={ForcePlate6MxCorrected,ForcePlate6MyCorrected,ForcePlate6MzCorrected}

{* Next we will define a new force plate so we can extract the APPLIED forces and moments as measured by the Nano
transducers*}

NewFP6=|-ForcePlate6FCorrected,-ForcePlate6MCorrected,PYLONCENT|

AppliedForce6=NewFP6(1)
AppliedMoment6=NewFP6(2)

OUTPUT(AppliedForce6,AppliedMoment6)

{* This generates vectors from abs values calculated above and puts them in the direction of the axes of the force transducer
(LOCAL)*}

F6_x = ForcePlate6FxCorrected*PylonAxes(1)
F6_y = ForcePlate6FyCorrected*PylonAxes(2)
F6_z = ForcePlate6FzCorrected*PylonAxes(3)


M6_x = ForcePlate6MxCorrected*PylonAxes(1)
M6_y = ForcePlate6MyCorrected*PylonAxes(2)
M6_z = ForcePlate6MzCorrected*PylonAxes(3)

{* Vicon Coordinates *}

CoordXV = {1,0,0}
CoordYV = {0,1,0}
CoordZV = {0,0,1}

{* The following converts the AMTI force vectors from the AMTI/PylonAxes (local) coordinate system to the Vicon (global)
coordinate system *}

Force6_XAV = COMP(F6_x,CoordXV) + COMP(F6_y,CoordXV) + COMP(F6_z,CoordXV)
Force6_YAV = COMP(F6_x,CoordYV) + COMP(F6_y,CoordYV) + COMP(F6_z,CoordYV)
```

```
Force6_ZAV = COMP(F6_x,CoordZV) + COMP(F6_y,CoordZV) + COMP(F6_z,CoordZV)

Moment6_XAV = COMP(M6_x,CoordXV) + COMP(M6_y,CoordXV) + COMP(M6_z,CoordXV)
Moment6_YAV = COMP(M6_x,CoordYV) + COMP(M6_y,CoordYV) + COMP(M6_z,CoordYV)
Moment6_ZAV = COMP(M6_x,CoordZV) + COMP(M6_y,CoordZV) + COMP(M6_z,CoordZV)

{* Calculates the x,y and z distances between the transducer centre and the joint centre 'RWJC'*}

X_6_Dist=(RWJC(1)-PYLONCENT(1))/1000
Y_6_Dist=(RWJC(2)-PYLONCENT(2))/1000
Z_6_Dist=(RWJC(3)-PYLONCENT(3))/1000

{* Transfers and recalculates the forces and moments in the Global co-ordinate system at the point 'RWJC'*}

Fx6_2=Force6_XAV
Fy6_2=Force6_YAV
Fz6_2=Force6_ZAV

Mx6_2=Moment6_XAV+Force6_YAV*(Z_6_Dist)-Force6_ZAV*(Y_6_Dist)
My6_2=Moment6_YAV+Force6_ZAV*(X_6_Dist)-Force6_XAV*(Z_6_Dist)
Mz6_2=Moment6_ZAV+Force6_XAV*(Y_6_Dist)-Force6_YAV*(X_6_Dist)

{* This generates vectors from abs values calculated above and puts them in the direction of the axes of the GLOBAL origin*}

FWrist6_x = Fx6_2*CoordXV
FWrist6_y = Fy6_2*CoordYV
FWrist6_z = Fz6_2*CoordZV

MWrist6_x = Mx6_2*CoordXV
MWrist6_y = My6_2*CoordYV
MWrist6_z = Mz6_2*CoordZV

{* The following converts these new force vectors from the GLOBAL coordinate system to the RForearm (LOCAL) coordinate
system *}

RWRIST_6_FX=COMP(FWrist6_x,RForearm(1))+COMP(FWrist6_y,RForearm(1))+COMP(FWrist6_z,RForearm(1))
RWRIST_6_FY=COMP(FWrist6_x,RForearm(2))+COMP(FWrist6_y,RForearm(2))+COMP(FWrist6_z,RForearm(2))
RWRIST_6_FZ=COMP(FWrist6_x,RForearm(3))+COMP(FWrist6_y,RForearm(3))+COMP(FWrist6_z,RForearm(3))

RWRIST_6_MX=COMP(MWrist6_x,RForearm(1))+COMP(MWrist6_y,RForearm(1))+COMP(MWrist6_z,RForearm(1))
RWRIST_6_MY=COMP(MWrist6_x,RForearm(2))+COMP(MWrist6_y,RForearm(2))+COMP(MWrist6_z,RForearm(2))
RWRIST_6_MZ=COMP(MWrist6_x,RForearm(3))+COMP(MWrist6_y,RForearm(3))+COMP(MWrist6_z,RForearm(3))

RWrist6_F_Res={RWRIST_6_FX,RWRIST_6_FY,RWRIST_6_FZ}
RWrist6_M_Res={RWRIST_6_MX,RWRIST_6_MY,RWRIST_6_MZ}

OUTPUT(RWrist6_F_Res,RWrist6_M_Res)

Wrist6FP=|RWrist6_F_Res,RWrist6_M_Res,RWJC|

{*   Now we need to combine both of these components to give the TOTAL Wrist Forces and Moments  *}

TotalRWrist_F={(RWRIST_5_FX+RWRIST_6_FX),(RWRIST_5_FY+RWRIST_6_FY),(RWRIST_5_FZ+RWRIST_6_FZ)}
TotalRWrist_M={(RWRIST_5_MX+RWRIST_6_MX),(RWRIST_5_MY+RWRIST_6_MY),(RWRIST_5_MZ+RWRIST_6_MZ)}

OUTPUT(TotalRWrist_F,TotalRWrist_M)

%ForceVectWR=TotalRWrist_F
EndForceVectWR=%ForceVectWR*RForearm

OUTPUT(EndForceVectWR)

{************* THUMB FORCES + MOMENTS **************}

{* Calculates the x,y and z distances between the transducer centre and the joint centre RD1P201*}
```

```
X_Th_Dist=(RD1P201(1)-NANOCENT(1))/1000
Y_Th_Dist=(RD1P201(2)-NANOCENT(2))/1000
Z_Th_Dist=(RD1P201(3)-NANOCENT(3))/1000

{* Transfers and recalculates the forces and moments in the Global co-ordinate system at the point RD1P201*}

Fx2=ForceXAV
Fy2=ForceYAV
Fz2=ForceZAV

Mx2=MomentXAV+ForceYAV*(Z_Th_Dist)-ForceZAV*(Y_Th_Dist)
My2=MomentYAV+ForceZAV*(X_Th_Dist)-ForceXAV*(Z_Th_Dist)
Mz2=MomentZAV+ForceXAV*(Y_Th_Dist)-ForceYAV*(X_Th_Dist)

{* This generates vectors from abs values calculated above and puts them in the direction of the axes of the GLOBAL origin*}

FThumb5_x = Fx2*CoordXV
FThumb5_y = Fy2*CoordYV
FThumb5_z = Fz2*CoordZV

MThumb5_x = Mx2*CoordXV
MThumb5_y = My2*CoordYV
MThumb5_z = Mz2*CoordZV


{* The following converts these new force vectors from the GLOBAL coordinate system to the RD1HAXES (LOCAL)
coordinate system *}

RDAXESFX=COMP(FThumb5_x,RD1HAXES(1))+COMP(FThumb5_y,RD1HAXES(1))+COMP(FThumb5_z,RD1HAXES(1))
RDAXESFY=COMP(FThumb5_x,RD1HAXES(2))+COMP(FThumb5_y,RD1HAXES(2))+COMP(FThumb5_z,RD1HAXES(2))
RDAXESFZ=COMP(FThumb5_x,RD1HAXES(3))+COMP(FThumb5_y,RD1HAXES(3))+COMP(FThumb5_z,RD1HAXES(3))

RDAXESMX=COMP(MThumb5_x,RD1HAXES(1))+COMP(MThumb5_y,RD1HAXES(1))+COMP(MThumb5_z,RD1HAXES(1)
)
RDAXESMY=COMP(MThumb5_x,RD1HAXES(2))+COMP(MThumb5_y,RD1HAXES(2))+COMP(MThumb5_z,RD1HAXES(2)
)
RDAXESMZ=COMP(MThumb5_x,RD1HAXES(3))+COMP(MThumb5_y,RD1HAXES(3))+COMP(MThumb5_z,RD1HAXES(3))

RD1H_F_Res={RDAXESFX,RDAXESFY,RDAXESFZ}
RD1H_M_Res={RDAXESMX,RDAXESMY,RDAXESMZ}
OUTPUT(RD1H_F_Res,RD1H_M_Res)

ThumbFP=|RD1H_F_Res,RD1H_M_Res,RD1P201|

OUTPUT(RDAXESFX)


%EndForceVectorTH=RD1H_F_Res
EndForceVectorTH=%EndForceVectorTH*RD1HAXES

OUTPUT(EndForceVectorTH)

{***************** HANDSEG FORCES + MOMENTS *******************}

{* Calculates the x,y and z distances between the transducer centre and the joint centre 'RHandSeg'*}

X_HandSegDist=(RHMidPoint(1)-PYLONCENT(1))/1000
Y_HandSegDist=(RHMidPoint(2)-PYLONCENT(2))/1000
Z_HandSegDist=(RHMidPoint(3)-PYLONCENT(3))/1000

{* Transfers and recalculates the forces and moments in the Global co-ordinate system at the point 'RHandSeg'*}

Fx6i_2=Force6_XAV
Fy6i_2=Force6_YAV
```

```
Fz6i_2=Force6_ZAV

Mx6i_2=Moment6_XAV+Force6_YAV*(Z_HandSegDist)-Force6_ZAV*(Y_HandSegDist)
My6i_2=Moment6_YAV+Force6_ZAV*(X_HandSegDist)-Force6_XAV*(Z_HandSegDist)
Mz6i_2=Moment6_ZAV+Force6_XAV*(Y_HandSegDist)-Force6_YAV*(X_HandSegDist)

{* This generates vectors from abs values calculated above and puts them in the direction of the axes of the GLOBAL origin*}

FHand6_x = Fx6i_2*CoordXV
FHand6_y = Fy6i_2*CoordYV
FHand6_z = Fz6i_2*CoordZV


MHand6_x = Mx6i_2*CoordXV
MHand6_y = My6i_2*CoordYV
MHand6_z = Mz6i_2*CoordZV

{* The following converts these new force vectors from the GLOBAL coordinate system to the RD1HAXES (LOCAL)
coordinate system *}

RHANDSEGFX=COMP(FHand6_x,RHandSeg(1))+COMP(FHand6_y,RHandSeg(1))+COMP(FHand6_z,RHandSeg(1))
RHANDSEGFY=COMP(FHand6_x,RHandSeg(2))+COMP(FHand6_y,RHandSeg(2))+COMP(FHand6_z,RHandSeg(2))
RHANDSEGFZ=COMP(FHand6_x,RHandSeg(3))+COMP(FHand6_y,RHandSeg(3))+COMP(FHand6_z,RHandSeg(3))

RHANDSEGMX=COMP(MHand6_x,RHANDSEG(1))+COMP(MHand6_y,RHANDSEG(1))+COMP(MHand6_z,RHANDSEG(1)
)
RHANDSEGMY=COMP(MHand6_x,RHANDSEG(2))+COMP(MHand6_y,RHANDSEG(2))+COMP(MHand6_z,RHANDSEG(2)
)
RHANDSEGMZ=COMP(MHand6_x,RHANDSEG(3))+COMP(MHand6_y,RHANDSEG(3))+COMP(MHand6_z,RHANDSEG(3)
)

RHandSeg_F_Res={RHANDSEGFX,RHANDSEGFY,RHANDSEGFZ}
RHandSeg_M_Res={RHANDSEGMX,RHANDSEGMY,RHANDSEGMZ}

OUTPUT(RHandSeg_F_Res,RHandSeg_M_Res)
HandFP=|RHandSeg_F_Res,RHandSeg_M_Res,RHMidpoint|

OUTPUT(RHANDSEGFX)

%ForceVectHA=RHandSeg_F_Res
EndForceVectHA=%ForceVectHA*RHandSeg

OUTPUT(EndForceVectHA)


{************* LID REMOVAL TORQUE - Now let's use the same approach as above to calculate the total lid removal torque
*******}

{* Calculates the x,y and z distances between each transducer centre and the Jar lid centre  'RHandSeg'*}

X_Torq5_Dist=(JARLIDCENT(1)-NANOCENT(1))/1000
Y_Torq5_Dist=(JARLIDCENT(2)-NANOCENT(2))/1000
Z_Torq5_Dist=(JARLIDCENT(3)-NANOCENT(3))/1000

X_Torq6_Dist=(JARLIDCENT(1)-PYLONCENT(1))/1000
Y_Torq6_Dist=(JARLIDCENT(2)-PYLONCENT(2))/1000
Z_Torq6_Dist=(JARLIDCENT(3)-PYLONCENT(3))/1000


{* Transfers and recalculates the forces and moments in the Global co-ordinate system at the point 'RHandSeg'*}

Fx5_Torq=ForceXAV
Fy5_Torq=ForceYAV
Fz5_Torq=ForceZAV
```

```
Mx5_Torq=MomentXAV+ForceYAV*(Z_Torq5_Dist)-ForceZAV*(Y_Torq5_Dist)
My5_Torq=MomentYAV+ForceZAV*(X_Torq5_Dist)-ForceXAV*(Z_Torq5_Dist)
Mz5_Torq=MomentZAV+ForceXAV*(Y_Torq5_Dist)-ForceYAV*(X_Torq5_Dist)

Fx6_Torq=Force6_XAV
Fy6_Torq=Force6_YAV
Fz6_Torq=Force6_ZAV

Mx6_Torq=Moment6_XAV+Force6_YAV*(Z_Torq6_Dist)-Force6_ZAV*(Y_Torq6_Dist)
My6_Torq=Moment6_YAV+Force6_ZAV*(X_Torq6_Dist)-Force6_XAV*(Z_Torq6_Dist)
Mz6_Torq=Moment6_ZAV+Force6_XAV*(Y_Torq6_Dist)-Force6_YAV*(X_Torq6_Dist)

FLid5_x = Fx5_Torq*CoordXV
FLid5_y = Fy5_Torq*CoordYV
FLid5_z = Fz5_Torq*CoordZV

MLid5_x = Mx5_Torq*CoordXV
MLid5_y = My5_Torq*CoordYV
MLid5_z = Mz5_Torq*CoordZV

FLid6_x = Fx6_Torq*CoordXV
FLid6_y = Fy6_Torq*CoordYV
FLid6_z = Fz6_Torq*CoordZV

MLid6_x = Mx6_Torq*CoordXV
MLid6_y = My6_Torq*CoordYV
MLid6_z = Mz6_Torq*CoordZV


JARLID_5_FX=COMP(FLid5_x,JarLidAxes(1))+COMP(FLid5_y,JarLidAxes(1))+COMP(FLid5_z,JarLidAxes(1))
JARLID_5_FY=COMP(FLid5_x,JarLidAxes(2))+COMP(FLid5_y,JarLidAxes(2))+COMP(FLid5_z,JarLidAxes(2))
JARLID_5_FZ=COMP(FLid5_x,JarLidAxes(3))+COMP(FLid5_y,JarLidAxes(3))+COMP(FLid5_z,JarLidAxes(3))

JARLID_5_MX=COMP(MLid5_x,JarLidAxes(1))+COMP(MLid5_y,JarLidAxes(1))+COMP(MLid5_z,JarLidAxes(1))
JARLID_5_MY=COMP(MLid5_x,JarLidAxes(2))+COMP(MLid5_y,JarLidAxes(2))+COMP(MLid5_z,JarLidAxes(2))
JARLID_5_MZ=COMP(MLid5_x,JarLidAxes(3))+COMP(MLid5_y,JarLidAxes(3))+COMP(MLid5_z,JarLidAxes(3))

JARLID_6_FX=COMP(FLid6_x,JarLidAxes(1))+COMP(FLid6_y,JarLidAxes(1))+COMP(FLid6_z,JarLidAxes(1))
JARLID_6_FY=COMP(FLid6_x,JarLidAxes(2))+COMP(FLid6_y,JarLidAxes(2))+COMP(FLid6_z,JarLidAxes(2))
JARLID_6_FZ=COMP(FLid6_x,JarLidAxes(3))+COMP(FLid6_y,JarLidAxes(3))+COMP(FLid6_z,JarLidAxes(3))

JARLID_6_MX=COMP(MLid6_x,JarLidAxes(1))+COMP(MLid6_y,JarLidAxes(1))+COMP(MLid6_z,JarLidAxes(1))
JARLID_6_MY=COMP(MLid6_x,JarLidAxes(2))+COMP(MLid6_y,JarLidAxes(2))+COMP(MLid6_z,JarLidAxes(2))
JARLID_6_MZ=COMP(MLid6_x,JarLidAxes(3))+COMP(MLid6_y,JarLidAxes(3))+COMP(MLid6_z,JarLidAxes(3))

JarLid5_F_Res={JARLID_5_FX,JARLID_5_FY,JARLID_5_FZ}
JarLid5_M_Res={JARLID_5_MX,JARLID_5_MY,JARLID_5_MZ}

JarLid6_F_Res={JARLID_6_FX,JARLID_6_FY,JARLID_6_FZ}
JarLid6_M_Res={JARLID_6_MX,JARLID_6_MY,JARLID_6_MZ}

TotalJarLid_F={(JARLID_5_FX+JARLID_6_FX),(JARLID_5_FY+JARLID_6_FY),(JARLID_5_FZ+JARLID_6_FZ)}
TotalJarLid_M={(JARLID_5_MX+JARLID_6_MX),(JARLID_5_MY+JARLID_6_MY),(JARLID_5_MZ+JARLID_6_MZ)}

OUTPUT(TotalJarLid_F,TotalJarLid_M)

OUTPUT(JarLid5_F_Res,JarLid5_M_Res,JarLid6_F_Res,JarLid6_M_Res)

%EndForceVector5=ForcePlate5FCorrected
EndForceVector5=%EndForceVector5*NanoAxes

OUTPUT(EndForceVector5)

%EndForceVector6=ForcePlate6FCorrected
EndForceVector6=%EndForceVector6*PylonAxes
```

```
OUTPUT(EndForceVector6)

{*********** LEFT WRIST FORCES AND MOMENTS ******************}


{* Calculates the x,y and z distances between the transducer centre and the left wrist joint centre (LWJC)*}

X_LW5_Dist=(LWJC(1)-NANOCENT(1))/1000
Y_LW5_Dist=(LWJC(2)-NANOCENT(2))/1000
Z_LW5_Dist=(LWJC(3)-NANOCENT(3))/1000

X_LW6_Dist=(LWJC(1)-PYLONCENT(1))/1000
Y_LW6_Dist=(LWJC(2)-PYLONCENT(2))/1000
Z_LW6_Dist=(LWJC(3)-PYLONCENT(3))/1000

Fx5_LW=ForceXAV
Fy5_LW=ForceYAV
Fz5_LW=ForceZAV

Mx5_LW=MomentXAV+ForceYAV*(Z_LW5_Dist)-ForceZAV*(Y_LW5_Dist)
My5_LW=MomentYAV+ForceZAV*(X_LW5_Dist)-ForceXAV*(Z_LW5_Dist)
Mz5_LW=MomentZAV+ForceXAV*(Y_LW5_Dist)-ForceYAV*(X_LW5_Dist)


Fx6_LW=Force6_XAV
Fy6_LW=Force6_YAV
Fz6_LW=Force6_ZAV

Mx6_LW=Moment6_XAV+Force6_YAV*(Z_LW6_Dist)-Force6_ZAV*(Y_LW6_Dist)
My6_LW=Moment6_YAV+Force6_ZAV*(X_LW6_Dist)-Force6_XAV*(Z_LW6_Dist)
Mz6_LW=Moment6_ZAV+Force6_XAV*(Y_LW6_Dist)-Force6_YAV*(X_LW6_Dist)


F_LWrist5_x = Fx5_LW*CoordXV
F_LWrist5_y = Fy5_LW*CoordYV
F_LWrist5_z = Fz5_LW*CoordZV

M_LWrist5_x = Mx5_LW*CoordXV
M_LWrist5_y = My5_LW*CoordYV
M_LWrist5_z = Mz5_LW*CoordZV

F_LWrist6_x = Fx6_LW*CoordXV
F_LWrist6_y = Fy6_LW*CoordYV
F_LWrist6_z = Fz6_LW*CoordZV

M_LWrist6_x = Mx6_LW*CoordXV
M_LWrist6_y = My6_LW*CoordYV
M_LWrist6_z = Mz6_LW*CoordZV

LEFTWRIST_5_FX=COMP(F_LWrist5_x,LForearm(1))+COMP(F_LWrist5_y,LForearm(1))+COMP(F_LWrist5_z,LForearm(1))
LEFTWRIST_5_FY=COMP(F_LWrist5_x,LForearm(2))+COMP(F_LWrist5_y,LForearm(2))+COMP(F_LWrist5_z,LForearm(2))
LEFTWRIST_5_FZ=COMP(F_LWrist5_x,LForearm(3))+COMP(F_LWrist5_y,LForearm(3))+COMP(F_LWrist5_z,LForearm(3))

LEFTWRIST_5_MX=COMP(M_LWrist5_x,LForearm(1))+COMP(M_LWrist5_y,LForearm(1))+COMP(M_LWrist5_z,LForearm(1))
LEFTWRIST_5_MY=COMP(M_LWrist5_x,LForearm(2))+COMP(M_LWrist5_y,LForearm(2))+COMP(M_LWrist5_z,LForearm(2))
LEFTWRIST_5_MZ=COMP(M_LWrist5_x,LForearm(3))+COMP(M_LWrist5_y,LForearm(3))+COMP(M_LWrist5_z,LForearm(3))

LEFTWRIST_6_FX=COMP(F_LWrist6_x,LForearm(1))+COMP(F_LWrist6_y,LForearm(1))+COMP(F_LWrist6_z,LForearm(1))
```

```
LEFTWRIST_6_FY=COMP(F_LWrist6_x,LForearm(2))+COMP(F_LWrist6_y,LForearm(2))+COMP(F_LWrist6_z,LForearm(2))
LEFTWRIST_6_FZ=COMP(F_LWrist6_x,LForearm(3))+COMP(F_LWrist6_y,LForearm(3))+COMP(F_LWrist6_z,LForearm(3))

LEFTWRIST_6_MX=COMP(M_LWrist6_x,LForearm(1))+COMP(M_LWrist6_y,LForearm(1))+COMP(M_LWrist6_z,LForearm(1))
LEFTWRIST_6_MY=COMP(M_LWrist6_x,LForearm(2))+COMP(M_LWrist6_y,LForearm(2))+COMP(M_LWrist6_z,LForearm(2))
LEFTWRIST_6_MZ=COMP(M_LWrist6_x,LForearm(3))+COMP(M_LWrist6_y,LForearm(3))+COMP(M_LWrist6_z,LForearm(3))


LeftWrist5_F_Res={LEFTWRIST_5_FX,LEFTWRIST_5_FY,LEFTWRIST_5_FZ}
LeftWrist5_M_Res={LEFTWRIST_5_MX,LEFTWRIST_5_MY,LEFTWRIST_5_MZ}

LeftWrist6_F_Res={LEFTWRIST_6_FX,LEFTWRIST_6_FY,LEFTWRIST_6_FZ}
LeftWrist6_M_Res={LEFTWRIST_6_MX,LEFTWRIST_6_MY,LEFTWRIST_6_MZ}

{* In the following two lines I've subtracted the vectors so we're only dealing the with difference *******}

Total_L_Wrist_F={(LEFTWRIST_5_FX+LEFTWRIST_6_FX),(LEFTWRIST_5_FY+LEFTWRIST_6_FY),(LEFTWRIST_5_FZ+LEFTWRIST_6_FZ)}
Total_L_Wrist_M={(LEFTWRIST_5_MX+LEFTWRIST_6_MX),(LEFTWRIST_5_MY+LEFTWRIST_6_MY),(LEFTWRIST_5_MZ+LEFTWRIST_6_MZ)}

OUTPUT(Total_L_Wrist_F,Total_L_Wrist_M)
OUTPUT(LeftWrist5_F_Res,LeftWrist5_M_Res,LeftWrist6_F_Res,LeftWrist6_M_Res)

Tilt_angle=<JarBodyAxes,1>
OUTPUT(Tilt_angle)


{*Ends dynamic trials*}
```

Appendix I: Jar opening motion analysis results

Appendix I Contents:

Appendix I Figures:

Figure I Tables:

I.i Kinetics of right hand on lid (scaled data in table, unscaled data in graphs)

a) Kinetics of right hand on lid:

Table I.1 Kinetic data for right wrist and thumb during jar opening captured at main analysis point. Scaling factors used

	Right Wrist							Right Thumb					
	Moments (Nm)			Forces (N)				Moments (Nm)			Forces (N)		
Subject No	x	y	z	x	y	z		x	y	z	x	y	z
1	2.05	2.54	-0.56	-27.95	9.57	8.22		2.22	0.03	-0.64	10.38	-35.78	64.21
2	0.60	-3.39	-0.79	3.18	6.59	9.41		-0.99	0.64	-0.63	15.62	108.28	17.38
4	-0.45	-3.77	1.01	8.50	15.00	8.90		0.27	0.42	-1.37	25.74	68.70	41.89
5	0.64	-4.36	0.08	-7.24	13.84	22.32		0.09	-0.13	0.27	31.61	74.06	55.44
6	1.16	-3.67	1.16	-11.91	43.16	24.75		-0.79	-0.26	0.08	25.39	45.27	71.71
7	0.07	-4.41	-0.76	14.08	1.13	21.89		0.26	0.64	-0.17	2.72	60.61	106.89
8	0.56	-3.41	1.41	-1.84	24.06	6.23		-1.37	1.00	-0.71	-1.50	93.74	21.91
9	2.88	-2.70	1.05	-20.28	29.03	20.70		-0.75	0.43	0.46	49.38	70.39	9.41
11	-0.38	-2.25	2.99	-15.11	53.79	-14.38		-0.75	1.46	-1.13	-9.40	72.97	66.96
12	-0.43	-3.51	-0.96	-9.95	0.96	11.39		-4.01	-1.73	-3.44	-70.30	167.06	-46.43
14	-1.17	-5.07	0.35	8.57	7.01	34.83		0.81	1.31	-0.05	27.40	-19.21	-41.67
15	-0.47	-3.82	0.80	-7.79	31.73	20.44		-0.39	0.75	-0.98	19.42	62.68	81.99
17	-2.21	-4.82	-0.39	4.23	-4.54	43.01		-1.41	-0.21	-1.95	-2.21	80.56	-21.88
18	-0.33	-3.95	-0.27	-0.80	16.40	23.06		-0.25	0.22	0.15	49.64	66.62	-0.70
19	-0.31	-3.97	0.27	8.03	8.38	16.74		0.47	-1.10	0.66	32.75	41.60	76.22
20	-0.25	-1.87	3.50	-3.88	35.23	-11.30		-1.95	0.41	0.72	15.00	69.95	-27.51
21	-1.96	-3.63	1.45	15.14	3.77	21.80		0.28	-0.15	0.06	27.34	34.16	-13.06
23	0.61	-4.53	0.68	-1.50	16.28	31.39		-1.32	0.18	-2.27	18.77	112.28	7.39
25	-0.09	-3.29	0.49	-4.36	26.67	11.11		-0.04	0.82	-0.31	11.85	25.00	75.24
26	-1.27	-2.96	1.92	4.51	40.96	9.27		-0.88	-0.02	-0.80	28.12	78.39	-4.04
27	-0.44	-2.82	1.03	-2.30	22.90	-0.24		-1.14	-0.34	-2.71	-14.89	78.84	-7.94
28	-0.86	-4.78	1.91	0.81	37.69	30.42		-0.79	-0.41	0.88	34.71	41.40	58.49

Table I.2 Kinetic data for right hand during jar opening captured at main analysis point. Scaling factors used

	Right Hand					
	Moments (Nm)			Forces (N)		
Subject No	x	y	z	x	y	z
1	4.32	4.86	-4.60	-80.87	33.89	-34.11
2	-6.02	-0.70	1.89	40.81	-40.70	104.64
4	-4.78	-0.41	2.88	50.15	-34.53	72.45
5	-6.97	-0.90	-0.44	-1.96	-52.97	98.68
6	-4.13	-0.77	0.99	30.41	-21.01	77.54
7	-6.14	-1.37	2.81	62.15	-57.30	120.88
8	-4.15	-2.24	1.82	53.60	-25.68	88.66
9	-3.51	-1.13	0.22	11.80	-31.69	74.79
11	-4.15	-1.52	1.61	38.58	0.34	83.75
12	-6.33	-2.08	3.64	108.60	-86.23	129.63
14	-3.83	-1.10	0.47	23.03	31.24	71.74
15	-4.48	-0.44	2.47	46.59	-62.05	81.97
17	-5.72	0.16	2.93	58.47	-29.72	107.50
18	-5.48	0.56	0.49	4.81	-25.96	93.34
19	-3.63	-3.20	0.81	18.74	-7.90	106.47
20	-2.58	-2.33	1.25	15.70	27.31	67.95
21	-2.44	-1.06	1.84	41.55	24.85	47.59
23	-6.37	1.32	1.27	16.88	-36.87	132.28
25	-4.15	0.14	0.46	14.52	-3.51	85.10
26	-3.72	-1.79	1.03	28.91	2.68	83.60
27	-2.98	-0.42	2.21	51.66	-29.42	54.56
28	-4.53	-1.87	0.21	5.00	-5.31	96.14

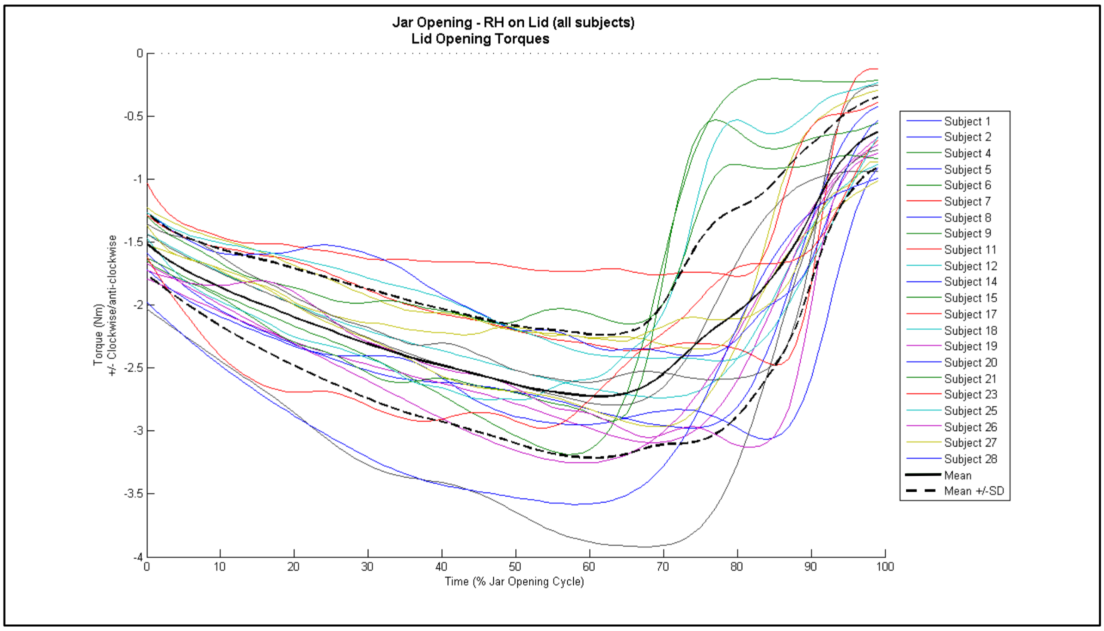


Figure I.1 Lid opening torque profiles for all subjects

Right Wrist Moments

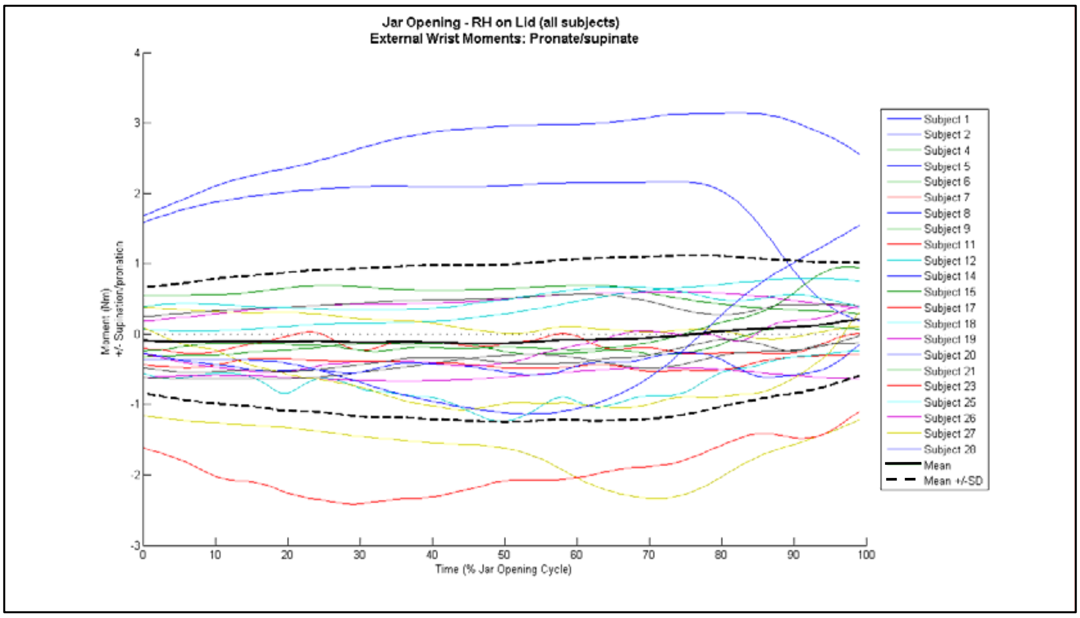


Figure I.2 External wrist moments about x-axis (+/- supination/pronation). Raw data before scaling.

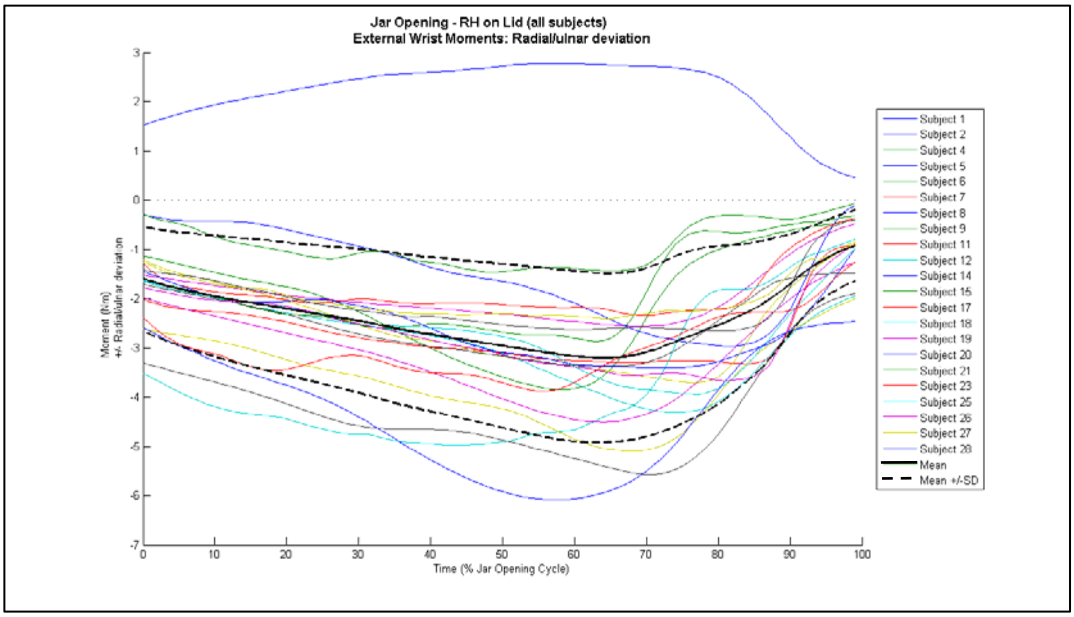


Figure I.3 External wrist moments about y-axis (+/- radial/ulnar deviation). Raw data before scaling.

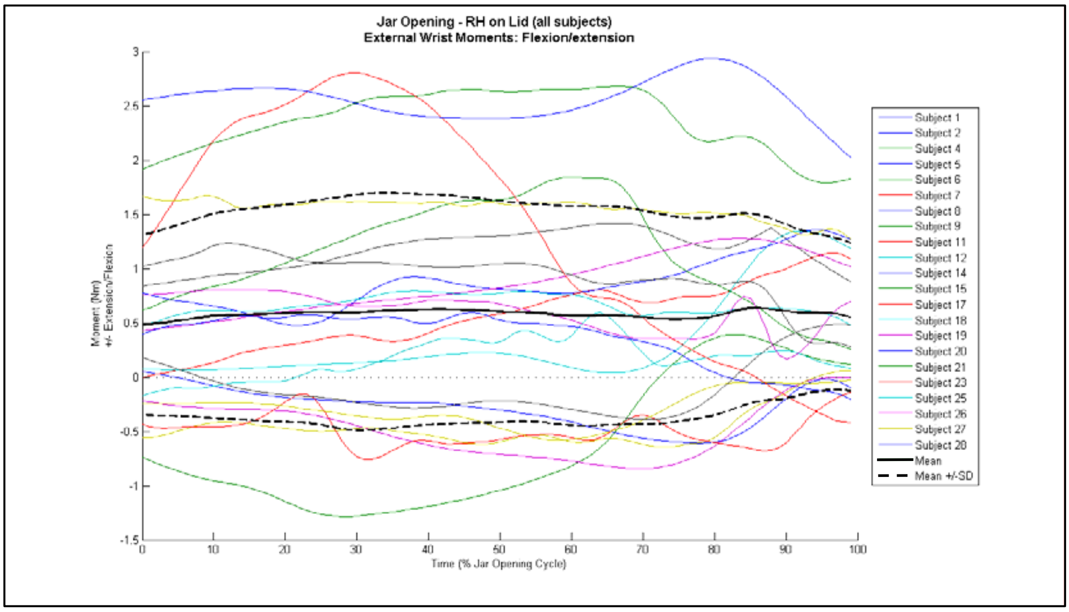


Figure I.4 External wrist moments about z-axis (+/- extension/flexion). Raw data before scaling.

Right Wrist Forces

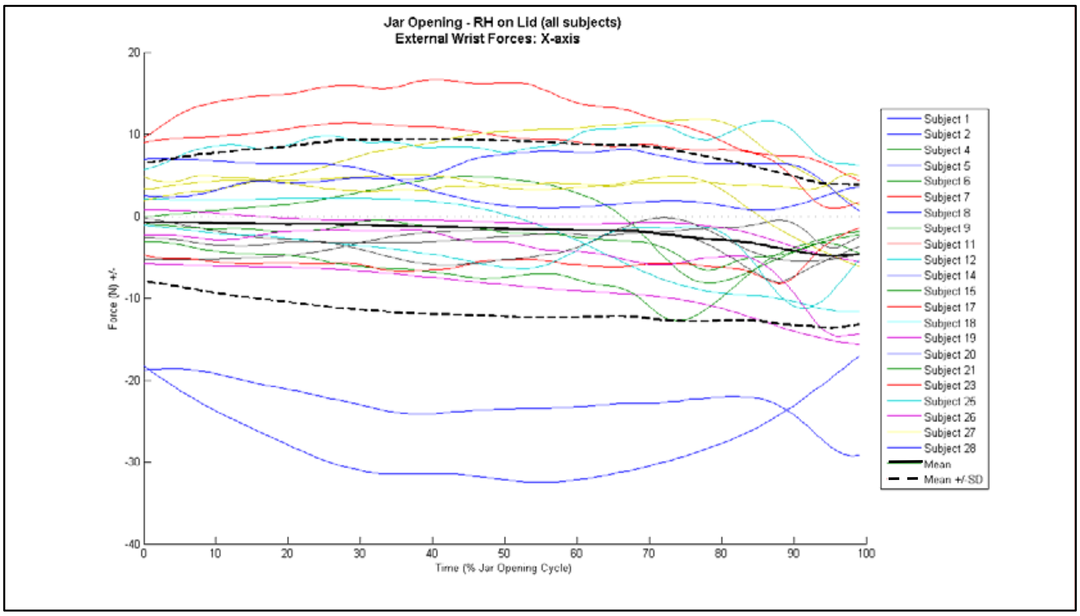


Figure I.5 External wrist forces along x-axis (+/- distal/proximal). Raw data before scaling.

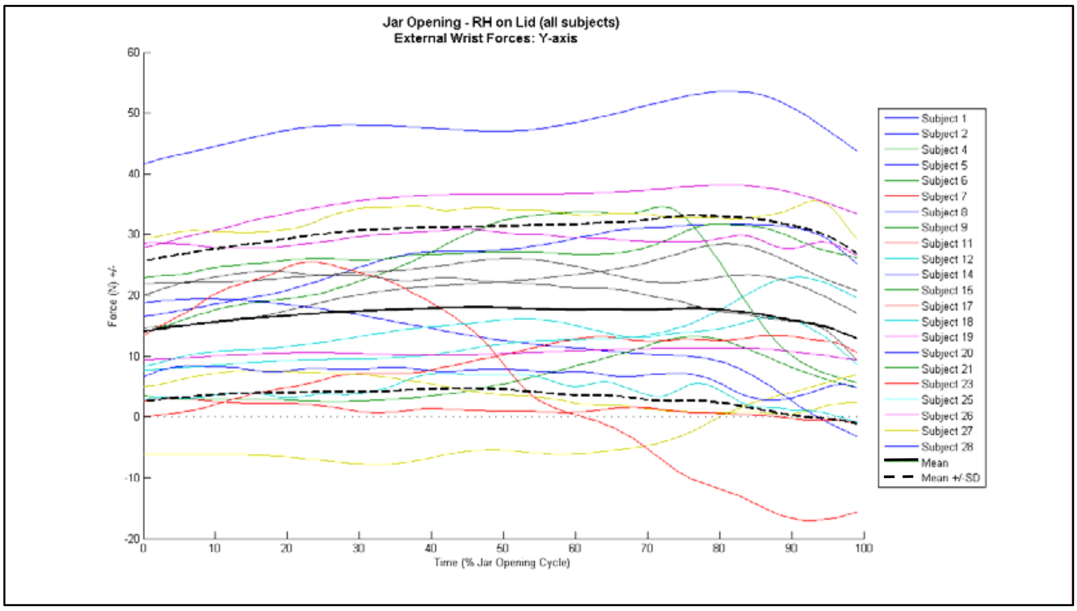


Figure I.6 External wrist forces along y-axis (+/- dorsal/palmar). Raw data before scaling.

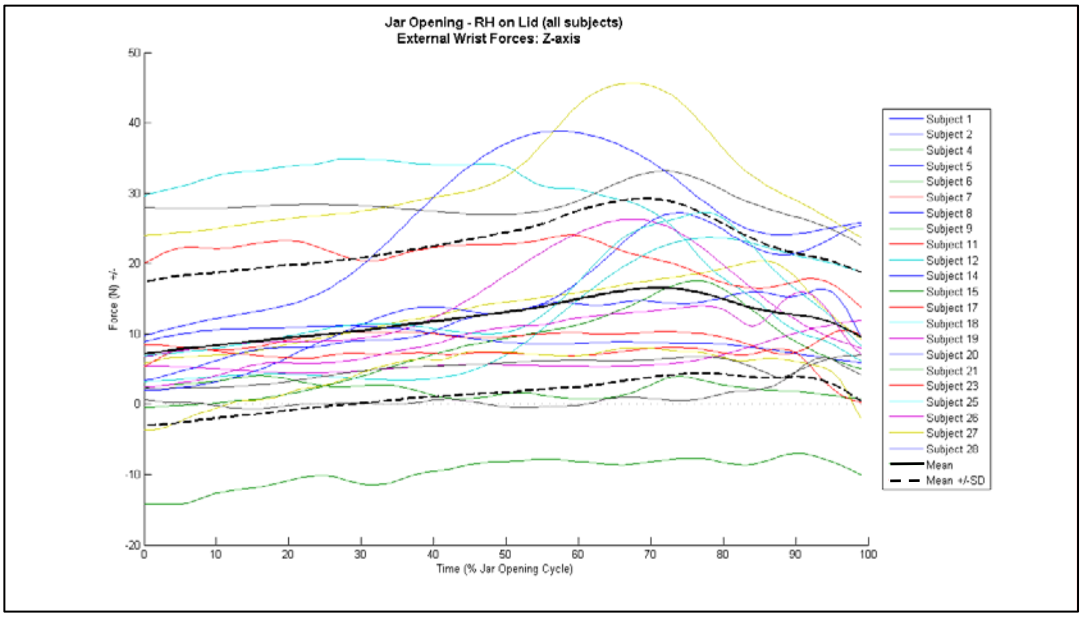


Figure I.7 External wrist forces along z-axis (+/- lateral/medial). Raw data before scaling.

Right Hand Moments

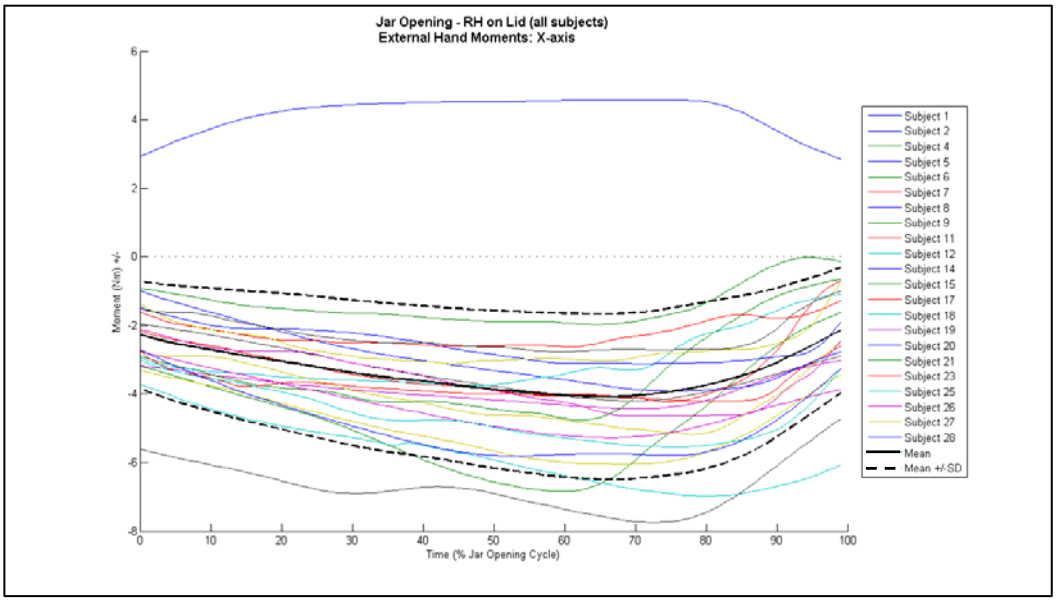


Figure I.8 External hand moments about x-axis (+/- supinate/pronate). Raw data before scaling.

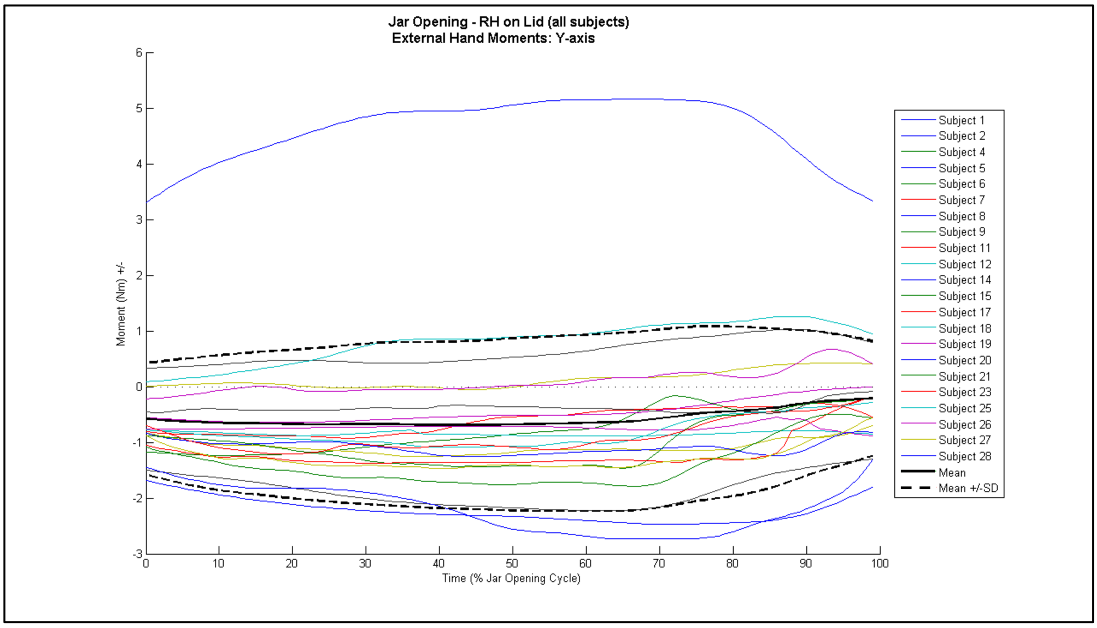


Figure I.9 External hand moments about y-axis (+/- radial/ulnar deviation). Raw data before scaling.

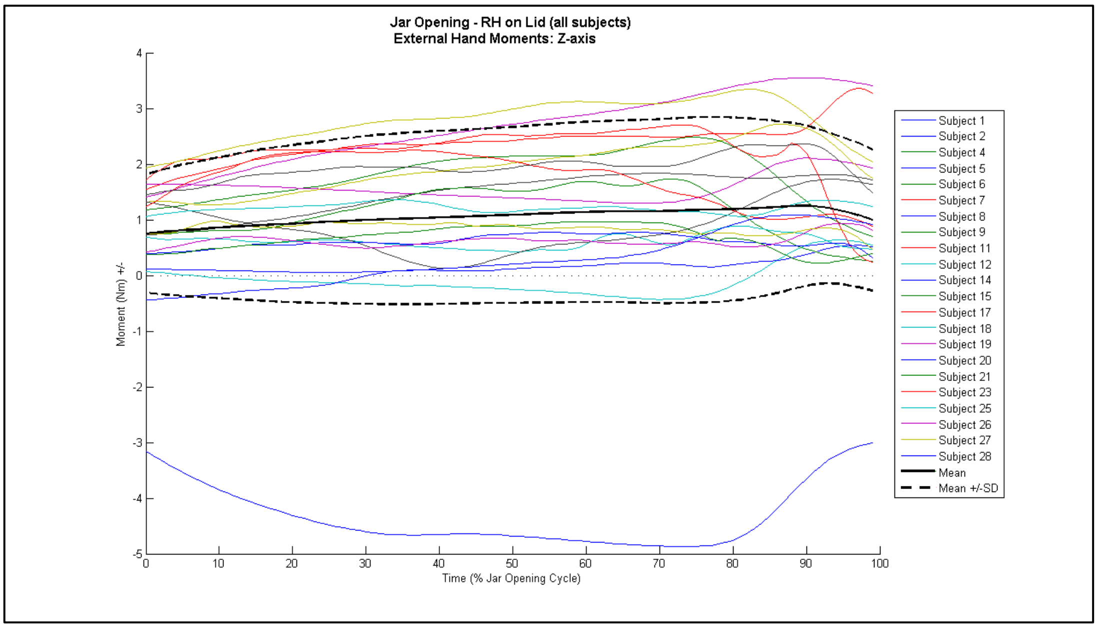


Figure I.10 External hand moments about z-axis (+/- extension/flexion). Raw data before scaling.

Right Hand Forces

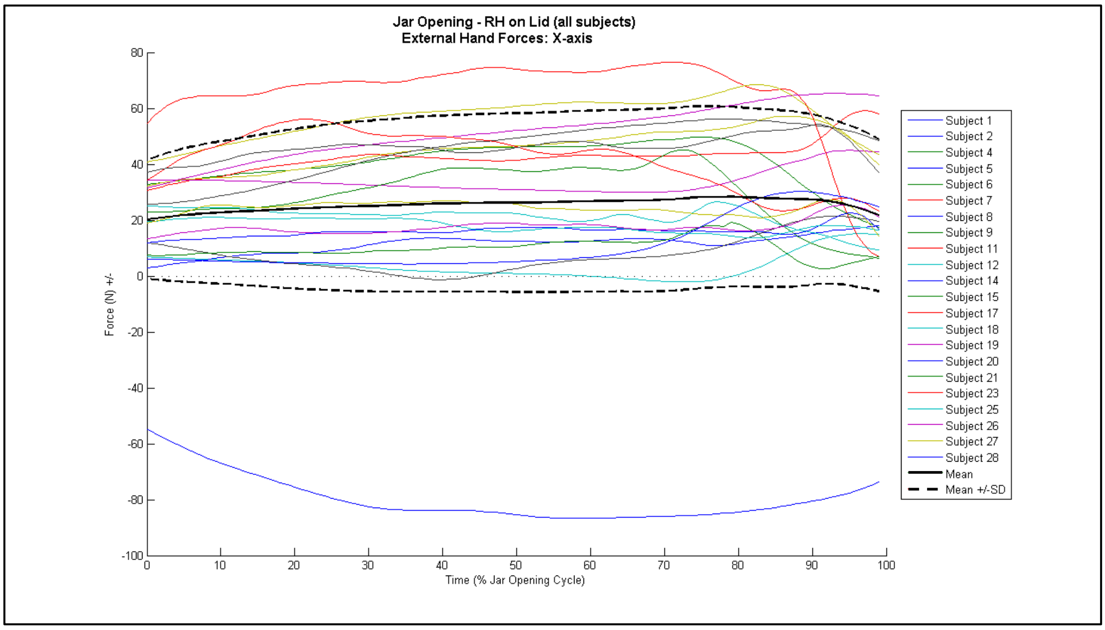


Figure I.11 External hand forces along x-axis (+/- distal/proximal). Raw data before scaling.

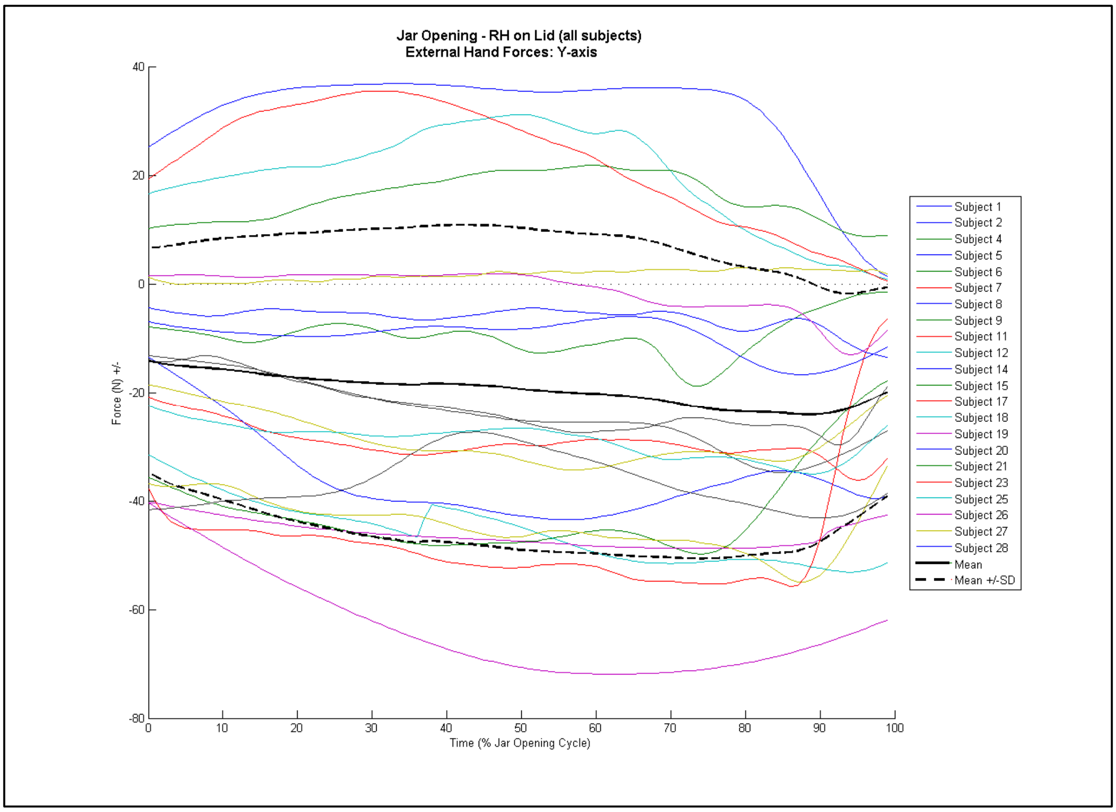


Figure I.12 External hand forces along y-axis (+/- dorsal/palmar). Raw data before scaling.

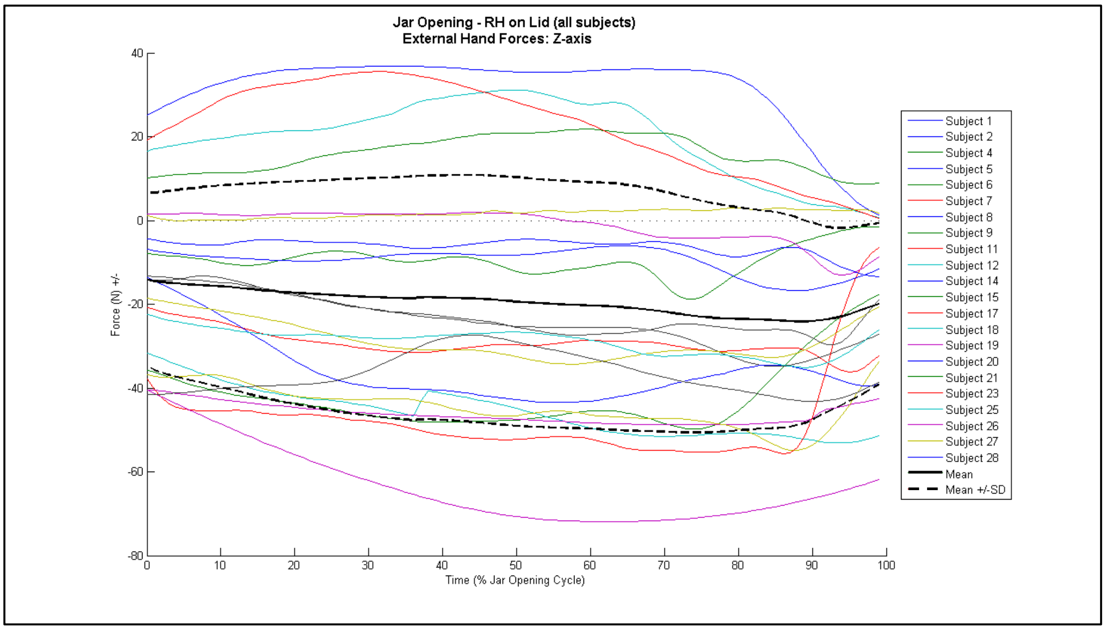


Figure I.13 External hand forces along z-axis (+/- lateral/medial). Raw data before scaling.

Right Thumb Moments

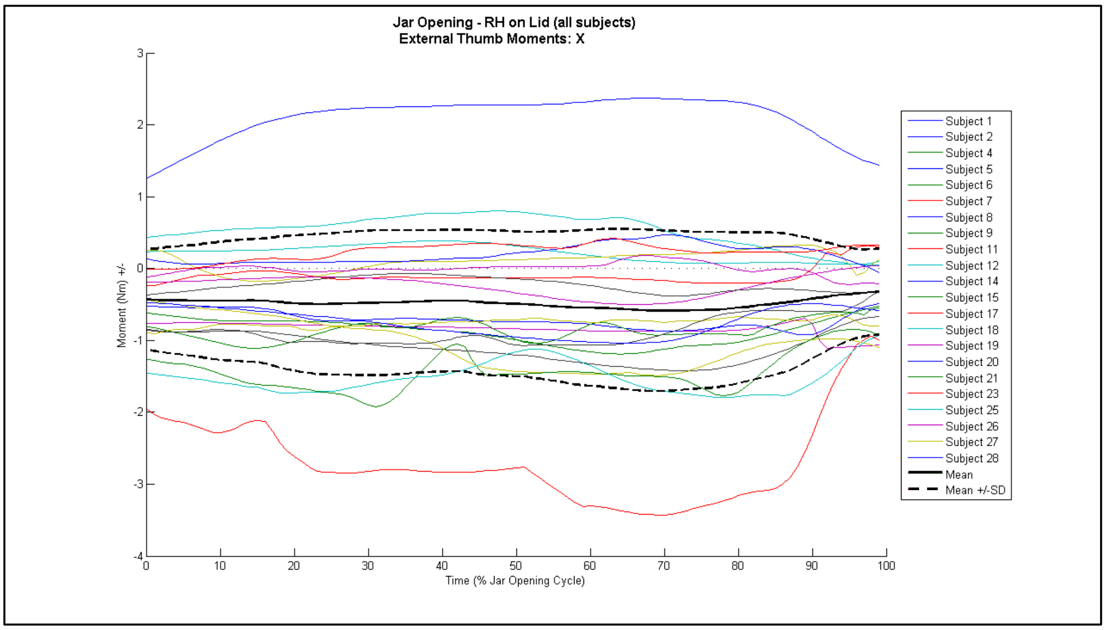


Figure I.14 External thumb moments about x-axis (+/- internal/external rotation). Raw data before scaling.

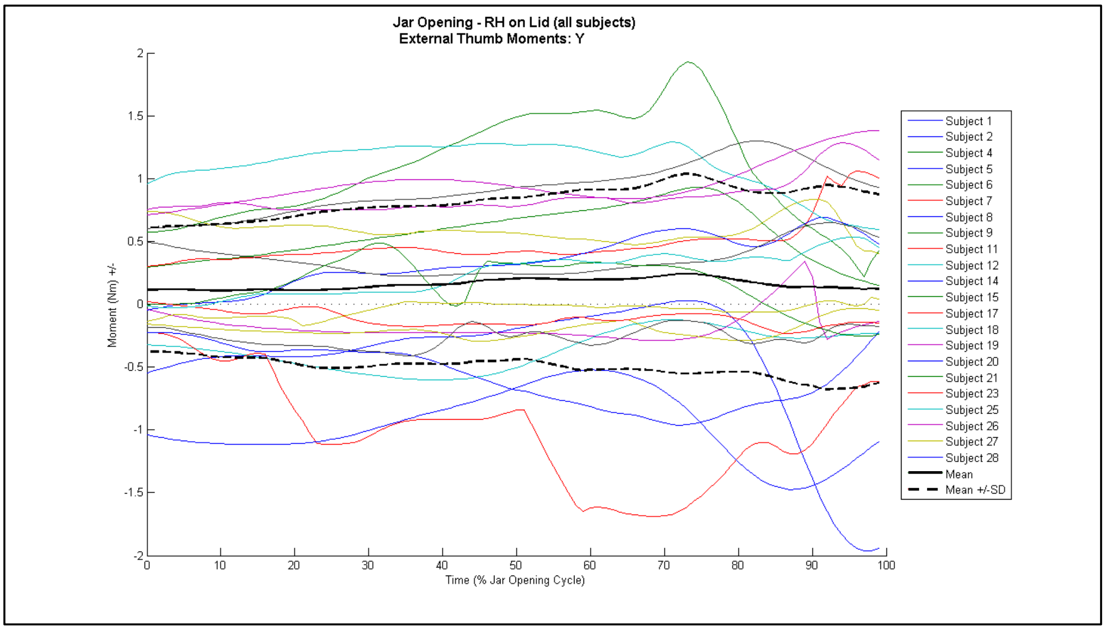


Figure I.15 External thumb moments about y-axis. Raw data before scaling.

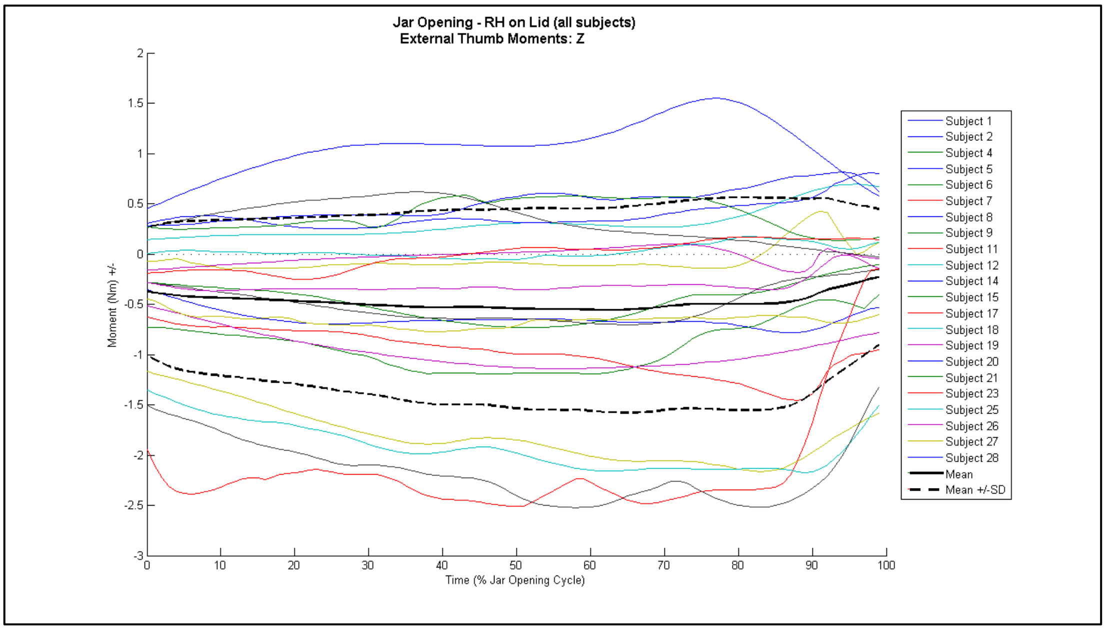


Figure I.16 External thumb moments about z-axis (+/- extension/flexion). Raw data before scaling.

Right Thumb Forces

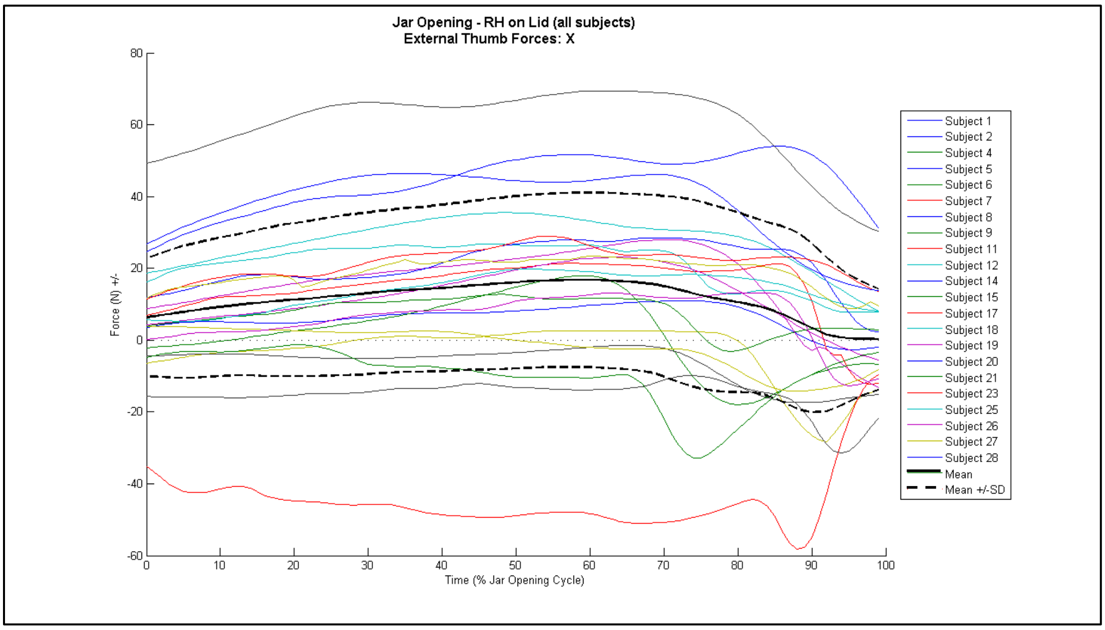


Figure I.17 External thumb forces along x-axis (+/- distal/proximal). Raw data before scaling.

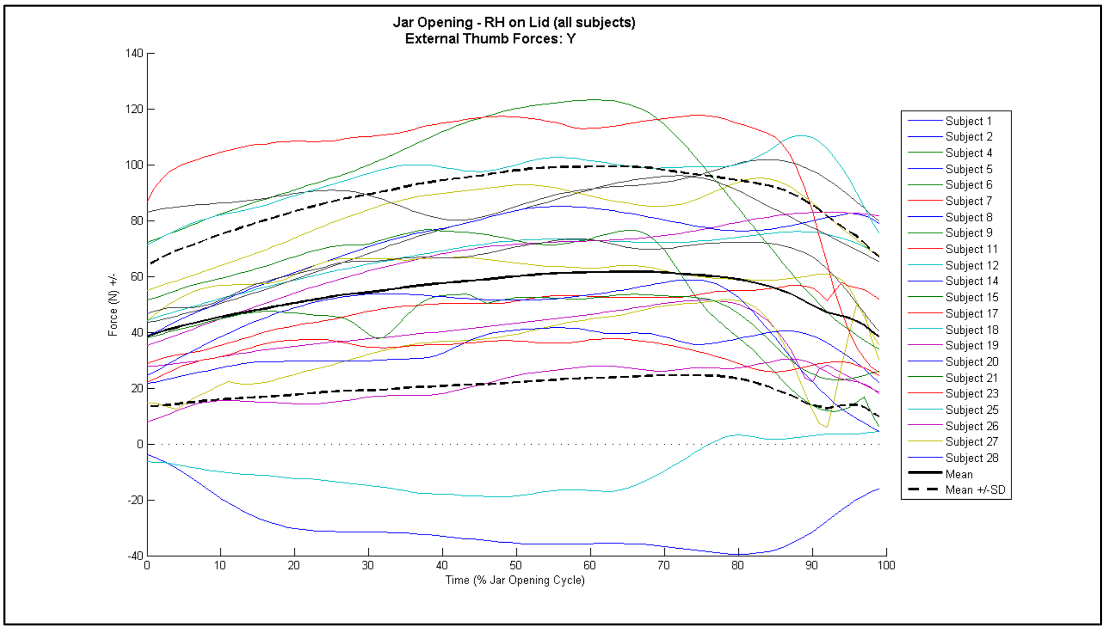


Figure I.18 External thumb forces along y-axis (+/- dorsal/palmar). Raw data before scaling.

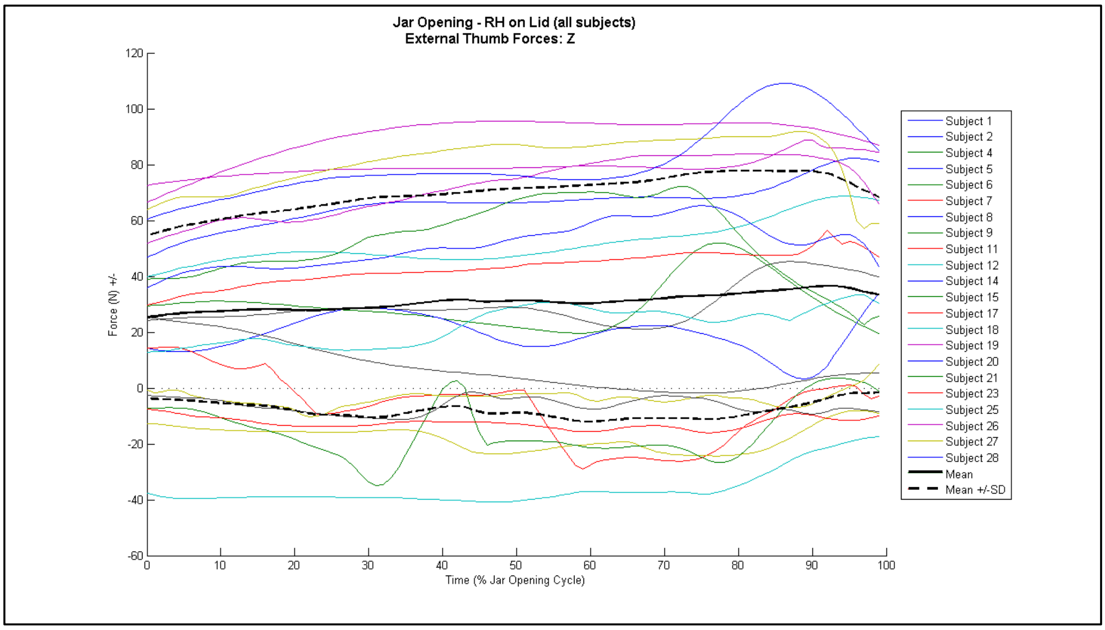


Figure I.19 External thumb forces along z-axis (+/- medial/lateral). Raw data before scaling.

I.ii Kinematics of right hand on lid

b) Kinematics

Table I.3 Joint angles for right wrist and MCP and PIPs (digits II-IV) during jar opening captured at main analysis point

	Wrist				Digit II			Digit III			Digit IV	
Subject No	X	Y	Z		MCP:X	PIP:X		MCP:X	PIP:X		R4MCP:X	R4PIP:X
1	1.80	28.72	-17.86		0.00	0.00		-25.81	-105.07		-63.07	-27.55
2	41.71	10.66	-0.84		-45.96	-40.28		-49.67	-36.09		-50.40	-15.51
4	29.34	7.43	-4.68		-53.38	-33.94		-36.35	-81.60		-41.96	6.64
5	35.21	-2.76	-10.61		-63.51	-30.87		-49.24	-39.72		-66.24	-10.40
6	18.22	8.48	-2.36		-39.47	-59.69		-48.80	-52.62		-51.23	-14.07
7	39.04	21.08	-7.36		-60.30	-10.28		-41.42	-38.89		-40.44	-1.14
8	43.23	0.27	-0.82		-42.00	-25.21		-11.80	-64.86		-16.97	-33.19
9	48.32	5.68	-4.84		-44.01	-52.14		-57.93	-52.74		-8.82	14.86
11	42.73	-6.82	-5.89		-34.39	-48.34		-33.29	-44.59		-32.82	-42.38
12	29.96	3.90	-13.21		-42.32	-56.60		-34.42	-56.11		-37.75	-26.49
14	38.95	2.09	-13.60		-48.51	-27.40		-39.89	-34.40		-23.33	-20.91
15	5.85	-18.58	-36.46		-31.21	-65.48		-41.67	-68.82		-46.06	-36.70
17	29.13	8.06	-20.35		-67.68	-15.22		-49.54	-18.79		-36.08	-16.92
18	32.69	8.57	-17.33		-72.47	-7.89		-50.81	-30.11		-27.08	-0.15
19	13.96	8.84	-16.53		-27.08	-24.36		-19.84	-56.72		-14.86	-68.79
20	28.91	0.76	-9.13		-24.70	-39.26		-14.58	-55.41		-2.35	-74.13
21	18.08	10.14	-13.13		-49.83	-45.67		-44.31	-52.64		-38.03	-41.11
23	37.82	4.61	-10.51		-73.71	-10.09		-59.52	-30.71		-37.57	-19.08
25	27.74	-0.38	-15.09		-47.98	-41.54		-47.11	-24.71		-45.18	-9.62
26	6.98	9.85	-12.02		-34.95	-48.85		-36.21	-27.45		-43.71	-2.00
27	38.61	-4.30	-6.94		-61.84	-14.74		-47.89	-42.32		-25.22	-56.01
28	12.05	7.50	-15.53		-46.47	-57.85		-61.77	4.83		-49.89	35.86

Right Wrist Angles

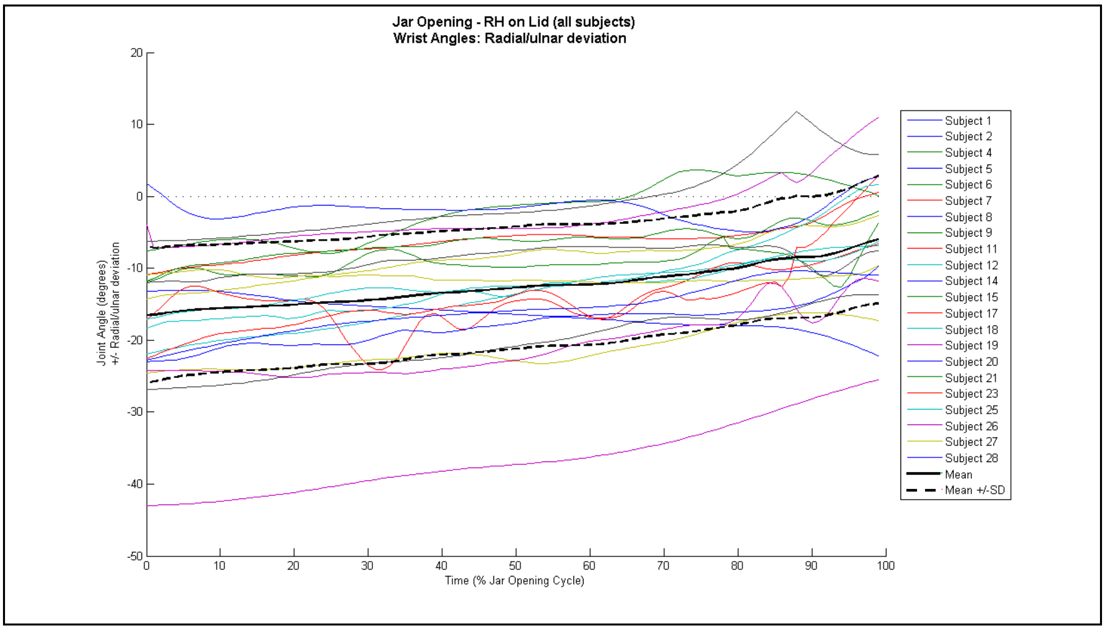


Figure I.20 Right wrist angles during jar opening. Rotation about y-axis (+/- radial/ulnar deviation).

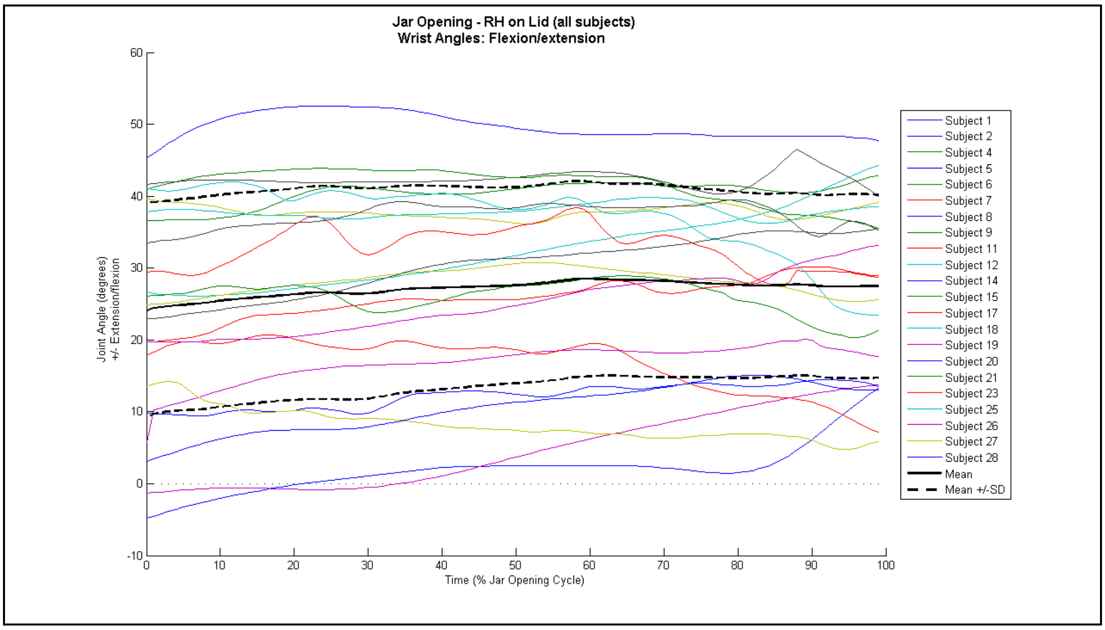


Figure I.21 Right wrist angles during jar opening. Rotation about z-axis (+/- extension/flexion).

Right Digit 2 MCP and PIP Angles:

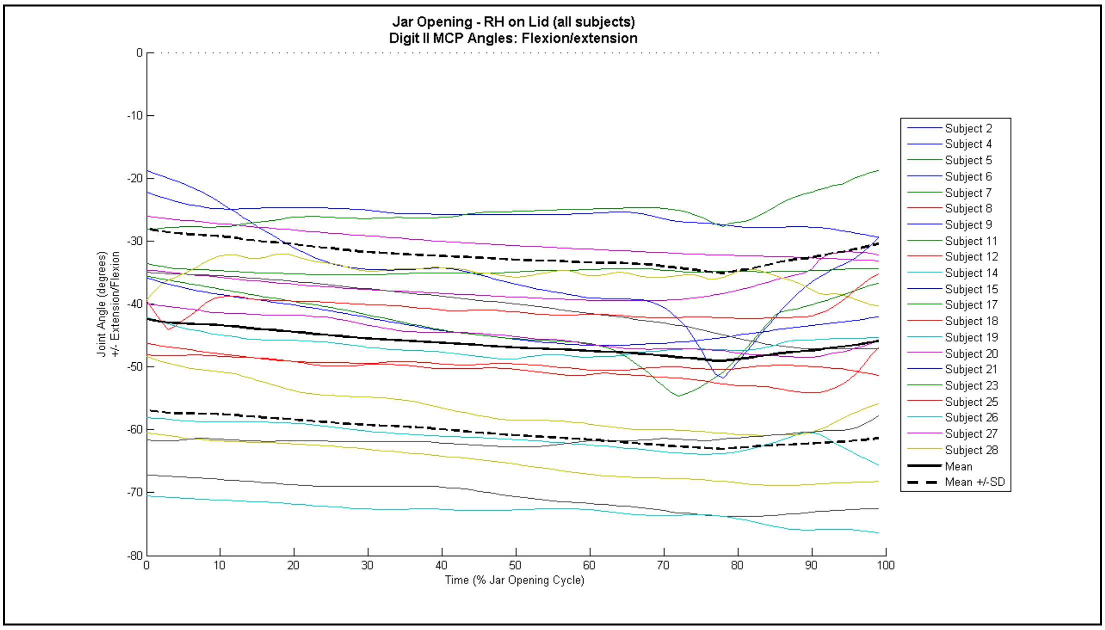


Figure I.22 Right digit II MCP angle. Rotation about z-axis (+/- extension/flexion)

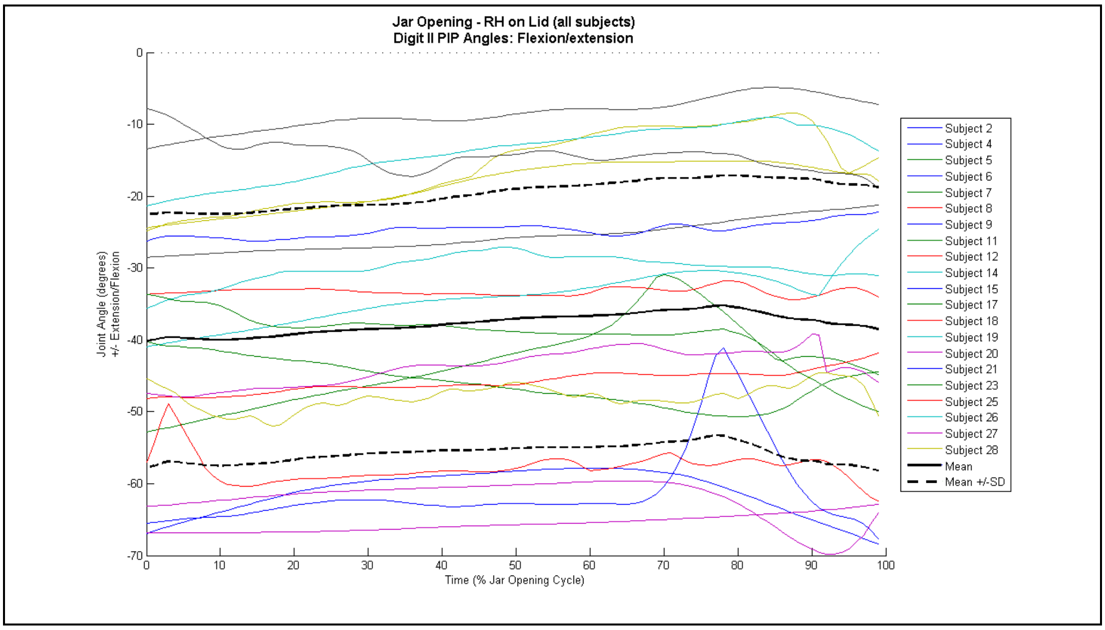


Figure I.23 Right digit II PIP angle. Rotation about z-axis (+/- extension/flexion)

Right Digit 3 MCP and PIP Angles:

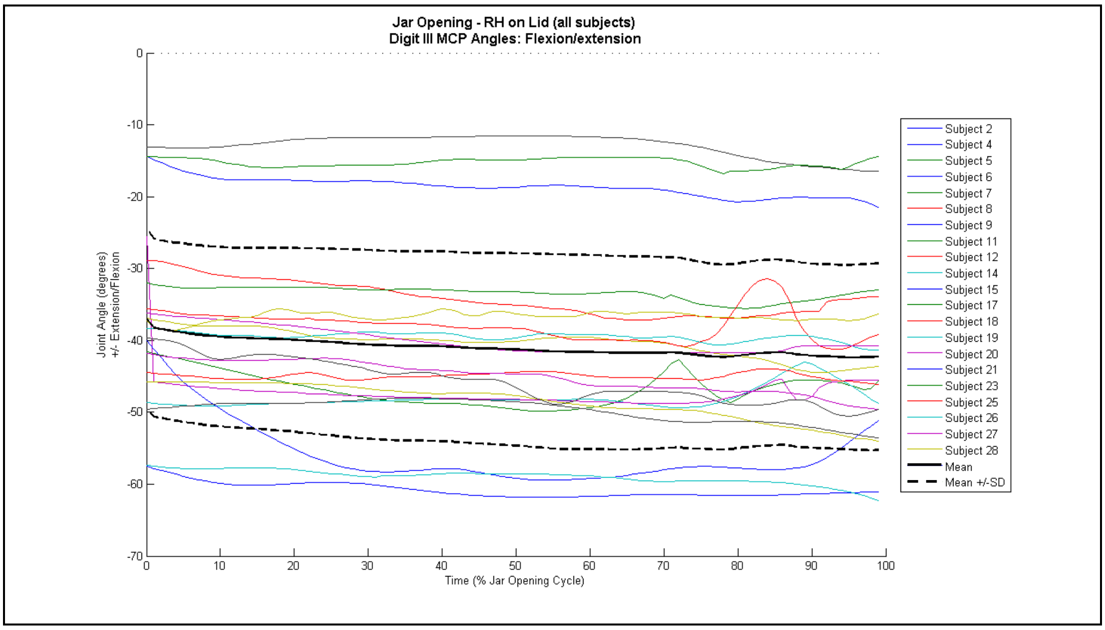


Figure I.24 Right digit III MCP angle. Rotation about z-axis (+/- extension/flexion)

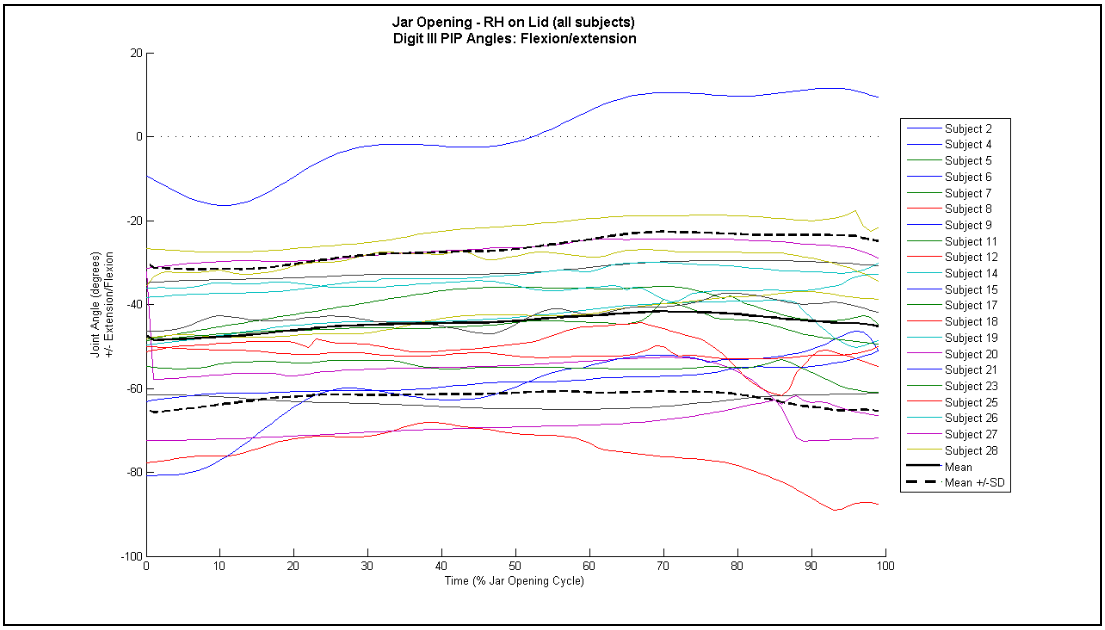


Figure I.25 Right digit III PIP angle. Rotation about z-axis (+/- extension/flexion).

Right Digit 4 MCP and PIP Angles:

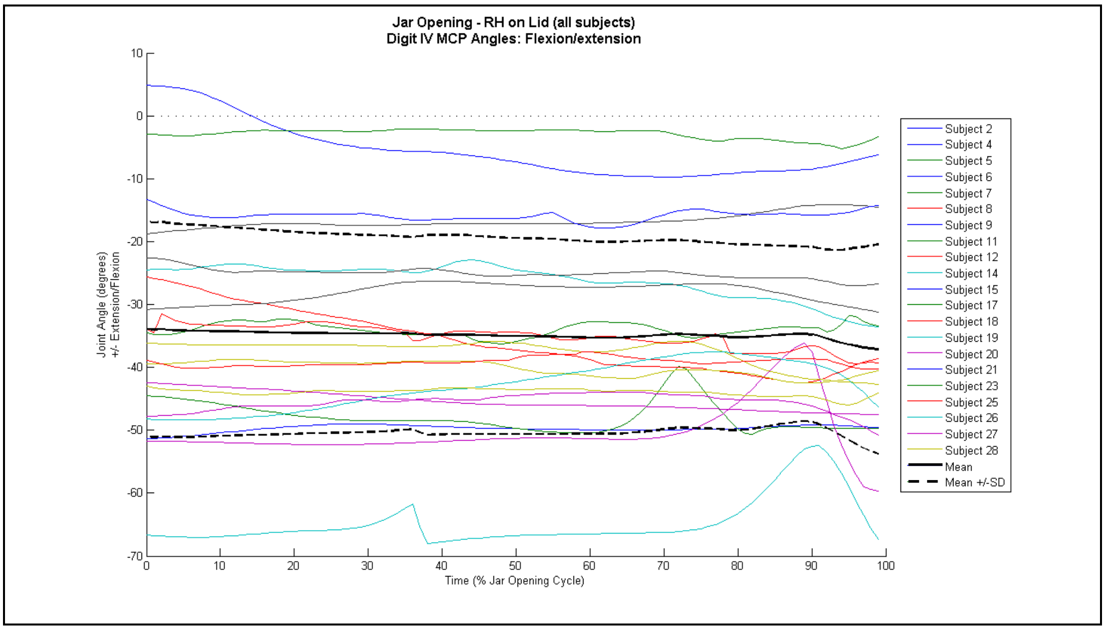


Figure I.26 Right digit IV MCP angle. Rotation about z-axis (+/- extension/flexion)

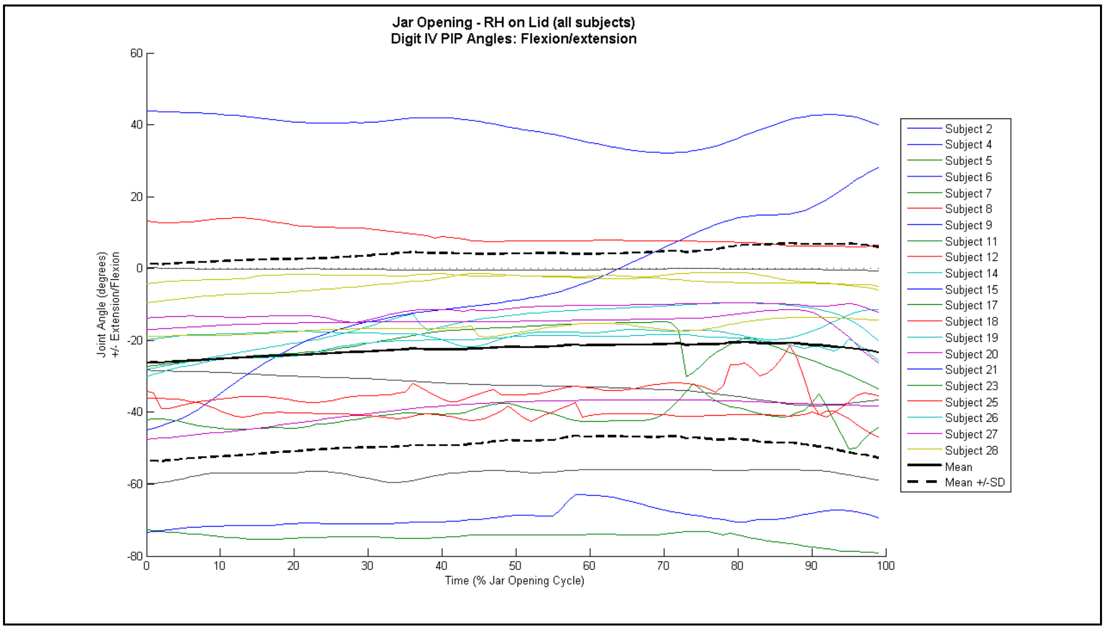


Figure I.27 Right digit IV PIP angle. Rotation about z-axis (+/- extension/flexion)

Left Wrist Angles

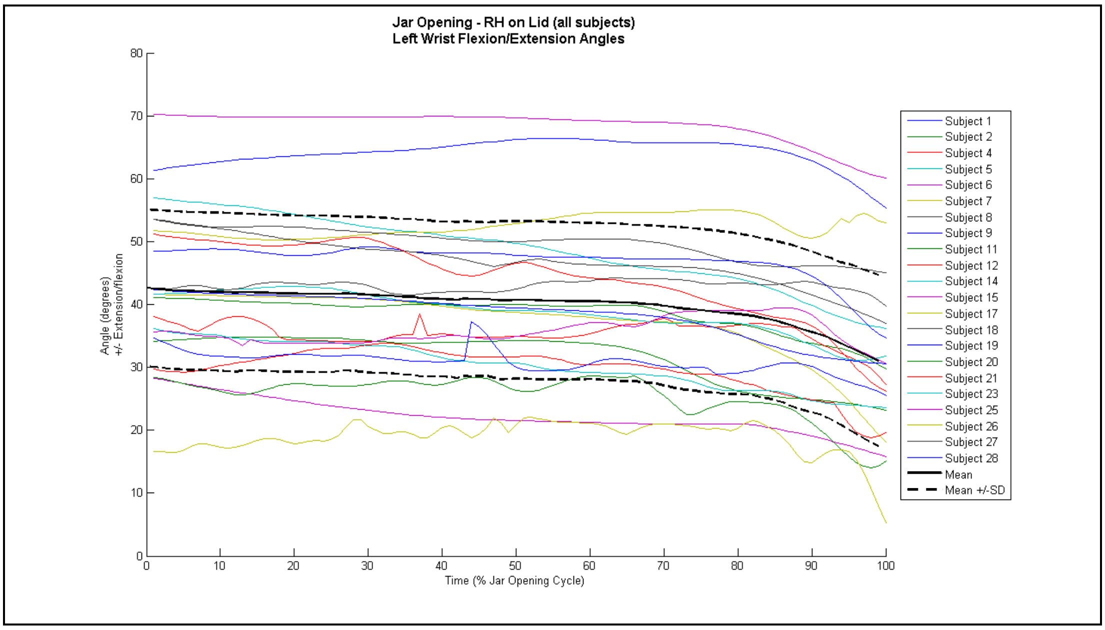


Figure I.28 Left wrist angles during jar opening. Rotation about z-axis (+/- extension/flexion).

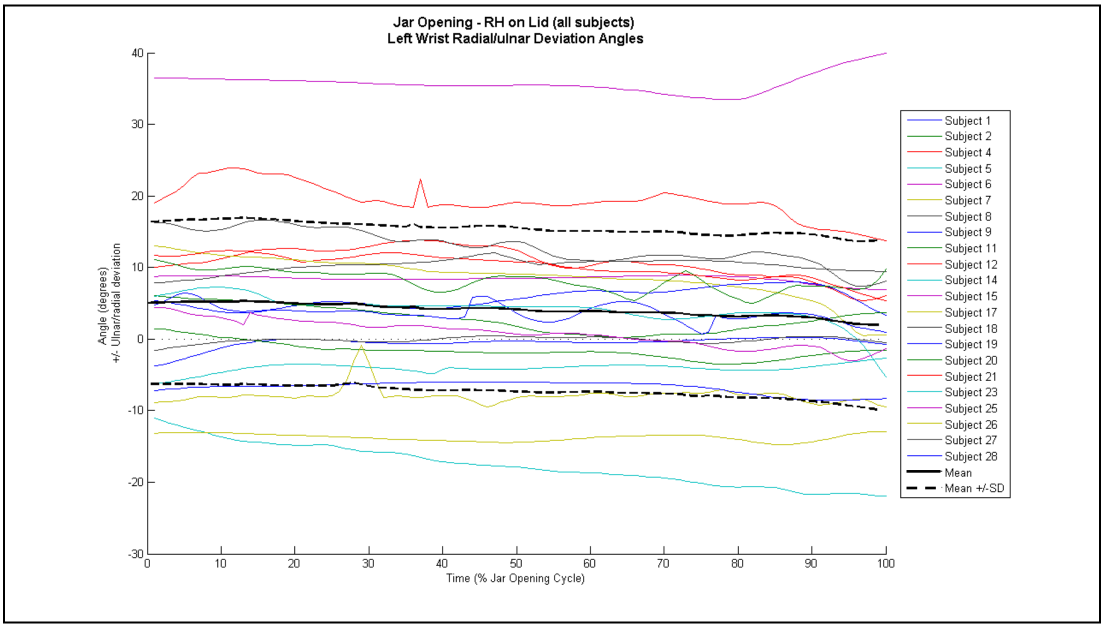


Figure I.29 Left wrist angles during jar opening. Rotation about y-axis (+/- ulnar/radial deviation).

I.iii Kinetics of left hand on lid (scaled data in table, unscaled data in graphs)

Table I.4 Kinetic data for left wrist and thumb during jar opening captured at main analysis point. Scaling factors used

	Left Wrist							Left Thumb					
	Moments (Nm)			Forces (N)				Moments (Nm)			Forces (N)		
Subject No	x	y	z	x	y	z		x	y	z	x	y	z
13	-0.26	-2.26	0.50	-32.89	6.20	-10.56		0.47	-0.21	0.98	-54.57	55.54	-16.33
16	0.49	-1.62	0.17	-9.75	27.39	-8.45		1.72	1.03	0.59	-60.88	35.41	-13.63
22	-0.48	-1.43	1.28	-10.28	40.78	-11.35		3.32	0.78	1.73	-43.93	79.20	3.80
24	-0.15	-0.21	2.77	-28.59	10.94	-49.41		0.31	0.52	1.75	-35.32	61.73	-62.60

Table I.5 Kinetic data for left hand during jar opening captured at main analysis point. Scaling factors used

	Left Hand					
	Moments (Nm)			Forces (N)		
Subject No	x	y	z	x	y	z
13	0.83	0.34	0.85	41.50	-22.33	-19.08
16	0.24	-0.17	1.64	56.58	-21.70	-4.00
22	0.59	0.01	2.27	70.53	-13.99	-18.71
24	2.18	0.16	4.33	72.59	-10.96	-43.11

LEFT Wrist Moments

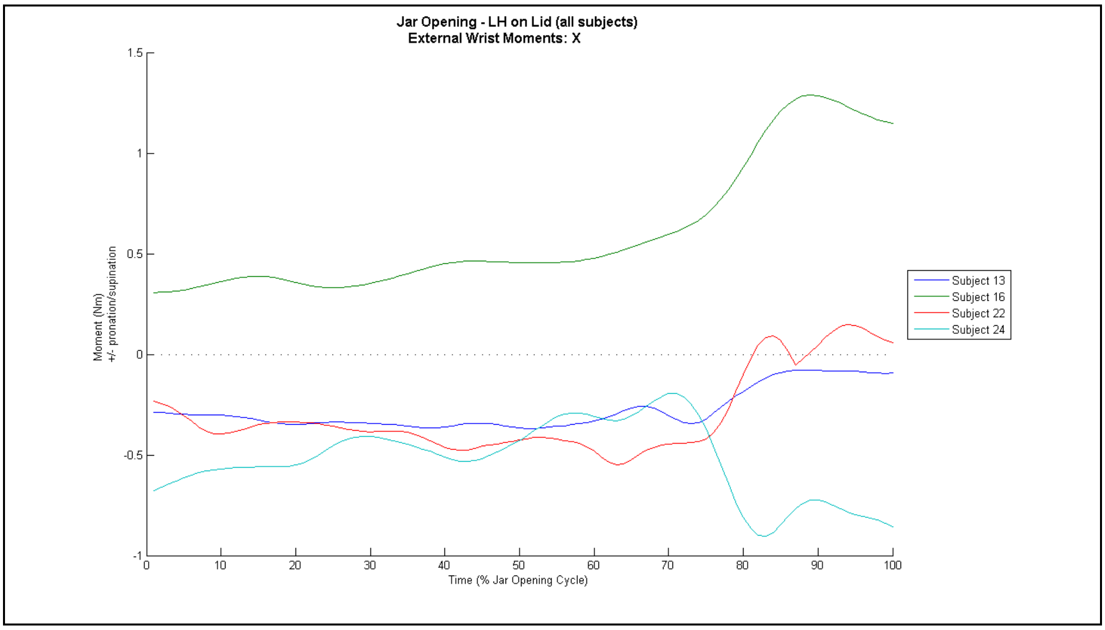


Figure I.30 External moments about x-axis of left wrist (+/- pronation/supination). Raw data before scaling.

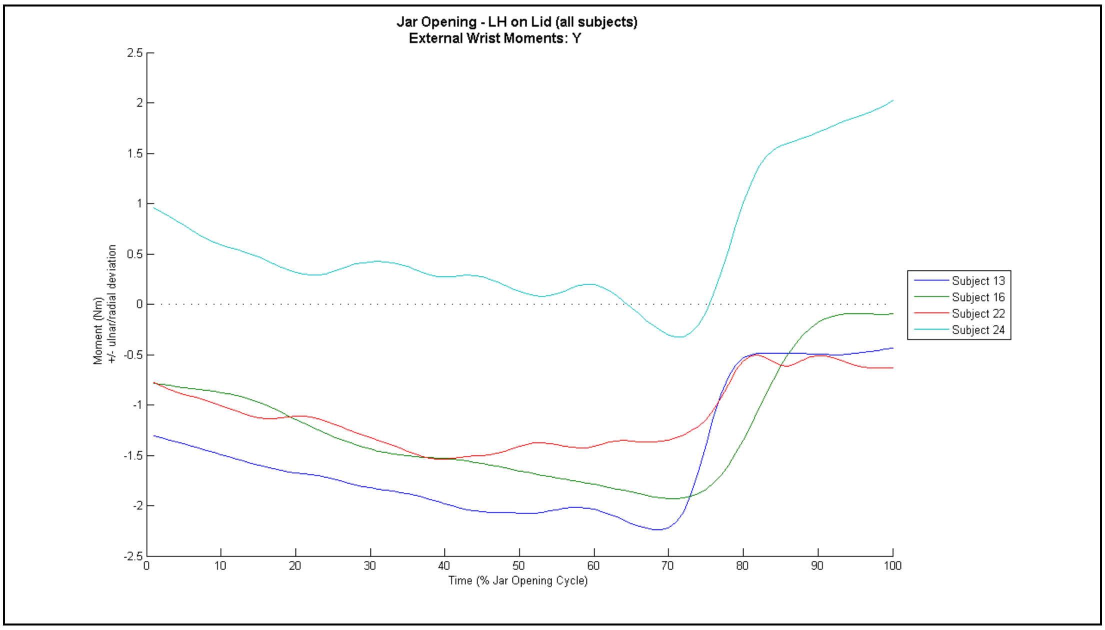


Figure I.31 External moments about y-axis of left wrist (+/- ulnar/radial deviation). Raw data before scaling.

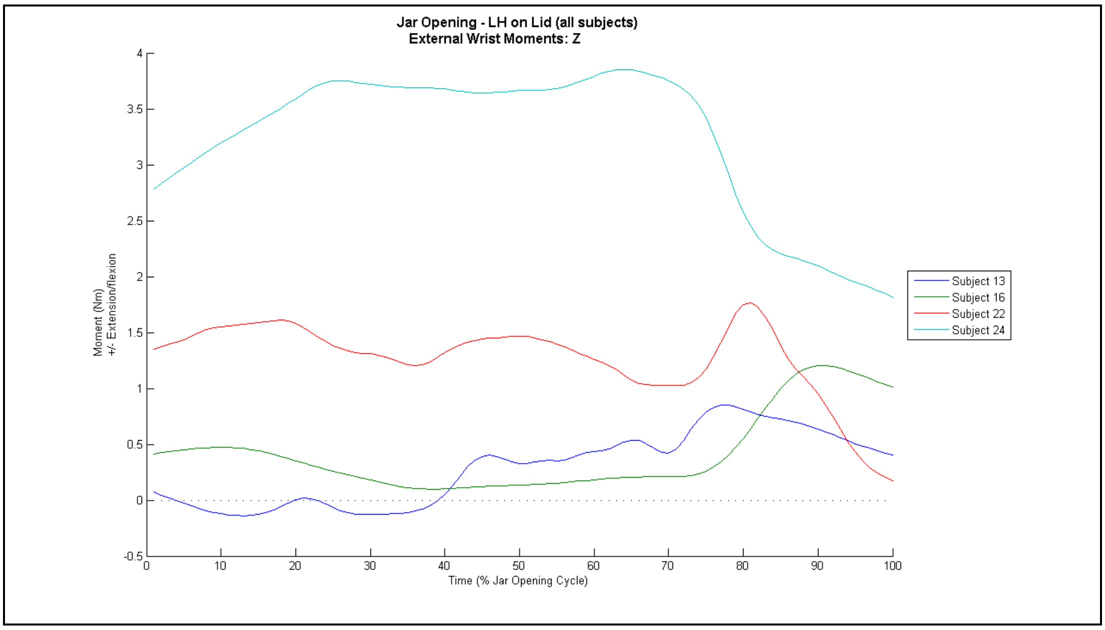


Figure I.32 External moments about z-axis of left wrist (+/- extension/flexion). Raw data before scaling.

LEFT Wrist Forces

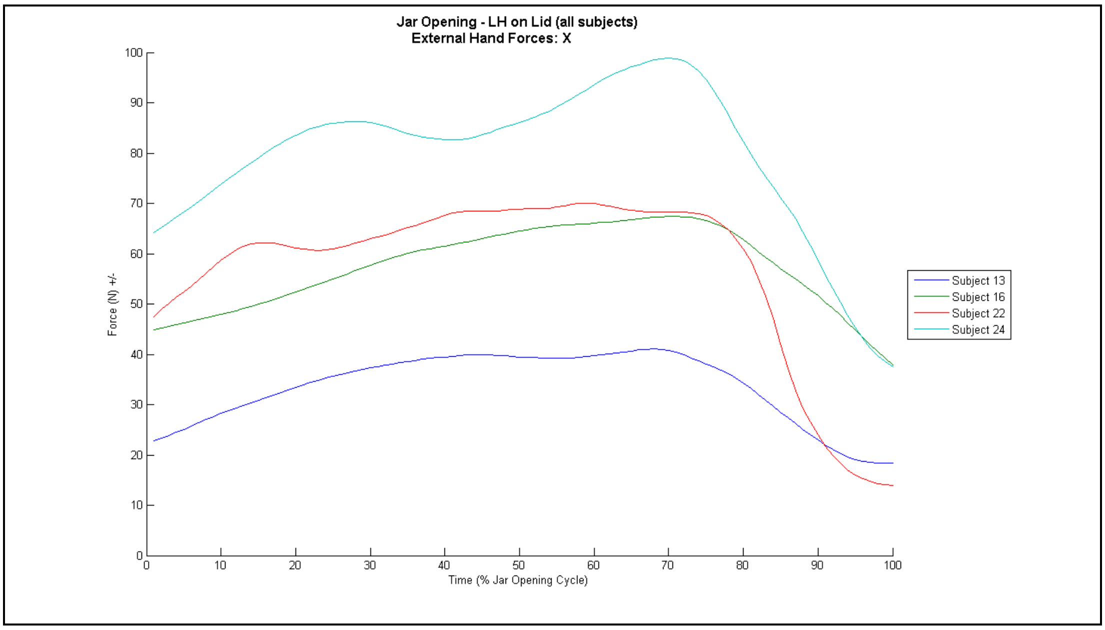


Figure I.33 External forces along x-axis of left wrist (+/- distal/proximal). Raw data before scaling.

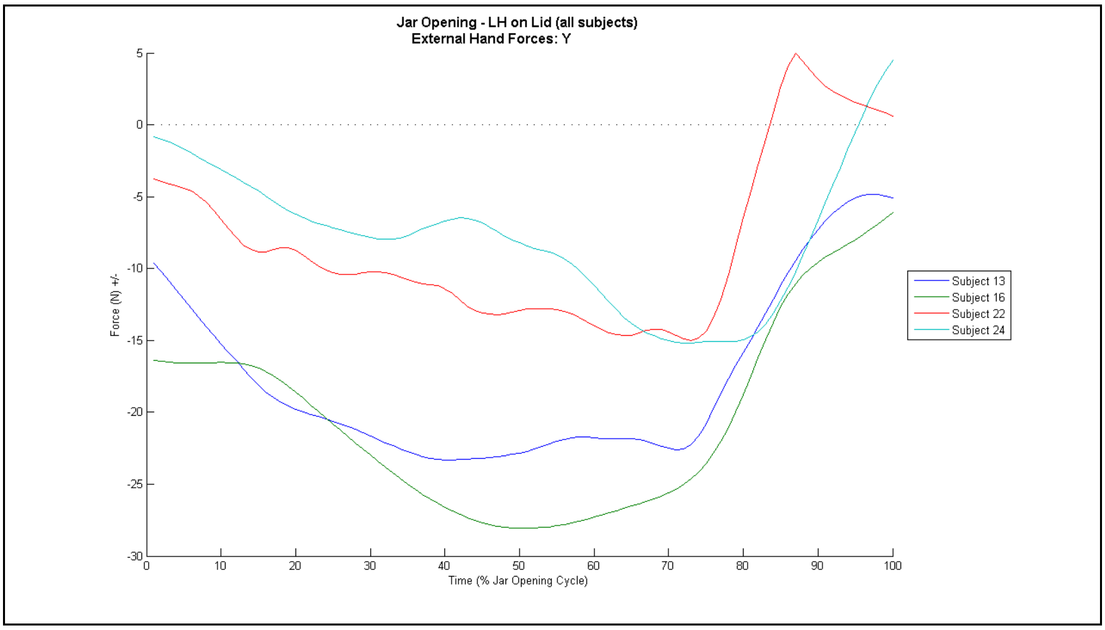


Figure I.34 External forces along y-axis of left wrist (+/- dorsal/palmar). Raw data before scaling.

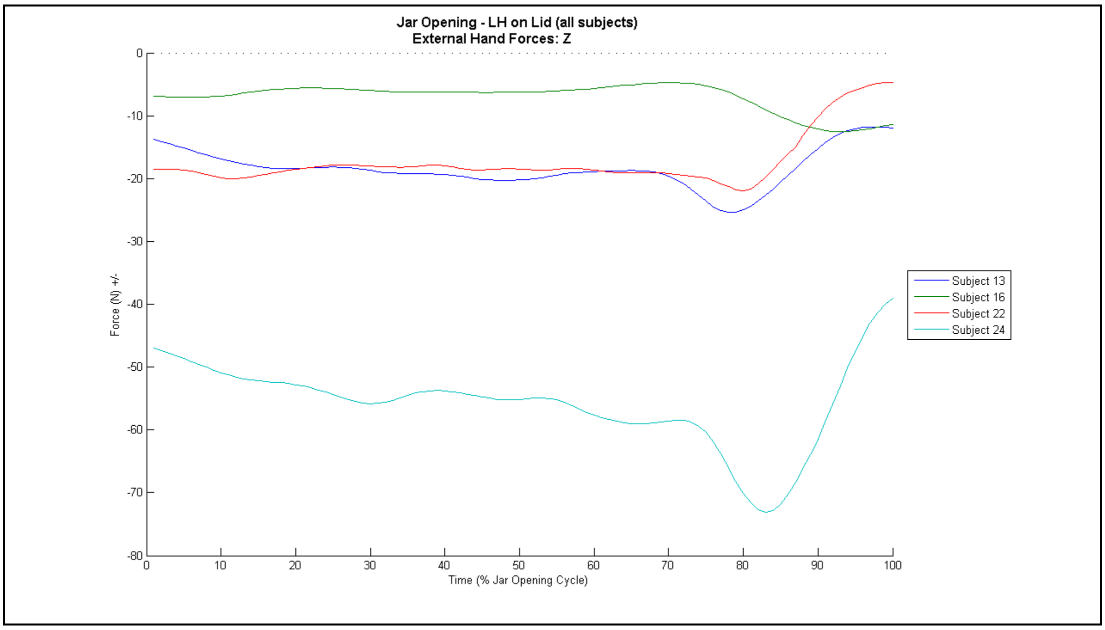


Figure I.35 External forces along z-axis of left wrist (+/- medial/lateral). Raw data before scaling.

Appendix J: Bottle Opening Motion Analysis Results (right hand on lid scaled kinetic results only)

Appendix J Tables:

Table J.1 Kinetic data for right wrist and thumb during bottle opening captured at point of peak opening torque. Scaling factors used.

	Right Wrist							Right Thumb					
	Moments (Nm)			Forces (N)				Moments (Nm)			Forces (N)		
Subject No	x	y	z	x	y	z		x	y	z	x	y	z
1	1.78	-3.38	0.79	-29.16	34.65	49.08		-0.92	0.03	0.26	37.01	46.95	61.26
2	0.17	-1.26	4.27	-9.22	56.02	-8.44		-0.77	-1.08	1.24	77.14	64.32	58.76
4	1.85	-2.49	2.63	7.00	43.13	4.52		-0.36	-0.60	-0.41	40.01	4.77	52.28
5	2.63	-3.42	4.32	-16.36	66.77	32.00		-1.43	-0.44	-0.78	9.75	-3.15	107.37
6	3.09	-3.03	3.31	-14.69	69.03	33.22		-1.03	-0.49	1.40	43.18	106.00	46.75
7	2.53	-2.42	0.83	-13.29	42.42	37.27		-1.33	-0.90	0.28	42.58	2.39	111.40
8	1.39	-0.83	3.55	-4.02	54.99	-15.95		-0.82	-1.07	1.27	77.14	63.87	59.25
9	4.71	-1.14	3.23	-34.25	55.75	30.55		-0.98	-0.50	1.26	73.87	62.57	53.78
13	3.27	-2.92	4.80	-23.19	64.49	26.34		0.10	-3.21	0.34	55.97	24.86	109.77
14	1.95	-2.64	2.19	-1.97	41.22	14.47		-0.79	0.05	2.18	92.53	49.52	14.41
15	2.24	-2.33	3.31	-16.58	85.09	18.90		-3.12	-0.41	-2.01	16.85	139.77	-16.89
17	1.50	-3.16	2.11	-1.93	46.81	25.54		-0.93	-0.46	0.20	45.47	-4.58	48.87
18	2.14	-3.55	1.68	-13.21	52.29	46.28		-1.44	0.66	-0.45	40.76	48.77	78.30
19	1.89	-2.63	2.67	-0.23	54.30	14.53		-1.39	-2.75	-0.80	53.37	-31.22	74.61
21	0.56	-2.52	1.72	-5.65	38.84	13.18		-1.26	-2.06	0.48	58.83	0.63	104.91
23	3.51	-0.71	3.31	-53.07	52.88	20.87		-1.59	0.59	0.13	57.80	48.53	77.22
25	1.64	-2.10	2.14	2.94	41.76	2.77		-0.33	-2.09	-0.02	42.07	6.33	102.95
26	0.76	-2.08	1.79	3.94	43.02	2.49		-0.76	0.30	1.03	79.33	51.38	12.65
27	2.99	-2.36	2.76	-28.44	67.01	33.35		-1.18	-0.38	-0.23	27.01	-26.68	64.77
29	2.41	-0.83	1.88	-28.42	46.84	2.23		-1.45	1.24	-0.77	44.65	73.13	79.53

Table J.2 Kinetic data for right hand during bottle opening captured at point of peak opening torque. Scaling factors used.

	Right Hand					
	Moments (Nm)			Forces (N)		
Subject No	x	y	z	x	y	z
1	-3.97	1.27	-0.18	-11.44	-44.33	76.95
2	-2.31	0.59	-0.58	-19.35	5.13	91.09
4	-1.37	0.90	-0.13	1.42	20.78	55.70
5	-3.07	0.61	0.37	-3.83	-36.08	56.06
6	-3.99	0.41	-0.03	7.57	-14.80	119.13
7	-3.36	0.42	0.24	9.26	-42.31	92.36
8	-2.37	0.59	-0.61	-19.87	5.00	90.98
9	-2.75	0.57	-0.12	-1.45	-34.96	82.40
13	-3.53	-0.60	-0.01	12.86	1.06	134.65
14	-2.98	2.23	-1.20	-36.45	4.50	104.67

15	-4.39	1.38	3.39	48.55	-56.54	92.37
17	-0.95	1.58	-1.18	-31.11	6.95	54.22
18	-3.99	1.58	0.82	4.79	-45.76	83.70
19	-2.06	-0.41	-0.43	-10.80	-3.36	86.03
21	-4.49	2.62	-0.14	-15.47	-26.51	117.39
23	-2.35	2.83	-1.00	-31.38	-1.59	93.37
25	-2.89	0.20	0.30	14.81	11.75	105.82
26	-2.08	2.11	-1.20	-29.30	9.61	91.22
27	-0.69	1.14	-1.47	-32.17	19.97	45.33
29	-3.14	1.62	-0.21	-13.62	-27.66	91.71