Application of biomechanical techniques to improved design of products and environments for an ageing population

Thesis

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Application of biomechanical techniques to the improved design of products and environments for an ageing population

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0.2 Abstract

This work describes the development of a technique for the evaluation of the performance of a product's physical user interface. The technique is intended to combine the best features of conventional user group testing with those of computer based biomechanical modelling.

A requirement for the new technique exists as social pressure demands that consumer products be optimised for users with a wide range of physical capabilities, while shortening product lifecycles leave less time for extensive user evaluation programmes.

A demonstration system was developed, based upon the use of an electromagnetic tracking system to gather upper limb motion data and a two segment, rigid link biomechanical model. Experimental work was carried out to test the effectiveness of the system at following limb movements and average error in reconstruction of hand position from segment angle data was 62mm (Standard deviation 41mm)

The modelling system was applied to the assessment of two types of product: cutlery and drinking vessels and the effectiveness of various statistical techniques in allowing the rapid identification of important design parameters was assessed. The use of Taguchi's smaller-the-better signal to noise ratio was found to be effective for the measurement of the effect of product design on shoulder and elbow forces. Cutlery with enlarged handles designed to reduce grip strength requirements tended to increase forces at the shoulder.

The method was also applied to an interface optimisation problem involving the design of a lever mechanism. Partial factorial design was used to minimise experimental cost during the assessment of multiple factors, but strong interactions were detected between interface parameters, reducing the value of the analysis. The overall height of the lever handle relative to the user's shoulder was found to be the most significant design factor, with an optimum operating situation existing where the lever was low enough to require almost full extension of the elbow during use.

The work concludes that biomechanical analysis holds further promise for the optimisation of interface parameters, provided the high experimental cost involved with present techniques can be reduced.

0.3 Contents

0.4 Table of figures

0.5 Research outline

0.5.1 Objectives

It is the principal aim of this work to investigate, create and assess new methods by which the interactions between products and users may be evaluated. A demand for such methods has been created by the need to mass-produce goods for a heterogeneous consumer population.

0.5.2 Outline of thesis

This thesis is presented in four main sections:

Section 1 outlines the context for the work described, it explains the need for product design that considers the varied needs of users, particularly those with disabilities (Section 1.2). It then examines the modern product design process, with the purpose of exploring the constraints upon, and the opportunities for, any new product assessment tool. The final two parts of Section 1 examine the methods currently available to assist in the design of user interfaces (Section 1.3) and the range of devices currently used to obtain quantitative information on human characteristics (Section 1.4).

Section 2 describes the development of the proposed interface evaluation tool: a motion analysis system linked to a biomechanical model that is capable of tracking the movements of the upper limb during product use and providing information on the forces and motions involved. Section 2 is divided into four main parts: Section 2.1 introduces the overall concept behind this approach to interface evaluation, Section 6 describes the choice of an appropriate motion analysis system, Section 2.2 discusses the design of the biomechanical model, and Section 2.4 discusses the analysis techniques that would be used to obtain useful design information from the modelling and analysis system.

Section 3 then describes the experimental uses to which the system was put, from validation of the model and sensor system (Section 3.2), through experiments designed to test the system's potential effectiveness (Section 3.3 and Section 3.4) to two main case studies: an evaluation of several existing product configurations (Section 3.5) and the use of the same techniques in a hypothetical product prototyping context (Section 3.6).

Section 4 summarises the work done, presents conclusions and discusses the possibilities for further use and development of the analysis approach.

References and additional pertinent material can be found in Sections 5 and 6, while experimental data and statistical calculations are shown in Section 7.

0.6 Document structure

This document is structured using four different heading levels.

Sections are numbered using the form **1.2.3.4**. Section headings are indicated by these numbers and by combinations of bold and italic type.

Level one

The first level indicates the overall phase of the work. The project took place in three phases:

1. Background

2. Development of methods

3. Experimental work

There are three further sections given heading level one:

0. This introductory section

4. An overall discussion of the work

5. The appendices

Level two

Second level headings take the place of chapter headings within each phase. There are between five and seven chapters in each of the main phases, along with **11 appendices.

Level three

Third level headings indicate individual sections within each chapter.

Level four

Fourth level headings are used to indicate sub-sections within a particular section.

1. Background

1.1 Introduction

This work is concerned with research into techniques to assist product designers in the difficult process of optimising the physical user interfaces of their designs. An optimally designed interface is one that can be used comfortably, effectively, and without risk of injury by the full range of a product's intended user population. It will be argued here that the current state of computer technology would allow the use of computerised biomechanical analysis systems to provide powerful support to designers conducting evaluations of product user-interfaces.

The work was inspired by the fact that the ageing population of much of the developed world is associated with an increasing incidence of physical impairment and disability. This has significant implications for product designers who up until now have largely been able to focus their product design efforts for a physically capable user population. If people with disabilities – largely but not exclusively the old – are to continue to take as full a role in society as is possible, they must they must have products that cater for their needs.

It should be noted at the outset, however, that no part of the work described here is intended to tackle specific areas of impairment or disability associated with ageing. Rather the aim has been to develop tools that would be applicable in design for an ageing population or any other physically heterogeneous user group. Indeed, it is hoped that the same techniques will prove useful for those working on products that try to reduce the incidence of cumulative trauma syndromes and other conditions affecting people of all ages. Ultimately it is likely, however, that the old will represent the largest target market for any individual or organisation seeking to use these techniques to produce better products.

The main body of the work is presented as follows:

Section 0 provides a brief historical overview of the problems involved in interface design, the tools and techniques that have been applied to the task of user interface design, and the culture within which any successful optimisation tool must operate. It then discusses the computer and sensor technologies available that would allow the realisation of a practical, inexpensive modelling and analysis tool.

This section is divided into four parts:

Section 1.2 concentrates in the issue of user heterogeneity, and discusses the reasons why product designers are being called to create interfaces that are accessible to people with an increasingly diverse range of physical capabilities.

Section 1.3 is concerned with design culture. The constraints presented by the demanding nature of the commercial product design process are discussed, and the opportunities presented by the new technologies which now dominate design methodology, are explored.

Section 1.4 provides a brief overview of the parts of the science of ergonomics that are most relevant to this work. Ergonomics is the branch of design and engineering that deals exclusively with user-product interface issues. It describes various philosophical approaches that have been followed in ergonomics and examines the state of the art in tools for ergonomic evaluation and optimisation.

Section 1.5 concentrates on the range of sensors and systems that allow designers to collect quantitative information on users' physical and performance characteristics. It is argued here that such devices provide a critically important link between the potential users of a product and the advanced modelling packages that will start to dominate ergonomic analysis in the years to come.

Section 1.5 provides a summary of all the important issues discussed.

1.2 The accessible society

1.2.1 Introduction

This section describes a major issue facing product designers in the industrialised world at the beginning of the third millennium: the need to cater for people with a variety of disabilities. It will examine the nature and size of the disabled population and the case for its inclusion as an important issue in both social and economic terms. Finally, it will argue that argue that product design has a crucial role to play in the dismantling of barriers that prevent people with disabilities taking up their full role in society.

1.2.2 Social and legal precedents

It has been a basic premise of most liberal societies in the twentieth century that prejudice and discrimination should be resisted in the strongest possible terms. The battles by women and by people from ethnic minorities to claim full and equal status are well known and well documented, and whilst many would argue that these battles are far from being won, the progress so far has been significant. One group of people however, still has every cause to feel that society's attitudes have not yet shifted to allow them a full and proper place: these people are those whose bodies fail to fulfil the unwritten criteria of appearance or performance expected by the majority: people who are in some way disabled.

The rights of people with disabilities have become a significant political and social issue in the last two decades. The importance of these rights has become manifest in several major pieces of legislation passed in various First-World countries during the 1990s:

1. In the United States the Americans with Disabilities Act of 1990 required that all businesses involved with the provision of employment, public services, transportation, public accommodations and telecommunications provide "reasonable accommodation" to people with disabilities.

2. In Australia the Disability Discrimination Act passed in 1992 sought to "eliminate, as far as possible, discrimination against persons on the grounds of disability" in many areas of society.
3. In Britain, numerous attempts to pass a law culminated in our own Disability Discrimination Act of 1995. Aimed firmly at employers, the act requires that they make "reasonable adjustments" to working practices and premises to ensure that disabled applicants are not disadvantaged.

Legislation is not the only way that society is altered of course. The main thrust of this section will be an examination of the effect that an increased awareness of the importance of disabled people as a significant and growing segment of the population is having on the commercial world, and in particular on those who design, manufacture and supply consumer products.

1.2.3 Types of disability

Before starting any discussion of the disability issue it is worthwhile briefly examining some of the types and causes of disability itself. Classification of disability is a highly complex issue, it has been attempted by many groups: - doctors, sociologists and actuaries to name but three, and the point is in many ways as much a political one as it is scientific. Since no clear consensus exists, [Marks, 1997] it is hoped that the classification used here will be sufficient to serve its limited purpose.

Disability can be separated into three broad categories:

1. **Sensory disability.** Blindness and deafness are the predominate disabilities in the category, although loss of tactile sensibility caused by diseases such as leprosy and diabetes can be a cause of considerable further problems. Impairments of taste and smell are not normally so severe in their effects on the daily lives of those affected, but their social effects can be quite profound.
2. **Mental disability.** Mental disabilities are probably the least well understood area in modern medicine, they can range from severe and destructive personality disorders to poor memory performance and dyslexia.
3. **Physical disability.** Physical disabilities are usually thought of as those affecting the musculoskeletal system, such as arthritis; or parts of the central nervous system responsible for

muscular control, in the case of spinal cord injury for example. A huge variety of conditions do fit this description, but an equally large number of others affecting the pulmonary, cardiovascular and digestive systems can have highly limiting effects on people's lifestyles.

It will be immediately clear that there is considerable crossover between these categories, and indeed a single cause can have a variety of debilitating effects.

1.2.4 The disabled population

Any explanation of the importance, or potential importance, of disabled people as consumers requires the examination of two essential issues: - the continually growing population of disabled people, and the changing demands of these people.

People with disabilities represent a significant fraction of the population of most countries. Estimates of their exact numbers vary according to country and to definition of disability, but can be as high as 30% [Poulson et al, 1996]

One factor alone is the cause of a tremendous increase in disability in industrialised countries: - the ageing population. After the post-war "baby boom" of the 1940s and 50s the birth rate in much of the industrialised world has dropped considerably. At the same time advances in diet, hygiene, and medical technology have resulted in a larger fraction of the population living on into old age [Coleman, 1993; Fullerton, 1983] As more people finish their lives in a steady decline, rather than having them abruptly terminated by war or disease, so they can expect to experience some form of disability in due time. In Britain almost 70% of the disabled population is made up of elderly people [Martin et al, 1988]

Inevitably, this demographic change will alter consumer demands. Much social pressure, resulting in legislation described above, has been applied by younger disabled people, but the majority of disabled people, the elderly, may have a far larger effect on society through shear weight of numbers and the leverage provided by spending power. As younger markets diminish and older ones increase, manufacturers will have to turn increasingly to them.

The volume of demand will not be the only new aspect however, the next generation of elderly people will be highly educated consumers, having lead their adult lives in the sixties, seventies and eighties they will be unwilling to "make do and mend", demanding instead well-designed, well-built products for which they, or those who support them, will be willing to pay.

1.2.5 Models of disability

Disability and disease are not synonymous, and there have been several attempts to consider the effects of disability separately from its causes. Of these models of disability, two will be discussed here: -

1. **The medical model.** The most widespread model is that set out by the World Health Organisation in the International Classification of Impairments, Disabilities and Handicaps (ICIDH) [World Health Organisation, 1980]. The ICIDH uses a three-level definition, suggested in the title. The first level, *impairment* refers to "disturbances at the organ level" that is the disease or medical dysfunction that is the root of the problem. The second level, *disability* refers to "disturbances at the personal level" that is the actions that the individual finds it difficult or impossible to perform as a consequence of the impairment. And the final level, *handicap* refers to "disturbances at the person/environment level" that is the social roles and functions that a particular individual finds it difficult or impossible to perform as a result of impairment or disability. The ICDIH places a strong emphasis on the fact that handicap is very much a consequence of a particular impairment upon a particular individual. For example, loss of fine finger mobility will have consequences that are much more serious for someone who makes their living from being a professional violinist than for someone who works as a gravedigger. This set of definitions has become known as the *medical model* of disability.

2. **The social model.** Sociologists such as Michael Oliver [Oliver, 1991; Oliver, 1990] argue that by assuming society to be invariant and defining handicap as a mismatch between individuals and this society, people with disabilities will inevitably be marginalised. The *social model* of

disability acknowledges the existence of physical symptoms, but defines disability as the failure of society to cope with the demands placed upon it by individuals with impairments.

1.2.6 Design for disabled people

There has been much discussion in the literature of design and gerontology as to the best approach to the design of non-medical devices for disabled people. [Kumar, 1992; Bouisset and Rossi, 1991; Smith, 1990; Kelly and Kroemer, 1990; Orpwood, 1990; Feeney and Galer, 1981; Stoudt, 1981; Nichols, 1976; Chapanis, 1974]. There have been two major paradigms for disability-related product design, which stem very neatly from the two models of disability discussed above:

1. In the medical model the concept of *assistive technology* is common, whereby people are provided with tools that help them to compensate for their impairments and interact successfully with the world around them.
2. The social model, on the other hand, proposes a concept known variously as *universal design* or *accessible design* in which "normal" products are designed and built to be useable by as large a fraction of the population as possible, thereby allowing more people to fulfil ordinary social roles and actually reducing the incidence of disability. Ian Parker puts the argument quite succinctly:

> ...in the medical model, a man in a wheelchair cannot get where he wants to because his body is not up to it. The social model acknowledges that the man has an "impairment", but sees the obstacle as the cause of disablement. [Parker, 1995]

It does not take much analysis to realise that true universal design is an unobtainable goal: - not everything in the world can be made operable by people with quadriplegia, for example, but it can also be argued that in many cases good accessible design results in an increase of potential market share and increased ease of use for the entire target group, not just those with impairments:

> [The universal design paradigm] aims at broadening the usability of mass-market products to people with a much larger spectrum of functional abilities, and therefore to larger markets. The ultimate goal of universal design would be to minimise the need for assistive technology, which would be rendered obsolete by products that are inherently accessible. Such products are characterised by large markets, competitive prices and widespread diffusion through mass marketing. However, mass market products are also, unfortunately characterised by vendors who often consider people with particular disabilities as

inconsequential components of their market, and who tend to be indifferent to these people as customers. [Harkins, 1995]

A commonly noted criticism in design for people with disabilities [George et al. 1988] is that there has been a tendency for designers to concentrate purely on the functional aspects of a product while ignoring its aesthetic qualities. Consumer purchasing decisions are rarely, if ever, made on the basis of functional performance alone and disabled consumers are no different in this respect. Indeed, under usage of many assistive products can be attribute to the fact that they are aesthetically unappealing rather than because of any functional limitations. It is therefore vital that psychological factors involving a consumer's feelings on the appeal of a product are taken into account along with its physical usability.

1.2.7 Summary

It has been the purpose of this section to demonstrate the following:

1. The disabled population is becoming larger and more politically and economically significant all the time.
2. Disability can be considered to be in whole or in part a product of the environment in which a person must function
3. The design of products for use by disabled people can, therefore, serve to reduce the degree of difficulty people must face during their daily lives.
4. Aesthetic factors are as important as functional ones in ensuring acceptance by disabled consumers.
5. Historically there have been two basic approaches to the design of products for disabled people: The assistive technology approach, which seeks to develop tools to allow people to interact successfully with the existing environment, and the universal or accessible design approach, which seeks to alter the basic design of the environment so as to maximise its accessibility.

Whichever model of design for the disabled is adopted, the critical issue will always be the matching of a product to a user with non-normal physical characteristics. Information on the physical abilities of the members of disabled populations is therefore of relevance to the designer of numerous items. Various studies have suggested that in many cases where assistive devices have been abandoned or underused [George et al, 188; Mann et al, 1993] or have proved inappropriate [Gardner et al, 1993] it is the design or selection of the human interface of the product that is at fault [Goble and Nichols, 1971], making the product either unusable, or unacceptable to the consumer.

The improvement of design usability is, therefore, a critical issue for the products that will be marketed in the Western world during the early part of the twenty-first century. The populations of these countries will be older than those of any previous society, and they will be used to a higher material standard of living. This combination will make unprecedented demands on the structure of society: the ratio between service consumers and service producers will increase enormously, and technology will be expected to make up the shortfall, providing care and taking on roles that are currently carried out by people. The more tasks that can be carried out unassisted by people with a variety of impairments and disabilities, the more generally autonomous those people's lives will become. This will lower the demands placed upon those responsible for their care, be they members of the family or employees of the state or some other care providing organisation.

The importance of usability in this context will require product designers to alter their perspective slightly and start to develop products in a different way. While aesthetic factors in products for the disabled require exactly the same treatment as any other design problem (indeed, it is simply the lack of this treatment to many assistive technologies that has created difficulties), the design of user interfaces requires a more specialised and less intuitive approach.

Before discussion is turned to the array of tools currently available to assist in the design of user interfaces attention will be given to the product design process itself. Without knowledge of the culture in which products are designed and the pressures under which their designers operate any discussion of improvements in interface design methodology would be inappropriate.

1.3 The product design process

1.3.1 Introduction

The nature of the product design process places important constraints on the way objects are designed for, and evaluated by, people with disabilities. It also opens numerous opportunities for new techniques to be adopted. To set a context for the discussion some important elements of the design process will be discussed here.

Sections 1.3.2 to 1.3.3 discuss two very traditional design issues: the difference between evolutionary and revolutionary design, different ways that technology is encapsulated in a product, and the formal representation of the design process as a series of iterative loops.

Recent trends in the way products are developed and in the range of tools available to designers themselves are having a profound effect on the way design work is carried out Sections 1.3.4 to 1.3.9 discuss a range of issues that have an effect on the context into which the current work must fit, or which provide tools that have been used in the work itself.

1.3.2 Evolutionary and revolutionary design.

It is generally held that products are designed in two fundamental ways, by evolution and by revolution. Revolutionary design, or invention, is the most famous form of product design but by no means the most common. In revolutionary design an entirely new approach to given problem is conceived and adopted, revolutionary designs often push technology forwards by significant leaps, and in doing so they often uncover problems that had previously not been considered.

Evolutionary design is the process of examining an existing product or system, noting its faults and weaknesses and attempting to eliminate these whilst still maintaining all the benefits of the original.

Most products available today have been through a lengthy process of revolution and evolution. The personal stereo cassette player is a good example. The original revolutionary concept: a tiny device that played stereo music cassettes without the ability to record on them, combined with unobtrusive, lightweight headphones, was brought about using technologies that had evolved in other products. Since its inception the Walkman has undergone countless stages of evolution so that those currently on the market are smaller, lighter, cheaper, better sounding, more elegant and more energy efficient than the early models.

Traditionally, user interface design has very much been an evolutionary process. Feedback from users (often in the form of complaints) allows interface problems to identified and fixed in the next generation of the product. Later parts of this section will discuss the limitations, according to modern design thinking, of such a "build-use-fix" approach to design optimisation.

1.3.3 The design cycle.

The cycle of design, from definition of specification, through conceptual and detailed design to full production, is a complex process. There have been many attempts to formalise this sequence both in the quest to understand the human creative process and in order to optimise the efficiency of commercial product design.

The conventional formal model of design represents a sequential process: - a design passes through discrete stages and after each stage undergoes some form of test. Failure of the test results in the design being passed back down the chain to undergo one or more processes again, success allows it to pass onto the next stage. In larger corporations, design departments would often be organised in the same sequential fashion, designs being passed through various teams as along a production line.

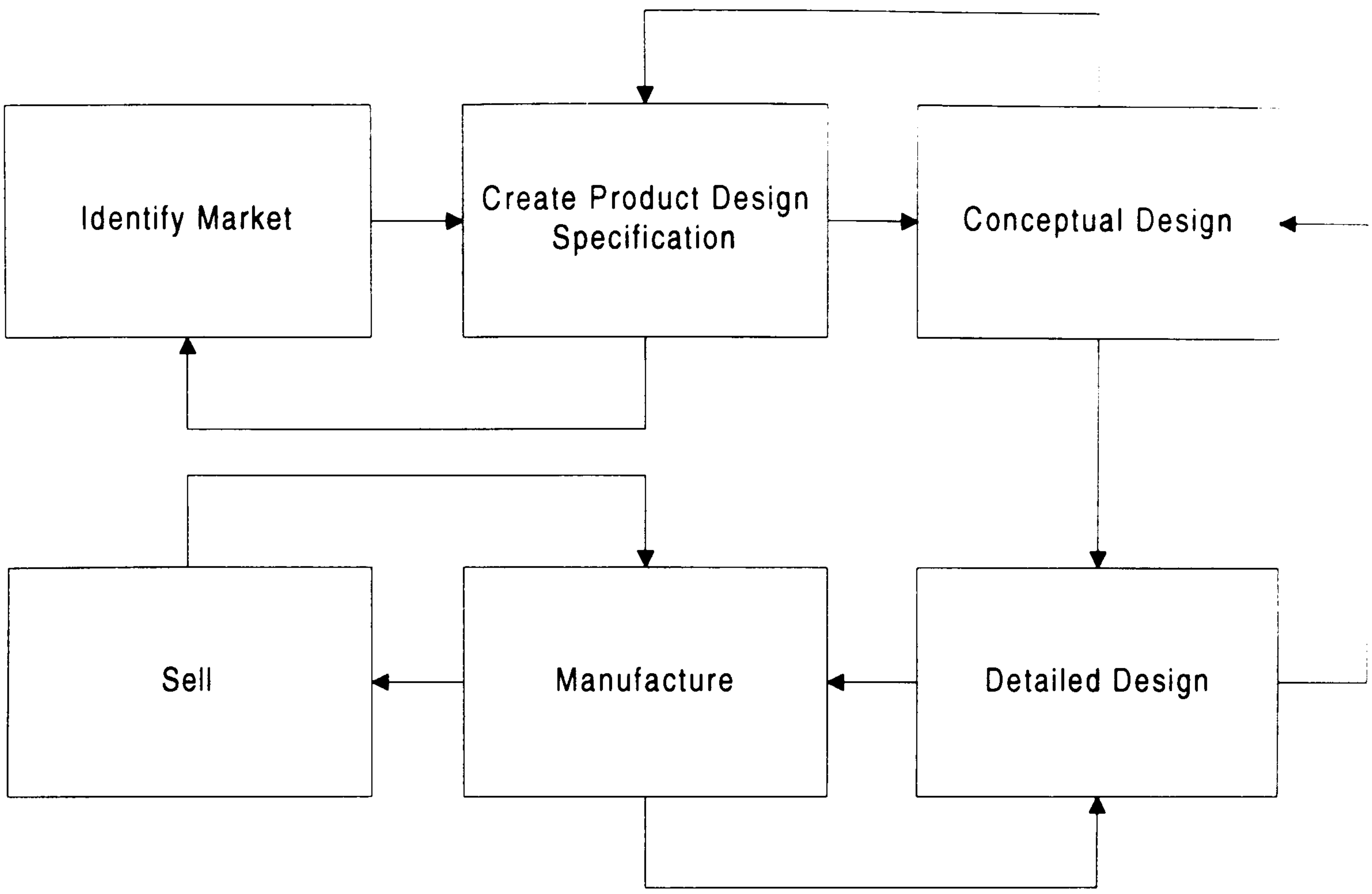

Figure 1: The engineering design process (adapted from [Pugh, 1991])

1.3.4 Technology in design

Technology itself can be applied to products in different ways: it can be *intrinsic* to a product or *extrinsic* to it. Intrinsic technology is encapsulated directly within the products that people use every day: computers, televisions and telephones all contain very advanced technologies. Extrinsic technology, by contrast is hidden further up the production process: A modern bicycle may be a collection of relatively simple components made from readily available materials, but each bicycle has the benefit of more than one hundred years of steady development and design optimisation behind it, today's bicycles offer greater fitness-for-purpose than their predecessors ever could. This work has been concerned with this encapsulation of knowledge within a product, its basic premise has been that design can be used to make a product easier to use, less likely to cause injury, and accessible to a greater number of people without it being necessary to include a micro-processor inside every toothbrush or door handle.

1.3.5 Shortening product life cycle

The accelerating progress of technology has been widely discussed [Toffler, 1973]. Manufacturing industry is simultaneously a principal cause of this accelerating progress and a slave to its effects. Modern products are becoming more complex than their predecessors, sometimes by orders of magnitude, and can expect to sell for a much shorter time before technological progress and altering consumer tastes make them obsolete. The economic advantages of putting a product on the market extremely rapidly are immense, indeed some major corporations are currently implementing as much as a ten-fold reduction in their design lead-up times [Toffler, 1973] Such an environment is extremely demanding for engineering and design teams; products have to be designed quickly and they have to function well after few prototypes have been tested.

This, however, is where the problems lie for the human-interface designer, because it is the numerous prototypes and the long period of time in which products were developed that gives those designers and engineers involved in the optimisation of usability the opportunity to ply their trade. By observing and talking to people using products, ergonomists have been able to identify problem areas and evolve the body of empirical knowledge upon which their science depends. Without these opportunities occurring during the design process, improvements in usability run the risk of being side-lined, shelved or reliant to the outcomes of customer feedback, or worse - litigation. To improve usability in this way is slow, and exceedingly undesirable. A product's users have no wish to be used excessively as guinea pigs in its development process. They spend their money in order to receive the benefits of previous research and development effort, not to take part in extended experimental trials.

The challenge therefore, is clear: methods must be found that use all the available technology in order to make usability optimisation a faster and more effective process.

1.3.6 Increased automation of the design process

Technological progress has changed the very process of design as much as it has altered the products of this process. Most significant has been the introduction of computers to all stages of design and manufacture. Computer Aided Design (CAD) programs have evolved from drafting aids into astonishingly sophisticated modelling systems in which components may be visualised, analysed for structural integrity, electrical and thermal performance, and compatibility with other elements of the same design. Even conformance to legal requirements can be checked before a single physical model of a new product exists [Clarke, 1996] Whilst products rarely go from conception to manufacture entirely in a virtual environment, with no physical prototypes ever existing, such a process is technically feasible and commercial adoption of such practices may not be far away.

The automated design process certainly facilitates reduction in design-time, but in doing so, it confounds the problems of lack of prototypes and testing opportunities that afflict the designers of user interfaces.

1.3.7 Concurrent design

As described in Section 1.3.3, taking a product from conception to manufacture has traditionally been considered a sequential process. Designers and engineers produce concepts, details are filled in and finally a completed design is passed to manufacturing engineers who try to build the product as cheaply and effectively as possible. However, as design lead times reduce it is seen as more effective to use a concurrent approach to design development in which manufacturing, maintenance and a host of other considerations are included in the design process from a very early stage. This trend can be explained in terms of risk reduction; when a new design is developed, there is no guarantee that it will eventually be a market success. It is generally accepted that the further into the design process one is, the surer one can be that a design is a good one, but to get to this point, where the risk of a design failing is minimal, a company will have to invest considerable resources. By making more crucial design decisions happen earlier, risk is reduced more quickly, so while initial design investment will be higher, this expenditure is offset by the reduced chance of discovering a critical error much later in the development process, when correction will involve considerably higher expense.

Concurrent design is effective in ensuring that the final design is not compromised by last minute fixes to problems that should have been considered earlier on, but it does have the effect of increasing the workload of the teams involved in the early stages of the design process. In fact it might be argued that all the developments in the process of design (concurrent design, computerisation, quality-centred design) have had this effect of piling responsibility for critical design decisions earlier and earlier in the product life cycle.

Increasing the design team's mental workload has a strong effect on user interface design. The human interface of a product has traditionally had a relatively low priority, particularly in companies who sell primarily on the technical rather than the aesthetic qualities of their products. If designers are under extreme pressure to resolve the conflicting demands of a variety of design criteria then optimal interface characteristics may be among the first casualties. It is vitally important in this context that interfaces can be assessed at minimum cost (in time, money and effort) and that the results of such assessment can be rapidly and clearly assessed in order that they can take their place on the discussion table along with all the other aspects of technical specification and manufacturing limitations.

1.3.8 Quality centred-design

In the last few decades, management experts have espoused various philosophies that can be summarised under the heading *quality-centred design*. The basis of this philosophy is that the primary objective of all commercial endeavours should be the enhancement of quality, quality being defined as *fitness for purpose* [Juran and Gryna, 1980] or *features and conformance to features* [Fowlkes and Creveling, 1995]. In other words, products should always do what they are intended to do. Whilst this idea may seem trivial, the quality movement has been responsible for the development and promotion of various sophisticated analytical techniques. It is these techniques that have perhaps been the most interesting development: quality is seen as an attribute that can be defined and measured quantitatively, thus allowing competing design and process options to be compared and improved on a very rigorous basis.

Quality centred design has two interesting ramifications for human interface designers. The first is the fact that build-test-fix solutions are less acceptable under the quality centred design philosophy: every attempt is made to ensure that products are designed right first time, thus reducing the downstream costs associated with product failures and alterations to designs that have already begun production. The second, and more positive effect is the possibility that some of the statistical approaches developed by the quality movement may be applicable to the optimisation of human interfaces, thus allowing interfaces to be improved rapidly and increasing the likelihood of a successful solution being adopted. Foremost among these techniques, and of most relevance to this work, is a collection of techniques known as robust design.

1.3.9 Robust Design

Robust design is one aspect of the quality improvement movement that has had an extremely significant effect on modern engineering design. Ideas first promoted in Japan by Dr. Genichi Taguchi, and often known as Taguchi Methods, have, it is claimed, been responsible for 80% of the quality improvements carried out by Japanese industry [Dertouzos et al, 1989] Robust design is based on the idea that the performance of any product is affected by sources of noise, be they variability in the manufacturing process, different environmental conditions or abuse by the user. Analytical methods are applied to quantify the effects of noise on the performance of a particular design and to select designs that are as insensitive as possible to noise, thus maximising the chance that the product will do what it is supposed to do and will continue to do so for as long as possible.

In fact, the statistical processes upon which most robust design methods are based have evolved from a scientific technique known as Design of Experiments, developed by R. Fisher who worked for the Department of Agriculture in Britain in the [Fowlkes and Creveling, 1995]. Design of Experiments is a set of statistical methods that form the foundation of almost all modern experimental research. These techniques are intended to maximise the efficiency of the experimental process and the validity of the conclusions drawn from experimental work. Taguchi methods simplify these approaches specifically for use in an engineering environment. Some statistical validity is lost during this simplification, but proponents of Taguchi methods argue that this loss is more than compensated for by the comparative ease with which the methods can be applied. In all engineering work the cost of an approach, be it measured in time or money, is critical, and a cheaper method that produces good results is to be preferred over a much more expensive one that provides a relatively small improvement in the final design.

1.3.10 Summary

Since the industrial revolution, the role of technology in society has been undergoing a slow and profound change. Pre-industrial societies relied on human and animal power for motive force, and on human direct labour to carry out every task. Thus, for one individual to live in physical idleness required the efforts of a considerable number of other individuals to be exercised on their behalf. This distribution of effort was both cause and indicator of social class: the higher classes relied on the efforts of those below them to live. In the modern world machines are rapidly replacing people as the principal sources of physical effort: sedan chairs are today and the agricultural labour force is many times smaller than it was two hundred years ago. In modern society very few people have servants, but almost everyone has a variety of machines at their disposal: washing machines, dishwashers, and photocopiers carry out tasks that would otherwise require extensive human effort. This replacement of human effort by technology is significant to the discussion of this work because of the expectations and aspirations it has engendered in society. Now that machines can carry out the roles of domestic servants in many areas, they are expected to be able to do so in all areas. Few people aspire to a life in which they are waited on hand an foot: the ideal is rather an easy independence. The same change in attitudes applies to the role of the carer in society. People who were unable to do things for themselves were looked after by relatives or servants, today technology is expected to carry out this role and the product designer is responsible for the creation of machines that are capable of doing this.

Design is a complex issue, and it has not been the intention of this section to provide a thorough background, but merely to bring to the reader's attention certain aspects of the modern design process that have a bearing on the problem of design for a diverse user population.

The modern product design process has been presented here as a complex, highly computerised environment in which designers are simultaneously being inundated with a tremendous armoury of new tools to assist them, and an ever-increasing number of responsibilities and considerations to deal with in shorter and shorter periods of time. It is into this context that any improvement in the way items for disabled people are designed must fit, as only by addressing designers on their own terms can a new technique hope to achieve widespread acceptance and use.

The next section addresses more specifically the tools and approaches that designers have available for the human interface optimisation process, these techniques are collectively known as *ergonomics*.

1.4 Ergonomics

1.4.1 Introduction

A large part of the work in any product development process is involved with the control of component variability, tolerance design, and the matching of separate components and subsystems. The human user of a product often forms the most variable component in the system; the control of this variability is very difficult and designing systems that cope with it represents a significant engineering challenge. The study of methods for producing designs that cope with variable human characteristics is called *ergonomics*. In the design of items for use by people with disabilities, particularly under the universal design paradigm, the challenge is to cope with unusually high levels of user variability. Therefore, by definition, ergonomics techniques should be of benefit.

The word *ergonomic* is derived from two Greek words, *ergo* - work and *nomos* - laws. The laws that govern human work. In practice, the umbrella of ergonomics covers a diverse range of activities and sciences, and its true extents are often poorly understood. Ergonomics research activities cover ever imaginable aspect of the study of human interaction with the artificial environment (the word *artificial* is used here in the sense of "The product of artifice", or "Man-made" rather than "Unnatural"). These activities range from the shaping of a handle so that it does not hurt when held to aspects of the management and control of the most complex systems and organisations human-kind has so far developed, nuclear power plants and military aircraft being notable examples.

Ergonomics has been criticised for lacking a central philosophy or paradigm [Kondraske, 1995], and it is true that the wide range of issues involved, from anatomy, physiology and mechanical design to psychology and control theory, make it difficult to follow a common thread through the labyrinth of ergonomics research and practice. Some ideas do however, arise with great regularity, and several of these will be outlined here.

This chapter will begin with a brief overview of the human-machine-systems concept, one that is fundamental to most ergonomics practice (Section 1.4.2). It will then summarise the range of areas that ergonomics work finds within its scope (Section 1.4.3), before concentrating on ergonomics as it relates to physical interface design with a short summary of anatomy, anthropometry and biomechanics (Section 1.4.7).

The second half of the section attempts to move away from the theoretical somewhat and examine the tools and approaches that ergonomists actually apply when designing the physical interface of a product. Two distinct approaches are presented, one traditional (Section 1.4.9), the other slightly more modern (Section 1.4.10). Next the idea of the ergonomic model is introduced (Section 1.4.11), which in its various forms is a basic ergonomic design tool. The final sections of the chapter look at the effect the computer-aided design process has had on the development of ergonomic models.

1.4.2 Human-machine Systems

The concept of the human-machine system is probably the most fundamental of all the main ideas in ergonomics. It arises primarily out of work carried out by WT Singleton during the Second World War [Singleton, 1974]. In essence, all artificial entities from the simplest hand tool to the largest power station or chemical processing plant, rely for their successful operation on the interaction between one or more human operators and the inorganic or non-human elements of the system. Even systems that operate automatically for most of their working lives require human intervention at some point in the assembly, maintenance or configuration process. In early industrial equipment all the relevant adaptation was done by the operators and those that failed to adapt simply lost their jobs or found alternative solutions to the problem a machine was designed to address. During the war, however, the need arose to ensure that mass-produced military equipment could be used by any member of military personnel with minimal adaptation; there simply was not a large enough supply of people available to select personnel to fit the machines. Human-machine systems analysis was born out of the attempts to address this problem. Singleton's approach was first to describe the function of a system, and then to allocate aspects of that function respectively to the human operator(s) and to the machine itself. A famous early example of this "separation and allocation of function" is the Fitts' list [Singleton, 1974], shown in Figure 2.

	Machine	Man
Speed	Much superior	Lag 1 second
Power	Consistent at any level. Large, constant standard forces	2.0hp for about 10 sec 0.5hp for a few minutes 0.2hp for continuous work over a day
Consistency	Ideal for : routine; repetition; precision	Not reliable: should be monitored by machine
Complex activities	Multi-channel	Single-channel
Memory	Best for literal reproduction and short term storage	Large store, multiple access. Better for principles and strategies
Reasoning	Good deductive	Good inductive
Input sensitivity	Some outside human senses e.g. radioactivity	Wide energy range (10^{12}) and a variety of stimuli dealt with by one unit; e.g., eye deals with relative location, movement and colour. Good at pattern detection, can detect signals in high noise levels.
	Can be designed to be insensitive to extraneous stimuli.	Affected by heat, cold, noise, and vibration (exceeding known limits)
Overload reliability	Sudden breakdown	Graceful degradation
Intelligence	None	Can deal with unpredictable and unpredicted; can anticipate
Manipulative abilities	Specific	Great versatility

Figure 2: The Fitts' list for allocation of function between humans and machines.

Once functions have been allocated, the best way to carry them out can be defined. For mechanical elements this would be the iterative design process discussed elsewhere in this document. For human elements, it might involve the selection and training of operating personnel. The critical work of the ergonomist however, arises in the design of the interface between the human and the machine. No matter how effectively the two sides may be able to carry out their individual functions, if they cannot communicate and interact successfully then the system is bound to fail. Examples of this failure are legion in the history of industrial safety from the Three-Mile Island and Chernobyl nuclear power station accidents to the difficulty people have every day opening the doors to public buildings. [Perrow, 1984; Norman, 1998].

1.4.3 Fields of study

Ergonomics practice can take an extremely diverse variety of forms, but is commonly broken down into three different areas using an analogy taken from the world of computers [Sanders and McCormick, 1992; Wickens, 1992], these areas are:

1. Input
2. Processing
3. Output

Inputs to humans take place via the senses: - sight, hearing, smell, taste, touch and the kinaesthetic senses. Processing is carried out by the brain and nervous system which in turn invokes the musculoskeletal system to achieve outputs. It should be noted that this analogy corresponds closely to the sensory/mental/physical taxonomy of disability presented in section 1.2.3 The exact forms that ergonomic analysis can take will limited to discussion of the output category in later sections, but an overview of the principal factors concerning the ergonomic designer will be presented here.

1.4.4 Input

In the vast majority of cases human control of a mechanical device takes the form a closed loop control system. The operator receives sensory input that provides information on the state of the system during the control process and takes controlling action as a result of this information. Therefore, one of the principal concerns of the ergonomist is the clear and effective presentation of information.

Any of the senses can be used to convey information, but in practice, the visual and aural modes are by far the most common.

1.4.5 Processing

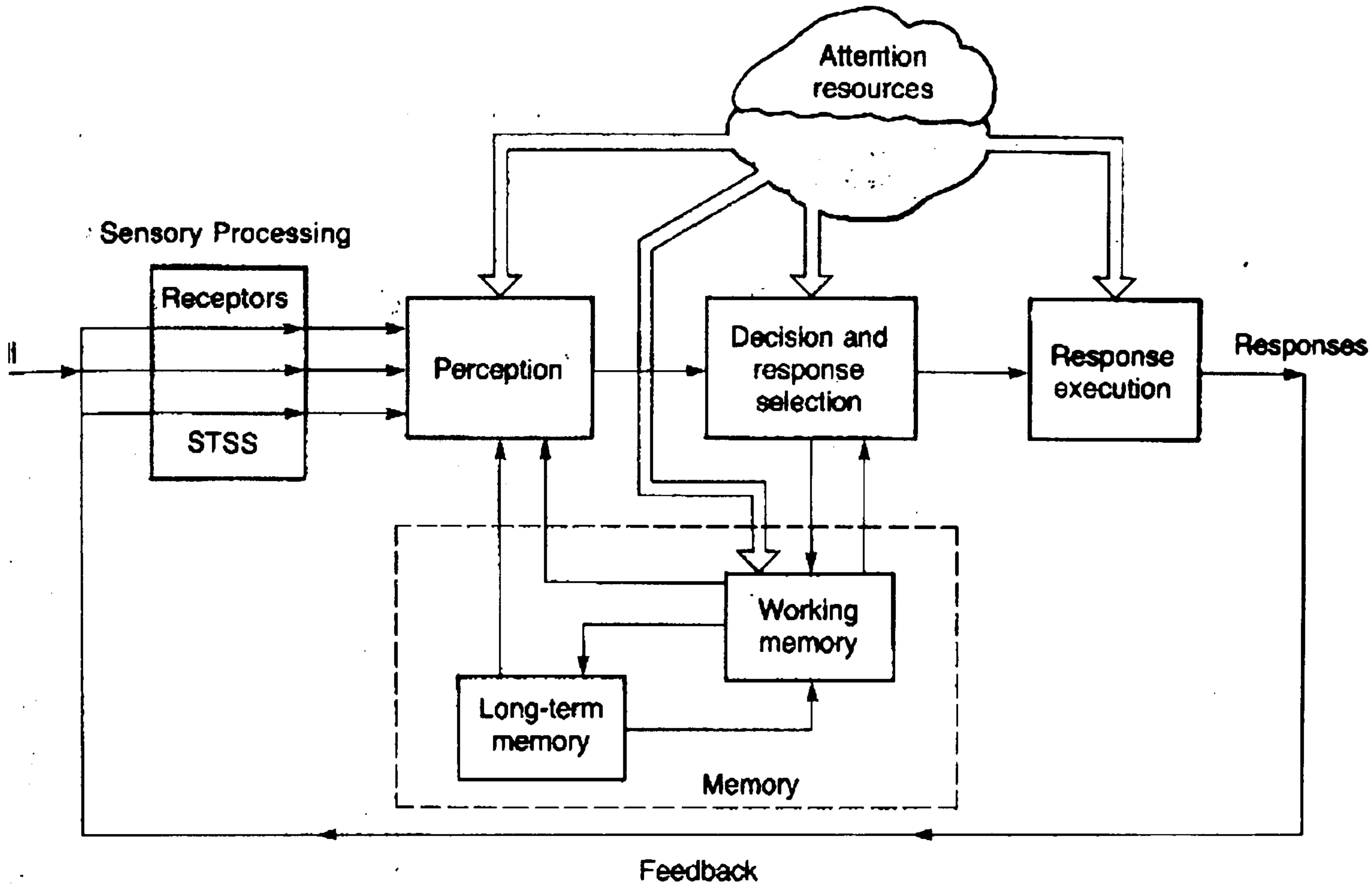

Figure 3: A model of human information processing. (From [Wickens, 1992])

The human brain is probably the most complex object known. While no psychologist would claim to have a detailed understanding of the operation of the brain, a number of models do exist that can be of great assistance to designers attempting to gain an idea of how human information processing capabilities will fit into systems that they create. The model described here is that given by Wickens [Wickens, 1992]. It is illustrated in Figure 3 and contains the following main elements:

1. Sensory processing

This can be considered as the hardware element of the senses, the eye and ear convert light and sound waves respectively into a format that can be dealt with by the brain. This information is then held in a *short-term sensory store* from which it can be accessed by the next stage in the process.

2. Perceptual encoding

Perceptual encoding is the process by which raw sensory information is converted into useful elements of information, the conversion of written symbols or spoken sounds into words is a good example of this encoding process.

3. Decision making

Once the brain has recognised the information presented to it, it then has to decide what, if any, actions must be taken as a response.

4. Execution of response.

If a response is to be made then the brain must trigger the processes required to execute the desired response, these would normally be muscular action of some sort, be it movement of the limbs, the formation of speech or simply a movement of the eyes to focus attention on a new target.

5. Memory

Memory is a resource that supports all the processes above, situations are compared with similar situations previously experienced, and this comparison ca help both in the encoding of sensory information and the selection of an appropriate response. Memory is also constantly receiving new information as processing continues. It is common to divide memory into *short-term* or *working* memory and *long-term* memory. Short-term memory is the place that information currently being processed is held for evaluation or comparison, while long-term memory is the store from which information elements are drawn.

6. Attention

It is normal to consider the brain to have a finite *attention resource* this resource is shared among the elements of the information processing task, thus it is more difficult to collect sensory information if one is carrying out a demanding decision-making process.

1.4.6 Output.

Once the operator has received the required information on the state of the system and made the necessary control decisions, he or she must then interact physically with the system in some way to communicate the desired actions. Whilst modern motor control theory suggests that it is unwise to consider motor action and information processing as separate and unrelated elements of the control cycle [MacKenzie and Iberall, 1994; Winter, 1990; Stelmach and Requin, 1992; Summers, 1992; Starkes and Allard, 1993; Bennett and Casteillo, 1994], conventional ergonomics following the computer metaphor described above often does so. In general therefore, the ergonomist would consider the body to be a robot, controlled in some unspecified way by the brain within it and acting physically on the environment around it. Several related sciences consider the characteristics and capabilities of this "robot body" notably anthropometry and biomechanics. As the bulk of this work in this project concentrates on the issues of designing to match human output capabilities, a more lengthy discussion of these topics is presented below.

1.4.7 Anatomy, Anthropometry and Biomechanics

Whilst it is clear that the human body is not a simple machine, and its treatment as such in some areas of ergonomic analysis has been fraught with problems (Section 1.4.9), it is nevertheless true that an understanding of the mechanical basis upon which the body operates can provide significant insight for the designer.

The mechanism of the human body has been studied in numerous ways, the three-part title of this section is intended to summarise three major topics in this area, so firstly these terms should be defined.

1. **Anatomy** is the broadest term given to the study of the human body: anatomical study is devoted to the description of the basic form of the components of the body and the functional relationships between those components.

2. **Anthropometry** is the science of the measurement of the human body. Anthropometry has been used historically in two areas: - firstly in anthropology, where scientists sought to describe regional and racial differences between groups of people by difference in body mass or skeletal measurements; and secondly in product design and ergonomics, where it has long been realised that we do not live in a world where one-size-fits-all. In pre-industrial days such items as clothes

and footwear would be made to the measurements of the intended user, more often than not by the intended user themselves, but the rise of large scale manufacture using inflexible production lines made this type of approach undesirable, and designers sought to find a minimum number of basic patterns or a minimum range of adjustability that would allow products to made that would fit the majority of the population. This need gave rise to the science of engineering anthropometry [Kroemer, 1989; Roebuck et al, 1975].

A telling example of the difficulty involved in creating a single product design for people with widely differing anthropometric characteristics is given by [Branton. 1984] in a study of back shapes intended to produce data for the design of railway carriage seats. Branton concluded that the variation in seated back profiles was so great that no single profile could hop to provide a reasonable match to a large majority of the expected user population. An identical problem is faced by the designers of car seats, with the added restriction that users must not only be seated comfortably, but must also be able to operate the vehicle controls successfully and view mirrors, windows and instruments. Most car designs tackle the problem through the use of adjustment built into the seat, with increasing numbers of degrees of freedom available as vehicle luxury (and price) rises.

Anthropometry itself has been sub-divided into several different types:

a. **Static anthropometry**: - this refers to the basic size and shape of the body and its parts

b. **Dynamic anthropometry**: - (kinematic or functional anthropometry) this refers to the ranges of motion available at the joints, and the implications of this for the design of equipment and environments, for example work places.

c. **Newtonian anthropometry**: - Concerns the forces acting on, and applied by the body when carrying out a task, Newtonian anthropometric information is used to support biomechanical analysis, discussed in the next section.

To be useful as an engineering concept, anthropometry must seek to simplify the infinite variability of human characteristics and to map their extents so that designers have some hope of dealing with a complete target population. Anthropometrists tackle this problem with various statistical techniques. Most statistics have one of two purposes, they either exist to allow information on a known sample to infer information about the population from which the sample was taken, or they exist to reduce a large volume of data so that useful information be taken from it: - the analyst ignores the trees, but gains a greater understanding of the wood.

The convention normally adopted for the representation of anthropometric data is based on the use of percentiles. Body measurements are usually assumed to be spread within the population according to a *Gaussian Normal Distribution*, the characteristics of which can be summarised using two numbers:

1. The mean value

2. The standard deviation from the mean

Once these numbers have been estimated by measuring a large sample group, designers then have the means of estimating the range the measurement would be likely to take in the central 90 or 99% of the population, and they can attempt to size their products accordingly.

While the use of mean and median measures is conventional in many areas of anthropometry, not all human characteristics follow a normal distribution. Where there is significant deviation from the normal, other statistical measures may be more appropriately used to represent the range of values, for example by the use of the median or mode values rather than the mean.

3. Biomechanics is the study of mechanics applied to the structure and movement of living organisms. Biomechanics itself, as can be seen from the preceding definition, is a broad topic, and biomechanical analysis varies in scale from the analysis of fluid motion through the smallest capillaries in the body to the study of the gross forces involved in large skeletal movements. In general it is at this larger scale that biomechanics has found application in the world of ergonomic design. As with anthropometry the term *engineering biomechanics* (or sometimes *occupational biomechanics* [Chaffin and Anderson, 1984]) is used to describe the branch of biomechanics that pertains to product design.

1.4.8 Design of the Human-machine Interface

All the sciences discussed above have a role in the interface design process, but attention must now be turned to the way this process is carried out. Human-machine interface design is a task that involves a process of matching, although it is far from a straightforward one. The capabilities and characteristics of a human cannot be written down on a simple specification sheet as they might be for an electric motor or a length of rubber tubing. Human characteristics vary widely between people and within individuals themselves. Thus the problem for the interface designer is that of identifying the likely range of user characteristics and designing controls, components or displays that can be comfortably used by people with this full range of characteristics (or which can be adapted by them to allow use).

The following sections will discuss the practice of interface design, starting in the broadest possible terms with two linked, but occasionally conflicting, paradigms (Sections 1.4.9 and 1.4.10), before going on to discuss the tools available to assist designers in the application of ergonomics knowledge to their work. In line with the basic approach of this work, discussion will be largely limited to tools that can be used in the design of a product's physical interface.

1.4.9 Task analysis

Task analysis has historically been one of the most successful tools of industrial ergonomics and one of the most unpopular with those who it has affected. The "time and motion man" is a villain of industrial folklore, but this popular symbol of the failure of ergonomics provides important lessons, some of which are still working their way into the consciousness of modern ergonomics practitioners. Frederick Winslow Taylor [Taylor, 1947] developed *Scientific Management* in an effort to improve the efficiency of industrial tasks. Taylor's method was to break tasks down into their simplest individual elements, for example single movements of the arm or eyes, and then to eliminate or combine as many of these elements as possible so as to accelerate the progress of the whole task. Frank and Lillian Gilbreth [Gilbreth, 1911] developed this system further using a system of symbols (Therbligs) to represent task elements. In the days before low-cost video recording equipment this made noting task elements by hand a more straightforward process. Taylor and Gilbreth's approaches did much to enhance knowledge of the way the human body operates as a machine, and to improve the use of that machine, but it has been argued that in the process they ignored the fact that people do not and cannot operate like machines: the extraordinary versatility and adaptability of human physiology is entirely unsuited to long stretches of highly repetitive work and the consequences of such work can be profound, both physically and psychologically.

Task analysis has also been criticised as being limited in terms of its usefulness as a design tool. By its very nature, the analysis can only take place in situations where products or at least mock-ups of products already exist. Therefore only designs that already exist can be analysed, forcing the ergonomist to carry out a build-test-fix process that modern design theory (Section 1.3.7) finds undesirable.

1.4.10 Affordance and compensation

Some approaches to ergonomic design have developed as a reaction to highly mechanistic task analysis techniques. The concept of *affordance* is an important one [Norman, 1988] used by engineering psychologists to describe the fact that people will tend to use a product or complete a task in any way they are able. For example, if a product "affords" operation by the feet, then some users will probably operate it in that manner.

Paul Branton was one notable ergonomist who did much to overcome the mechanistic approach to task analysis and improvement. Coming from a background in philosophy and psychology, Branton argued for a human-centred approach to ergonomics analysis. Branton's approach has been neatly summarised by Oborne et al [Oborne et al, 1993]:

> An important variation on this Brantonian Theme is that the physiological and psychological make-up of humans is such that people learn to compensate for their biological, or other, "weaknesses". This perspective, then, stresses that the ergonomist's task is to design a supportive enough environment to facilitate such compensating behaviour. [Oborne et al, 1993]

This *person-centred* attitude to ergonomics requires that designers concentrate on the creation of stimulating and varied environments in which people have ample opportunity to do the same tasks in a number of different ways.

1.4.11 Modelling

The theories described above, along with the Human-machine-systems approach discussed in Section 1.4.2, form a framework into which much ergonomics work is made to fit. Thus, a lot of ergonomic analysis work involves the following activities:

1. The separation and allocation of function between human and machine.
2. The breaking of tasks into their basic elements.
3. The matching of machine demands to human capabilities.
4. The deliberate inclusion of "space" into a design to allow operators to take advantage of their natural flexibility, versatility and ingenuity.

It could well be argued that much current ergonomics practice has not gone beyond the first three items in the list above, but the intention to do so is often present. Below the level of theory, however, is the one of practice. If techniques are not available to apply these theories in a systematic way then their value is greatly diminished. The next sections look at some of the tools and techniques available to ergonomics practitioners to help them fulfil their overall goals. This problem can be divided into two basic elements, first the quantification and collection of data on human characteristics, and secondly the use of such data in the design process.

The process of ergonomic design can take place in two fundamental ways, existing systems can be analysed and their faults corrected in the next generation of design, or alternatively the ergonomist's input can begin before a full working product or prototype has been realised. If the latter is the case then the ergonomist, unable to study real operators interacting with the system, is forced to make use of some sort of ergonomic or anthropometric model.

In order to apply data collected on human capabilities in a design context, a designer must create some form of *model*: a simplified representation of the relevant aspect of human performance, and then collect appropriate data from people to construct the model with sufficient accuracy. The challenge for the designer is then one of matching the input requirements of a design to the available outputs, and it is methods for the analysis and optimisation of this matching process that will form the main body of this work.

The modelling techniques used in ergonomics practice are as diverse as the characteristics they simulate. In order to maintain focus and set the scene for later discussions, three key elements of the analysis of human outputs will be outlined below.

The simplest anthropometric model is the table of static anthropometric data, available in textbooks of engineering anthropometry [Pheasant, 1988; Croney, 1981; NASA, 1978; Woodson and Conover, 1964] or as electronic databases such as People Size or Ergobase [People Size, 1993; Ergobase, 1989].

Such information is very useful when designing clothes or living spaces, but only of limited value in applications that require significant manual work input from the user. In these situations, information on muscular strength and range of motion is required. Such information is available in similar forms to static anthropometric data [Boone and Azen, 1979], but must be applied with somewhat more care since strength is highly posture-dependent [Imrhan, 1994] and limits of voluntary motion may greatly exceed comfortable, or acceptable ranges of motion for repeated actions.

1.4.12 Ergonomic information at the design stage

The first approach used to assist designers during the initial stages of their work is to ensure that the maximum amount of ergonomic design information is transferred from other ergonomic studies and experiences and incorporated into the product while it is still on the drawing board or within the CAD system. As the amount of research and experience in the field increases, so it becomes important that designers have easy access to the information without having to devote years to becoming ergonomics experts. Both the quality of the information and the form of its presentation become crucial issues and much work in recent years has gone towards tackling this set of problems.

Ergonomic information is typically imparted in the form of checklists: a series of questions that designers can ask about their product to ensure that they have considered all the relevant human-interface factors. The checklist approach has been criticised [Sanders and McCormick, 1992] for encouraging a "blind" approach to ergonomic design: designers tick boxes and feel content without ever considering in detail how their product will actually be used. It might also be said that a checklist approach is incompatible with the principles of concurrent design. By encouraging designers to design first and fix the ergonomics afterwards the design process is lengthened and costs are increased.

1.4.13 Computer-aided ergonomic evaluation

The second approach is to allow the characteristics of a user interface to be evaluated using a virtual model. Just as finite element methods are beginning to replace much destructive testing of models, by allowing the designer to apply mathematical loads to a computer model, so it is foreseen that a designer might be able to apply an electronic user to a computer model and receive feedback on the aspects of a product's usability.

Work in this field has advanced tremendously in the past few years, but such systems are still far from widespread. A brief discussion of the common features of current ergonomic modelling systems will serve to reveal something of the capabilities and limitations of the technology.

1.4.14 Human modelling systems

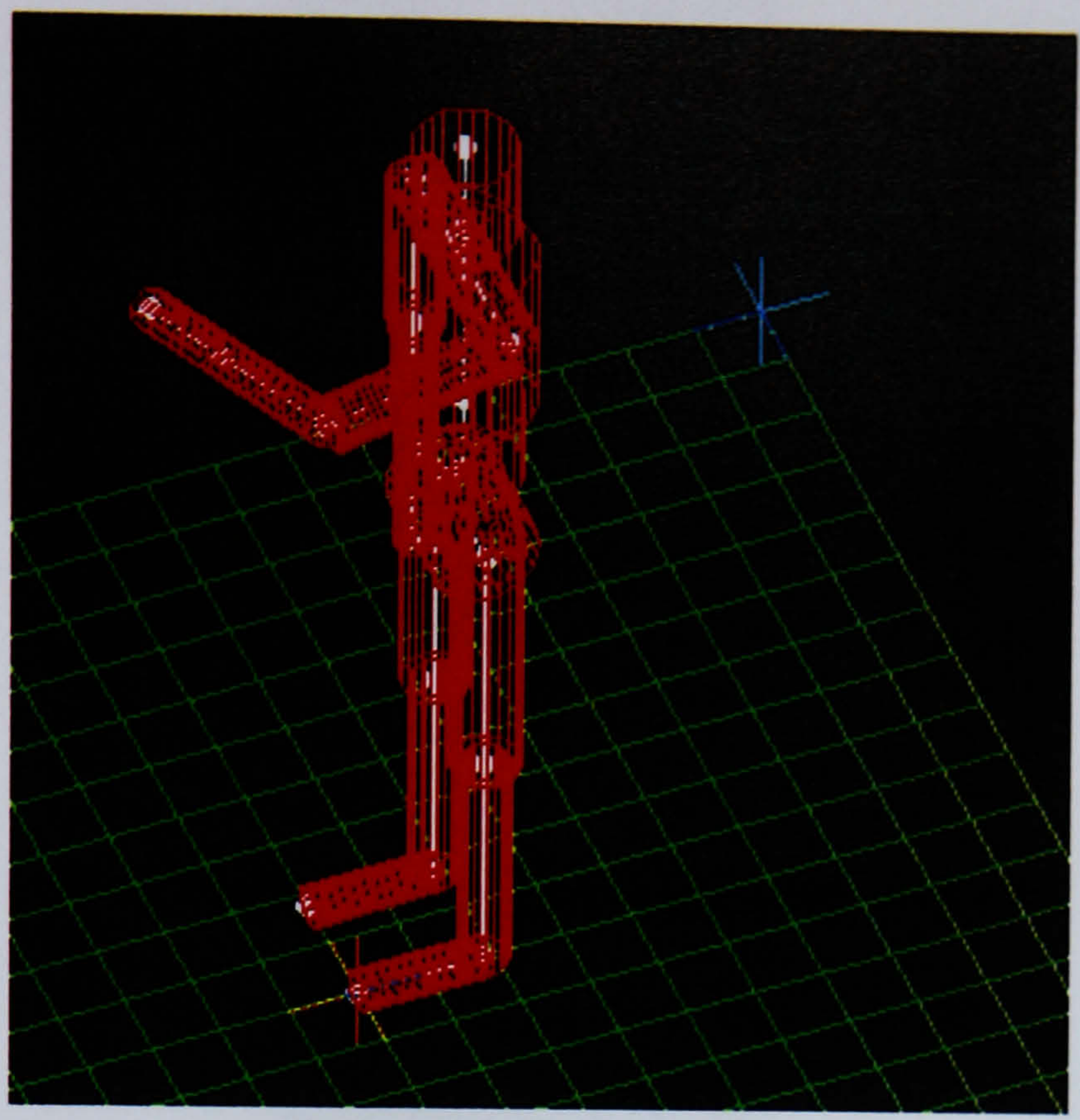

Figure 4: A simple human modelling program produced by the author.

Most computer aided ergonomic systems are some form of "man-model" [Taubes, 1994; Badler et al, 1993; Jung et al, 1993; Baber, 1993; Porter et al, 1990; Case et al 1991; Eriksson et al, 1992; Sengupta and Das, 1993; Das and Sengupta, 1993] (the term is not intended to imply any form of sexual stereotype, most CAD systems contained sufficient data to construct models of men, women and children.) In their simplest incarnation, man-models are an electronic version of the two-dimensional mannequin templates that have been used on drawing boards by designers for a number of years. Most systems add layers of sophistication to this, the first and almost universal development is to use the three dimensional representation techniques of the computer to make the model a solid one, or at least a representation of the boundaries of the human body in three dimensions. Such three dimensional models can be used to check the fit of an operator into a machine or workspace with much more accuracy than can be done with a simpler mannequin on a drawing board. Mannequins are then usually equipped with realistic joint range-of-motion limits to ensure that they can only be posed in postures that are physically possible (although there is no guarantee of their comfort).

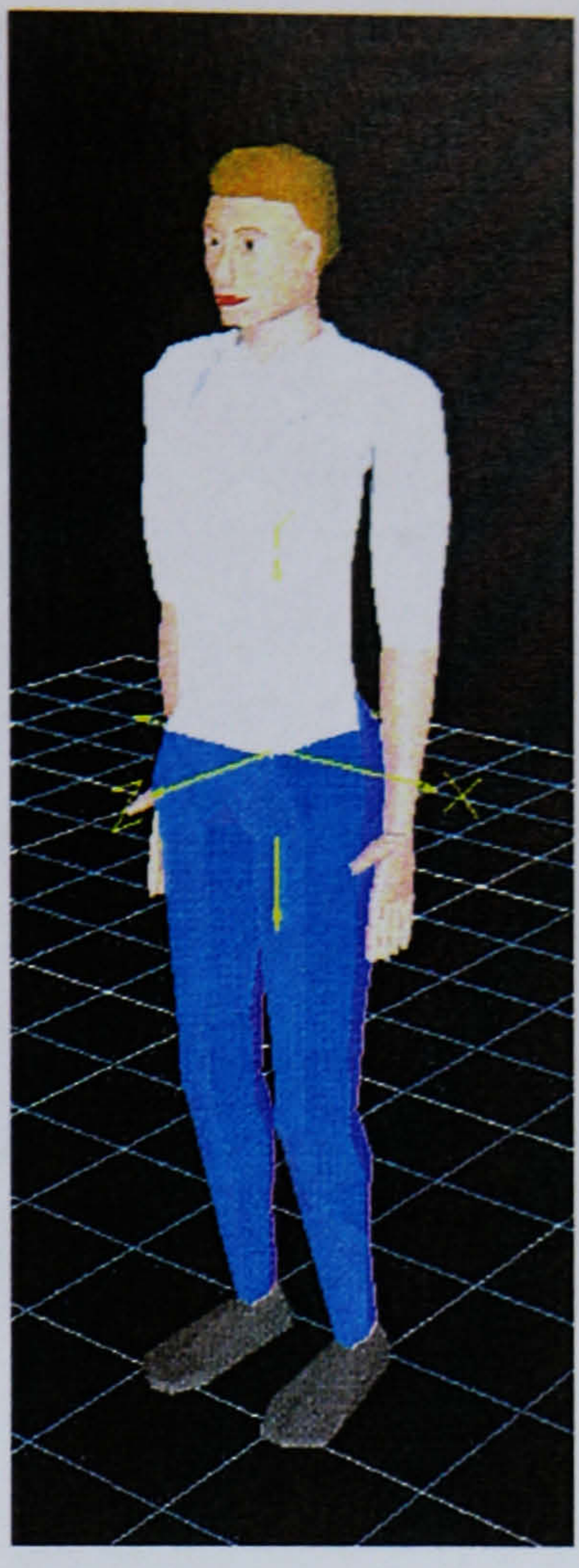

Figure 5: The JACK human modelling system

The posing of a many-jointed figure is a laborious process, so many modern man-modelling systems use algorithms to make the fitting of the figure into the system easily. These are usually kinematic algorithms that allow the figure to be positioned in space and linked to other points, for example a figure might be seated in a motor vehicle and have its hands constrained to the controls. The system would then use this information along with its data on range of motion to select a suitable posture automatically.

The same approach can be used to evaluate all the possible postures a figure can achieve, and so create a *reach envelope*: A space within which all controls must be placed if they are to be immediately accessible. Such a process is shown in Figure 6.

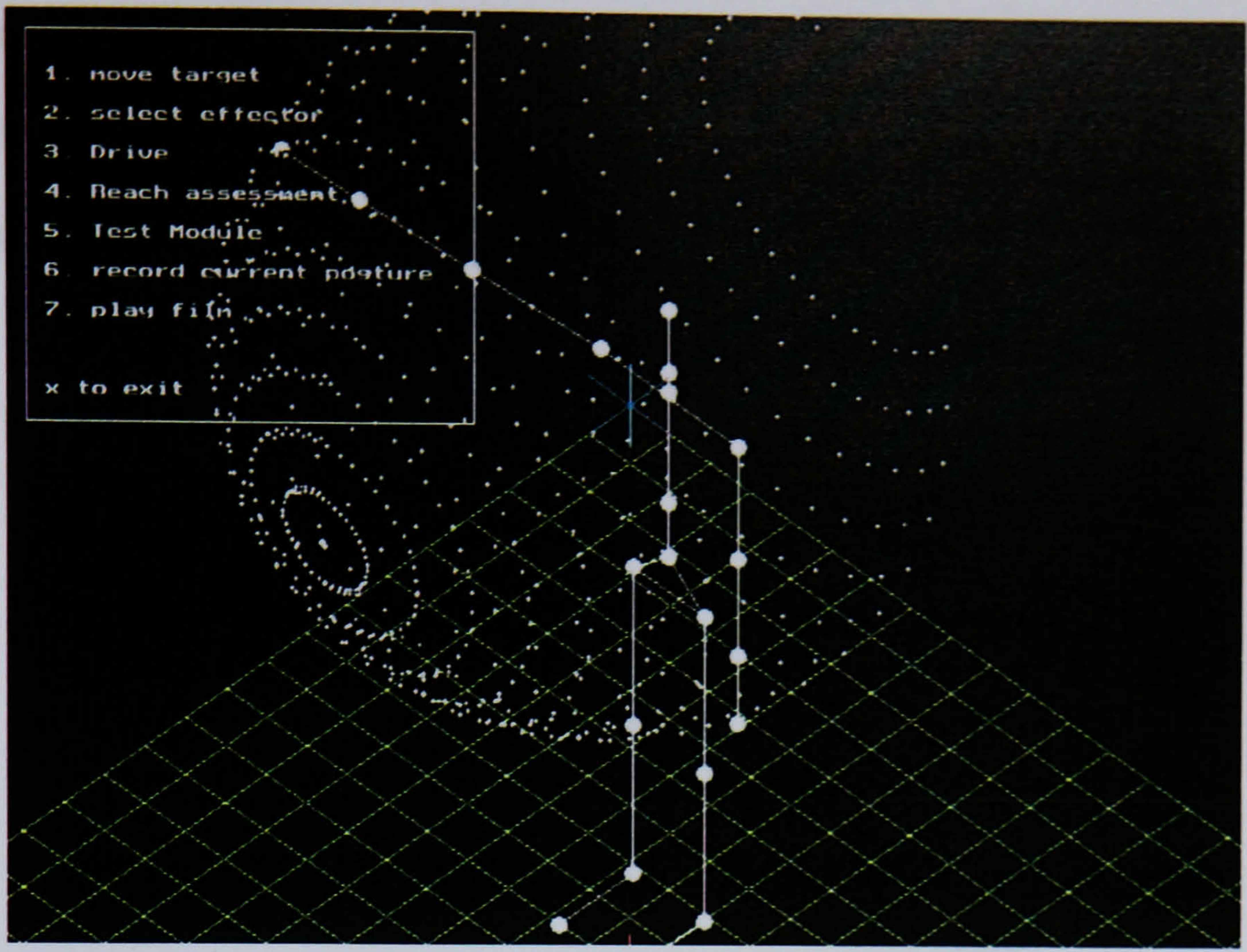

Figure 6: A reach envelope displayed by a simple human model.

The final ergonomic assessment that can be carried out using simple geometry is the evaluation of line of sight. Once a figure is positioned the system can construct an image seen "through its eyes" to allow the visibility of displays, controls and other crucial elements to be evaluated. Most systems, being used extensively for car design, also allow mirrors to be modelled.

1.4.15 Biomechanical models

Whilst anthropometric models that include strength and range-of-motion data help the designer to predict whether a product will be useable by its intended population, they do not provide much information on the consequences of the long term use of the product, this is particularly relevant since extended use of poorly designed products can contribute to musculoskeletal disorders [Goswami et al, 1987].

There are, however, models that allow the effects of a product on muscles, tendons, ligaments and joints to be predicted. The musculoskeletal system is an extremely complex, flexible mechanism, and accurate quantitative analysis or prediction of its performance is a similarly complex process. Various mathematical models do exist that provide a useful approximation of musculoskeletal action. The study and development of such models belongs to the science of biomechanics. Simple biomechanical calculations can be carried out manually, but more sophisticated three dimensional dynamic analyses usually require an iterative numerical approach using a computer [Burstein and Wright, 1994; Nordin and Frankel, 1989; Soderberg, 1986; Chaffin and Anderson, 1984]

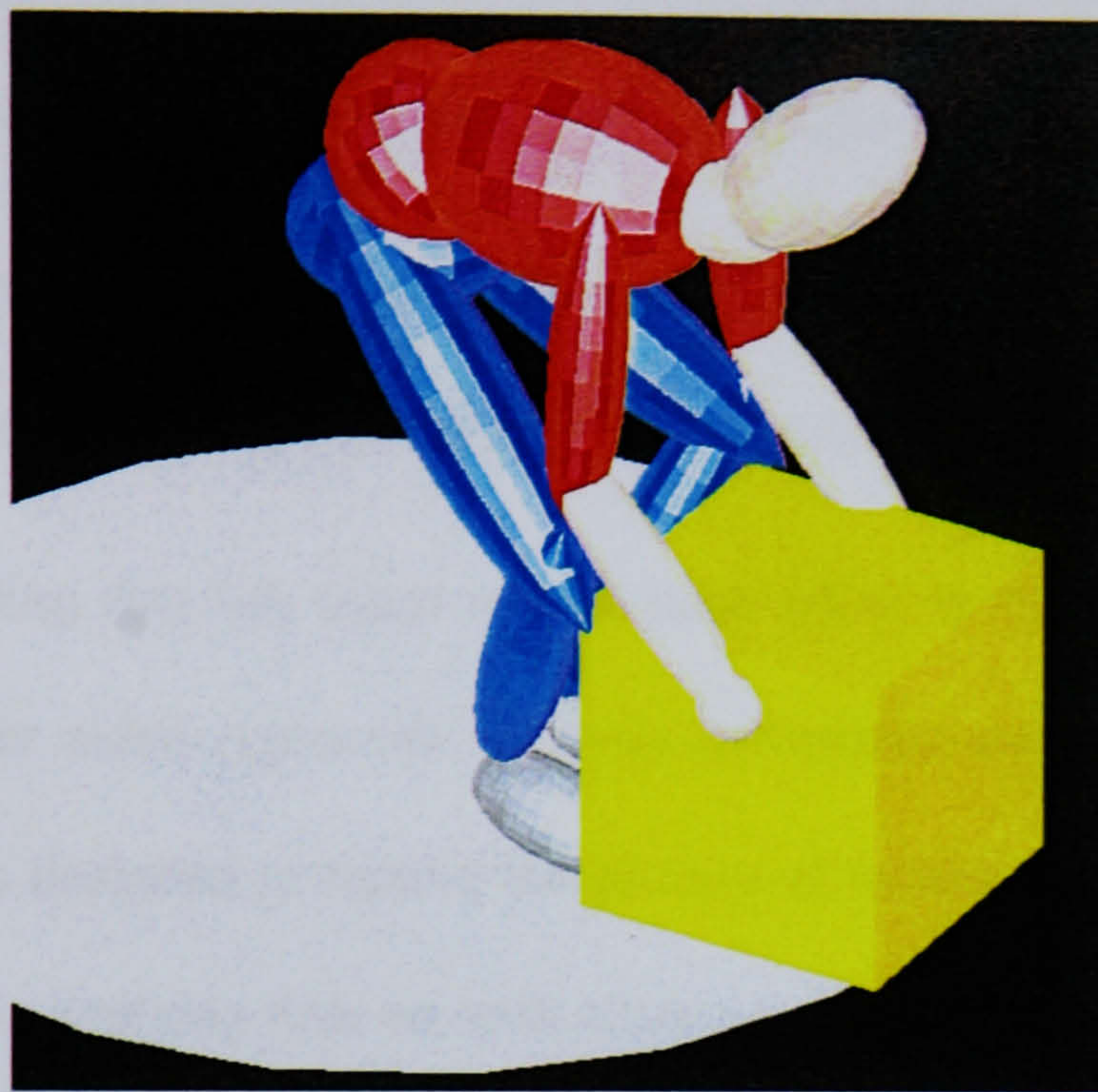

Figure 7: A biomechanical modelling system using the ADAMS mechanical analysis program.

Biomechanical models can be used to simulate a product operation task by applying kinematic data (generated by one of the motion analysis systems described in Section 1.5.4) taken from observation of a real human-machine system to an appropriate model [Yun et al, 1994]. The model will allow calculation of the forces required to produce the observed movements and the forces occurring in the joints or muscles of the subject can be estimated. The designer can then observe the aspects of the product's use that generate unacceptable peak forces and can seek to alter the mode of operation to eliminate these effects. As an alternative to the use of kinematic data, some authors have suggested methods by which a subject's motions might be predicted, either by analysis of the forces required to complete the task [Grieve and Pheasant, 1981], or through the use of motion patterns generated from data collected in other situations [Taha et al, 1996].

1.4.16 Summary

It has been the purpose of this chapter to demonstrate the broad range of activities encompassed by the science of ergonomics, and then to examine the techniques used by practising ergonomists in one particular section of their work: the design of physical user interfaces.

Emphasis has been placed on the use of models in ergonomics to simplify complex and varied human characteristics and allow deign decisions to be more easily made.

The approach to modelling that has taken up the most effort in the last few years has been the development of computer aided ergonomic analysis techniques using man modelling systems. A man modelling system is designed to replace the process of testing a product with a real sample of users as far as possible by applying data on such attributes as size, strength and visual acuity which has been collected in previous studies, to the new design problem. A man model is effectively a friendly interface to a large ergonomic and anthropometric database, and it is this database that creates the biggest problem for the designers of such systems.

A basic geometric representation of the human body is a highly complex thing to create, and in order to represent the true variety of size and shape that would be seen in a real population of users one must expect to increase this complexity many-fold. If human performance characteristics such as strength, flexibility or sensory capacities are included, the complexity increases even further, not least because the very collection of this data is difficult. Models, however complex, are only as good as the data upon which they are based, and the lack of appropriate and reliable sources of data places a severe restriction on the usefulness of many modelling systems [Roebuck, 1994]. In some cases, data is simply not available for population groups, such as the elderly, who might be of interest to a designer seeking to increase the accessibility of their products [Rogers et al. 1996], whilst data required for dynamic strength or motor behaviour modelling barely exists at all.

It has been proposed [Badler et al, 1993] that the next stage in the development of human modelling systems will be the introduction of autonomous behaviour: the model will simply be instructed to "lift the box" or "open the door" and the program will automatically generate an appropriate motion sequence. Such a complex simulation remains a distant pipe dream at the moment and questions remain as to the effectiveness of such an approach as a design tool rather than as a curiosity or demonstration of great programming skill. To walk through a series of product interactions with a sample population of model humans might be as time consuming and would almost certainly be less informative than carrying out such a trial with real humans. In particular, human users are quite capable of exhibiting entirely novel behaviour when confronted with a novel situation, it is unclear at the moment whether computers will ever be able to carry out such a process, although advances in computing techniques using such adaptive search techniques as neural networks and genetic algorithms may offer this potential in the future.

Models do, however have certain advantages over real people that apply regardless of the amount of time and the number of people available to take part in a trial: It is possible to look inside a model as it operates and examine the forces and torques passing through its body. Such information has the potential to provide profound insights into the nature of the users' interactions with the product, and it was upon these insights that this work sought to capitalise. In order to do this, a system is required that allows data to be collected rapidly from product users and passed to a computer model. Chapter 1.5 examines the range of devices available to carry out such a process.

1.5 Data collection devices

1.5.1 Introduction

Section 1.4 sought to demonstrate that information on human characteristics is crucial to successful ergonomic design. As the design process itself becomes highly computerised it becomes more important that this data is available in a quantitative form: the modern design process provides neither the time nor the opportunity for ergonomists to rely on qualitative feedback from their user population as the sole form of analysis. It is the purpose of this section to look at the range of tools available for the collection of quantitative data on human characteristics. Such tools are to provide a vital link in the biomechanical analysis approach proposed in the main body of this work.

The structure and performance of the body can itself be assessed and measured in numerous different ways and a classification of techniques is no straightforward task since many methods can be applied to different types of measurement. The human body is notoriously difficult to measure reliably and repeatably, its shape and the forces it can generate vary significantly with posture, and absolute datums are not easy to identify without considerable expertise [Stelmach and Requin, 1992]. Means of collecting data on the human body have been developed by scientists working in a variety of fields including anthropometry, ergonomics, biomechanics, sports science, physical therapy, occupational therapy and orthopaedic medicine. The assessment of sporting performance and clinical techniques in many fields (for example the assessment of spinal deformity and the analysis of pathological gait) has engendered sophisticated tools with wide potential application. The following classification of measurements will be used here:

Section 1.5.2 Length.

Section 1.5.3 Shape.

Section 1.5.4 Motion.

Section 1.5.5 Strength.

Section 1.5.6 Skin Pressure.

Section 1.5.7 Workload

1.5.2 Length

In anthropometry, length measurements are those that concern the overall linear dimensions of the body. They are used to define spatial considerations in human interfaces, and in biomechanics to estimate the lengths of the various segments that together form a biomechanical model. Traditionally, measurements are taken by trained staff using simple tools such as tape measures and callipers to record the distances between defined landmarks on the body. These are usually palpable bony protrusions. Standard linear measurements are related by empirically derived equations to joint-centre distances used in biomechanical models. The equipment required for these measurements is inexpensive, but the process is time consuming and skilled. To achieve adequate repeatability the subject's posture and the amount of distortion of soft tissues during measurement must be very closely controlled and this can sometimes result in measurements that bear little resemblance to the dimensions that actually constrain the design problem in question.

Various photographic and stereographic techniques have also been used to speed up the process of anthropometric measurement, since photographs can be quickly taken and then analysed later at no inconvenience to the subject [Li et al, 1990]. Such methods are discussed in more detail below. Photographic techniques are subject to errors caused by parallax and lens distortion, and single camera techniques are prone to perspective errors, although often the errors can be kept within acceptable bounds by careful positioning of camera and subject [Paul and Douwes, 1993]. Measurement landmarks are also harder to identify without physical contact [Kroemer, 1989].

1.5.3 Shape

Knowing the body shape of likely users can be extremely helpful to designers when shaping any parts of a product that are likely to come into contact with them, seats and hand-controls being examples. Shape data can also be used to calculate body segment volumes. Body segment volume is of interest to the designers of biomechanical models since the information helps to predict the masses and centres of gravity of segments and thus allows the effect of their own weight to be included in calculations. Volumes can be estimated using water-displacement techniques [Chaffin and Anderson, 1984] or by calculation from shape data generated by the means described below. This data can be combined with estimates of body segment density in order to estimate their mass characteristics, which is vital for effective mechanical analysis.

Unfortunately, the shape of the human body is an extremely complex combination of three-dimensional curved surfaces. In addition, it exhibits considerable inter-personal variability and during normal patterns of motion the shape itself changes quite considerably with the contractions and extensions of the underlying musculature. These factors result in a difficult measurement task involving the interpretation of large quantities of data.

There has been much clinical interest in shape measurement for the assessment and treatment of spinal deformities such as scoliosis, and for the design of orthotic and prosthetic devices; it is in these fields that much work on shape measurement has been carried out [Whittle and Harris, 1985; Harris and Copeland, 1978; Burwell, 1978].

Shape measurement techniques can be divided into methods that require physical contact with the body and those which do not. In general, non-contact techniques are preferred since the action of measurement will not alter the shape of the body, sensitive regions such as the area around the eyes can be measured without discomfort, and the measurement can be less intrusive for the subject. However, contact measurements usually use simple and relatively inexpensive equipment which is an advantage in situations where budgetary constraints are tight, or when a physical copy of the measured shape is needed, for example in the construction of custom-moulded seating [Gargano et al, 1986]. The main methods of contact shape measurement can be summarised below: -

1. Casting and moulding techniques using plaster of Paris and similar materials allow shape replication without quantitative measurement. The resulting models can be measured later at no inconvenience to the subject or used directly in the manufacture of products, a good example being foot orthoses.

2. Kyphometers and rod matrices use a rigid frame, in which various pins are mounted, the pins are free to slide along their longitudinal axis and are graduated to allow their protruding length to be

recorded. In use the device is pressed against the part of the body to be measured until all pins are in contact with the body, it can then be carefully removed and the shape data recorded manually from the pin positions.

3. The vector stereograph is a mechanical device using a pointer connected to three strings, which are mounted in separate positions on a rigid frame. These are attached to instrumented bobbins as the pointer is moved over the surface of the body. Their relative lengths are recorded and triangulation principles are used to calculate the path taken by the pointer itself, which can then be plotted and analysed [Burwell, 1978].

4. More modern equivalents to the vector stereograph have been developed using the same technology as the non-contact motion analysis techniques discussed below. Markers are attached to a probe, which is then passed repeatedly over the surface to be measured, the spatial co-ordinates of the probe tip are recorded and surface models constructed from the data using mathematical techniques.

Measurement of shape during physical activity or measurement of whole body shape requires techniques that do not interfere physically with the subject. A variety of such techniques is available.

1. Airborne ultrasound has been used to measure body shapes [Mauritzon et al, 1985; Lindström et al, 1982]. Transducers focus sound waves into a narrow beam that is projected onto the subject, the time between transmission of the signal and detection of the echo defining the distance of the subject from the transducer. To build up shape data, the system works either by scanning a single transducer over a body surface or by using an array of transducers to take spot measurements at fixed points.

2. Other shape measurement techniques are usually based on some form of optical or infrared system, using either normal or laser light. Some systems use photographic or videographic means to produce one or more images from which shape data can be obtained by further

analysis, whilst others produce numerical shape information which can be processed directly by a computer system.

3. In Moiré fringe tomography, a contour pattern of shadows is produced on an image of the subject's body. The fringes are produced by the interaction of light projected through a fine grating with the shadows of the same grating on the subject. In practice, the image can be produced in a number of ways [Burwell, 1978; Moreland et al, 1981; Turner-Smith and Harris, 1985]. Moiré images can be interpreted manually by skilled observers, or they can be digitised in a number of ways for analysis on a computer system [Yatagi and Idesawa, 1981]. The complexity of the digitisation and analysis process, has however lead to Moiré techniques being very much superseded by other automated techniques.

4. Stereographic methods use the comparison of two-dimensional images from multiple cameras to locate a reference point in three-dimensional space. Stereographic techniques can use still picture cameras to take static measurements or video and cinema cameras for the analysis of motion. Various reconstruction techniques can then be applied to obtain three-dimensional co-ordinates from points digitised on two separate images, the most common being the direct linear transformation (DLT) [Ball and Pierrynowski, 1987; de Haan and Brinker, 1988] which uses a number of known points (from a calibration frame or similar, placed in front of the cameras) to derive 11 calibration parameters for each camera. Digitised points are then transformed using these parameters to give their positions in space.

5. Raster Stereography can be considered to be a variation of Moiré fringe tomography [Frobin and Hierholzer, 1981; Hierholzer and Frobin, 1981] or a form of stereography in which one camera is replaced by a grid projector and all shape information is encoded in a single image. The technique uses a square grid or a system of horizontal or vertical lines which are projected onto the surface to be analysed and then photographed or videoed using recording equipment positioned a known angle and distance from the source of projection. The distortion of the grid caused by the body is analysed to produce data on the body shape. Some systems [Turner-Smith and Harris, 1985;Ko et al, 1994;Jones et al, 1989] use a light slit scanning system whereby a

single projected line is passed over the body and photographed or digitised at various intervals. Such an approach does not produce a complete image, but it can make automatic digital image processing easier.

6. Laser light can be used in a number of ways as a shape measurement system. The most common methods are laser contouring systems in which a laser beam is passed over the subject and the angle of its reflections measured by a linear detector array and triangulated to produce shape data [Jaliko and Case, 1986], and holography where laser light is used to expose a photographic plate, producing in image that contains three dimensional information. Some systems require a laser to view the resulting image, whilst others produce an image that can be seen in normal light.

The data from sophisticated optical measurement techniques tends to be quite noisy, and various mathematical smoothing algorithms are often applied to improve the image [Kroemer, 1989].

It is worthwhile considering some of the limitations on the use of accurate shape measurements in product design. Shape variation between subjects, [Branton, 1984], in a study of back-seat interfaces for railway carriages noted that the variations in detailed lumbar profile between members of the population are so great that any attempt to use shape data to design an accurately fitting seat would be unlikely to satisfy more than a small minority of the population.

A device constructed to accurately fit a body in one position may become inappropriate, uncomfortable or even dangerous when the shape of the body changes during normal use. A device that accurately follows a body's contours may produce undesirable pressures on soft tissues during use [Frymoyer, 1985].

As computerised data analysis becomes more powerful, however, and rapid shape measurement techniques more effective, there is every possibility that the boundaries between shape and motion analysis (see below) will begin to blur, possibly resulting in new levels of rapid, unobtrusive and accurate motion analysis.

1.5.4 Motion

The motion of the joints of the body is of interest to the product-designer in several ways. The limits of comfortable motion define the positions and postures that it will be acceptable for a user to adopt when operating a product. Posture has a considerable effect on strength and comfort, and motion paths are vital for dynamic mechanical analysis of tasks (see below).

Biomechanical motion data is usually expressed as angular movements of various joints relative to three principal planes, which by convention are said to have their origin at the body's centre of gravity. Summaries of the language conventions used to describe human movement are available in numerous textbooks of kinesiology and biomechanics [Nordin and Frankel, 1989; Gowitze and Milner, 1980]. Techniques for the analysis of motion are reviewed by Atha [Atha, 1984] and by Tyson and Das [Tyson and Das, 1990]

Data concerning the normal limits of joint motion can be collected manually using a goniometer, which is a protractor system, consisting two rigid arms a pivot and a scale. When the arms are aligned with body segments the angle between the segments can be recorded. Fluid filled goniometers work in a similar way, but angles are recorded relative to the horizontal using a graduated circular tube containing oil or water [Goodwin et al, 1992]. Of more interest to the designer, however, is the range of motion experienced by the joints during real activities. Manual measurement would be far too slow and intrusive to be useful in these situations so some form of automated recording is required.

Measurements of the motions of a single joint in use can be made by various types of electromechanical goniometer:

1. Potentiometric goniometers use a system of potentiometers attached to an exoskeleton to measure joint motion in one or more planes, the angle measurement being output as a varying electrical resistance which is recorded by a computer or specialised data logging device [Schoenmarklin et al, 1994; Snijders et al. 1987]. However, the bulky exoskeletal system required to support the potentiometers can be unwieldy to use.

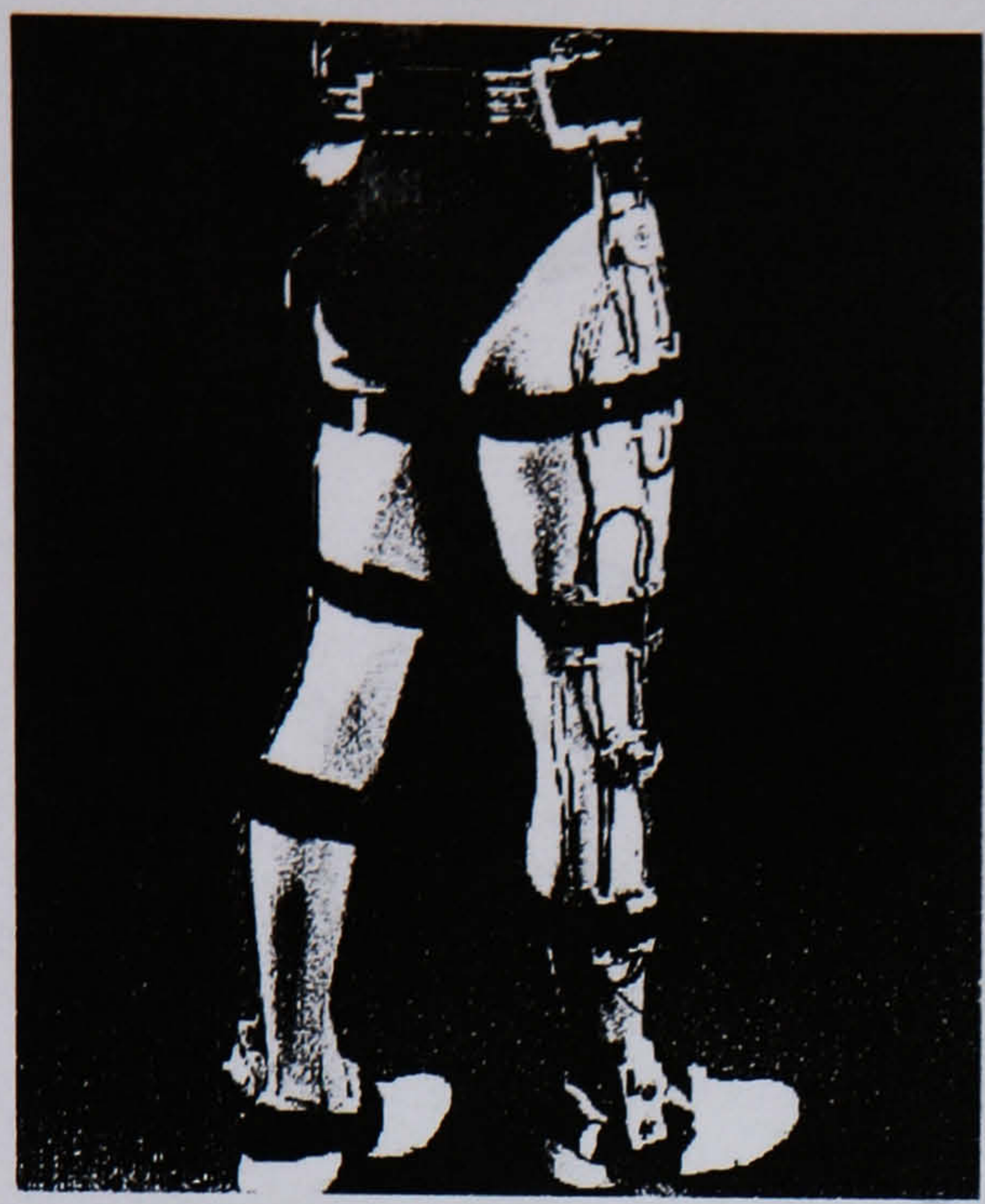

Figure 8: Electromechanical goniometers being used for gait analysis.

2. Flexible electrogoniometers are the smallest and most compact electronic goniometer system. They use a strip of metal foil that is equipped with strain gauges. The strip is attached to the skin across the joint and the strain gauges output its deflection in use as a varying electrical resistance [Nicol and Beveridge, 1988].

Figure 9: Flexible electrogoniometers.

3. Inclinometer systems use a small pivoting weighted potentiometer or liquid in a curved tube to record the angle of the device relative to gravity. Using two or more inclinometers attached to adjacent body segments allows the angle between them to be calculated. Unfortunately, motion can only be sensed relative to gravity, so horizontal angular changes are not recorded, and acceleration caused by rapid movement of the limb can cause measurement errors by altering the direction of the device's perceived gravity.

4. Accelerometer devices utilise this effect with a weight attached to a thin beam that is equipped with strain-gauges, acceleration applied to the device by movement of the body segment to which it is attached causes deflection in the beam which can be recorded as varying electrical resistance in the strain gauges. They are often mounted in sets of three to allow movement in all planes to be detected.[Harrington et al, 1995]

Compact goniometer systems can be used in conjunction with portable data-logger systems to record joint activity with minimal intrusion. Data loggers can record information into digital memory [Boocock and Jackson, 1994] or as analogue signals onto magnetic tape. Data on angular position recorded over time can be differentiated to provide information on the velocity and acceleration of limb segments. Likewise, acceleration data can be integrated to provide velocity and position.

It must be recognised that all systems that measure joint motion from the skin can suffer inaccuracy as the skin and attached measurement device move relative to the joint itself during use.

Electro-mechanical goniometers require extensive wiring to connect the sensors to recording equipment. Data transmission cables can themselves restrict motion, to reduce or eliminate this problem various systems have been developed using optical or electromagnetic means to collect data remotely from markers positioned on the subject's body, such systems are often termed TRAK systems (Telemetered Rapid Acquisition of Kinematics) [Rowell and Mann, 1989]. The main types of system are described below.

1. Electromagnetic position sensors such as the 3SPACE ISOTRAK system (Polhemus, P.O. Box 560, Colchester, Vermont, U.S.A.) operate by generating a magnetic field which is detected by sensors containing sets of orthogonal coils. The sensors are attached to the subject's body and the signals from them can be interpreted to give both the position and orientation of the sensor in three-dimensional space. However, sensor units are quite bulky and still require cable connections to a central control unit, but the large amount of data collected by each sensor means fewer sensors are required for full monitoring of segment movements.

Other Systems use infrared, visible or laser light to collect data from markers of various sorts.

2. Polarised light goniometers use small light emitting diode (LED) units attached to individual body segments. The LEDs are placed behind polarising filters of known orientation and are triggered electronically to light in a determined sequence. A detector unit is positioned behind a rotating polarising filter and the timing of a signal from a given LED indicates its angular position.

3. Photographic media can be used to store information about movement in two basic ways: - multiple images may be taken on different film frames over a period of time or multiple exposures may be made on the same piece of film, this is usually done by opening the camera shutter and exposing the image with a rapid series of light pulses [Bullock and Harley, 1972]. The equipment required for the stroboscopic recording is much less expensive than that for cinematography, but the method is limited in usefulness by the fact that lighting conditions must be closely controlled and the amount of information recorded on a film must be limited to stop the image becoming too cluttered to analyse.

4. Multiple images can also be stored electronically by means of video systems. Such systems are increasingly popular as a result of their relatively low cost and ease of image processing.

Video, ciné film and stroboscopic images can be taken with a single camera or with multiple cameras as with the static stereographic techniques discussed above. Pictures are analysed manually or by the use of digital image processing systems, the use of either method is simplified by marking the body of the subject with active (LED) or passive (reflective) landmarks which are recorded rather than a full image and used in the construction of a link model of the body. Some work has used video-mixing equipment to combine video images of a subject directly with product images from a CAD system [Bullinger et al, 1988]. Such an approach allows the designer to easily visualise the user in a number of different scenarios. Zoom lenses can be used to scale the image of the user to represent different population percentiles. Modern video camcorder systems and video processing equipment available for personal computers has made video an inexpensive and effective medium for analysis. [Tyson et al, 1993].

5. Various types of automatic motion analysis system operate by tracking markers across a certain field of view. Markers are made to stand out from the rest of the image in a number of ways, often by simply covering them with a retro-reflective material and shining a bright light from the position of the detection devices. The detectors themselves are video cameras, often operating at a much higher frame-rate than conventional video cameras to provide better temporal resolution. To obtain three-dimensional information several cameras are used and the two-dimensional data from each is combined and transformed to determine the position of the marker in space. However, In field situations it can be difficult to arrange for there to be sufficient contrast in the detected image for the system to automatically locate the markers. Correspondingly, many systems are adapted to operate in the infra-red spectrum, which helps to alleviate this problem, but can cause additional difficulties when materials and objects that are not very reflective to visible light turn out to produce strong infra-red reflections that can confuse the system.

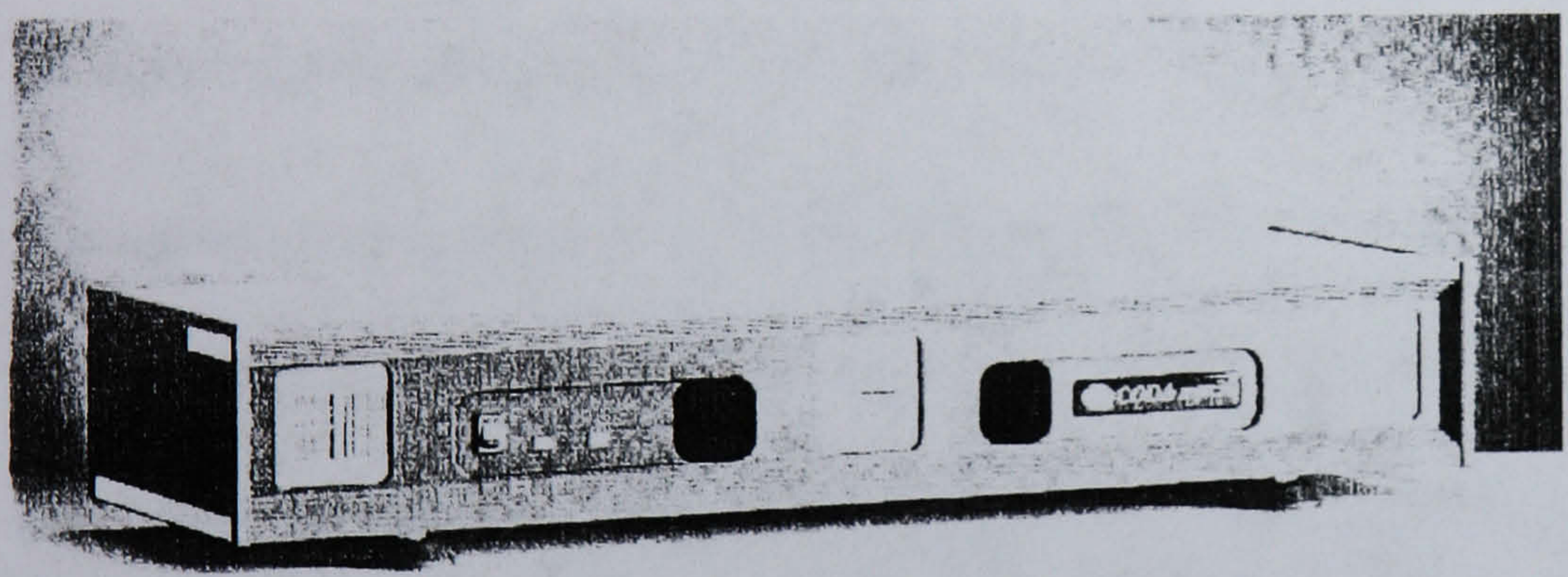

Figure 10: An infrared array spot locator.

Systems that use reflective, or passive, markers can also have difficulty identifying individual markers, since all are likely to be in the field of view at all times. To solve this problem some systems use active markers, which are small infrared light emitting diodes, or arrays of LEDs that are controlled electronically to light in a rapid and pre-determined sequence. In this method, only one marker is detected at a time and the system always knows which is which. Unfortunately, adopting this approach means that the detecting cameras themselves have to operate at very high speeds in order to ensure that position data on all the markers can be collected in a short enough time. Some systems utilise the fact that they only need to locate one bright spot per frame by not recording an image at all. Instead, systems can just record the position of the centroid of the brightest object in view, considerably reducing the amount of data reduction required. Systems do this in a number of ways, either by having square arrays in each camera that return two voltages, proportional to the X and Y positions of the target spot or linear detector arrays are used, normally positioned perpendicular to one another. The arrays consist of a strip of infrared sensitive semiconductor devices that can record the linear position of a given LED signal. A pair of arrays can be used to obtain the X and Y positions of each LED marker and a third allows the Z distance to be calculated by triangulation [Klein and DeHaven, 1995].

6. Spot location systems have been developed using several laser beams that rapidly scan the subject and identify reflective markers, or are detected by active markers on the body. The time of reflection or detection correlates to a certain point in the scan cycle and thus the position of the detector can be identified.

In general, it is considered an advantage to be able to obtain an image that can be examined with the naked eye in addition to exact mathematical data [Tyson and Das, 1990]

Automated motion detection systems have proved to be extremely useful tools in a number of fields. By removing the hours of tedious measurement and digitisation that is required by manual video or film-based motion analysis systems they have allowed motion analysis to become a practical, clinical assessment technique instead of simply an esoteric research area. These systems are extremely expensive, however, and their successful use requires much care. To ensure full collection of three-dimensional information, each marker must be in view of at least two cameras at all times. During task analysis, this may require the use of multiple cameras and careful control of the subject's position and clothing. If one is assessing product interaction the products themselves can obscure markers or produce undesirable reflections that ruin the results. Active marker systems either require trailing control wires that can restrict the subject's mobility, or use infra-red remote triggering, which can create a further line-of-sight consideration.

1.5.5 Strength

Strength measurement is one of the most notoriously inconsistent areas of anthropometry [Kroemer, 1970; Bishop et al, 1990] Strength can be measured under a variety of different conditions: - with the active body segment in motion or stationary, with fixed or variable loads and accelerations, with isolated muscle groups or the whole body being used to supply force Unfortunately, strength is also one of the most critical if human-modelling systems are to become serious tools. The ability to run complex task simulations and obtain reasonable information on the amount of physical strain involved in the use of a product is a basic need for the next generation of modelling systems.

Strength measurement devices come in two basic forms:

1. Mechanical dynamometers are available in different forms, each intended to measure a specific form of strength, pinch strength and grip strength being common examples.

2. Maximal force output by a given body segment or segments in a given position and direction is relatively easy to measure, using an electronic load cell, which records applied loads by means of strain gauges. These can be designed to measure loads applied in a single direction [Tyson et al, 1993] or along multiple axes [Runciman and Nicol, 1993] and combined with a velocity sensor for dynamic strength analysis.

However, as noted by Imrhan [Imrhan, 1994] in an extensive review of strength considerations in design for the elderly and by Kumar [Kumar, 1992], maximum strength is highly dependent on the subject adopting an optimum posture. Information on this optimum is therefore essential for efficient design. This implies that strength data should be recorded in combination with body movement information so that the relationship between the various factors can be established. Maximum recorded strength also differs from acceptable strength requirements for a given task. Various studies have proposed a relationship whereby acceptable strength can be estimated from maximum recorded strength. Alternatively, a psychophysical approach may be adopted with a subject allowed to alter the loads required for given test task until he or she finds them acceptable [Kahlil, 1987]. This approach, combined with the analysis of tasks that the subject already considers acceptable in terms of their strength requirements will often provide more useful data than simple measurement of peak strength. The initial speed of muscular contraction also has a significant effect on the peak forces achieved, with faster contractions tending to result in lower forces [Chaffin and Anderson, 1984].

One of the most common areas of difficulty for people with disabilities is in the handling of packaging such as bottles, cans and cartons. Various studies [Berns, 1981;Imrhan and Loo, 1988] have used model packages with instrumentation in the form of strain gauges to record applied opening and closing forces. Similar studies have been done on domestic water tap handles of various designs [Bordett et al, 1988].

In some tasks where physical work output is very high, for example stair climbing or manual wheel-chair ambulation, issues of aerobic work capacity may become relevant. Work capacity is most accurately measured with oxygen uptake detection systems, but heart rate variability is commonly considered to be closely correlated enough to be a useful measure, and is less expensive and intrusive to measure.

1.5.6 Skin pressure

Certain disabilities and diseases, notably spinal injuries, diabetes and strokes can leave their victims with anaesthetic skin, often in combination with muscular paralysis. Such a situation can easily lead to pressure sores and considerable resultant damage if the distribution of pressure on the skin is not carefully managed. Ischaemia, or reduction in blood supply is also considered to be a major cause of postural discomfort for other users too, and is particularly noticeable in the design of seating [Branton, 1969].

Simple analysis of skin contact at the human-device interface has been carried out using ink prints on the hands during investigations into handle design [Benktzon, 1993] whilst more sophisticated methods have used pneumatic systems [Bader et al, 1985] or grids of strain gauge pressure transducers to analyse seating [Ferguson-Pell et al, 1985;Drummond et al, 1982]. Sophisticated systems of pressure transducers have been used in clinical gait analysis systems to examine events at the foot-floor interface during walking; some such systems can measure shear forces in addition to direct loads.

1.5.7 Workload

In some classes of task, notably walking, lifting and other more strenuous activities it can be desirable to measure the overall work being carried out. A number of measures exist to do this, and have been used extensively by sport scientists during the analysis of athletic performance.

Two of the most common workload measures are heart rate and oxygen uptake. Oxygen uptake measurements require gas analysis equipment to measure the oxygen consumed in the air breathed during a task, and therefore require the subject to either operate in a sealed chamber or, more commonly, to wear a mask during performance of the task. By contrast, heart rate can be simply recorded, either manually or using a variety of electronic devices, and the elevation of heart rate during work as proved to be a good measure of overall workload.

In gait analysis, more sophisticated workload measures have been developed to assess the efficiency of a subject's performance by comparing workload with a measure of task performance. The Physiological Cost Index (PCI), first proposed by MacGregor [MacGregor, 1979] combines heart rate increase with walking velocity to provide such a measure. It is calculated using the following equation:

$$PCI = HW - \frac{HR}{v}$$

Where HW is the hear rate recorded while walking, HR is the resting heart rate recorded before the task commenced and v is the average walking velocity. PCI is normally expressed in units of beats/m.

1.5.8 Summary

This chapter has described the range of techniques available for the quantification of human characteristics. Ergonomic analysis for the purposes of accessible design requires such techniques because a suitable body of data does not already exist. The computerisation of the ergonomic analysis process provides an additional need for ergonomic data to be collected in a quantitative form. This data is vital for the construction of effective human models and its collection and rapid analysis forms the core of the work under discussion here.

1.6 Background summary

The arguments presented in Section 0 can be summarised in nine points:

1. The population is ageing, with this ageing process comes an increasing incidence of disability.
2. There is considerable social and political pressure to consider the rights of disabled people, and to cater for their specific needs.
3. The usability of the designed environment has a major bearing on the difficulty that people with disabilities have in their daily lives. In an environment that people find accessible, their impairment ceases to be a disability and they can take a full and productive part in the activities of society.
4. Designing accessible products is a problem of matching the demands that a product places upon its user to the capabilities of that user.
5. Ergonomics is the science of matching machine demands to human capabilities, but traditional ergonomic design techniques are often time-consuming and expensive.
6. The product design cycle is now a highly computerised and extremely rapid process, leaving little room for the application of traditional ergonomics techniques.
7. In an attempt to alleviate this problem ergonomic models, particularly computer models, have increased greatly in sophistication
8. Computer modelling approaches require extensive quantitative data to function reliably.
9. A variety of techniques is available to collect quantitative data on human characteristics.

The necessary approach now seems obvious: researchers must conduct extensive studies, collecting data on all aspects of a full range of people, including particularly those whose characteristics lie at the edges of what might be considered the normal population range: notably the elderly and disabled. Computer programmers and human modelling experts must then improve the sophistication and usability of their models, incorporating all the new data. In this way designers will be able to complete their entire product evaluation process with the product still only a model in the computer's memory, perhaps leaving the machine to run overnight trying out the product with five or six thousand "virtual users" and providing a statistical summary of the performance of a design in the morning.

Unfortunately both the data and the modelling systems are still some years away, and it might be argued that until we have computers that are as intelligent as humans, we cannot hope to have ones which simulate human activity effectively, event if they manage to simulate human form in great detail. It will be argued here, therefore, that the replacement of user evaluation with computer simulation is unlikely to provide a solution to the problem of accessible design in the short term. An alternative solution is therefore proposed that seeks to combine the best aspects of the user trial with the benefits of modelling and measurement technology, it is this approach that is discussed in Section 2.

2. Methods

2.1 Introduction

As described in the previous section, one approach to the integration of ergonomics techniques and a computer-based product development process is to eliminate the use of user-testing altogether through the use of human-modelling systems. The potential advantages of such an approach are very appealing: a computer simulation program provides designers with access to an infinite number of different test subjects, who are able to work long hours at high speed testing as many product configurations as required.

The current state of technology however, limits the scope of such techniques. While it is quite possible to make a computer model that looks like a human being, and even one that has the same apparent physical strength and freedom of movement and mass characteristics, no-one has yet created a model that comes close to being able to *behave* like a human being.

Work has been done [Taha et al, 1996] to model typical human movements using neural network systems that are trained using data collected by automated motion analysis. The network, once trained is capable of reproducing the desired motion, pattern (usually gait) and of altering in an appropriate fashion according to changing input parameters. Unfortunately, at the present time the amount of input data required to train a network effectively makes the experimental effort needed to produce useful results very expensive. It may well be the case that as motion analysis techniques become more popular the available motion data for network training will be more complete and training may be easier and cheaper. This author contests the overall validity of the approach at the present time, however, since it is unclear whether enough is known about human motor strategies to be able to predict the type of motion pattern that will be selected in the interaction with a new product configuration, even if that pattern can then be reproduced effectively using data from a movement database to appropriately train a neural network.

It is argued here that a more effective approach to computer-aided ergonomic analysis is to use computer-modelling techniques in conjunction with a more conventional user-testing approach. Users demonstrate the nature of real human responses to a product's interface and provide qualitative feedback on the design, while a computer model that copies and quantifies their actions provides information about biomechanical parameters. User responses quickly identify unpopular designs, while the biomechanical analysis will provide an insight into factors that might have a more subtle, long-term effect on user comfort, accessibility or even injury. This approach will maximise the amount of information obtained from a limited number of user trials, thereby increasing the value of those trials to the design or ergonomics team that conducts them and accelerating the process of thorough evaluation. The availability of a large amount of quantitative data on task performance will also serve as a useful resource for those seeking to develop better human simulation systems.

The aims of the approach can be visualised using the following sequence of block diagrams. Figure 11 shows the traditional approach to ergonomic analysis through user evaluation on the left, with the computer simulation approach mirroring it on the right. Data resources from elsewhere, be they studies of similar products or more general anthropometric data, support the designer and the analysis process.

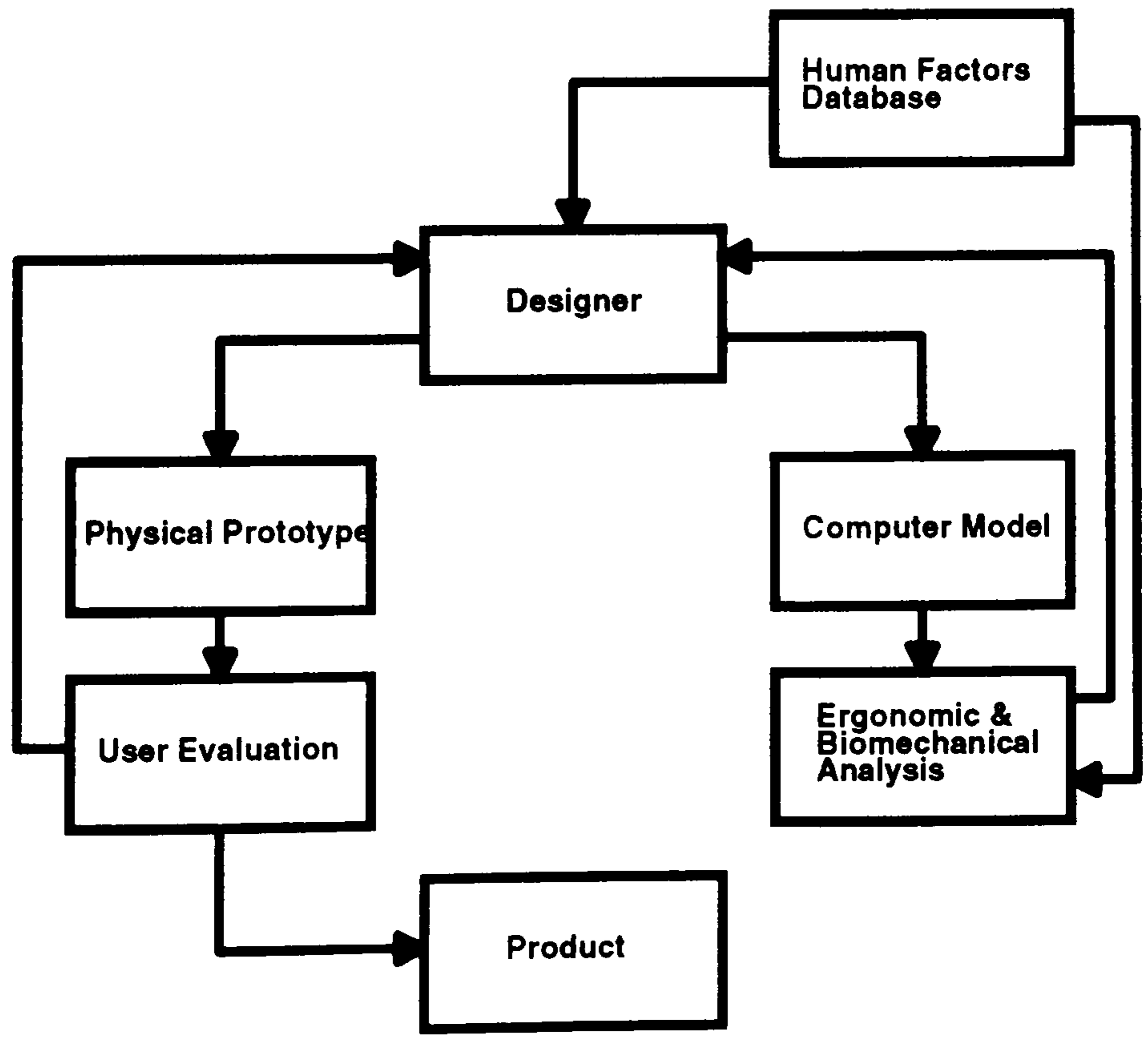

Figure 11: The traditional and computer-aided ergonomic analysis processes.

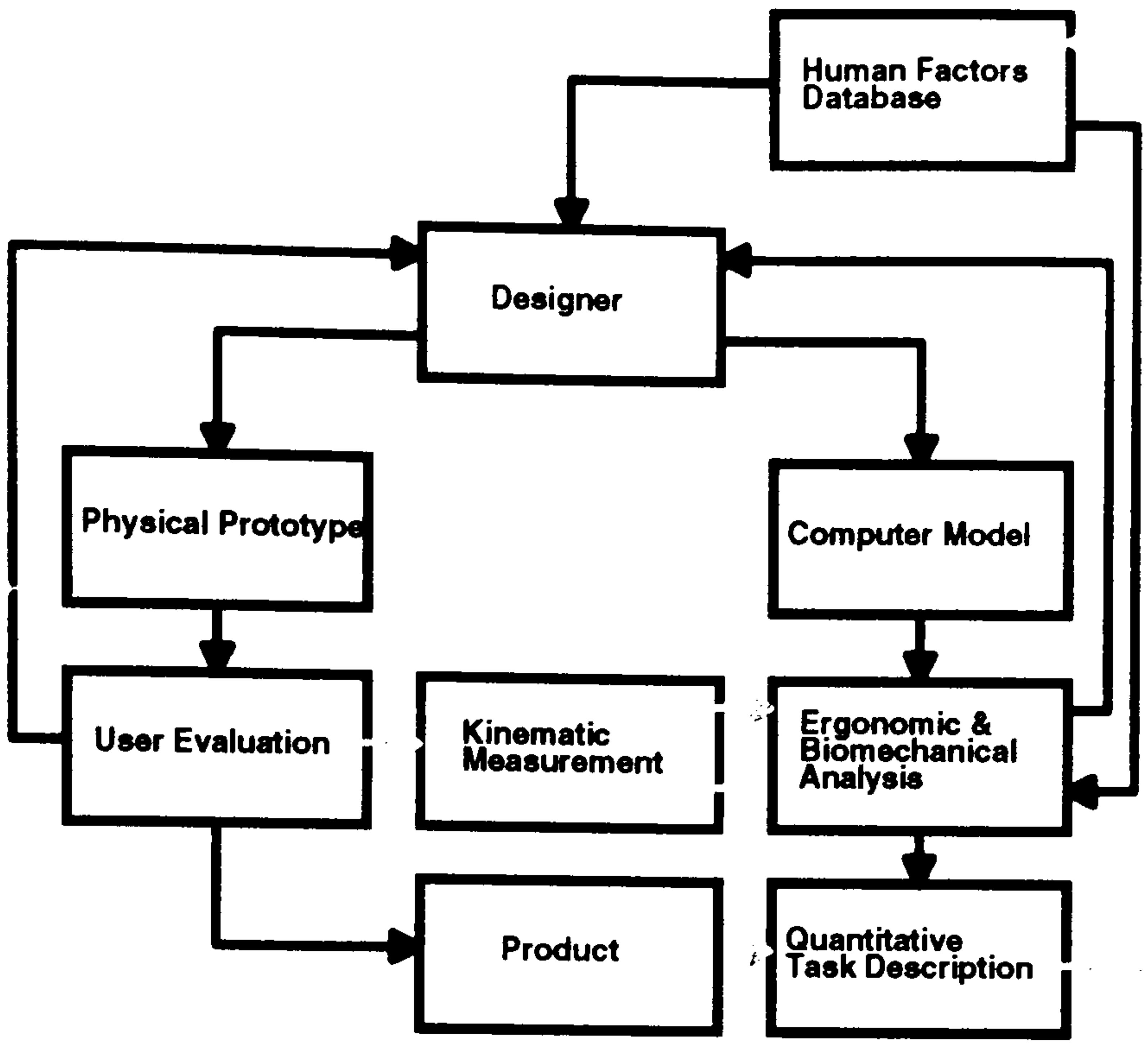

Figure 12: The proposed link between the user evaluation process and computer modelling.

The proposed approach under discussion here is one that provides a link between real users and computer models (Figure 12). This form of analysis would serve to provide useful additional information from user tests and to validate and improve modelling techniques.

2.1.1 The composite approach

The approach adopted in this work has three essential elements.

1. A measurement system that collects data from controlled interactions between members of an intended user population and a product designed for them.

2. A modelling system that uses the collected data to reconstruct an electronic representation of the user-trial.

3. An analysis system that distils the data produced by the model into useful information that can be used to evaluate the relative performance of different design options and indicate potential areas of difficulty.

The proposed composite approach is depicted in Figure 13.

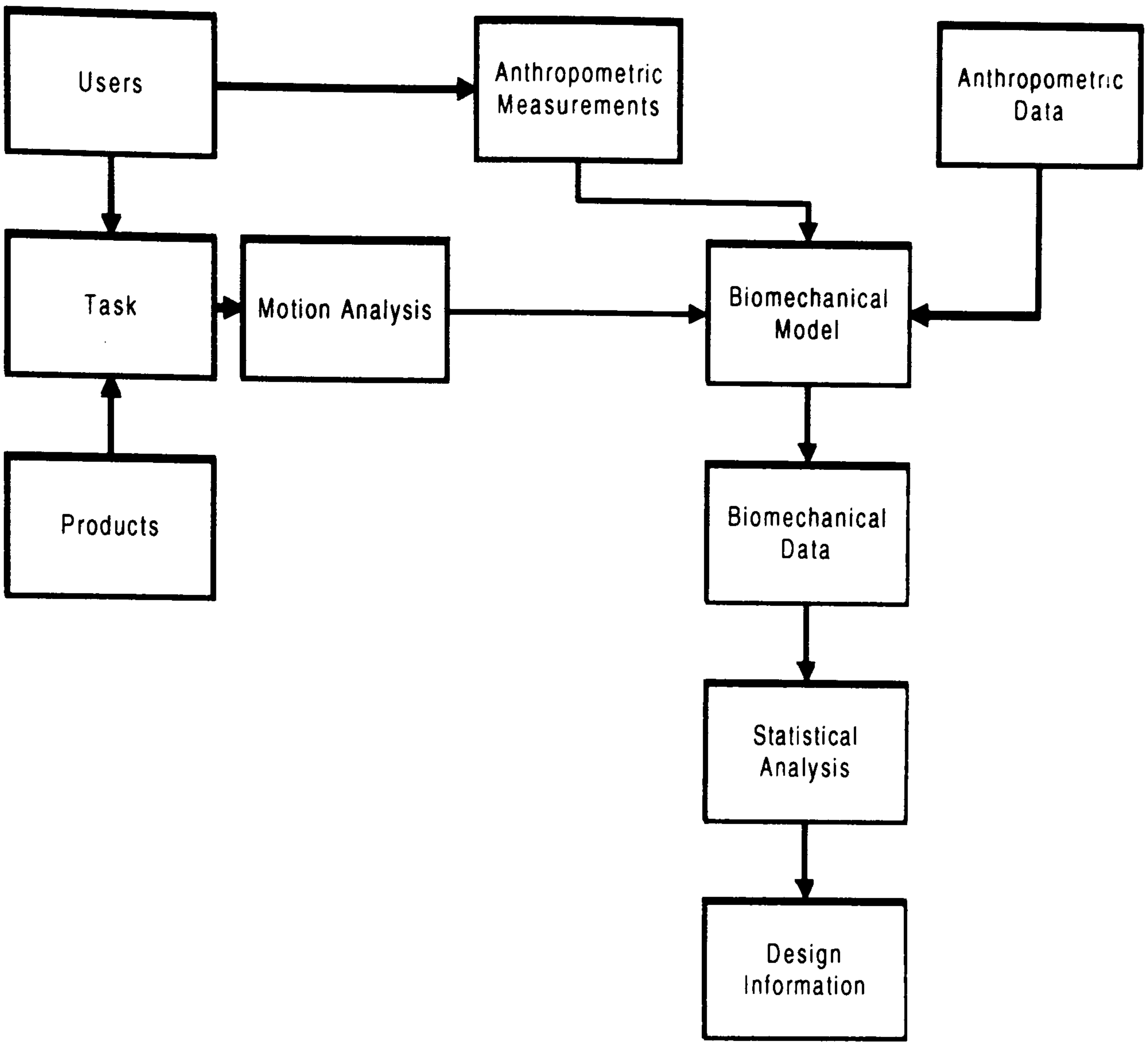

Figure 13: A schematic diagram of the proposed analysis system.

2.1.2 The context

It is obviously impractical to attempt the development of a universal ergonomic analysis system. The selection of an appropriate sub section of the field of ergonomics to which the approach described here could be applied depends upon a combination of two factors:

1. The area of analysis must lend itself well to the use of a computer model: it must be possible to construct a suitable model, which has a high likelihood of producing reasonable valid results.
2. The results produced must be likely to provide information that would be useful to a designer: the modelling process must be of an aspect of human-product interaction that causes difficulty or damage to users if done wrongly, or one that significantly enhances user satisfaction if done exceptionally well.

It was decided therefore to concentrate in this work on gross movements of the upper limb, ignoring the numerous small joints in the hand. This choice was felt to fulfil the requirements specified above because:

1. The upper limb is an ideal opportunity for biomechanical modelling techniques, with a small number of separate components (particularly once the hand has been ignored) and joints that are reasonably well understood.
2. Upper limb motions resulting from the operation of products of various sorts have been associated with a large number of injury mechanisms, collectively known as *cumulative trauma diseases*.
3. In Europe, 6.1 million people are believed to suffer from some form of upper limb disability [Poulson et al, 1996].
4. The vast majority of consumer products are designed to be operated and manipulated with one or both hands. It makes sense therefore, to address issues of upper limb mobility and strength in any modelling process.

2.1.3 Principal challenges

Two major hurdles stand in the way of this approach: these are the problems involved in the identification of useful factors and of the generalisation of results.

1. If biomechanical modelling produces more information than would otherwise be available to the designer, it also creates the requirement that this information be sifted through and reduced to a form in which it can be used to answer questions such as "is design A better than design B?" and "What part of the use of product X is likely to cause problems for an elderly user?"
2. If the sheer size of the variety that is present in human anthropometry and human performance acts a block to effective simulation, what guarantee is there that any information may be successfully generalised from the modelling of a few real subjects?

The experimental phase of this work was designed to address these problems, and to see if they actually presented insurmountable obstacles. The experimental phase is described in Section 3. The body of this section describes the implementation of the system itself.

2.1.4 Section contents

The remainder of Section 2 discusses in detail the theory and development of the proposed system.

Section 6 describes the selection of an appropriate measurement system.

Section 2.2 describes the development of the biomechanical model used in the analysis process.

Section 2.4 describes approaches to the analysis of products using the system.

2.2 Hardware selection

2.2.1 Introduction

Numerous measurement and data collection devices have been described in Section 1.5. Of these, only those useful for the dynamic collection of position and motion information are appropriate for the analysis system being described here. The purpose of this section is to outline the considerations involved in the selection of a measurement system that will form part 1 of the approach described in Section 2.1.1.

There is a highly specialised, but reasonably large market for such devices, predominately for the analysis of gait, sporting performance and the movements of industrial robots. It makes sense therefore to examine existing devices to determine if any are appropriate for an upper limb modelling application. The great variety of competing approaches to the problem of collecting motion data is a good indicator that a universally applicable solution has not yet been developed, and in many cases a trade-off has to be made between various desirable but competing features. A formal selection process is described in Section 6. The systems evaluated and the overall score obtained (higher the better) are shown in

System	Score
Fibre-optic goniometer	10.26
Flexible conductive polymer goniometer	10.26
Potentiometric goniometer	10.36
Liquid filled inclinometer	10.10
Mechanical inclinometer	10.10
Flexible metallic goniometer	11.06
Accelerometer	10.23
Alternating current electromagnetic system	10.92
Direct current electromagnetic system	10.41
Polarised light goniometer	8.11
CCD array spot locator	8.42
Active marker, multiple camera infrared spot locator	8.92
Passive marker, multiple camera infrared spot locator	9.42
Manually digitised Video	8.93

Figure 14.

System	Score
Fibre-optic goniometer	10.26
Flexible conductive polymer goniometer	10.26
Potentiometric goniometer	10.36
Liquid filled inclinometer	10.10
Mechanical inclinometer	10.10
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Polarised light goniometer	8.11
CCD array spot locator	8.42
Active marker, multiple camera infrared spot locator	8.92
Passive marker, multiple camera infrared spot locator	9.42
Manually digitised Video	8.93

Figure 14: The results of the system selection matrix.

Initial trials were conducted with a set of electromagnetic goniometers [Rowe et al. 1989] but the system was soon found to be inappropriate for the measurement of shoulder motion because suitably secure mounting points could not be found. Additionally, the goniometer system under evaluation only allowed measurement of rotation about two axes, and as will be discussed later (Section 2.3.5), three axis rotational measurement is really required for effective description of limb movement in three dimensional space. Therefore, the system eventually selected, and upon which the majority of this work has been based, is an alternating-current electromagnetic sensor system: the 3Space Insidetrak manufactured by Polhemus Inc. of Colchester, Vermont. This system is described more fully in Sections 2.2.2-2.2.4, along with the software developed to control it and the problem of effective mounting of sensors on the limbs of human subjects.

2.2.2 The Polhemus 3Space System

The Polhemus 3Space Insidetrak electromagnetic tracking system is part of a range of low frequency magnetic field motion tracking systems. All the systems manufactured by Polhemus operate on the same fundamental principles, but differ in the nature of their control electronics, their speed of operation, measurement range and the number of active sensor units they can drive.

The Insidetrak device has three main constituent parts: a field generator, a system electronics board that fits inside a conventional IBM PC compatible computer, and either one or two sensors. The elements of the system are illustrated in Figure 15 and Figure 16.

The magnetic field source contains three mutually perpendicular coils in which the fields are generated. These fields cause a corresponding signal to be generated in the sensors, which also consist of three coils sealed into a plastic case. The signals are decoded by an analogue to digital converter on the system electronics board, which then converts the data into position and orientation information. The electronics board uses digital signal processors to control the generated fields and decode the sensor readings. It adjusts the strength of the generated fields according to the distance of the sensors from the source, and carries out filtering to reduce noise and improve output stability. Each measurement has a lag of approximately 120ms and with two sensors operating, measurements take place at 30Hz. The manufacturer's performance specifications for the Insidetrak are given in Figure 17. Sensor calibration is completed at the factory, but extensive control and adjustment of the output data format is possible through the computer's communications bus. A full description of the system principles is given by Kalawsky [Kalawsky, 1993].

The main limitations of the Insidetrak system are its sensitivity to magnetic field distortions caused by large metal objects or electrical apparatus operating in close proximity to the sensors and the relatively low frame rate. The frame rate limitation was not a significant problem in measurement of the relatively low speed upper limb movements under analysis in this work, but great care had to be taken during all the experimental work to avoid potential sources of magnetic field distortions.

Figure 15: The Polhemus Insidetrak transmitter unit.

Figure 16: A Polhemus Insidetrak sensor. The sensor is shown mounted on an epoxy base to give it extra stability. As an indicator of scale, the nylon webbing passing through the base is 20mm wide.

Attribute	Specification
Update Rate	60 Updates/sec divided by number of active sensors
Static Accuracy	0.5" RMS for x,y,z position, 2° RMS for orientation
Range	Up to 5 feet

Figure 17: Manufacturer's specifications for the Polhemus Insidetrak system.

2.2.3 Tracker interface software

The Polhemus tracking system was supplied with only a very basic piece of software. This program allowed instructions to be passed from the keyboard to the tracker's system electronics board for control purposes and allowed data output to be displayed in numerical form on the screen or saved directly to disc. This software was considered insufficient on two counts:

1. It did not allow graphical display of the sensor locations and orientations, making it very difficult to check that the system was functioning properly. This was particularly true with the orientation data output; while Cartesian coordinates are intuitively straightforward for an experienced observer to interpret, angular data expressed as Euler angles or direction cosines is far less so (Section 6.3.2).
2. Control of disc file output was difficult and unwieldy. In any experimental work, it is vital that the experimenters have immediate control of the data recording process.

In yet another example of the importance of ergonomic design, the control software provides the interface between product and users, in this case the motion analysis system and those people involved in experimental data collection. An inappropriate interface limited the effectiveness of both the analysis hardware and the experimental process.

For these reasons, it was important that an enhanced interface program be developed. The programming demands for display and data output were not highly intensive, but it was critical that processing was rapid because any display and file output activities had to be completed within the space of a single measurement cycle i.e. 1/30th of a second if two sensors were being used.

In order to maximise the speed of operation; a compiled programming language was essential. C was selected as an appropriate language for this reason and also because it allowed easy integration of the original Polhemus interface program's source-code for communication activities with the Tracker unit.

The enhanced interface program was entitled *ETALOT* (Electronic Tracking And Logging Of Tasks) and offered the following features:

1. Graphical display of one or two sensors in a parallel projection, with full control of viewing angle and distance.
2. Numerical display of sensor outputs.
3. Output of any number of data sets to disc in a directory of the user's choice.
4. Automatic allocation of file names to speed experimental data collection.
5. Transmission of various control commands to the Insidetrak system electronics unit.
6. Recording and display of sensor paths.
7. Some prototype limb modelling and display functions.

Figure 18, Figure 19 and Figure 20 show typical screen outputs from the program.

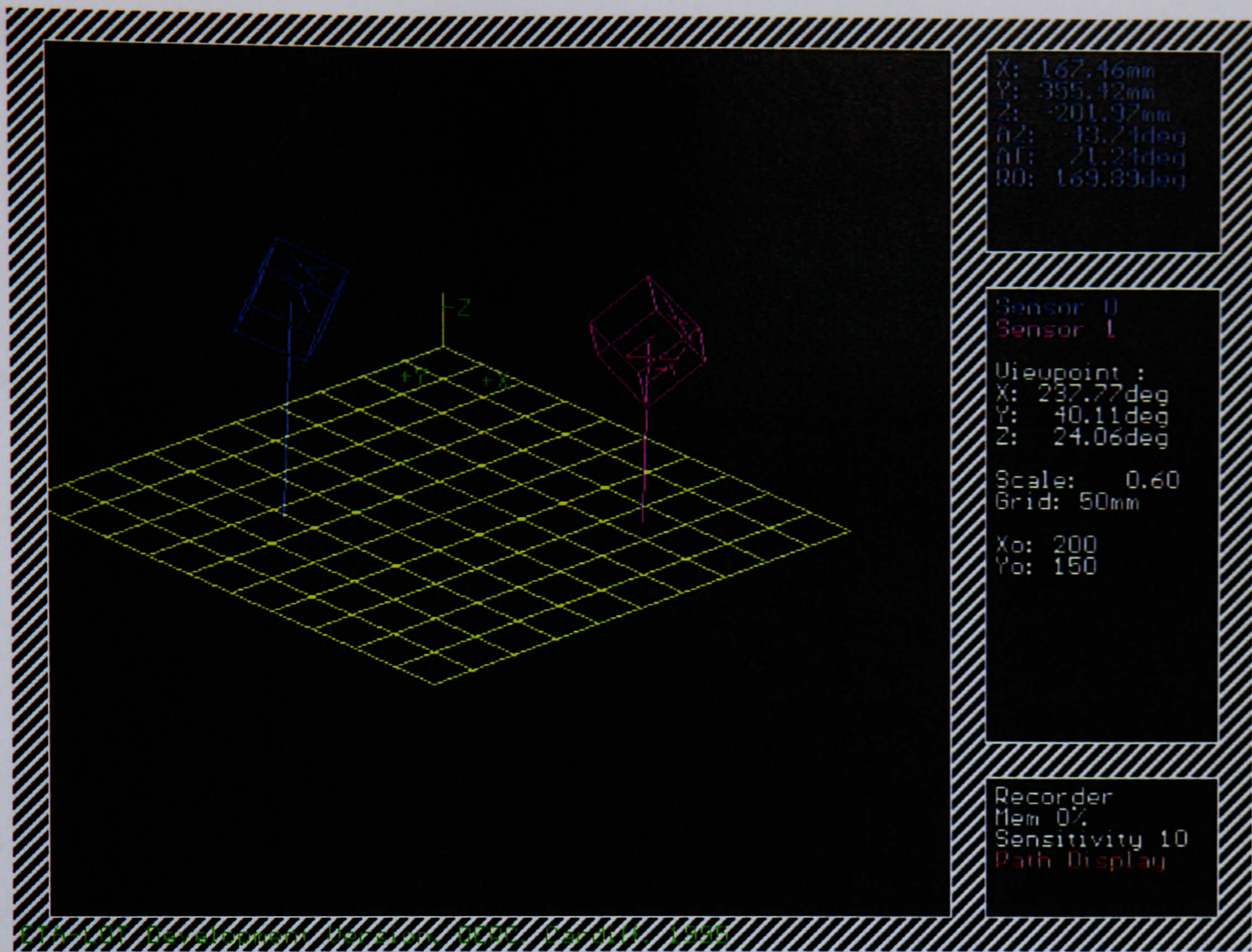


Figure 18: Typical screen output from theETALOT program

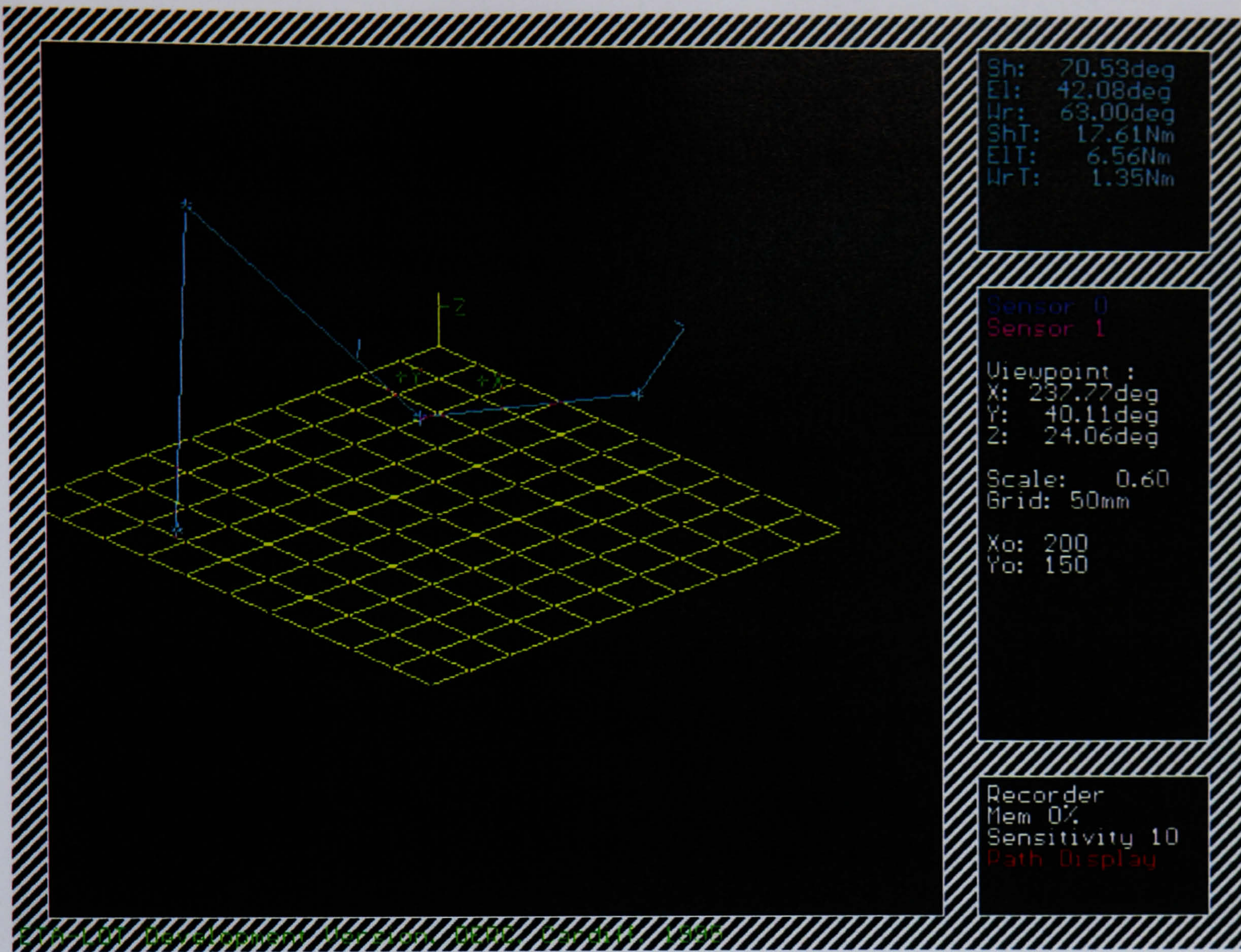


Figure 19: The ETALOT program showing an experimental limb model constructed in real time from sensor data.

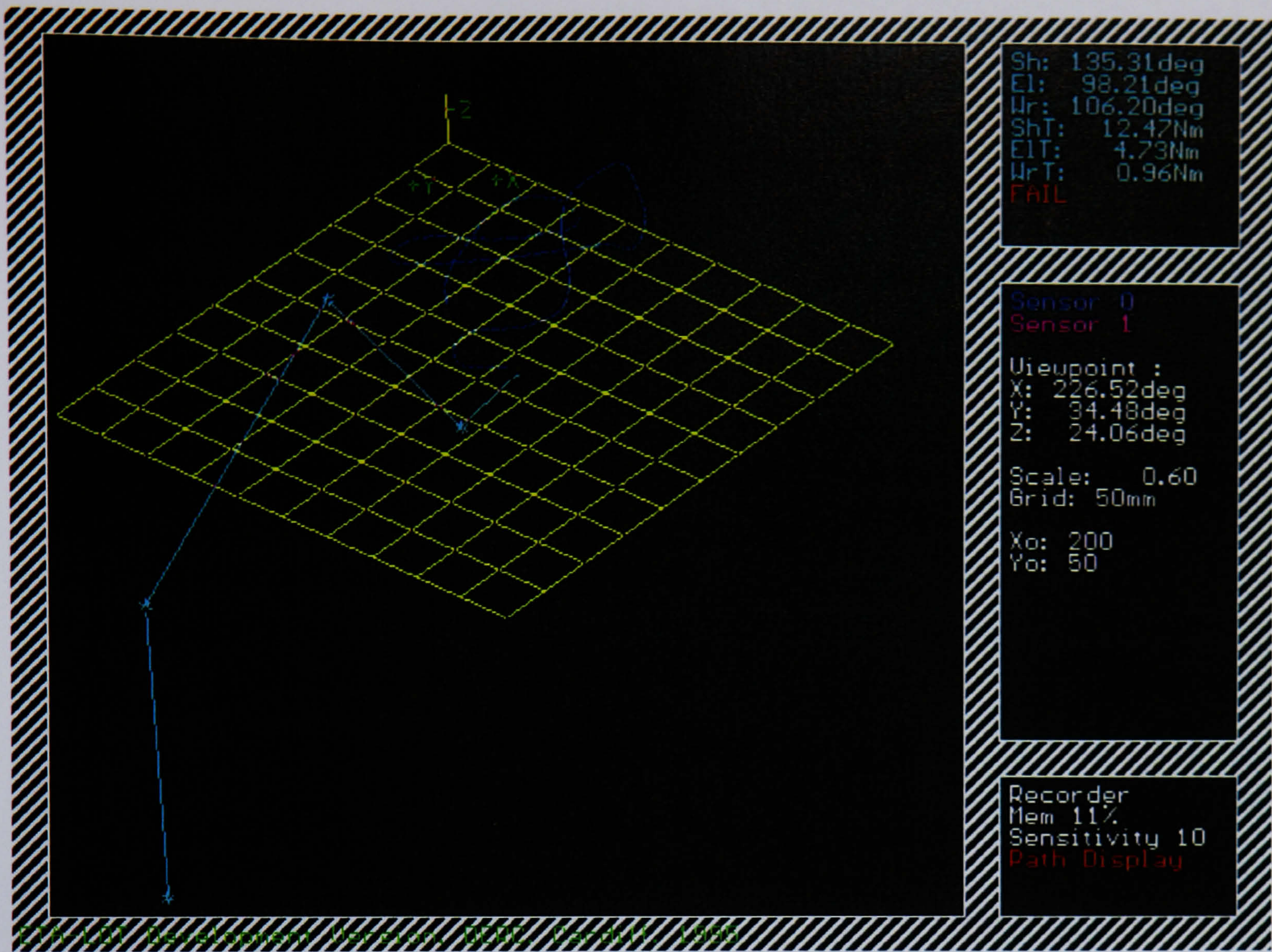


Figure 20: The ETALOT program showing recorded sensor path data.

2.2.4 Sensor mountings

The mounting points of the sensors or markers for any motion analysis system are very important, markers must be firmly attached to the segment or segments they are intended to measure, but the attachment system must be carefully designed to avoid restricting or interfering with the subject's movements. Mounting systems must also be adjustable to allow fitting to a wide range of subject anthropometries, making sensor mounting a significant human-machine systems problem in itself.

The use of the Polhemus tracking system does avoid some important problems that often affect motion analysis systems, notably:

1. The need to maintain a wide viewable angle that plagues some optical marker systems
2. The requirement of goniometer systems to find marking points on two limb segments in close proximity.

However, there are different difficulties associated with any system that collects angular data from a single sensor, and inclinometers, accelerometers and electromagnetic trackers all fall into this category. In order to collect angular data effectively, the Insidetrak sensors have to be fixed in a manner that minimises rotation of the sensor with respect to the limb segment. Unfortunately, muscle contraction and skin movement can both have a considerable effect on the angle of a particular portion of the segment's surface.

Three factors were therefore considered important in the design of sensor mountings:

1. The location of points on each segment that suffered the minimum amount of soft tissue movement.
2. Maximising the contact area of the sensor with the skin or clothing to provide the securest possible platform on which the sensor would be located.
3. Ensuring a firm physical connection between the limb segment and the sensor.

Additional materials selection constraints were placed upon the design of the mounting system by the need to avoid metallic elements that might interfere with the local magnetic fields. These factors will be discussed in turn below.

2.2.5 Sensor position

During the development of the modelling system, three possible sensor-mounting positions were assessed:

1. The dorsal surface of the hand, between the metacarpophalangeal joints and the radiocarpal joint
2. The dorsal surface of the wrist, just proximal of the distal radiocarpal joint, in the position at which one normally wears a wristwatch.
3. The lateral surface of the arm, approximately half way between the shoulder and the elbow.

These three positions were found appropriate for the collection of data about the position and orientation of the hand, forearm and upper arm respectively. Unfortunately, the number of sensors fitted to the Insidetrak system was limited to a maximum of two. Section 2.3.7 discusses the eventual selection of a model and correspondingly appropriate sensor mounting positions.

2.2.6 Maximising surface contact

The small base area of the sensors (20 x 25 mm) was increased by the addition of epoxy mounting plates, constructed directly from CAD information using the Stereolithography process. These plates have an under-surface of 50mm diameter that was considered to be the largest mounting area that would still fit securely to a very small subject. To improve their fit the undersides of the plates are concave to match the curve of the limb. The mounting plates have a rotating top part that allows the sensors to be oriented in a number of pre-set positions without the need to alter the nylon mounting screws. They also contain slots that allow the connection of straps or elastic webbing in a number of configurations.

2.2.7 Physical attachment

There are three basic ways that markers or sensors can be attached to limb segments:

1. Adhesive bonding to the skin with a double-sided tape.
2. Strapping to a flexible or rigid collar around the limb
3. Attachment to a pin inserted into a bone.

The third option is clearly unacceptable for purposes of product assessment, although it does have the benefit of eliminating any effect of soft tissue movement. Adhesive mounting was attempted, but eventually rejected in favour of nylon webbing straps and plastic buckles which offered greater security, rapid mounting and removal of sensors and facilitated their installation over the top of loose fitting clothing.

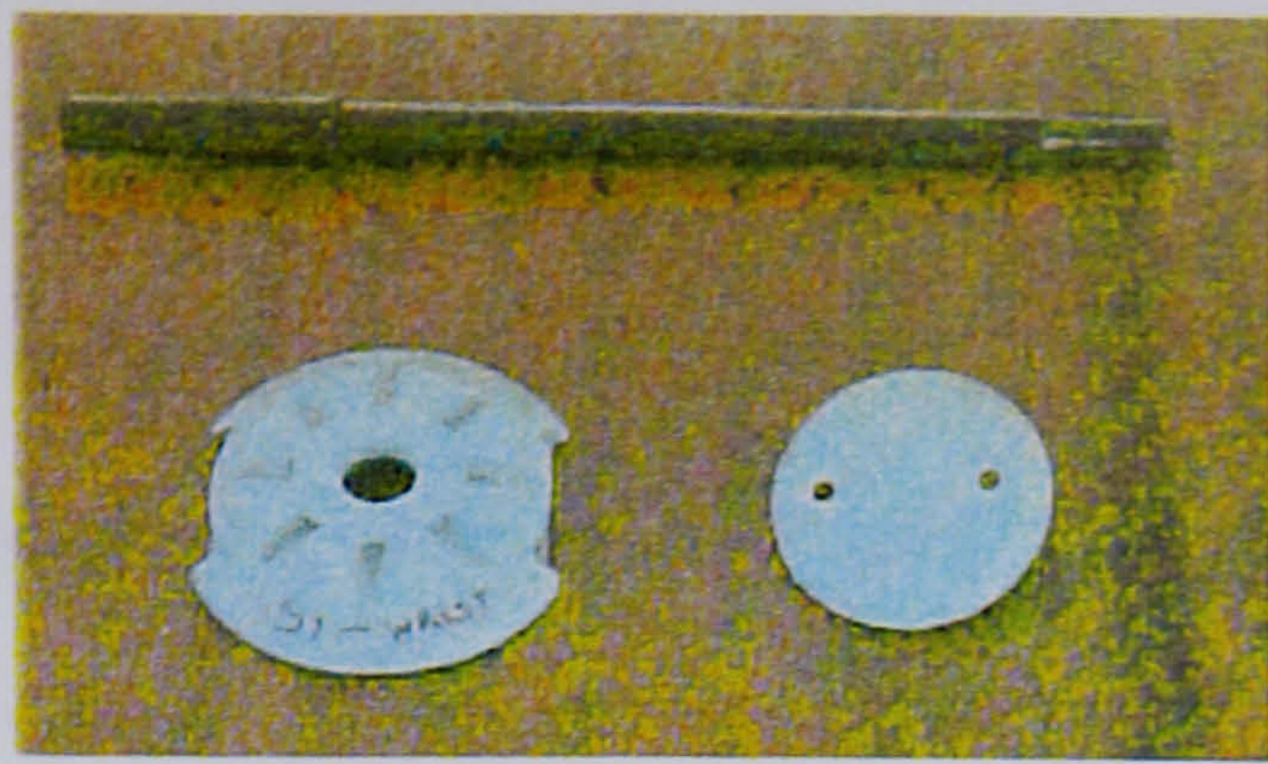
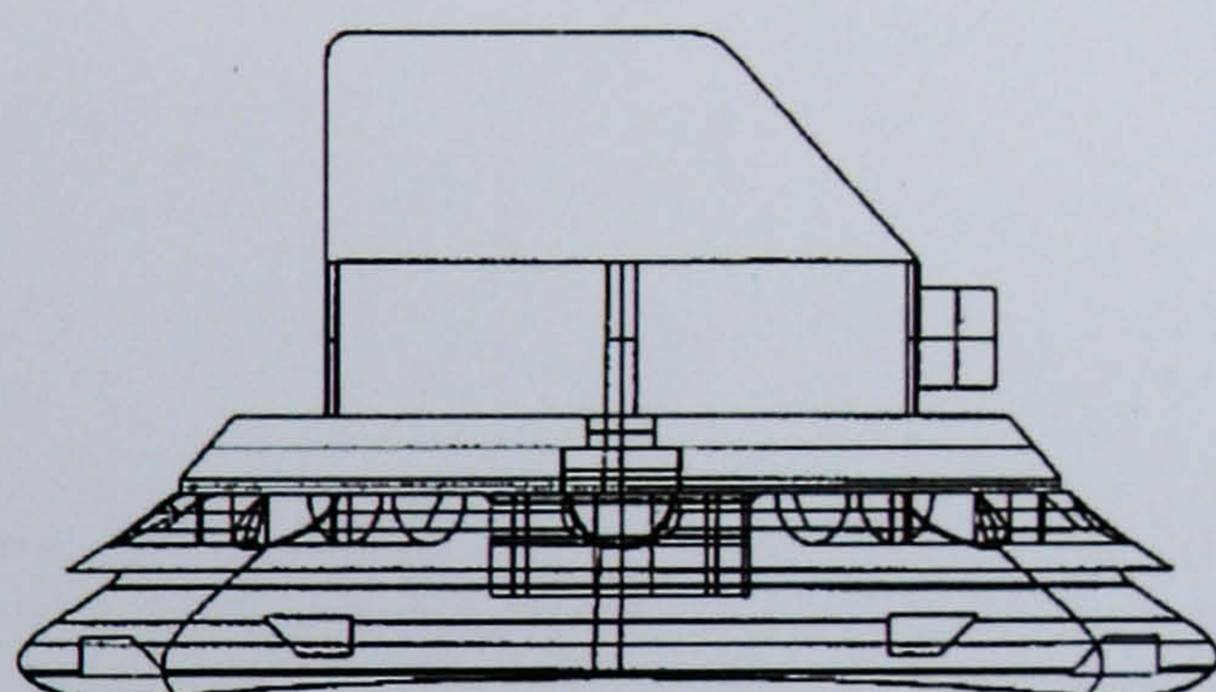
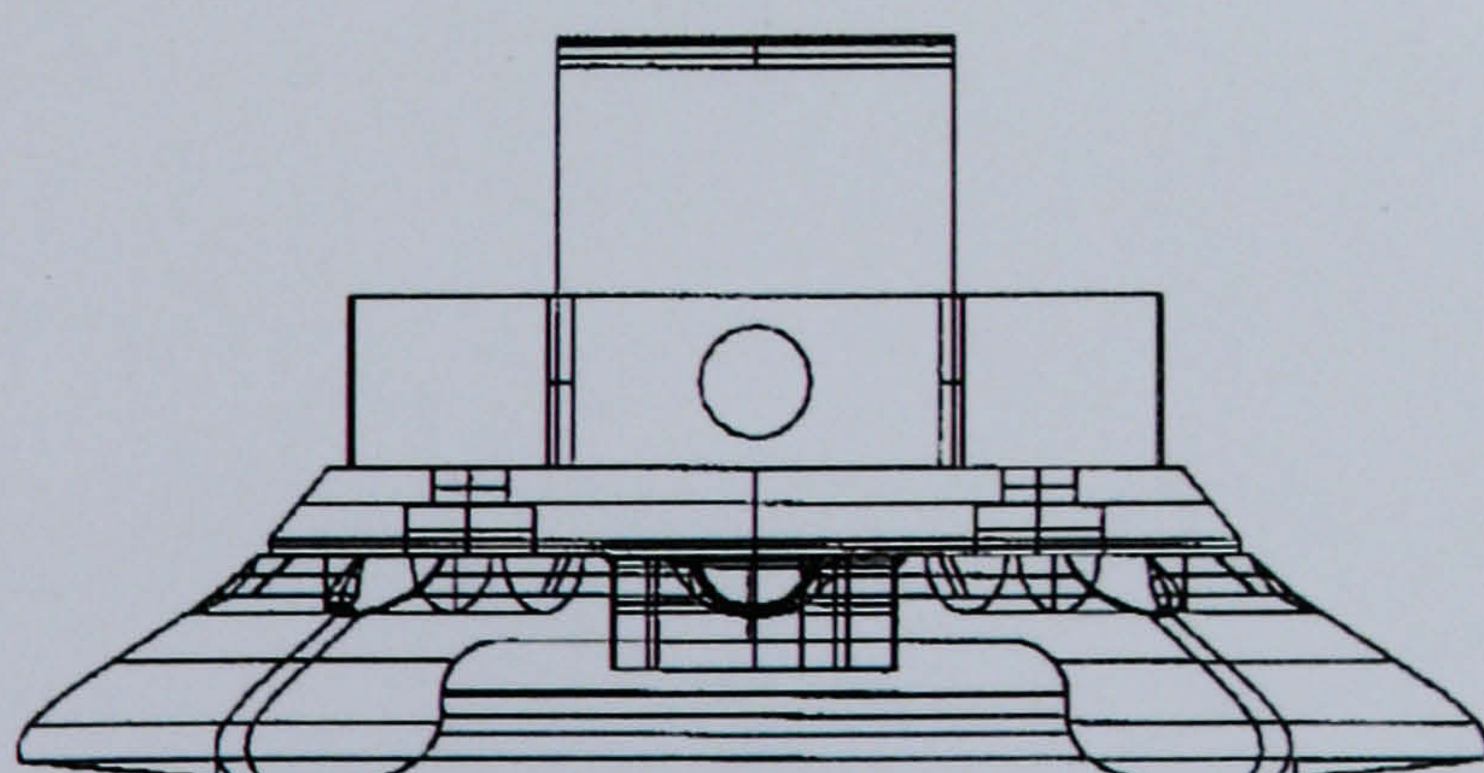


Figure 21: A sensor mounting plate showing the notches for angular adjustment.

Figure 22: The underside of a sensor mounting plate showing the strap slots.





2.2.8 Summary

This section has described the selection of motion analysis system the purpose of which is to collect information on upper limb motions with which to drive a biomechanical model. The system eventually chosen was a six degree of freedom electromagnetic tracker.

The development a software interface for the tracker system was described, as was the development of a hardware interface to allow the tracker sensors to be fixed to the limb of a test subject.

Chapter 2.2 describes the development of the biomechanical model that was designed to run using the collected motion data to simulate limb actions. The nature of the sensor system chosen has strong implications for the type of model used, and so the discussion of the Polhemus Insidetrak sensor system will continue in the next chapter, particularly in Section 2.3.16 which concerns the interface between the sensor system and the model.

2.3 Biomechanical Model

2.3.1 Introduction

The second essential stage in the development of the analysis system was the design or selection of an appropriate biomechanical model. As with the hardware selection process, there was a choice to be made between adapting a commercially available human model, such as those described in Sections 1.4.14 and 1.4.15, or developing one specifically for this work The latter approach was selected as the ready availability of general computer modelling and analysis packages was considered to make the design of a model from scratch a more straightforward proposition than the possibly lengthy and complex process of adapting one of the existing modelling packages to accept motion analysis data. The problem can be considered in four stages:

1. The anatomy of the upper limb must be considered: The underlying system that the model is designed to simulate. Anatomy is discussed in Section 6.2
2. Available modelling methods must be evaluated.
3. The detailed design and construction of the model must be carried out.
4. The problem of using motion data collected from sensors to drive a biomechanical model must be overcome

2.3.2 Modelling Methods

Biomechanical modelling techniques are derived from the mechanical analysis methods used in more general engineering. As with all engineering models, a biomechanical model is a considerable simplification of the real structure under analysis, the degree of simplicity depending upon the model's application. Models of small parts of the body, usually individual joints, have been constructed in detail by biomechanics researchers, using sophisticated finite-element methods. Typical of the detailed, joint-level approach to biomechanical analysis is the work of [Werner and An, 1994], among others. These models have provided useful insights into the operation of the body, helping the understanding of disease mechanisms and the prediction of surgical outcomes. At another extreme, in some aspects of automotive safety analysis the entire human body might be represented by a single point mass.

It is clear that modelling the human body as a single solid mass would not be very informative if one wished to analyse user-product interaction in any detail, and the tendency might be to construct as sophisticated a model as possible in order to gain the maximum potential insight into the task under examination. Large, complex models do however, have a number of drawbacks:

1. They are extremely data-hungry, requiring information that is difficult and expensive to obtain, (such as geometrical data from CAT (Computer-aided Tomography), or similar medical scanning systems), or impossible to collect *in vivo* (such as the precise stiffness of tendon tissue).
2. A very precise model requires information from a particular individual, it might therefore be suggested that the more precise a model is in its construction, the more difficult it will be to generalise the results obtained to a larger, untested population. This generalisation of conclusions is an essential requirement in the product design context.
3. Large models are computationally very expensive to run, requiring complex mathematical techniques and powerful computers.
4. The more complex a model is, the more complex will be the results it generates, and therefore the more difficult the analysis required to obtain useful and relevant design information; biomechanical assessment of tasks is not a science in which all measurements must be taken at a sub-microscopic level, and accessible approximate results are likely to be of much more use to a product designer than reams of accurate but potentially impenetrable data.

2.3.3 Ergonomic models

For the reasons described above, ergonomists have tended to avoid both the simplest and the most complex biomechanical models when attempting to analyse tasks. Perhaps also because of ergonomics' strong historical links with engineering rather than medicine, ergonomic models have drawn heavily on work involving the simulation of robots.

Ergonomists have used various levels of abstraction in previous work, but almost without exception these models have been based on what is known as the *rigid body* approach.

2.3.4 Rigid body models

In the rigid body approach to modelling, the areas under analysis are considered to be divided into a number of rigid segments, each of constant mass and size. The number and arrangement of these segments depends upon the particular model under investigation. The segments are considered to be connected by joints that can provide rotational or translational motion between them. The joints may also be able to transmit torques (Figure 24 A), or muscles and tendons may be modelled that apply tension to the segments in order to generate motion or resist external forces (Figure 24 B).

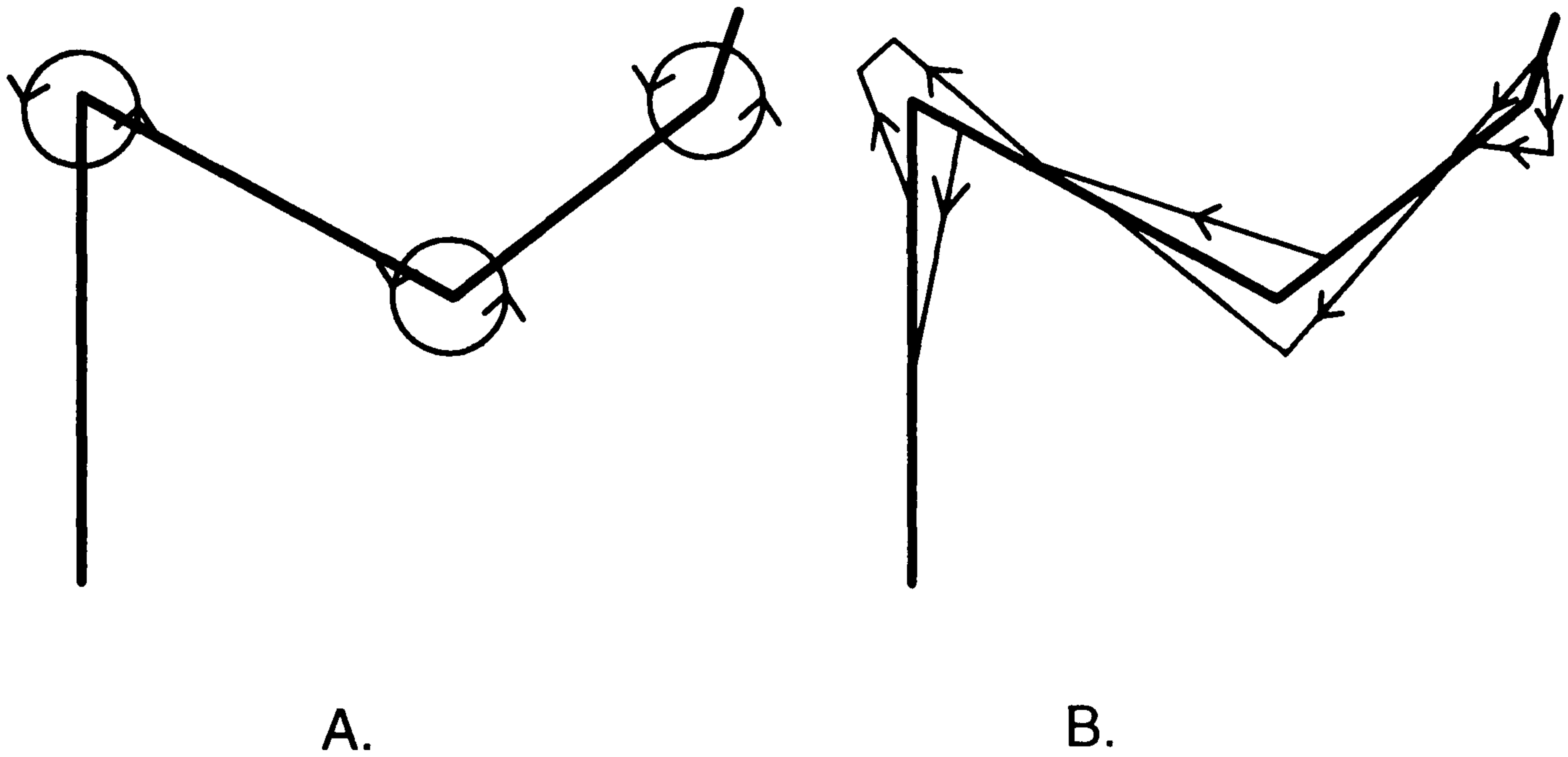


Figure 24: Two possible types of rigid-body model. A) Using joint torques to simulate movement and resist forces. B) Modelling the lines of action of muscles and tendons.

In general, models that simulate the actions of muscles are computationally much more costly than those which produce torques in the joints, this is because, as discussed in Section 6.2.2, the muscles of the body operate in a highly redundant fashion and a required force might be produced in whole or in part by any of a number of muscles.

Within the confines of the rigid-body approach to biomechanical modelling there are further decisions that must be made about the nature of the model and the analytical techniques applied to it. Two of these are described below.

2.3.5 Two and three dimensional models

Analysis can take place in two or three dimensions.

1. Two dimensional analysis is considerably simpler, particularly when dynamic calculations are taking place, but the highly three-dimensional nature of most upper-limb activities, particularly product interactions, means that the approximations required for 2D analysis may be unacceptable.
2. Three dimensional analysis can offer considerably more realistic results, but at a cost of additional computational complexity.

Detailed experimental work comparing the use of 2D and 3D modelling techniques was carried out by [Bone et al, 1990]. The context of their work was that of a manual task, and their results concluded that the 2d approach produced good results for a large number of lifting situations. It should be noted, however, that in simple lifting tasks most of the movement takes place in a single plane and the authors point out that care must be taken to ensure that, if photogrammetric methods are used to record motion data for 2D analysis, the camera is positioned so that limb segments which are experiencing maximum moment are aligned with the image plane. In this work the requirement that planes of motion be carefully predicted and controlled was considered unrealistically restrictive. All the modelling work carried out here therefore was three dimensional.

2.3.6 Static or dynamic analysis

Biomechanical analysis can also be quasi-static or dynamic.

1. Quasi-static analysis ignores the effects of momentum and acceleration during the analysis process. It treats individual frames of motion as if they were stationary limb positions. Computationally, static analysis is relatively straight-forward, but for high speed motions the dynamic effects on body forces may be considerable and the errors imposed by static analysis could prove unacceptably high.

2. Dynamic analysis overcomes the problems of errors in high-speed movement, but the approach carries a severe computational cost and requires additional data on the moments of inertia of limb segments to be collected or derived. Whether product interaction tasks in the home or work environments (as opposed to, for example, sporting and athletic tasks) necessitate this complexity is arguable, since the constant acceleration caused by gravity will tend to far exceed any inertial forces created by the motion of the limb segments.

In this work the quasi-static approach was considered an acceptable level of approximation, and was adopted. The assumption was tested in Section 3.3.13 and found adequate for the tasks under analysis in this work.

2.3.7 Model Design.

Having chosen to construct a three dimensional rigid segment model of the upper limb, a number of design decisions had to be made. These decisions fell into two categories.

1. The choice of segments
2. The nature of the joints between the segments

The factors will be discussed in turn.

2.3.8 Choice of segments

1. **Upper arm.** The upper arm contains a single bone, the humerus, and is suitably modelled using a single segment.
2. **Forearm.** Although the use of two segments in the forearm might be useful if interactions between the radius and ulna are of interest, for general purposes the forearm can be modelled using a single segment.

2.3.9 Design of joints

It has become conventional [Sengupta and Das, 1993; Leppanen and Mattila, 1987; Chen and Ayoub, 1988; Ramadan and Plummer, 1987; Kerk et al, 1994; Kromodihardjo and Mital, 1986;

Kayis and Iskander, 1994] to construct models of the human body using only combinations of revolute joints. This makes an effective compromise as the rotational freedom of a joint nearly always far outweighs the translational freedom. This assumption was adhered to during the design of the model for this work, with a notable exception at the shoulder joint, discussed below:

The shoulder. The number of degrees of freedom at the shoulder and the complex construction of the whole joint area make modelling of the proximal end of the arm difficult. A common solution is to use two joint regions connected by a link that represents the clavicle. The clavacular link pivots at its medial end and allows spatial movement of the glenohumeral joint at its lateral end. This approach to shoulder complex modelling was adopted by Badler et al [Badler et al, 1993] The solution adopted in this work however, was to allow the glenohumeral joint to float, giving it three degrees of spatial freedom. In a context where the torso and the rest of the body are not being modelled, such a free floating joint obviates the need to unnaturally restrain the upper body of experimental subjects, (the approach used by some studies, notably [Pandya et al, 1992]) without introducing the large errors that would be caused if measurements from a moving shoulder were forced to fit onto a restrained model. The glenohumeral joint itself was given three rotational degrees of freedom.

1. **The elbow**. The humeroradial and humeroulnar joints are often represented as a simple revolute joint with a single degree of freedom. Pronation and supination represent a single additional degree of freedom. As the rotation takes place at the three radioulnar joints along the length of the forearm it is possible to model this rotation as movement at the elbow or at the wrist. The choice depends upon the degrees of freedom provided at the wrist and the source of data used to drive the model. In this work, the majority of the modelling work was done with separate hand segment and with forearm position data collected at the wrist. This sensor position meant that the forearm data contained all the pronation/supination information, a situation that would not necessarily have occurred if a sensor had been placed proximal to one or more of the radioulnar joints. Forearm rotation was therefore included as a second degree of freedom at the elbow.

2.3.10 Denavit-Hartenberg Parameters

The model used for the majority of the experimental work in this work had two segments and five degrees of freedom. The Denavit-Hartenberg representation was used to construct the model mathematically (Section 6.4.6). Further discussion of the use of kinematic chains in the description of human biomechanical models can be found in [Badler et al, 1993] pp 28-34. Figure 25 shows the Denavit-Hartenberg coordinate frame assignment for the model. The Denavit-Hartenberg parameters are given in Figure 26.

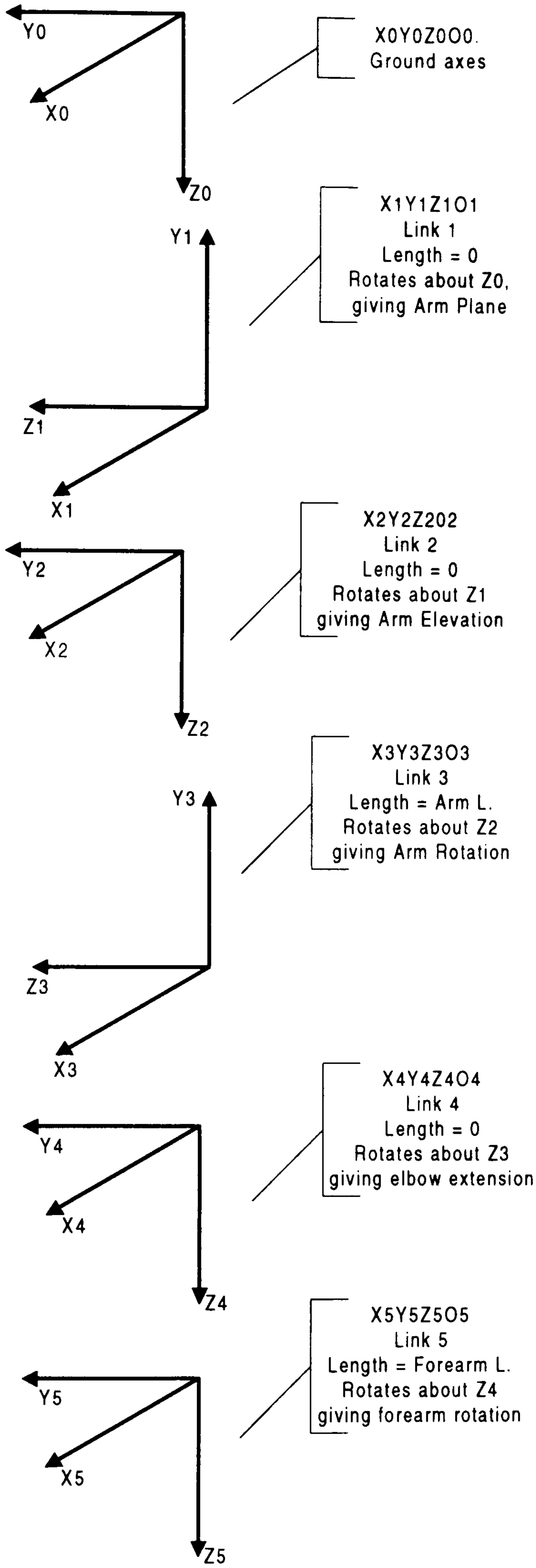


Figure 25: The Denavit-Hartenberg coordinate frame assignment for a two segment, five degree of freedom limb model.

Link	Degree of freedom	α	a	θ	d
1	Arm Plane	-pi/2	0	0	0
2	Arm Elev.	pi/2	0	0	0
3	Arm. Rot.	-pi/2	0	0	Upper arm length
4	El. Bend.	pi/2	0	0	0
5	Forearm rot.	0	0	0	Forearm/hand length

Figure 26: Denavit Hartenberg parameters for the five degree of freedom limb model.

2.3.11 Joint state description

In more conventional terms the five degrees of freedom in the model can be described as:

1. The vertical plane in which upper arm elevation takes place; with zero being the sagittal plane posterior to the shoulder.
2. The angle of extension or abduction of the upper arm with zero being the anatomical position.
3. The angle of internal or external rotation of the upper arm, with 0 being the anatomic position in which the axis of the elbow lies in the frontal plane and the elbow, if flexed, would cause the forearm to rise to the anterior of the body in the sagittal plane.
4. The angle of elbow flexion.
5. The angle of pronation and supination at the forearm.

2.3.12 Anthropometric parameters

To have any chance of producing valid results, a biomechanical model must be supported by appropriate anthropometric data. The exact data required varies according the model being developed. Models that simulate the body surface for spatial fit assessment purposes require extensive data on the surface morphology of limb segments [Roebuck, 1994] which can be obtained from living subjects using a variety of fairly expensive and time consuming techniques discussed in Section 1.5.3. The data required for a simple rigid segment mass model such as that being utilised here is much more limited in scope, but unfortunately some of this data is impossible to collect from living subjects. The data needed fall into three sections:

1. Segment length. The linear distance between joint centre of rotation.
2. Segment mass. The mass of the tissue that can be considered to rotate with each segment.
3. Segment centre of gravity. The position of a point mass equivalent to the distributed mass of a segment

Additionally, dynamic mechanical analysis requires information on the moments of inertia of each segment. The quasi-static analysis adopted in this work obviates the need for such data.

None of these values can be obtained by direct measurement, and the usual way of estimating them is to use regression equations developed from the study of cadavers. This technique is open to criticism since very few cadaveric studies of segment length and mass characteristics have been conducted, and those that have have used a relatively small number of subjects. However, with no alternative sources of data available, the use of segmental regression equations was adopted for the development of most of the models in this work. The methods used for each data element are described below.

2.3.13 Segment Length

Segmental length estimates were derived using the equations published by Dempster [Dempster et al, 1964]. These equations allow segment lengths to be derived from measurements taken of the radius. The measurement protocol is defined as the distance from the radial styloid process to the centre of the palpable sulcus behind the elbow.

Segmental length parameters were then calculated as follows, all dimensions are in mm:

Upper arm segment length = 58.0752 + (0.9683 x measured radial length)

Forearm segment length = 1.0709 x measured radial length

2.3.14 Segment mass

A number of techniques are available for the estimation of segment mass. Two options were considered for this work.

1. Expression of segmental mass as a fraction of total body mass.

2. Calculation of segment mass from estimates of segment volume and density.

Option 2. was selected for two reasons:

1. The method makes allowance for different limb segment proportions between subjects.

2. It does not require subjects to reveal their total body mass (a dimension which many people are reluctant to make available).

Segment density data was found in [Chaffin and Anderson, 1984]. This was a reprint of [Miller and Nelson, 1976] which in turn reported data collected by Harless (1860) and Dempster (1955). The values used in this work are shown in Figure 27.

Segment	**Density g/cm^3**
Upper arm	1.07
Forearm	1.13
Hand	1.16

Figure 27: Segment density values.

Segment volume estimates were based upon the work of Yeadon and Morlock [Yeadon and Morlock, 1989]. The assumption was made that limb segments could be modelled as cylinders of constant density. Three perimeter measurements were taken from each subject for each segment:

1. Proximal perimeter

2. Distal perimeter

3. Maximal perimeter

These values were then averaged with double-weighting given to the maximal perimeter value in order that the mass estimate should err on the large side. Perimeter volume was calculated using the equation in Figure 28:

$$v = \frac{p^2 l}{4\pi}$$

Figure 28: The segmental volume equation.

Where p is the mean perimeter, l is the segment length and v is the volume.

2.3.15 Segmental centre of mass.

The centre of mass of a segment is normally assumed to lie on the centre line of a segment. The conventional way of expressing its position is as a fraction of the total segment length. This convention was adopted here, using data obtained from Dempster via Chaffin [Chaffin and Anderson, 1984]. Figure 29 gives the values used.

Segment	% distance of CoG from proximal end of seg.
Arm	43.6
Forearm	43
Hand	49.4

Figure 29: The position of segmental centres of mass.

It should be noted that in the Denavit-Hartenberg representation of models used in this work the coordinate frames did not necessarily have their origins at the proximal end of each segment, so in some cases the centre of gravity position had to be expressed as a distance from the distal end. Additionally, the use of a single segment to represent both the forearm and the hand required that their individual centres of gravity be combined using moments. Figure 30 gives the equation used where L is the position of the combined centre of gravity expressed as a distance from the proximal end of the forearm. The l_x values are the distances of the individual centres of gravity from the proximal end of the forearm and the M values are the masses of each segment.

$$L = \frac{l_1 M_1 + l_2 M_2}{M_1 + M_2}$$

Figure 30: The equation used to combine segment centres of mass.

Similar methods were used by [Badler et al, 1993]

2.3.16 The sensor-model interface

Once a model has been established, the proposed system requires that it be driven by data collected from an external motion analysis system. The logical way to do this would be to establish points on the model that correspond with the positional and angular data being collected by the motion analysis hardware, and adjust the model's joint variables so that the model data equals that being collected. Unfortunately, things are not quite so simple in practice. As has been stated previously, the human body is not a simple rigid-body structure, therefore whilst the model is constrained to adopt certain positions according to its geometry, the body being measured is unaware of these constraints. When biomechanical information is being collected using some form of automated motion analysis system, the problem is one of ensuring the closest possible correlation between the data values collected from the system and the data values allowed by the constrained model.

Errors in correlation between data and model can come from two basic sources:

1. Differences between the model and the actual biomechanical configuration
2. Noise caused by inaccuracies in the motion detection system.

Sensor error caused by noise is an unavoidable aspect of the operation of any motion analysis system, but it is worth taking a brief look at the sources of error that cause the biomechanical model to differ from the biological system it approximates. Again, there are two principal factors:

1. The articulations of the skeletal structure are not based on simple revolute joints. Sliding and rolling actions within the joints cause the effective lengths of segments and positions of centres of rotation to change slightly during movement. While this movement is unlikely to be of interest to a study of gross limb motions, it might be enough to prevent sensor data form conforming to a revolute jointed model.
2. The positions of markers or sensors for motion tracking systems must by necessity be on the skin. Skin and underlying layers of fat and muscle tend to move relative to the bone during

motion, thus the position of the sensor on the segment can change. This problem was discussed in Section 2.2.4.

There are a number of ways to circumvent these problems and allow the model to be resolved. Three basic approaches might be:

1. To introduce extra degrees of freedom into the model whose values can be altered so that a "legal" configuration for the main degrees of freedom can be adopted.
2. To ignore the status of some of the degrees of freedom in the model, allowing these to assume values that are inconsistent with the data collected
3. To search among the legal model configurations until the one that most closely matches the sensor data is located, thus spreading the overall error through all the degrees of freedom available, but hopefully keeping the error in each individual degree of freedom to a low level.

Solution 2. was adopted for the majority of the experimental phase of this work. The model was solved by ignoring totally the spatial position of the sensors and forming a model whose angular parameters matched exactly the collected data. This approach meant that there was no guarantee that the end effector of the model would be in the same position as the subject's hand. Such a method would not be appropriate in situations where the position of the end effector in the environment is a critical design factor, the positioning of controls in a vehicle cockpit being a good example, but as joint forces, which are a function of limb orientation during product interaction were of primary interest, it was deemed acceptable to ignore precise spatial accuracy. The method had further advantages in that it obviated the need for information on the precise position of the sensor relative to the segment coordinate system to be collected. This reduced the time taken to set up and calibrate the sensor system considerably since the sensors only had to be attached and set by software to a position of zero alignment while the limb segment was held in a corresponding position before data collection could commence.

2.3.17 The two segment sensor data fitting algorithm.

To collect motion data for the two segment limb model, sensors were attached to the lateral side of the arm and the dorsal surface of the wrist (Section 2.2.5). They then had to be calibrated so that their zero rotation position matched that of the limb segments to which they were attached.

The arm sensor was set to zero with the arm in the anatomical position: straight by the side of the torso and the palm facing forwards.

While it was quite possible for the forearm sensor to be set to the zero alignment position with the arm arranged as above, it was desirable to bring the sensor as close as possible to the transmitter during calibration to minimise angular error. Therefore the forearm sensor was reset with the forearm placed flat on a surface, aligned with the transmitter X axis, palm facing downwards and with the fingers pointing towards the transmitter. It was then necessary to swap certain axes of the sensor angular matrix after data collection to match the zero rotation position of the sensor data with the neutral position of the arm.

Figure 31 shows the position of the arm during the sensor calibration process. The axes of the hand sensor were swapped such that

1. $x \rightarrow -z'$
2. $y \rightarrow y'$
3. $z \rightarrow x'$

Where x'y'z' were the original sensor values and xyz were the new ones. This meant that the palmar surface of the hand faced backwards rather than forwards in the zero position, (an arbitrary decision made during the original testing of the algorithm. Adding or subtracting π from the forearm rotation angle would give the joint a zero value with the arm in the anatomical position.

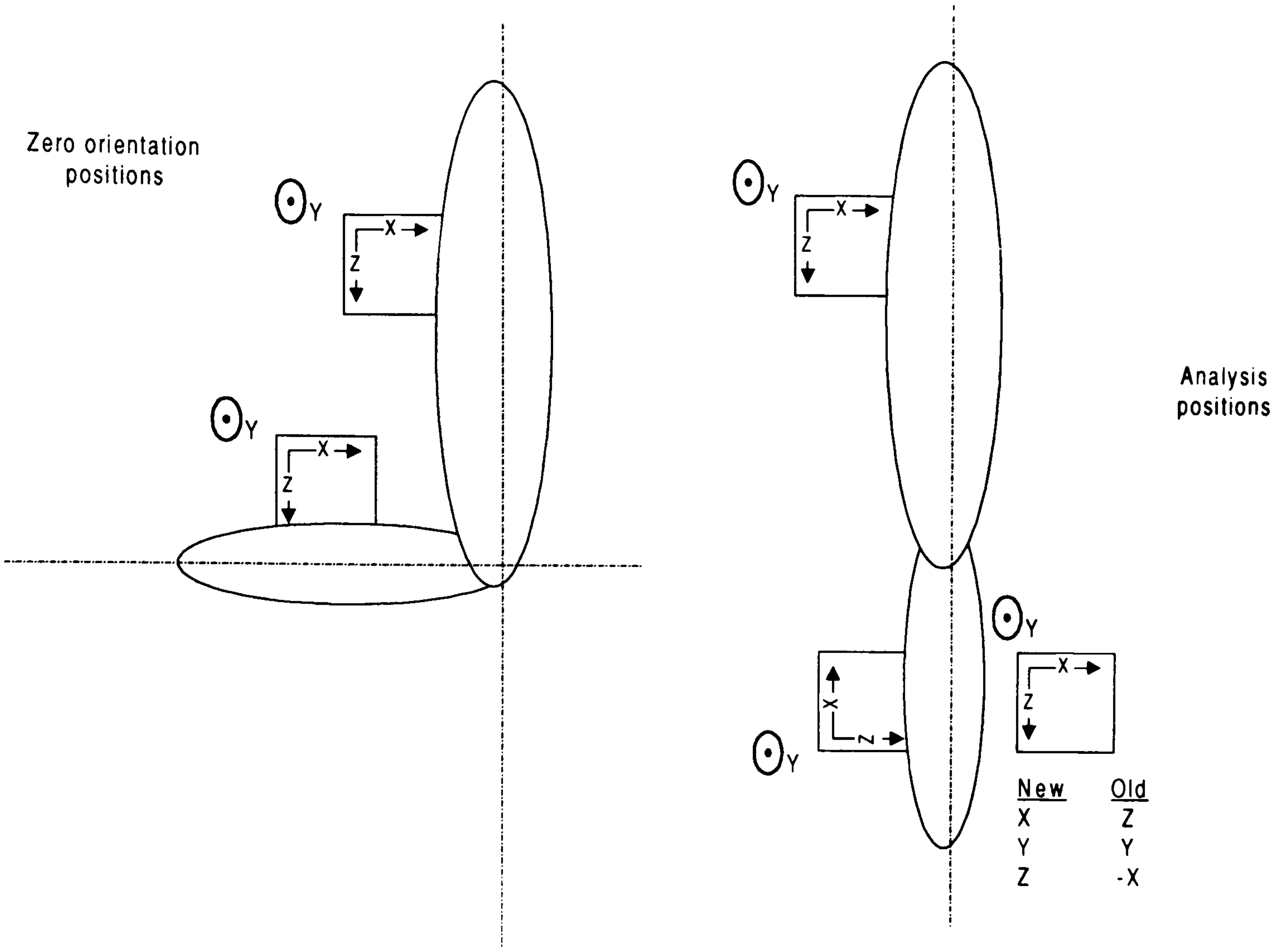


Figure 31: Arm and sensor positions for the two segment limb model.

The transformed sensor output matrices now represented the global orientations of the two limb segments. The upper arm sensor was assumed to be rooted in the global coordinate system: rotation of the torso was ignored. This meant the shoulder angles for the model could be derived directly from the upper arm sensor matrix. However, in order to calculate the elbow and forearm angles, the transformation between the upper arm segment and the forearm segment was needed. It was assumed that:

1. (shoulder matrix)(elbow matrix)=(forearm matrix)

Therefore the elbow matrix could be calculated by multiplying the forearm matrix by the inverse of the shoulder matrix. It should be remembered that the inverse of an orthogonal matrix is equal to its transpose, therefore:

2. (elbow matrix)=(shoulder matrix)^T(forearm matrix)

Joint angles were then collected by obtaining Euler angles from the shoulder and elbow transformation matrices. The equations used are given in Figure 32

$$Plane = \tan^{-1}\left(\frac{m_{23}}{m_{13}}\right)$$

$$Elev = \tan^{-1}\left(\frac{\cos(plane)\cdot m_{13} + \sin(plane)\cdot m_{23}}{m_{3,3}}\right)$$

$$Rot = \tan^{-1}\left(\frac{-\sin(plane)\cdot m_{11} + \cos(plane)\cdot m_{21}}{-\sin(plane)\cdot m_{12} + \cos(plane)\cdot m_{22}}\right)$$

Figure 32: Equations to obtain Euler angles from the transformation matrix *m*.

This produced six angular degrees of freedom. It will be remembered however that the two segment model only had five degrees of freedom. The disparity occurred because the sensor readings allowed the plane of elbow elevation to alter, whereas the model assumed that the elbow was a revolute joint whose plane of elevation was always zero. A difference might be caused by deviation at the elbow joint, by soft tissue movement under the upper arm sensor or by poor initial rotational alignment of the sensor. To fulfil this assumption the elbow's plane of elevation angle was added to the upper arm rotation angle and all rotation of the plane of the elbow joint was assumed to take place at the shoulder. Figure 33 shows the angles and their corresponding Denavit-Hartenberg link numbers.

Link	Value
1	Arm sensor plane of elevation
2	Arm sensor angle of elevation
3	Arm sensor angle of rotation + forearm sensor plane of elevation
4	Forearm sensor angle of elevation
5	Forearm sensor angle of rotation

Figure 33: Angular data used to drive the two segment limb model.

2.3.18 Model implementation

The model describe above was implemented using the MATLAB system [Th Math Works Inc., 1995] running on a 66Mhz 486DX PC with 32MB of RAM. The calculations involving the manipulation of Denavit-Hartenberg parameters to obtain torques and end-effector positions used routines provided in the Robotics Toolbox [Corke, 1996], a set of MATLAB routines designed for the simulation and analysis of robots.

2.3.19 Summary

Section 2.2 has discussed the approach to biomechanical modelling adopted for the ergonomic design tool under development in this project. The decision was made to use a two-segment, three dimensional rigid body model with joints providing five degrees of freedom.

Of the available methods for implementing such a model it was decided to use a robotics simulation approach as it was felt that this allowed suitable control over the model parameters whilst still providing the convenience of tested, off-the-shelf analysis routines.

The problems involved with the linking of motion data collection systems to biomechanical models was discussed, and a solution proposed that relied upon the collection of only angular data from the motion analysis system. The success of this approach is evaluated in Sections 3.2.4 and 3.2.5.

Section 2.4 goes on to discuss analysis techniques that would make appropriate use of the data collection and modelling system described here.

2.4 Analysis

2.4.1 Introduction

Even if a product designer has access to a perfectly accurate motion analysis system, coupled to a superb model of the entire human body, there is no guarantee that it will be able to produce any useful information about the design problem under analysis. It is the conversion of biomechanical data to design information upon which rests the success of failure of the entire approach under discussion in this work. This section discusses the basic approach to the collection and analysis of biomechanical data that has been used here.

Section 2.4.2 outlines the nature of the human-interface optimisation problem, and describes a proposed approach for the use of motion analysis and biomechanical modelling techniques as a partial solution. Sections 2.4.4-2.4.8 then discuss the various elements of the proposed method in more detail.

2.4.2 Approach

The improvement of a product design through biomechanical analysis can be considered as an under-constrained optimisation problem [Medland, 1986]: a very large number of acceptable solutions can be chosen, some of which will be preferable to others. The problem therefore is one of choosing the "best" solution from the available possibilities. The analysis process, therefore, contains the following stages:

1. Characterisation of typical task elements.
2. Selection of a *quality characteristic*. This is the criterion or criteria against which designs should be judged.
3. Expression of the quality characteristic in terms of the data produced by the modelling process.
4. Design of an experimental scenario that allows the effect of product design parameters to be efficiently assessed.

5. Selection of appropriate subjects.

6. Analysis of the results produced by the experiment in order to separate the effects of inter-subject variability from those caused by design variables and to visualise the responses of the quality characteristic to the varying design parameters.

These stages are discussed below in greater detail.

2.4.3 Characterisation of typical task elements

Task characterisation can take place at many different levels. [Bennet, 1971] carried out work on the use of a qualitative task taxonomy, using verbs such as "lift", "listen", "manipulate", to describe task elements. Such an approach was also adopted by [Brown et al, 1995] in the development of a user-friendly anthropometric database, designed to present data to designers on their own terms. At a somewhat finer level of detail, [Corlett et al, 1979] developed a method known as RULA which used a system of charts to record body posture and ranges of movement during tasks as recorded by skilled observers. The method, while not providing joint angle data in a form that would be useful for detailed biomechanical modelling, was at least an attempt to relate physical stress to body posture. It is interesting to note the authors' comments in the discussion of their work however: -

> What is currently lacking is a reasonable comprehensive model of posture and its effect sufficient for establishing design and performance criteria...at the moment our ability to measure is better than our interpretation of the data and it is from a better understanding of the effects and meaning of posture that the next steps will be made. [Corlett et al, 1979]

2.4.4 Selection of a quality characteristic

The choice of optimisation criteria is the most critical part of the analysis process; firstly because it is the key transformation point between data and information, and secondly, because it is always easier to find something if one knows at the outset what one is looking for.

[Kondraske, 1995] comments extensively on the lack of an appropriate, generalised model for the evaluation of human performance, both in itself and in relation to the artificial environment. Kondraske proposes the use of a number of basic units of performance, elements that occur at a simple enough level to be task independent, but which are also general enough to ensure consistent and straightforward measurement. For example the action of elbow flexion would be considered a basic element of performance, while the study of the muscle groups that caused the flexion would not be considered. Kondraske goes on to suggest that Taguchi methods would be an appropriate technique to tackle the large amount of variation that will inevitably be experienced in the measurement of human performance, but the experimental work is not carried out in a manner that allows the performance of a product to be evaluated rather than that of a person.

The selection of a quality characteristic for biomechanical analysis is limited by the nature of the data available. Biomechanical models produce data on the postures assumed by the subject during analysis and the stresses experienced by the body. These factors are all collected over a known period so, by differentiation, information on the velocities and accelerations of the limb segments and the rates of change of limb loading is accessible. It is also possible to integrate the data to obtain estimates of physical work done during a task and of required power outputs. This data will be available for individual joints in the model, which confounds the problem of criteria selection since it is highly likely that many product designs will entail a trade-off between different parts of the limb (the transfer of load from the elbow to the shoulder for example).

At present, little consensus exists as to the choice of quality criteria for the assessment of product design, this is mainly due to the relatively small amount of biomechanical analysis work that has been done in the consumer product domain. A large amount of such work has been conducted in other fields however, and it is worthwhile examining the optimisation criteria the have been used elsewhere.

1. The majority of occupational biomechanics work has taken place in the context of very high load activities such as whole-body lifting, in which joint stresses often approach dangerous levels and the limitation of peak torque becomes critical.

2. In research work on the causes of cumulative trauma disorders in which researchers are interested in the nature of repetitive movements [Schoenmarklin, 1994], velocities and angular motion limits become important.

3. Sports scientists may be interested in maximising power output in tasks such as sprinting or jumping.
4. Another goal of sports biomechanics is to maximise the precision and repeatability of athletes' movements. This approach would be applicable in gymnastics or figure-skating
5. A number of researchers have attempted to identify a relationship between muscular activity and product design using electromyographic measurements [Hamrick, 1990,Kahlil et al. 1998]. EMG serves as an indicator of which muscles are active at a given time, but the relationship between exerted muscular force and electric activity is a complex one. [Kahlil, 1973] carried out experiments using a measure of overall limb EMG activity to compare handles of different types. Similar work has also been conducted by [Wells et al, 1990]. The difficulty involved in producing a direct relationship between EMG and work output has so far prevented a successful model from being developed.
6. Attempts to use available strength models in combination with simulation techniques as a method for the evaluation of task designs and postures have been made by [Badler et al, 1993], but little experimental work has been carried out to validate their approach, indeed it has been recorded [Kondraske, 1995] that the model used in the work of Badler et al was not considered by its designers to be valid, rather a model was included as an example of one potential computer aided ergonomic analysis tool'

All these options are available to experimenters seeking to assess product design, and part of the purpose of the experimental phase of this project was to assess the validity of a variety of quality characteristics. The requirements of a quality measure are quite demanding. It must be derivable from the biomechanical modelling system's data output, it must be presented in a form that makes intuitive sense, and it must be directly related to the actual performance of a design. Selection of a quality characteristic therefore entails questions about the fundamental nature of a design's performance: what makes one design better than another? How can a designer predict usability from biomechanical variables? Is there an ideal design configuration, achievable or otherwise?

The last question is probably a good starting point. A series of assumptions have been made throughout the main body of this work that may be summarised thus: a given task requires a certain amount of physical work to be provided by the limbs. This work may be provided by the actions of different muscle groups, motion in different joints, or with the limb in different orientations. Theoretically the nature of the these loads is defined by the usage mode afforded by the product's user interface combined with the motion pattern selected by the user.

Typically a design will not fully constrain its user so that only one motion pattern is possible, but changes in design configuration may move the range of possible motion patterns around, making it more likely that one is actually used than another. So the designer has a variety of possibilities open to them. One approach might be the minimisation of overall torque, or it might be desirable to adjust motion patterns so that most torque occurs around axes that are well supplied with muscles. For example, the shoulder is stronger in flexion than in rotation, so by maximising shoulder flexion torque and minimising rotation, the same torque is generated using a smaller percentage of the available strength and is thus likely to be less stressful [Grieve and Pheasant, 1981] Spreading torque over a number of joints might also have a beneficial effect, firstly by allowing different users to recruit their own strongest muscle groups and allowing compensation to take place; and secondly by minimising peak torques at any particular joint.

The whole idea of treating torque as a critical factor may be called into question however. The torques required to operate many consumer products are well below the maximum available torques for the majority of users, therefore does it really make a difference if someone is using 20% or 25% of their total strength? It is quite possible that no injury or discomfort would occur until they were using 50%.

Cumulative trauma disorders are interesting from this perspective in that they are normally associated with repetitive motions at force levels well below the maximum available. The damage is caused not by force but by posture and repetition. Posture, of course is the basic measure of the motion analysis tool, and therefore it would be a straightforward task to check for undesirable postures such as wrist deviation (provided, of course that the model in use had a wrist joint).

Repetitiveness is a different problem. All the experimental data sets collected during this work involved repetition of some sort, and the recorded repetitions were notable for their high consistency. It might be argued that variability would be more desirable in a task context where repetitive strain might be a risk, and it is likely that the true range of variability in an individual's use of a product would only emerge during extended use, the measurement of which would call for different monitoring, data storage and data reduction techniques, such as those used by [Anderson et al, 1996]: No individual trial in this work lasted for more than a minute, realistic monitoring might have to continue for hours, creating enormous problems in areas such as task element identification.

Another key factor in the identification of quality measures is possibility of a trade-off between different sources of stress or difficulty. This effect is clearly demonstrated in Section 3.5. The thick handled spoons tested were found to increase shoulder rotation torque, an effect that was considered to be undesirable, but the modelling process adopted did nothing to measure the different grip strength and hand mobility requirements created by the adapted designs. However, it was to tackle the latter issues that the cutlery was designed. To equate such different factors on a single scale might be impossible, the demands of different users would put emphasis on one factor or another and multiple solutions or some poor compromise might be the only answers. It is in this context that the judgement of the design team will always be more important, biomechanical analysis will in the end only serve to support argument rather than providing a single, ideal solution.

In the medium to long term, quality measures must be the result of empirical work: as experimenters gather knowledge of products that work well and products which do not, it will be possible to analyse their use and identify the key differences between them. This was the approach attempted in the evaluation of cups and spoons in this work.

Once a quality measure has been identified, the ergonomist is then faced with the task of evaluating the given design or designs at the minimum possible experimental or analytical cost. Ergonomics suffers already in the design environment: "It's obvious" or "just take the sharp corners off" are common comments. As has already been discussed, there is normally very little time for user evaluation in a real product development process. If biomechanical modelling methods are to be used they must be arranged in such a way as to squeeze information rapidly from the minimum number of experimental runs. The final experiment in the sequence in this work attempted to do just that by applying some of the techniques that are known variously as Taguchi Methods or Robust Design. Taguchi methods are discussed in a general sense by [Lochner. 199: Pignatiello and Ramberg, 1991; Pereira and Aspinwall, 1993].

The two critical elements of Taguchi methods applied here were the use of partial factorial experimental design and the analysis of results using signal to noise ratios. Partial factorial design is discussed in Section 2.4.6. Signal to noise ratios are discussed below.

Signal to noise ratios are central to Taguchi's methodology as they provide a convenient way of combining measurement of mean and variance in a single measure. In the case of the smaller-the-better SN ratio that was used in this work a better score emerges when the mean value is minimised, and the use of the mean square penalises large variances. There is however, some reason to question the use of such measures in this work. While it is clearly the intention of this approach to produce interface designs whose effects on biomechanical parameters are predictable, it might not be in the designer's interest to minimise variability, particularly in situations where cumulative trauma risk is perceived. Indeed it could be implied that an optimum solution for certain torque measures might be a low mean with a high variance, implying that the design affords considerable freedom in its operation (this also depends on the data processing method used, and whether any averaging of repeated movements took place). It could also be argued that it was the graphical techniques used to visualise the signal to noise ratios rather than the measures themselves that provided most of the benefit in the product evaluation experiment. Such methods were used in the lever optimisation experiment to display data in its original units, and satisfactory results were achieved.

Another important feature of robust design philosophy that is apparent in the use of signal to noise ratios is the idea that one is designing towards an optimum value. even if that optimum is zero as was the case in this work. There are other design philosophies that concentrate on keeping designs away from tolerance limits, rather than on one particular target, the six-sigma process developed by Motorola for example [Fowlkes and Creveling, 1995]. For quality measures such as those dealing with joint angles and ranges of motion this might be a more sensible approach: there is no optimum elbow angle, for example, but there are reasonable limits to the amount of flexion and extension that someone might be expected to comfortably adopt.

2.4.5 Selection of appropriate variables.

Once a quality characteristic has been selected, it must then be expressed in terms of the biomechanical variables available from the model. Many of the characteristics described above are in fact directly available or obtainable with the minimum amount of data manipulation: torque, joint angle, velocity and acceleration for example. Further decisions must be made before analysis can take place however. Most factors will vary during the course of a task, therefore the designer must consider which of these values is of interest, Four examples are

1. The peak values
2. The mean
3. The minimum values
4. Some measure of the variability, such as standard deviation

If the value of a factor over a number of joints is of interest then the designer might wish to choose some method of combining values to obtain an average that allows the overall biomechanical stress of a product to be estimated.

2.4.6 Efficient experimental design

The way that a quality characteristic is tested is critical to the success of the analysis process. Unfortunately, it is not possible to test every possible combination of design and user. Tests with human subjects are difficult, time consuming and expensive. In a realistic product evaluation context with tight financial and temporal constraints it is likely that very few tests will actually be carried out. Therefore some way must be selected of ensuring that all the important factors that might contribute to the success or failure of a design when measured against the chosen quality characteristic are tested in the smallest possible number of trials. Design of experiments is an advanced science in itself and numerous books have been written on the subject [Fisher, 1970]. A number of different methods were used in the experimental sections of this work. The basic choice in approach was between full and partial factorial designs.

Partial factorial experimental design was adopted in order to evaluate the effects of a number of interface simultaneously. The use of an orthogonal array allows considerably fewer experimental runs than would be required by a full factorial design in which every combination of factors is tested, but at a certain cost: the ability to evaluate the effect of interactions between interface parameters is reduced or lost. It is a central theme of robust design that parameters should be selected and adjusted to promote additivity (i.e. interactions should be minimised) such designs are said to be "robust" because a single parameter can be adjusted, or allowed to vary, without necessitating alterations to all the others. It remains to be seen however, whether user-interface parameters can be made to exhibit this additivity. Indeed it was clear from the analysis of the results of the lever optimisation experiment that interactions were strong: a critical factor in the process was the vertical position of the user's hand, and a number of the parameters under analysis affected this factor. It would have been possible however, with prior knowledge gained from more extensive experience of product testing, to have predicted that hand height was going to be a critical factor and to have altered the experimental design in such a way as to have separated hand height from the other parameters under test.

2.4.7 Selection of subjects

The approach to the selection of subjects for an experiment can take one of several forms, for example:

1. If nothing is known about the variation taking place within a particular population, then a random sample of subjects may be chosen. This approach is often used in classic design-of-experiments techniques or in sampling from a production process in order to test variation.

2. If the variation of the population is known, then attempts can be made to take a representative sample, choosing group members that have specific characteristics. Such an approach is common in the compilation of public opinion polls.

In some robust design methods a slightly different approach to selective sampling is used to account for normally uncontrollable factors:

It is assumed that a number of main factors will have an effect on the design's performance, laboratory experiments are then carried out with normally uncontrolled factors artificially restricted and factor effects are recorded. Once the factor effects are known, a sample of factors can be collected in such a way as to maximise their combined effect in a particular direction. This approach is indicated diagrammatically in Figure 34.

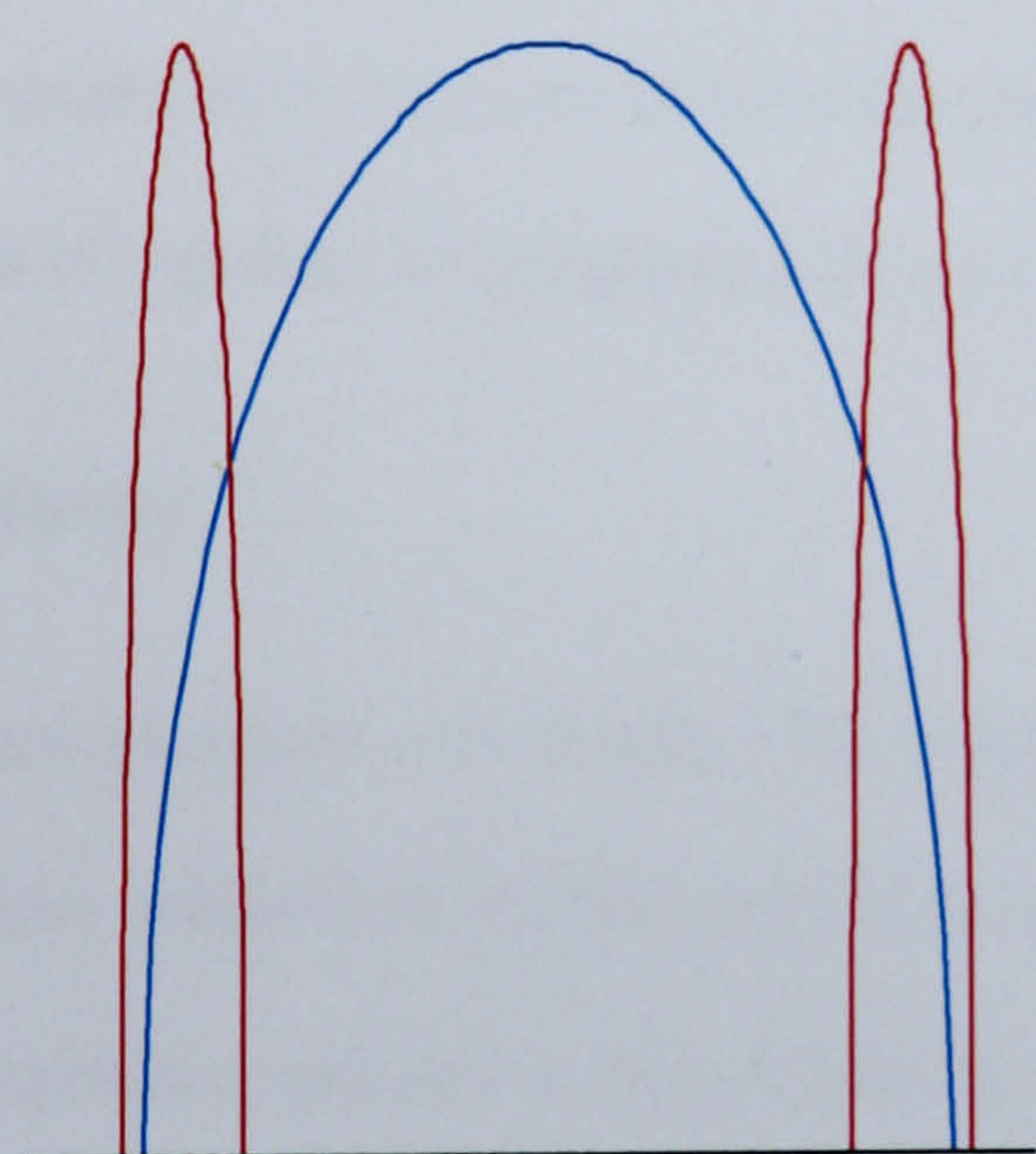


Figure 34: A comparison of population variability (central curve) and subject variability (outer curves) for a typical robust-design experiment.

The central curve in the figure represents the variation of quality characteristic seen in the expected user population, while the two outer curves represent the variation of the selected sample groups. By controlling noise factors and selecting sample groups in this way, experimenters can gain an insight into the likely performance of a design under all expected noise variation, conditions whilst only having to test a relatively small sample.

For the selection of human subjects, this problem is complicated by the fact that anthropometric and biomechanical variables cannot be controlled independently without access to an enormous pool of potential subjects from which to select optimum candidates.

2.4.8 Examination of results

Drawing conclusions from the results of biomechanical task analysis is made difficult by one critical factor: the very variability between users that these methods seek to address creates a lot of noise, uncontrolled variability in the data that can disguise the effects that the experimental work is seeking to identify. Simply plotting the results on a graph or listing them in a table makes identification of trends very difficult. There are however, a variety of statistical tests available which allow inferences to be made about trends that underlie noisy data.

As important as the use of appropriate statistical tests is the clear presentation of results. Graphical methods can allow large numbers of variables to compared and contrasted with great rapidity.

2.4.9 Signal detection and additivity

A biomechanical modelling system produces a lot of data. The analysis process is fundamentally a process of signal detection: is there information hidden inside this data that relates to the specific user interface characteristics of a product, not just to the performance characteristics of a user or the random effects of sensor noise? If no such information exists then the whole approach is invalid.

By simple observation it is clear that altering the type of grasp one uses to pick up a product will alter the angles one's arm adopts, and probably therefore the forces within it, thus the likelihood of no signal existing at all was quite small. Of more serious concern was the prospect that interactions between subjects and products would be so strong as to make consistent effects undetectable or useless in terms of design information content. This is a problem of *additivity*.

In an ideal world the noisy biomechanical data would consist of a number of different signals superimposed on one another: a basic motion pattern, some quirks peculiar to an individual user, some effect attributable to the particular product configuration under test, and some sensor noise. In this situation, analysis would simply be a case of lifting out the product-based effects and examining them. If however, the effects of the product on the motion patterns interacted strongly with the users' individual characteristics (each user reacted to changes in product configuration in a different way), then the information drawn from the model could become useless to the designer since it would be impossible to generalise from a study. It should be emphasised that the mere existence of interactions does not make the collected data useless, interactions could take two forms: an interaction could change the size of an effect, or it could change its direction. Changing the size of an effect would not be bad news from the designer's perspective, since they would be sure that any design changes they made would always have the desired positive effect, although that effect would be stronger in some users than in others. Changing the direction of an effect would be much more serious, since the designer could expect a configuration change to improve the usability of a product for some users, but worsen it for others. Such a result would still be useful, however, if the analysis also revealed the particular sub-sample for whom product performance was improved and allowed it to be targeted directly at them, examples of such products are common: the computer mouse being used in the editing of this document is optimised for a right-handed user. In the experimental phases this issue certainly arose, and interactions undoubtedly took place, but there were enough signs of a reasonably consistent, detectable response to suggest that the analysis process might be useful to a designer

2.4.10 Summary

This chapter has described a four stage process to the interpretation of data produced by a the motion analysis and modelling system being discussed in this project. A crucial factor in the process is that analysis actually begins long before any data has been collected. The design and execution of the data collection process is of at least equal importance to the success of the analysis as the graphical or statistical treatment of the results.

Section 3 goes on to discuss a number of experiments that were carried out using the system, and provides opportunity for a more detailed discussion of the experimental design and analysis process.

2.5 Methods summary

Section 2 has described in detail the development of a process that is intended to assist designers with the design of product-user interfaces by providing a link between traditional forms of analysis and the additional techniques offered by computer-modelling processes.

While traditional analysis, obtaining direct feedback from users, is an effective and flexible technique, it is time consuming to conduct and difficult to generalise. It is hoped that by adding a layer of quantitative data to the analysis process designers can be assisted in the objective analysis of their designs and can achieve a deeper understanding of the effects of interface parameters on users' bodies.

The technique has been designed to be of particular benefit to designers hoping to make products that are accessible for people with "unusual" capability ranges (in design terms this would normally mean people with disabilities) since it attempts to minimise its reliance on previously collected data and to maximise the amount of useful data that can be collected from a particular individual or population sample. This means that the technique should be highly applicable to those population sub-groups from whom little anthropometric or ergonomic data has been collected.

The system itself consists of a motion analysis system and a number of software elements that operate together to collect the data and process it using a simple biomechanical model to provide information on the joint motions and torques involved with the use of a product. If the process is applied in a systematic way it is hoped that useful comparisons between different product configurations may be made in terms of the stress they are likely to put on the user's body.

Section 3 goes on to describe a number of experiments in which the proposed system was applied in order to validate its effectiveness at providing biomechanical information and evaluate its usefulness as a potential design tool.

Before the experimental work is discussed in detail it would be well worthwhile to spend some time commenting on the way the motion analysis and biomechanical modelling systems were implemented, since one must be careful to separate the limitations imposed by the equipment used in the experimental work from the limitations of the whole analysis approach itself.

The use of an electromagnetic tracking system and the choices facing anyone who wishes to select a motion tracking technology are discussed in considerable detail elsewhere in this work. After extensive experience with the tracking system it is felt that the selection of the device for use in this work did not present a significant limiting factor, indeed the tracking system was the only technology currently commercially available the allowed the use of the simple relative-orientation algorithm in the model construction process. This algorithm was greatly favoured because it is an extremely computationally inexpensive method of linking a motion analysis system to a biomechanical model, it eliminated the requirement for exact sensor positioning, and it avoided the need for complex error reduction algorithms or the assumptions required by inverse-kinematics solutions that might alter the modelled limb posture to such a degree as to invalidate the results. There are other potential technologies however, that might overcome the electromagnetic tracking system's limitations such as susceptibility to field interference, limited range, and relatively slow frame-rate. Notable among these technologies would be the use of gyroscopes and possibly accelerometers.

The two segment biomechanical model used in the analysis was possibly the simplest and most abstract model that might have produced sensible results. The choice of such a model was made partly because of the limited number of sensors available in the tracking system, although it should be noted that by the use of a slightly more complex model fitting algorithm (therefore abandoning many of the advantages of the algorithm chosen) it would have been possible to use more of the sensor system's twelve available degrees of freedom to supply enough information to drive a three segment model. A second and perhaps more useful reason for the choice of a two segment model was in order to keep the amount of model output data down to a manageable level. The model used had five degrees of freedom, each of which had associated angle, torque, velocity, and acceleration values, this is a lot of information to analyse. In fact, during this work, time derivatives were ignored, and only torque and angle values were examined.

The most obvious criticism of a model of this simplicity is the lack of any form of wrist joint or hand segments. The wrist and hand are areas that are associated with a large number of potential injuries and disabilities, from arthritis to cumulative trauma disorders. It could probably be safely assumed that for any biomechanical modelling system to be useful in a real commercial environment, it would require modelling of the wrist joint at the very least, and probably some modelling of the motions of the fingers - a requirement that would greatly increase the required sensor capacity and also place severe constraints on sensor size.

Of course the model used here was not intended to be a full commercial system. it was intended to operate as simply and as accurately as possible in order to answer fundamental questions about the usefulness of a biomechanical modelling approach to design evaluation. To do this it had only to prove itself capable of matching the movements of the person it was modelling with reasonable accuracy, and this it did as was demonstrated in an initial series of experiments.

The next questions that must be asked of the model therefore are about the sort of information it produced. The model consisted of five simulated revolute joints and analysis produced a record of the torques occurring in these joints, but no such joints exist in real human arm: we do not have small motors generating torques in our elbows and shoulders, so of what relevance is information produced by such a model? Here again the answer is to do with a compromise between a set of values that are relatively easy to interpret and a much more complex group of values whose reliability would be doubtful. A model that included muscles and tendons would have many more layers of redundancy inherent within it: in both its construction and its operation multiple assumptions would have to be made and the more assumptions the modeller has to make about the masses, stiffnesses and positions of model elements the less confidence one can have that the results eventually produced would be reliable. Additionally, the more data a model produced the more difficult the interpretation of this data would become. There can be no doubt that there is a role for such complex models in, for example the prediction of surgical outcomes, but in the world of product design a more abstract model seems to be a better starting point in an attempt to correlate product configuration with biomechanical performance.

3. Experimental Work

3.1 Introduction

Section 2 described the development of a tool that is capable of exploiting the strengths of both a traditional user-evaluation approach to human interface design and those of modern computer modelling techniques. This section of the work is concerned with the application of such a system to a variety of increasingly complex design problems in order to validate it and assess its true usefulness.

The analysis system described in Section 2 relies on three essential factors in order to become a useful tool. These factors are described below:

1. **The validity of the approach**. Motion analysis and biomechanical modelling can evaluate only a limited number of the many factors that contribute to the success of a product's user interface. A very simple model, such as that being described here, reduces the number of quantified factors even further. For the process to be a success the quality characteristics under analysis must have a real bearing on the quality of the interface as a whole. For example, if a designer assesses two competing designs, one of which consistently exhibits the need for lower maximum elbow torque, he or she must then be sure that this lower torque value will translate itself into increased comfort, reduced risk of injury, or accessibility to a larger number of potential users.
2. **The transferability of data**. Any attempt to model human performance relies on there being sufficient correlation between the data collected from the sample group under analysis and the target population as a whole. In the context of the modelling system under discussion here, this means that people must all tend to interact with a given product in a basically similar way, so that changes to that product's interface result in a consistent improvement in performance, regardless of the actual end user.
3. **The cost of the approach**. It is an overriding aim of this work to develop a tool that might be applied to genuine design problems, with all the constraints on cost and time discussed in Section 1.2. If successful analysis using the approach discussed here requires hundreds of subjects and thousands of hours of analysts' time then the approach as originally conceived can

be considered to be a failure; and while biomechanical analysis may continue to contribute to the body of ergonomics knowledge, its application may be restricted to the work of large research organisations: where more expensive hardware, more complex modelling approaches and more rigorous experimental designs than those discussed here would be appropriate.

These were the three principal factors addressed by the experimental phase of this work. The work itself took place in four parts. The first part was designed to evaluate the modelling and measurement system itself, whilst the following three phases addressed the key points described above. The development of the experimental phase of the work is shown schematically in Figure 35, while the layout of the entire Section is described below.

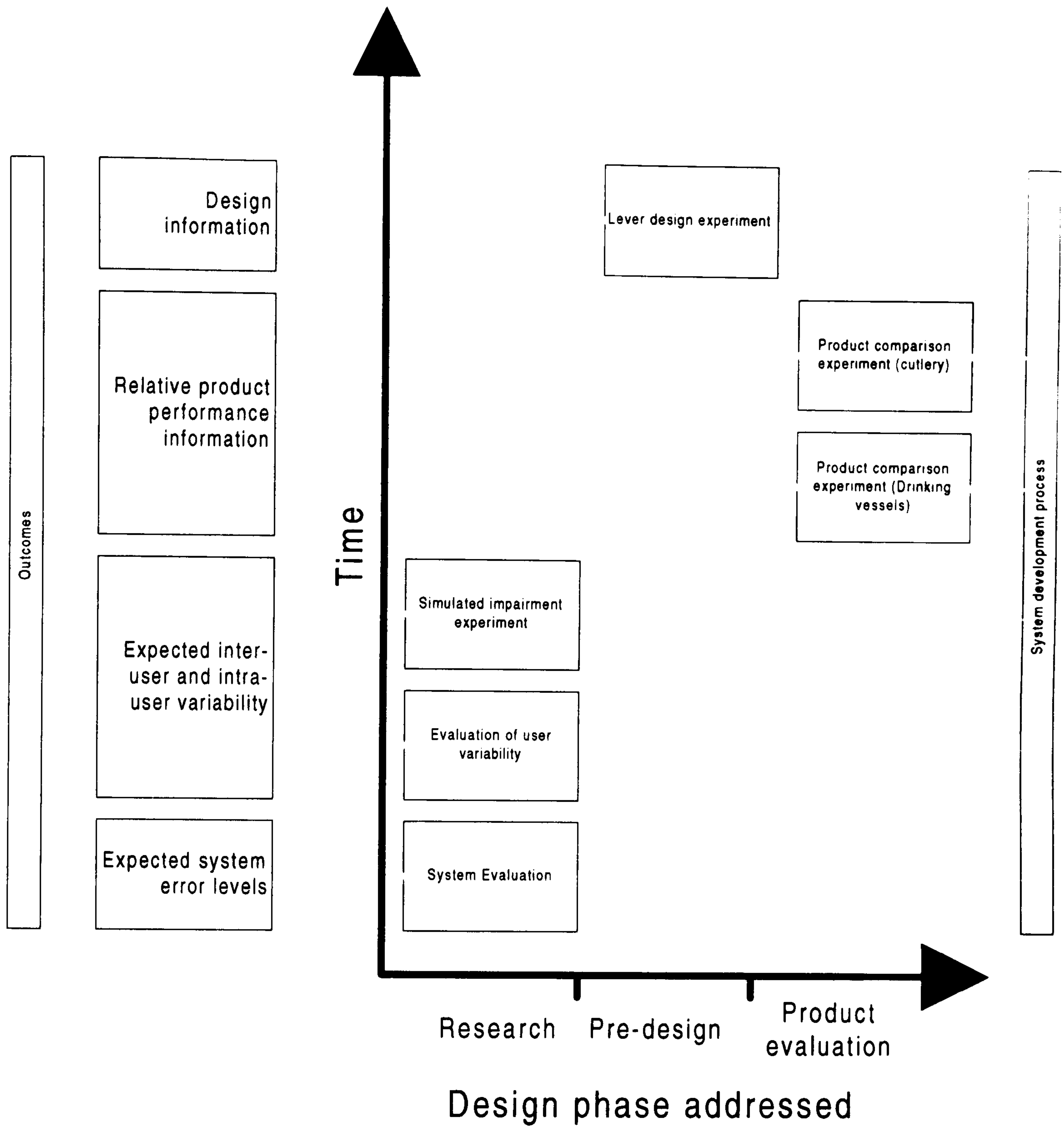


Figure 35: A schematic diagram of the experimental work undertaken

Section 3.2 Validation of the modelling approach

The initial experimental phase was intended to check the validity of the data being collected from the sensor system, and to gauge the degree of error introduced by the model-fitting algorithm described in Section 2.3.17

Section 3.3 and 3.4 Quantification of user variability

The purpose of this phase was to investigate the degree of intra- and inter- subject variability that occurred in data collected from the analysis of a highly simplified, closely controlled task. This phase was designed to address the problem of transferability of data described in point 2 above.

Two experiments were run, the first simply compared different subjects and different task configurations whilst the second attempted to investigate the effects of a minor impairment by artificially restricting the motion of the wrist joint during a task. This work addresses the question of transferability of data in a very general way.

Section 3.5 Evaluation of existing products

This experimental phase was intended to bring the work more firmly into the product design domain. Two classes of products were investigated. Subjects completed the same task using similar products with different physical interface characteristics. The effect of the different interfaces on biomechanical parameters was examined. This work attempted to evaluate the transferability of data problem in the context of real products (point 2 above), discusses the relative worth of different measures of interface quality (point 1 above) and also addressed issues of analysis cost by using various techniques to allow conclusions to be drawn rapidly from the collected data (point 3 above).

Section 3.6 Product design optimisation

The intention of these experiments was to simulate a product at the pre-design stage. A number of interface variables were investigated simultaneously with the intention of selecting the optimum combination for the design problem. The process took place in two phases; the first designed to examine relative factor effect sizes and the second to select the optimum parameter set. This work explored the way the biomechanical modelling process might be used by designers working on the development of an entirely new product and attempted to deal with points 1, 2 and 3 above.

3.2 Validation of the modelling approach

3.2.1 Aims

The aim of the system validation process was to estimate the effectiveness of various parts of the motion tracking and biomechanical modelling process. The experiments took place in four stages:

1. An estimate of the error in spatial measurements made by the Insidetrak device
2. An estimate of the error in angular measurements made by the Insidetrak device
3. An evaluation of the effectiveness of the algorithm used obtaining relative joint angles
4. An evaluation of the magnitude of the errors inherent in the sensor-model fitting algorithm,

Knowledge of system error levels was an important part of the entire experimental process, since it allowed the levels at which changes in value were considered to be irrelevant, or simply due to noise, to be estimated, thus helping experimenters identify significant results.

3.2.2 Spatial measurements

3.2.2.1 Aims

This experiment was designed as a simple test of the accuracy of spatial measurements collected by the Insidetrak system.

3.2.2.2 Method

A single sensor was attached to a flat cardboard rectangle with a side length of 50mm. A grid of 50mm squares was printed, marked with a number of measurement locations (Figure 36). The grid was aligned with the sides of the Insidetrak transmitter cube and fixed securely to a flat, horizontal, wooden surface.

The system was set to record data from a single sensor, and the board to which the sensor was attached was placed on each numbered square in turn, aligned with the edges of the square and held there for a period of five seconds.

	2		1
3		4	
	6		5
7		8	
	10		9
11		12	

Figure 36: The 50mm grid used for the spatial evaluation experiment.

3.2.2.3 Results

The complete recorded data file was loaded into the MATLAB program and the sensor spatial coordinates were plotted. Visual inspection was used to identify points that corresponded to each of the twelve measurement locations: at these points the sensor had been held stationary for a period so they appeared as flat regions on the graph.

Measurement 1 was taken as the origin value. This alleviated the problem of locating the precise origin of the tracker system's global coordinate system, which lies within the transmitter unit itself. The x, y and z values from measurement location 1 were subtracted from all twelve sample measurement values.

As all the test measurements took place in the xy plane, all z values were expected to be zero. In practice, the standard deviation of the recorded z values from zero was found to be 2.55mm. By contrast, the x and y values were varied during the experiment. Plotting the measured values against the actual sensor position at the time of the measurement revealed a linear error between the actual and the measured values (Figure 37 - Figure 38). This effect was attributed to poor alignment between the sensor system's global coordinate frame and the grid used to collect the sample data points. To correct this, the method of least squares was used to place lines of best fit through the x and y data points. These lines are shown on the figures. The gradients of the best-fit lines were used as linear factors to correct for the poor alignment. The measured values were transformed by the correction factors and then the standard deviation of the transformed measured values from the actual values was calculated.

The measured x values were found to have a standard deviation of 2.25mm, while the y values were found to have a standard error of 3.05mm

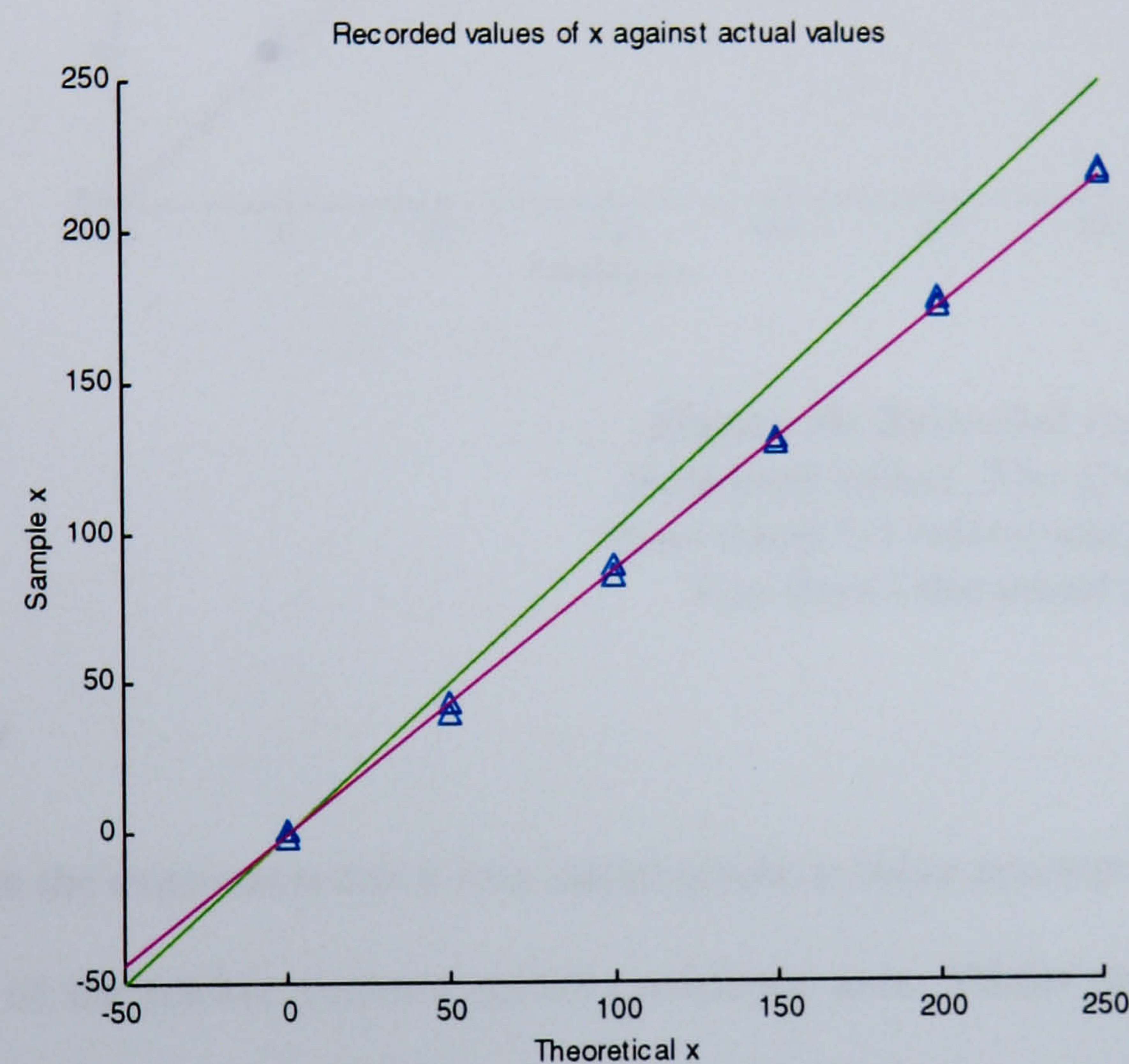


Figure 37: Recorded values of x against measured values. The green line shows the theoretical 1:1 relationship, the magenta line shows the actual line of best fit.

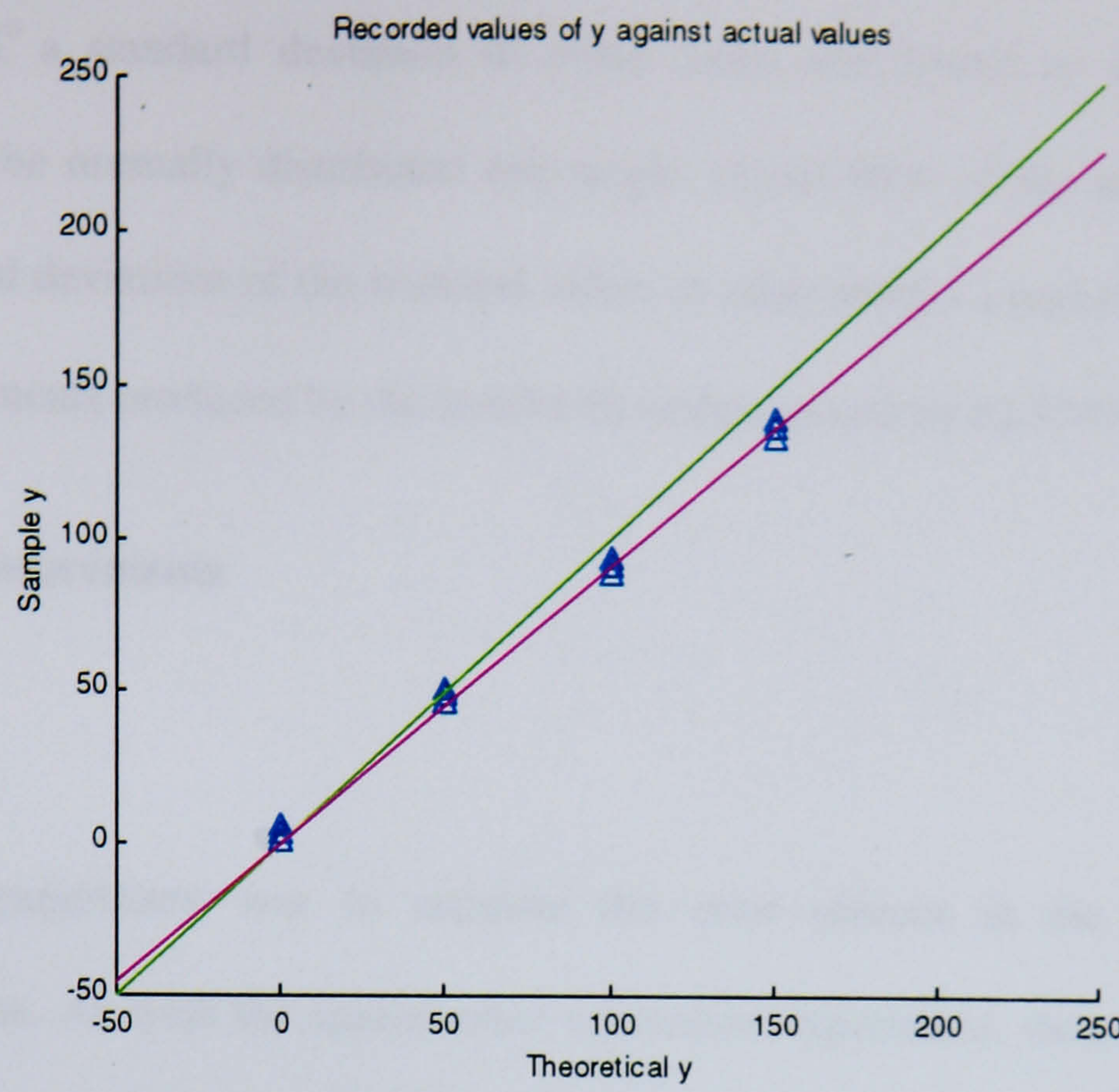


Figure 38: Recorded values of y against measured values. The green line shows the theoretical 1:1 relationship and the magenta line shows the actual line of best fit.

3.2.2.4 Discussion

It became clear from the experiment that it was inappropriate to make assumptions about the factory pre-set orientation of the tracker system's global coordinate axes. Whilst the axes are nominally aligned with the transmitter box, considerable misalignment was evident. This error can be corrected by calibrating the coordinate system in software before measurements begin or, less satisfactorily, by transforming the data after measurements have been completed, (as was done here because the error was only discovered once data collection had been completed).

All the measurements during the testing process took place within a 250mm square region, no part of which was more than 500mm from the transmitter unit. In these conditions the sensor system might be expected to perform with somewhat higher accuracy than at the longer ranges that would normally be involved in the system's use during actual biomechanical measurements: the effects of noise become stronger as increasing sensor distance from the transmitter reduces the detected signal strength.

With this in mind, a standard deviation of some 3mm was found in spatial measurements. Assuming error to be normally distributed one might expect 99% of the measured values to be within 2.33 standard deviations of the nominal value: in other words, a realistic accuracy figure for the spatial measurements produced by the Insidetrak system would be $\pm 2.33*3=\pm 7$mm

3.2.3 Angular measurements

3.2.3.1 Aims

The aim of this experiment was to estimate the error present in the Insidetrak's angular measurement process. As with the spatial error estimation experiment, measurements were to be taken in a single plane to simplify both the experimental process and the analysis of the results. The assumption was made that accuracy would remain constant regardless of the measurement plane.

3.2.3.2 Method

The same single sensor and mounting board arrangement was used as Section 3.2.2. A new grid was plotted (Figure 39), which consisted of a 150mm diameter circle graduated with radii at 30° intervals.

In order to compensate for any global misalignment the sensor's mounting board was aligned with the "0" radius and a command was sent to the system electronics board to reset the attitude parameters of the sensor to zero.

The system was then set to collect data from a single sensor and the sensor was then moved around the grid, aligned with each marked radius and held there for a period of five seconds.

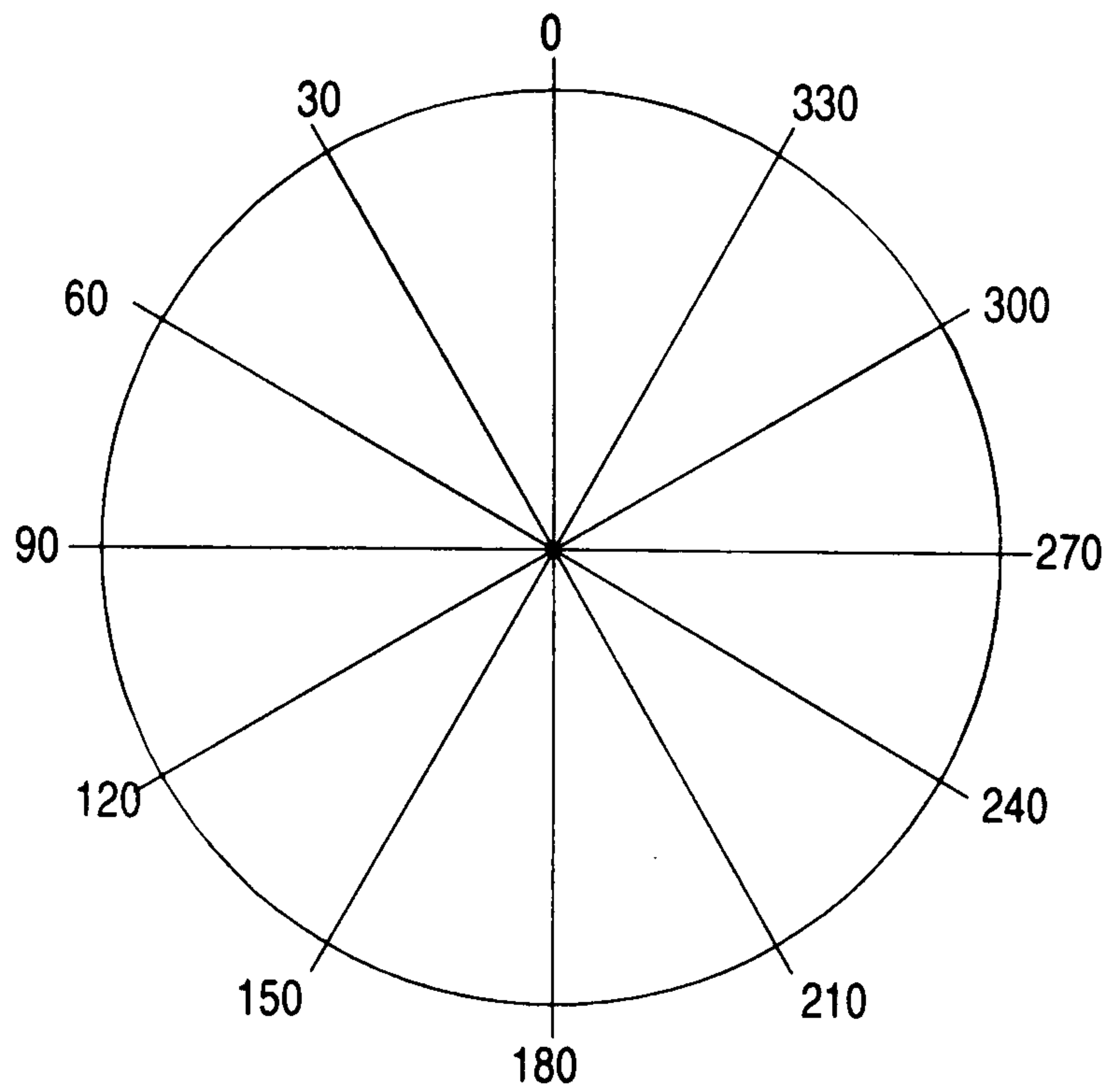


Figure 39: The grid used for the angular error evaluation experiment

3.2.3.3 Results

The collected data were loaded into the MATLAB program and transformed in order to obtain Euler angles from the direction cosine values. The orientation of the sensor during the measurement process was such that the second rotation value was likely to be zero or close to zero at all times, resulting in problems of gymbal lock caused by the coincidence of the first and last axes of rotation (Section 6.3.2). Various techniques have been used by other authors to overcome this problem, notably [Badler et al, 1993], who point out that an intuitively obvious solution to the problem has not yet been discovered.

To avoid these problems certain axes were transposed (new x=old z, new y=old y, new z=-old x). This arrangement ensured that the all rotation actually took place around the x axis, the second rotation in the series.

The Euler angles were plotted and the position of flat regions on the graph of rising elevation values was used to manually locate a sample of points for analysis in a similar manner to that used to obtain sample points in the spatial accuracy experiment.

The sample values were then plotted against their theoretical values in order to check for any consistent errors such as those seen in Section 3.2.2 (Figure 40). No such errors were identified.

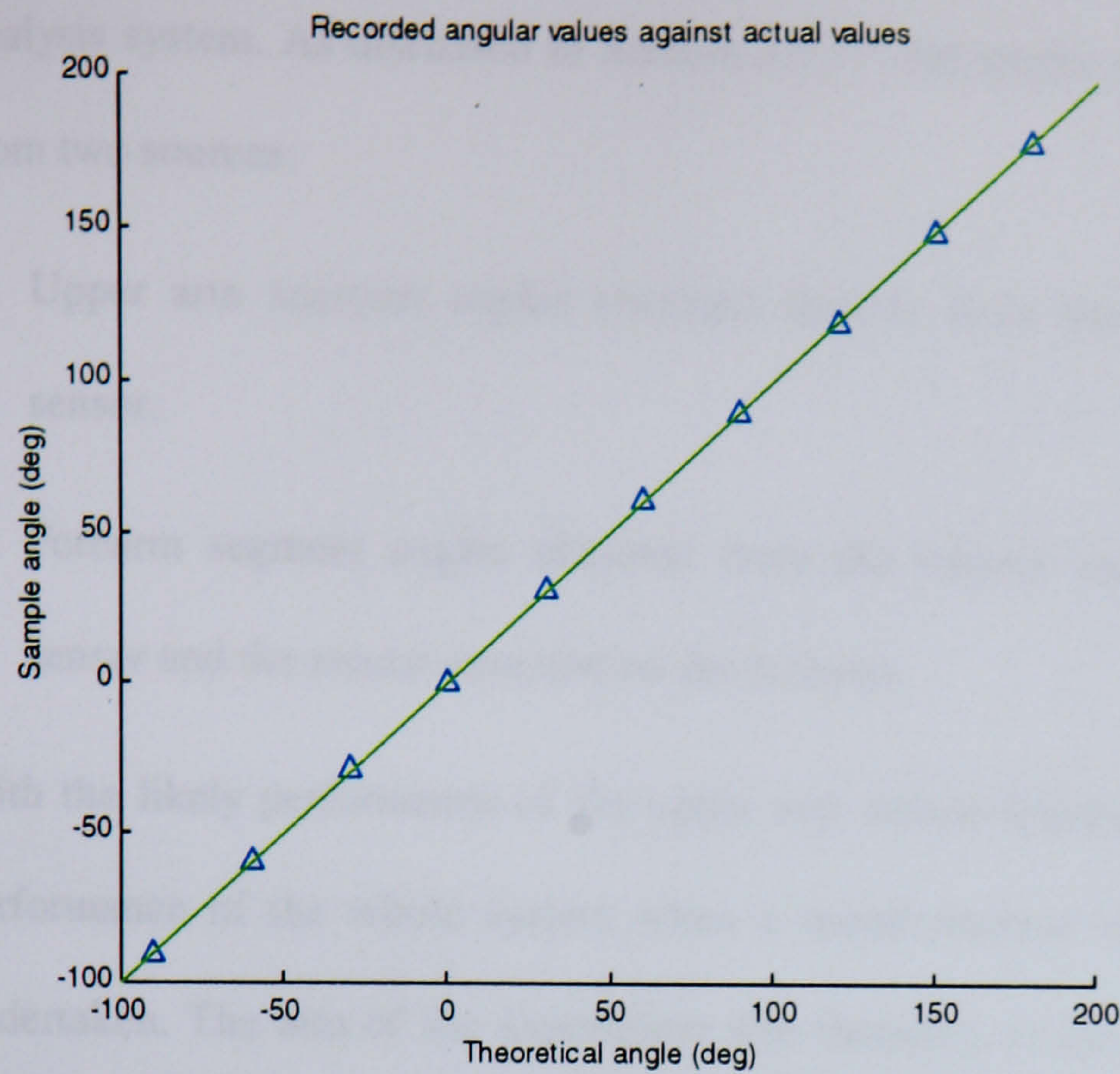


Figure 40: The sample angular measurements plotted against the actual angular values. The green line indicates the ideal 1:1 relationship.

The standard error of the varying measure was found to be 0.57°. The other two angles, whose values did not vary during the measurement process, but remained at 90 and 180° respectively, were also tested for error. Their deviations were found to be slightly higher: 1.57 and 2.06°.

3.2.3.4 Discussion

The standard deviation of the angular measurements was found to be approximately 1.4°. Therefore, using 2.33 standard deviations as a 99% confidence interval, it would probably be reasonable to assume an angular accuracy of ±3.2° during the measurement process.

The software alignment process that was completed before measurements began was successful in ensuring acceptable overall correlation between the expected and actual values.

3.2.4 Evaluation of the sensor-model fitting process (I)

3.2.4.1 Aims

Having gained information in the performance of the sensor system itself, attention was directed at the methods used to obtain biomechanical angles that would be used to drive the model in the analysis system. As discussed in Section 2.3.17, the angles used in the model were to be obtained from two sources:

1. Upper arm segment angles obtained directly from the global orientation of the upper-arm sensor.

2. Forearm segment angles obtained from the relative transformation between the upper arm sensor and the sensor mounted on the forearm.

With the likely performance of the upper arm sensor known, it was of interest to investigate the performance of the whole system when a transformation involving data from two sensors was undertaken. The aim of the experiment was therefore to see if the sensor-model fitting algorithm actually proved successful in detecting individual joint movements.

3.2.4.2 Method

A very simple physical model designed to represent the upper limb was constructed. The model consisted of a piece of foam board 42mm wide and 150mm long, which was scored across its middle to form a simple hinge. A sensor was taped to a wooden block placed 100mm from each side of the hinge. The apparatus is illustrated in Figure 41.

Once complete, the apparatus was free to move to any overall position or orientation, but relative motion between the two sensors was restricted to a single degree of freedom around the hinge. This arrangement was similar to the arm itself, with a free moving shoulder joint, but only a single degree of freedom at the wrist.

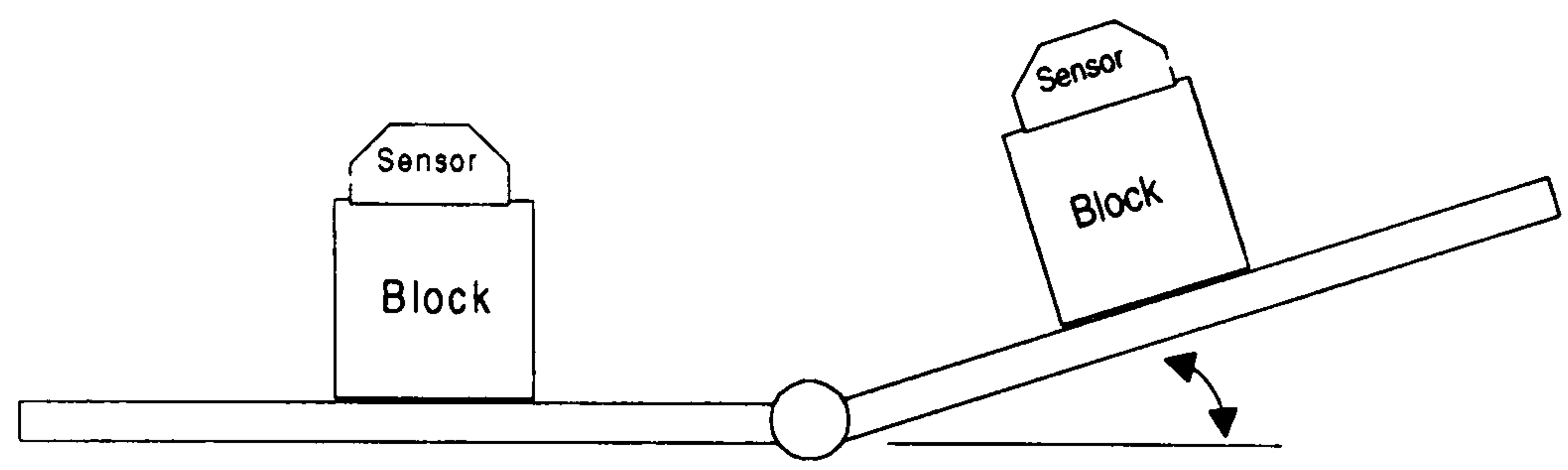


Figure 41: The sensor arrangement for the first evaluation of the sensor-model fitting process.

The apparatus was placed flat upon a wood desk and the orientation-reset command was sent to both sensors. This meant that both sensors were in the zero orientation position at the start of the test. The system was set to record from both sensors and the apparatus was rotated in space in an arbitrary fashion whilst at the same time the hinge was flexed and extended repeatedly.

The objective of the analysis process was then to separate the motion patterns of the hinge flexion process from the rotations of the whole model.

3.2.4.3 Results

Displaying three dimensional rotation parameters in a meaningful fashion is a difficult process. Figure 42 and Figure 43 show a sample of 50 data points taken from the 500 readings collected from each sensor. The three Euler angles are superimposed on the same axes. It is impossible to identify the action of the hinge by examination of this data.

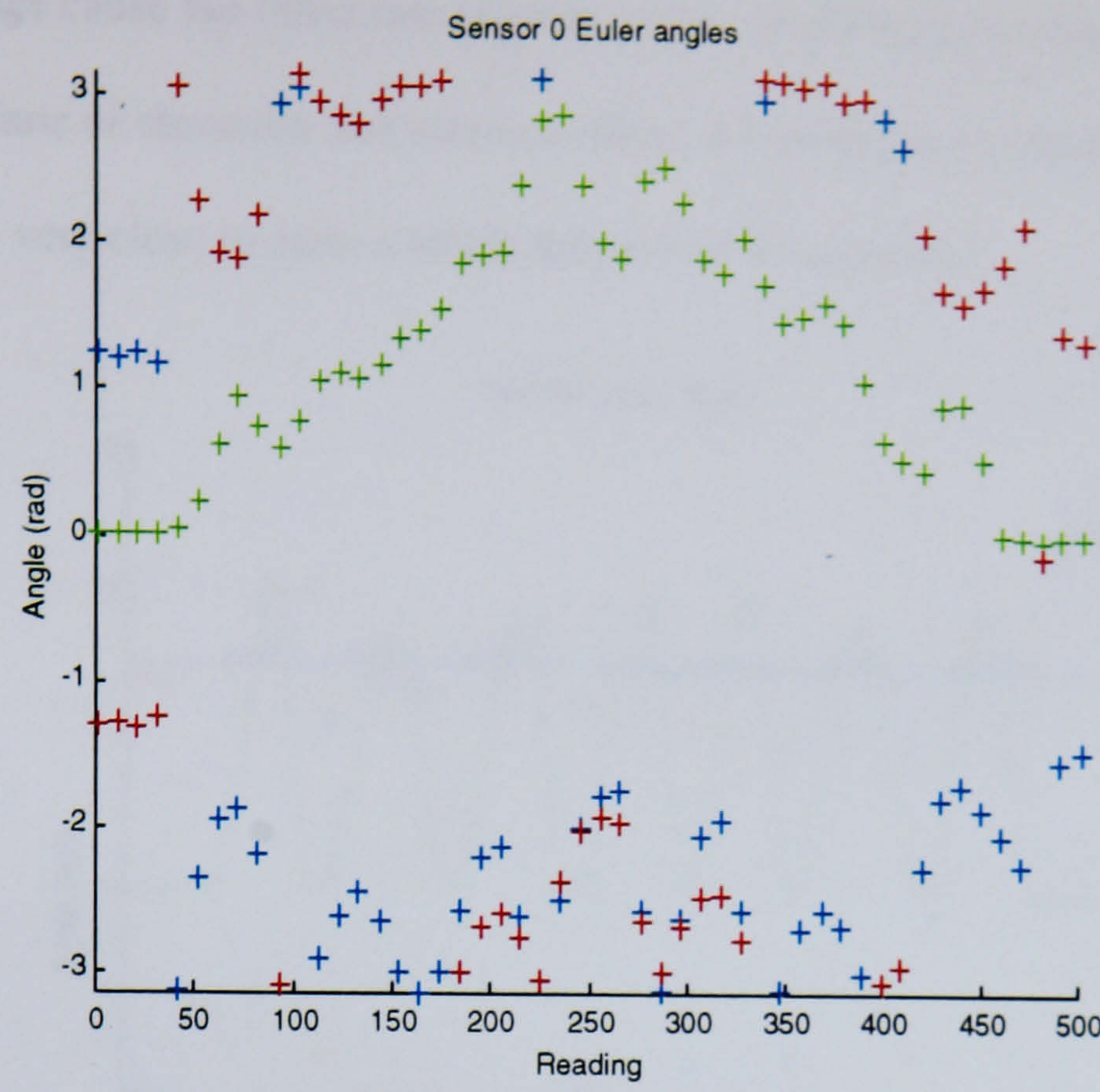


Figure 42: Sample angles from Sensor 0. Red = plane of elevation, Green = elevation, Blue = rotation.

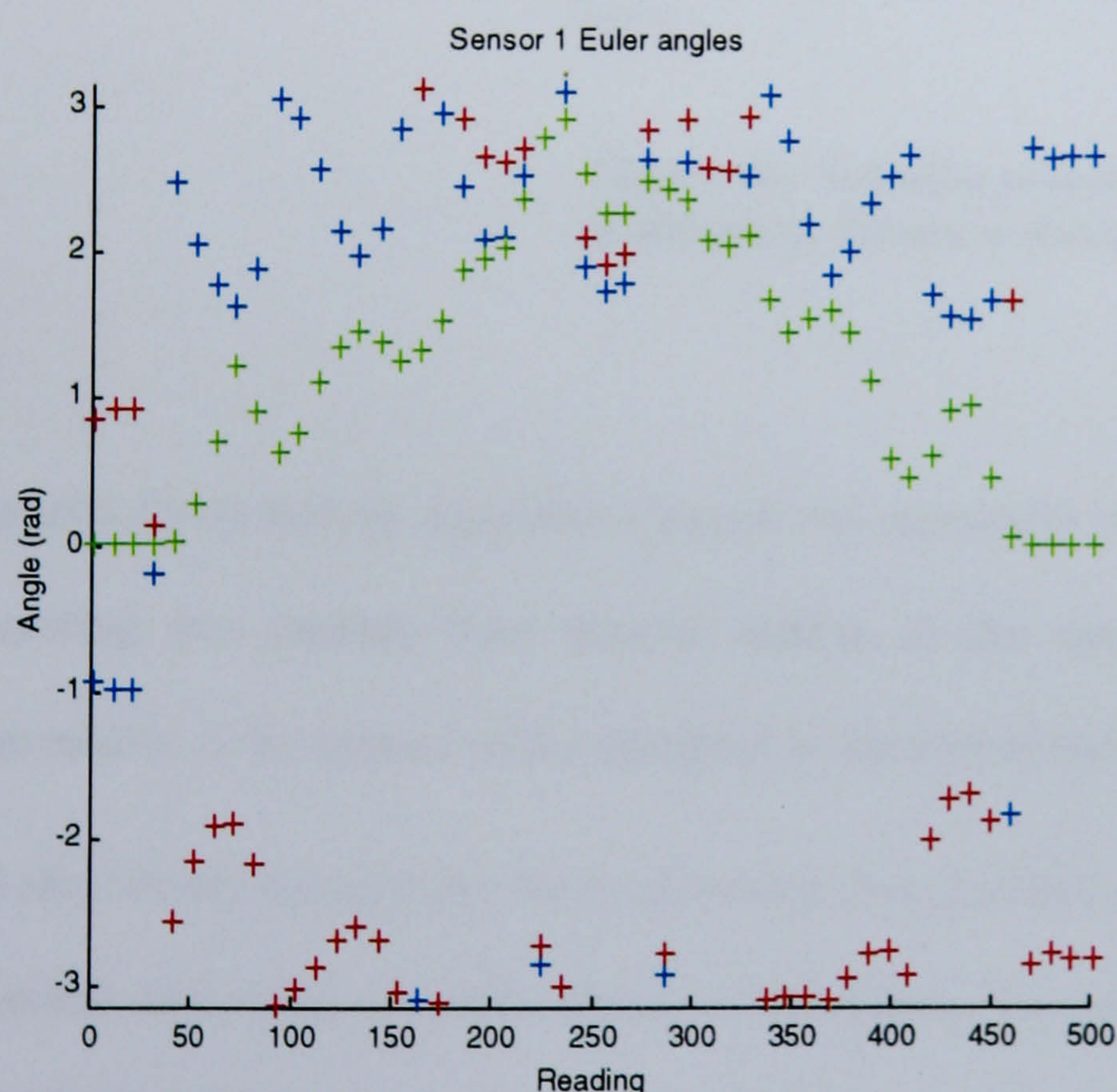


Figure 43: Sample angles from Sensor 1. Red = plane of elevation, Green = elevation, Blue = rotation.

Figure 44 shows the Euler angles obtained from the relative transformation matrix. The green line is the full set of elevation values, while the red and blue lines are the nominal plane of elevation and rotation values respectively. It can be seen that when the elevation values are close to zero, numerical difficulties cause the other two angular values to swing quite dramatically. It should also be noted that the plane of elevation and rotation values are symmetrical about the angle=0 line, thus their sum is always very close to zero, a result that would be expected.

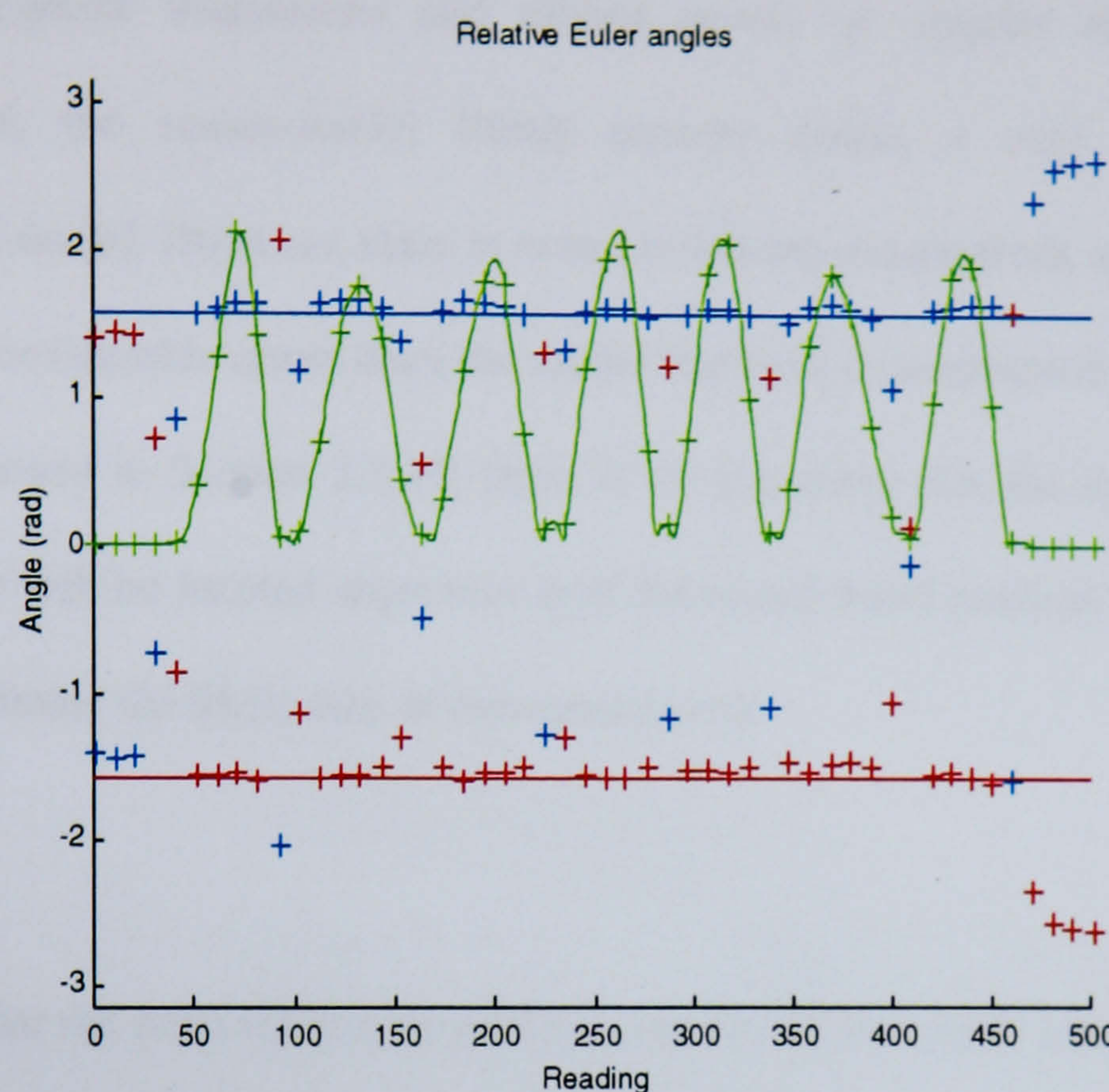


Figure 44: Relative sensor angles. Red = plane of elevation, Green = elevation, Blue = rotation.

3.2.4.4 Discussion

It is clear from the graphs above that the algorithm adopted was successful in detecting elbow joint movement and separating this element from general motion of the entire limb model. This knowledge allows the process to be applied with confidence to the evaluation of real subjects.

The results obtained also vividly demonstrate the troublesome characteristics of Euler angles: there are the obvious numerical difficulties at certain phases of the motion, but just as interesting is the fact that because the hinge action under analysis was a simple rotation about the sensor y axes (which were parallel) it was expressed in Euler terms as a complex combination of two z and one x rotation.

3.2.5 Evaluation of the sensor-model fitting process (II)

3.2.5.1 Aims

By ignoring limb segment dimensions and relying purely on angular data to construct the biomechanical model, the sensor-model fitting process makes it very easy to produce a computationally valid model. However, there is concern that the assumptions made in the modelling process may lead to considerable errors once the model has been reconstructed within the computer. In particular, as discussed in Section 2.3.16, there is no guarantee that the spatial position of the modelled end-effector will be located anywhere near the actual hand position. The purpose of this experiment was to estimate the likely size of this spatial error.

3.2.5.2 Method

The method adopted for the error estimation process was based on a more complete analysis of the data collected using the electromagnetic tracking system. It should be recalled (Section 2.2.2) that the Insidetrak system is capable of recording both orientation and position of its sensors, but that only orientation data was used in the model construction algorithm (Section 2.3.17). Thus the relative spatial position of the two sensors exists in two forms in the collected data:

1. The original coordinates collected by the tracker system.

2. The reconstructed coordinates emerging from the model.

In this experiment it was postulated that the difference between these two sets of coordinates would be representative of the size of error produced by the modelling system.

The reconstructed coordinates are dependent on the limb segment lengths entered into the modelling system. However, the nature of the modelling process offers an opportunity to optimise these segment parameters in order to minimise overall error. The model is assumed to have rigid segments of fixed length (Section 2.3.4), but for each recorded limb posture a different set of limb segment parameters might produce the minimum spatial error. Therefore, to minimise overall error, a searching process was employed. This was intended to find the set of segment length parameters that minimised the error over the entire set of collected results. The process was as follows:

1. An arbitrary series of limb movements was recorded from 9 subjects

2. The collected sensor position data was stored in an array. To remove the effect of any torso movement from the calculations, the position data was recorded as the position of the wrist sensor relative to that of the upper arm sensor.

3. The limb modelling routine was invoked with a number of different limb parameters in order to reconstruct the wrist sensor position. In order to do this, two segment length parameters were required, these were the distances of each sensor from the axis of the elbow.

4. Once this process had been completed for a sample of points taken from each motion data record, the set of segment length parameters that produced the minimum overall distance between recorded and reconstructed relative wrist position was selected as the optimum and the size of the error found using this configuration was recorded.

3.2.5.3 Results

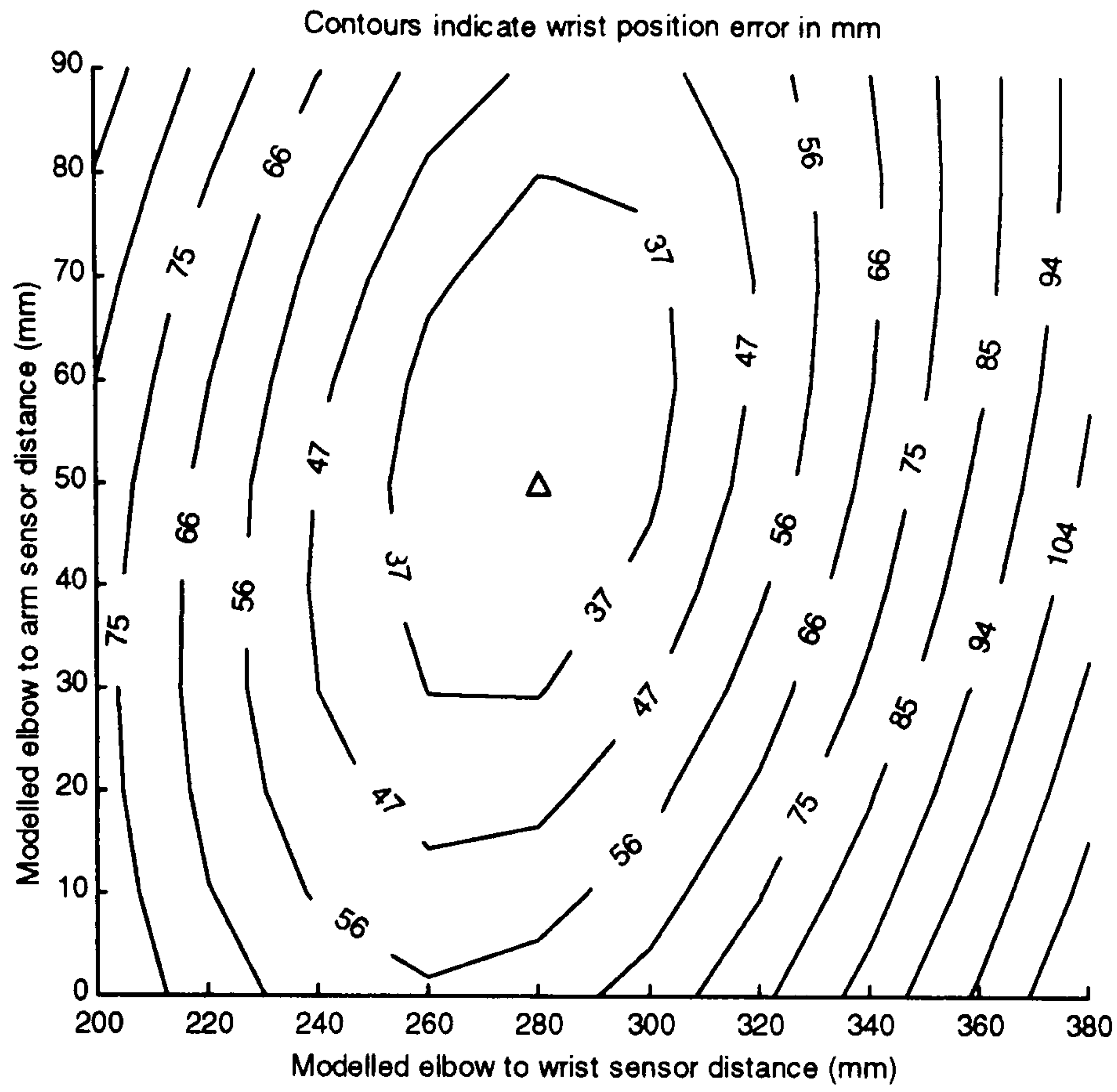


Figure 45: A graph showing the segment length optimisation process. The contour lines show the size of the error for different combinations of segment parameter. The triangle in the centre is the optimum configuration.

Figure 45 shows typical output from the segment length optimisation process. The results for all nine subjects are shown below:

Subject	Upper arm sensor -elbow (mm)	Elbow -wrist sensor(mm)	mean error
1	65.0000	310.0000	20.2967
2	74.5455	260.0000	30.9951
3	90.0000	280.0000	46.3964
4	21.8182	296.3636	73.8154
5	7.2727	354.5455	135.2107
6	57.2727	330.9091	80.2644
7	72.7273	327.2727	26.7565
8	35.4545	318.1818	115.0513
9	88.1818	236.3636	33.4167

Figure 46: best limb segment parameters and mean error sizes for all subjects.

Overall, the mean spatial error was found to be 62mm, with a standard deviation of 41mm.

This mean value corresponds to an angular difference of about 10°.

3.2.5.4 Discussion

The results of this experiment demonstrated that the assumptions made in the construction of a limb model from tracker system data did not introduce unacceptable errors. According to the manufacturer's specifications (Figure 17), one might expect a mean error of 25mm if one was simply measuring the linear distance between two sensors (although, according to the findings of Section 3.2.2, the combined error would be expected to be 14mm). All the additional sources of error introduced by flesh movement and the rigid link assumption only served to increase the error by a factor of 2.5, an additional 40mm.

With this said, it should be noted that if the error found was caused simply by differences between the recorded and actual limb angles, over a typical limb length the spatial error corresponds to a total angular disparity of 10°: a combined error of 10° at the shoulder and at the elbow would result in the modelled wrist being 60mm away form its true position. Thus it might be assumed that ascribing significance to single measurements with differences of less than 5° at either the shoulder or the elbow would be unwise.

3.3 Quantification of user variability

3.3.1 Context

The previous series of experiment had ascertained the likely degree of error inherent in the motion collection and analysis system. The next stage in investigating the experimental landscape was to examine the variability caused by experimental subjects themselves.

3.3.2 Aim

The aim of the experiment was to answer questions about the transferability of data collected from a small group of potential subjects (factor 1. in section 3.1). In order to do this, quantitative information on the inter- and intra-subject variability of biomechanical parameters was required. This information was obtained by performing motion analysis in a highly simplified task context.

3.3.3 Sources of variation

Variation in biomechanical parameters could be expected to come from a number of sources:

1. Noise inherent in the sensor system
2. Differences between ostensibly identical task elements performed by the same subject (intra-subject variability)
3. Differences between ostensibly identical task elements performed by different subjects (inter-subject variability).
4. Differences between similar task elements performed using products with different user-interface characteristics.

The final category is especially interesting in this work. The effects of product configuration on biomechanical parameters hold the key to the success of biomechanical analysis for the evaluation of design effectiveness.

No attempt was made to assess the effect of electronic noise on the measurements taken in this experiment. The assumption was made that noise levels would be similar to those seen in Sections 3.2.2 and 3.2.3.

Intra-subject variability might also be considered an uncontrollable source of variation. On the principle that you can lead a horse to water, but you cannot make sure it sips exactly the same amount each time, it is impossible to control precisely the movements subjects carry out when operating a product. However, it is a basic premise of this work that changes in interface characteristic can have some overall effect on subjects' movements.

Differences between subjects performing the same task can be attributed to two separate factors:

1. Anthropometric differences between the subjects. A subject with a very short arm will probably need to assume a different posture to reach an object then will a subject with a very long arm.
2. Performance differences between subjects. The skeletal system of the upper limb has many redundant degrees of freedom; this allows subjects who are identical in all anthropometric parameters to choose to carry out a task in a slightly different way.

The nature of the analysis process under discussion here allows anthropometric parameters to have a very strong effect on collected data. In particular, larger subjects will tend to have much higher limb segment masses, and therefore they can expect to exhibit higher joint torques in tasks where most force is generated by the limb's own weight. Fortunately, many anthropometric parameters can be collected by the experimenter at the time physical measurements are carried out. This will allow them to be taken into account when the results are analysed, and to a large degree their effects can be de-coupled from those caused by differences in product configuration.

Differences in performance are another factor, similar to intra-subject variability, that lie outside the control of the designer or experimenter. The success of the biomechanical analysis process as a design tool depends upon the effects of differing product configuration being greater than the uncontrollable factors under analysis.

To examine the relative sizes of these effects, an experiment was designed that involved the application of the analysis system developed in Section 2 to a very simple task: that of moving an object from one position on a desk to another.

3.3.4 Apparatus

The products chosen for evaluation in this experiment were wooden cubes with a side length of 41mm. The task was that of moving the blocks individually from a starting area to one of a number of pre-defined finishing areas. Figure 47 shows the layout of the experiment. The layout markings were printed out at full scale and taped to the working surface (a wooden desk). Subjects were seated during the task.

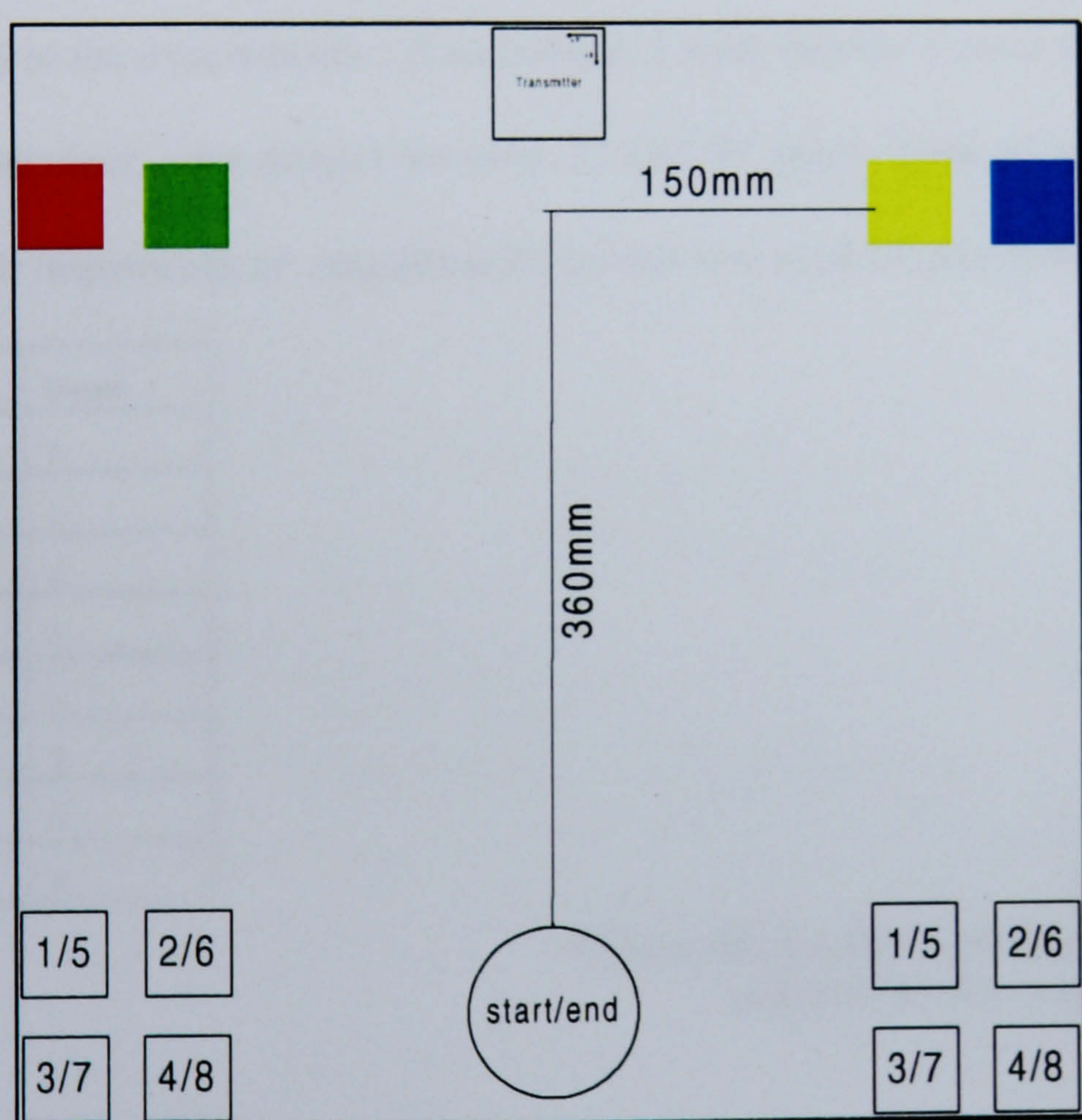


Figure 47: The layout markings for the initial evaluation experiment.

Figure 48: The blocks used in the experiment

3.3.5 Subjects

8 subjects were used in the experiments: - 6 were male, 2 were female; 6 were right hand dominant, 2 were left hand dominant; ages ranged between 22 and 46 years. None of the subjects had any history of upper limb impairment or, (significantly for this test method only) colour-blindness.

Subject	Gender	Hand
A	M	R
B	F	L
C	M	R
D	M	R
E	M	L
F	M	R
G	F	R
H	M	R

Figure 49: Gender and dominant limb of the 8 subjects in the evaluation experiment.

3.3.6 Method

Initially the blocks were stacked on the numbered squares (the left hand set was used for subjects with a dominant left hand, and vice-versa). 8 blocks were used - two each of four colours, stacked 2 high.

The subjects were given the following instructions: -

Instructions.

In this experiment the movements of your arm will be analysed during a simple manipulation task. The experiment should take approximately fifteen minutes.

The experimenter will fit two electromagnetic sensors to your arm using elastic straps, he will then position you in your seat and lead you through a series of calibration exercises. You should try not to move your chair once it has been positioned by the experimenter.

The experimental procedure is as follows: -

Place your hand on the grey "start/end" circle.

When told to start by the experimenter, carry out these actions: -

Working clockwise from the top-left, pick up the blocks and place them on squares of the corresponding colour. Move all the top layer of blocks first, then the lower layer. Place the second block of each colour on top of the first one.

When you have moved all the blocks return your hand to the grey start/end circle.

The initial order of the blocks was randomised and recorded for each subject.

In the experiment the subjects made 8 separate block manipulation actions. The experimental procedure was repeated twice with each subject. The main difference in product configuration was simulated by the difference between the two groups of block finishing positions: the red and green blocks on the left of the task area and the blue and yellow blocks on the right.

3.3.7 Data treatment.

The raw sensor data first underwent a series of validity checks. Next, before analysis could begin certain transformations were required to break the data down into useful elements. These processes are described in Sections 3.3.8 and 3.3.9.

3.3.8 Left and right handed subjects

During the experimental process the set-up was reversed for the two left-handed subjects, who were allowed to use their dominant hand. In order to simplify analysis however, the data pertaining to these subjects was mirrored in the xz plane (all y values in the sensor matrices reversed) so that they could be analysed in exactly the same manner as the right handed subjects.

3.3.9 Task element separation

As all tasks had been conducted in one continuous series of movements, with all output being sent to a single data file, it was necessary to identify the places in the data record where individual task elements began and ended. The large number of individual points requiring identification (8 subjects, 2 repetitions of 8 movements per subject, two points per movement, totalling 256 points) made the automatic identification of these points desirable.

An algorithm was developed that used the vertical position (z coordinate) of the wrist-mounted sensor to identify the beginnings and ends of the task elements. The algorithm took advantage of the fact that during task execution, subjects' hands were at their lowest position at the moment the blocks were picked up and the moment they were put down. By identifying these low points, the readings that corresponded to each pick and place action could be identified. The algorithm functioned as follows:

1. All records whose z value was lower than either of the adjacent records were identified.
2. If a group of "low" records were bunched closely together (the gap between them was less than 1/28th of the total number of readings in the record), suggesting that they were actually part of the same picking or placing action, then the lowest of the group was taken and the rest ignored.
3. If any 'low' records actually had z values higher than a specific cut-off point (normally a z value of -200mm), they too were abandoned. This was designed to eliminate points of inflection that might occur at other stages in the task.

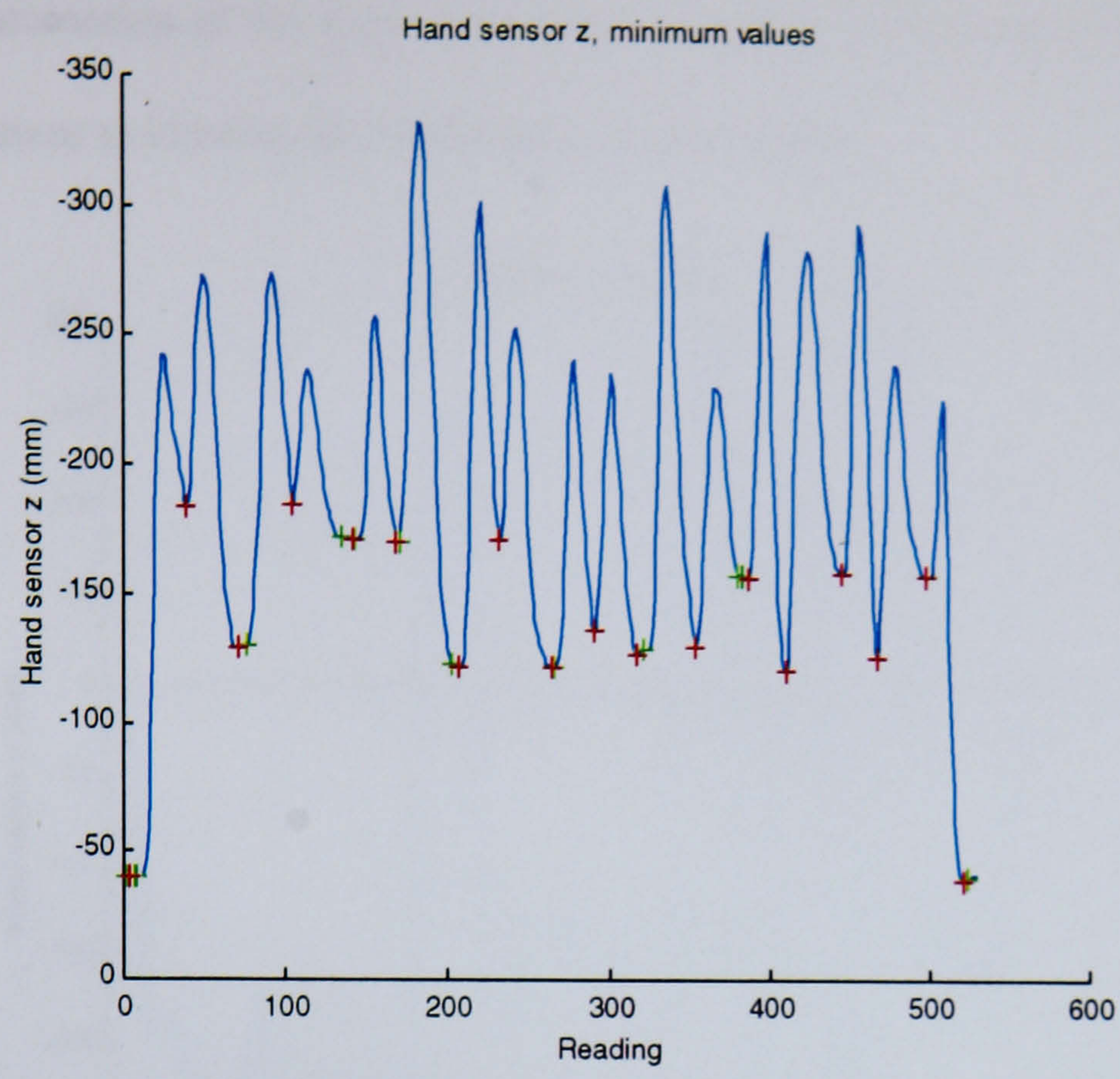


Figure 50: an example of the pick and placement point location process. The green crosses indicate all the "low" points located; the red ones are those selected to represent pick and place positions.

In practice, the routine identified the correct number of points in about 80% of cases. Graphical output was produced to allow any errors to be identified visually. Erroneous values were corrected manually using magnified plots of the affected areas of the data.

3.3.10 Identification of placement area.

The experimental instructions requested subjects to pick up the blocks in a specific order. The initial placement order of the blocks was randomised and recorded so that theoretically the end positions of the blocks should have been identifiable purely by the position of each movement operation in the sequence. Unfortunately, not all subjects obeyed the experimental directions exactly. This suggested poor experimental design since the purpose of the experiment was not to test subjects' abilities to remember and follow instructions. However, the same problem of task element identification now presented itself in the identification of block placement locations. Usefully, it was quite straightforward to identify from the hand sensor positional data which of the two main placement regions had been selected for each task element. As the global origin (located at the centre of the transmitter unit) was positioned half-way between the left and right block placement areas, examination of the sign of the hand sensor's y coordinate at the moment of block placement was sufficient to identify the block placement position.

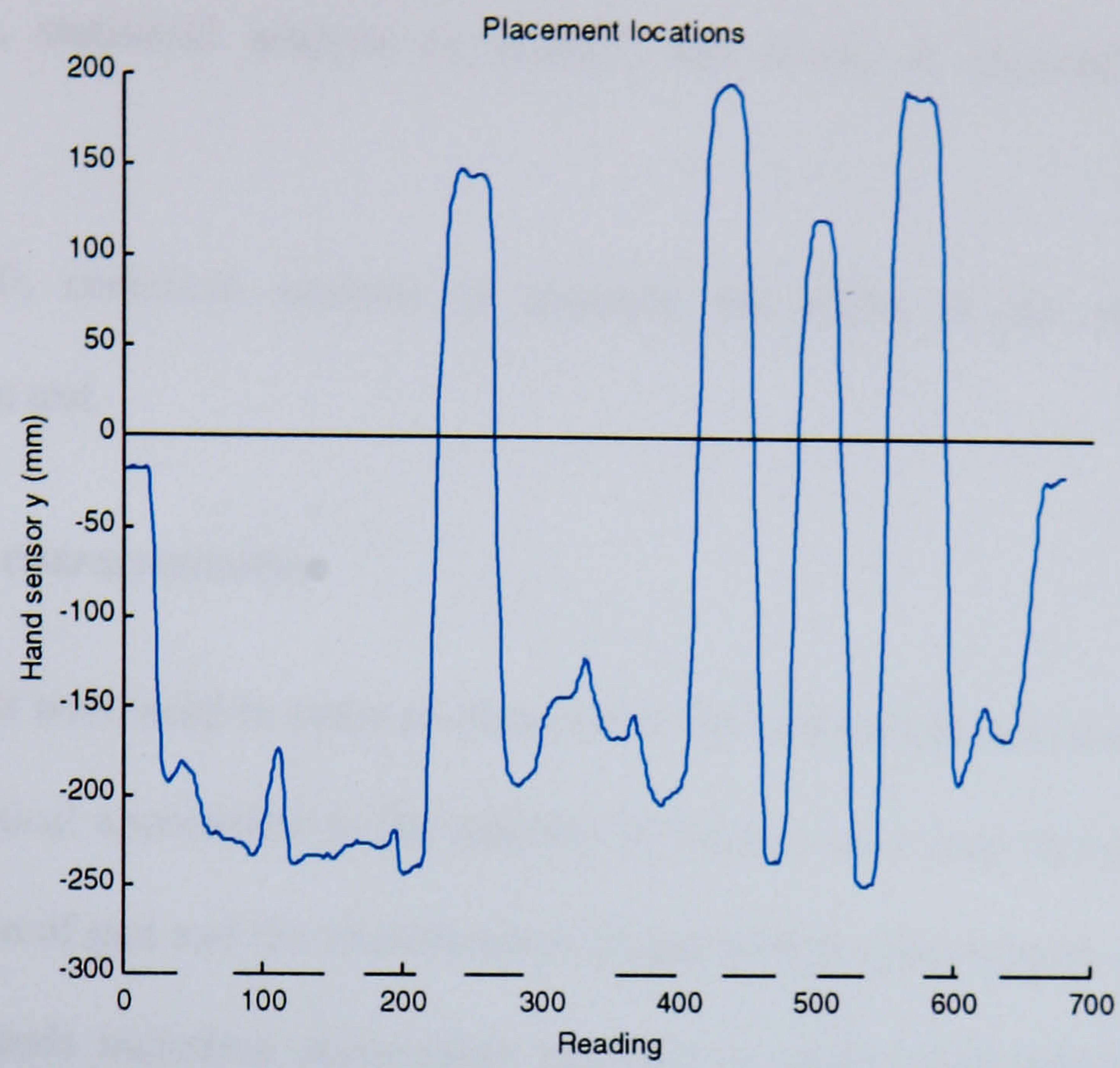


Figure 51: Identification of block placement positions. The vertical grey stripes represent the block lifting elements of the task, the y position of the hand sensor at the right hand edge of each grey bar defines the placement position, negative = close, positive = far

Figure 51 shows an example of this process. The process was conducted automatically with a 100% success rate.

3.3.11 Calculation of torques and angles.

Limb segment angles were derived using the process described in Section 2.3.17, and torques were obtained by the recursive Newton-Euler process using mass data derived from anthropometric variables as described in Section 2.3.12. The blocks themselves were assumed to be of negligible mass compared to that of the limb segments, and so block mass was ignored.

3.3.12 Results

Analysis of the results took place in three phases:

Section 3.3.12.1, visual inspection of the data to provide an overview of the general motion patterns and the amount of variability exhibited by individual subjects.

Section 3.3.12.9, statistical analysis to quantify the levels of intra-subject and inter-subject variability.

Section 3.3.12.10, statistical analysis to quantify the effect of the two different "product configurations" on test.

3.3.12.1 Motion characterisation

Graphical methods were used in order to characterise the motion patterns associated with the block lifting task. Graphical approaches to the analysis of motion have been developed, particularly for the characterisation of gait and the identification of gait defects. [Hurmuzulu et al, 1994] have used a number of methods including phase-plane portraits in which joint angular position is plotted against velocity. Such diagrams make the relationship between position and velocity easy and intuitive to read, which is very useful for the analysis of gait when the clinician is interested in changes in the different phases of the gait cycle. For the analysis of product design, however, the analyst is not seeking to compare product operation performance to an accepted standard pattern, but rather to identify areas of the interaction process which are likely to result in poor performance over time. For this process the phase-plane will not be suitable.

In the graphs below (Figure 52-Figure 58), a simpler approach is adopted - one that ignores velocity data completely. Individual task element data are superimposed on the same axes. The data have been normalised with respect to time to allow direct comparison of the results. The colours of the lines indicate the block placement area for each motion: green lines indicate "near" blocks and blue lines indicate "far" ones. Although both angular and torque values varied between subjects, the overall patterns seen in the data were similar. Therefore, only the data for a single representative subject are shown here.

3.3.12.2 Shoulder plane of elevation

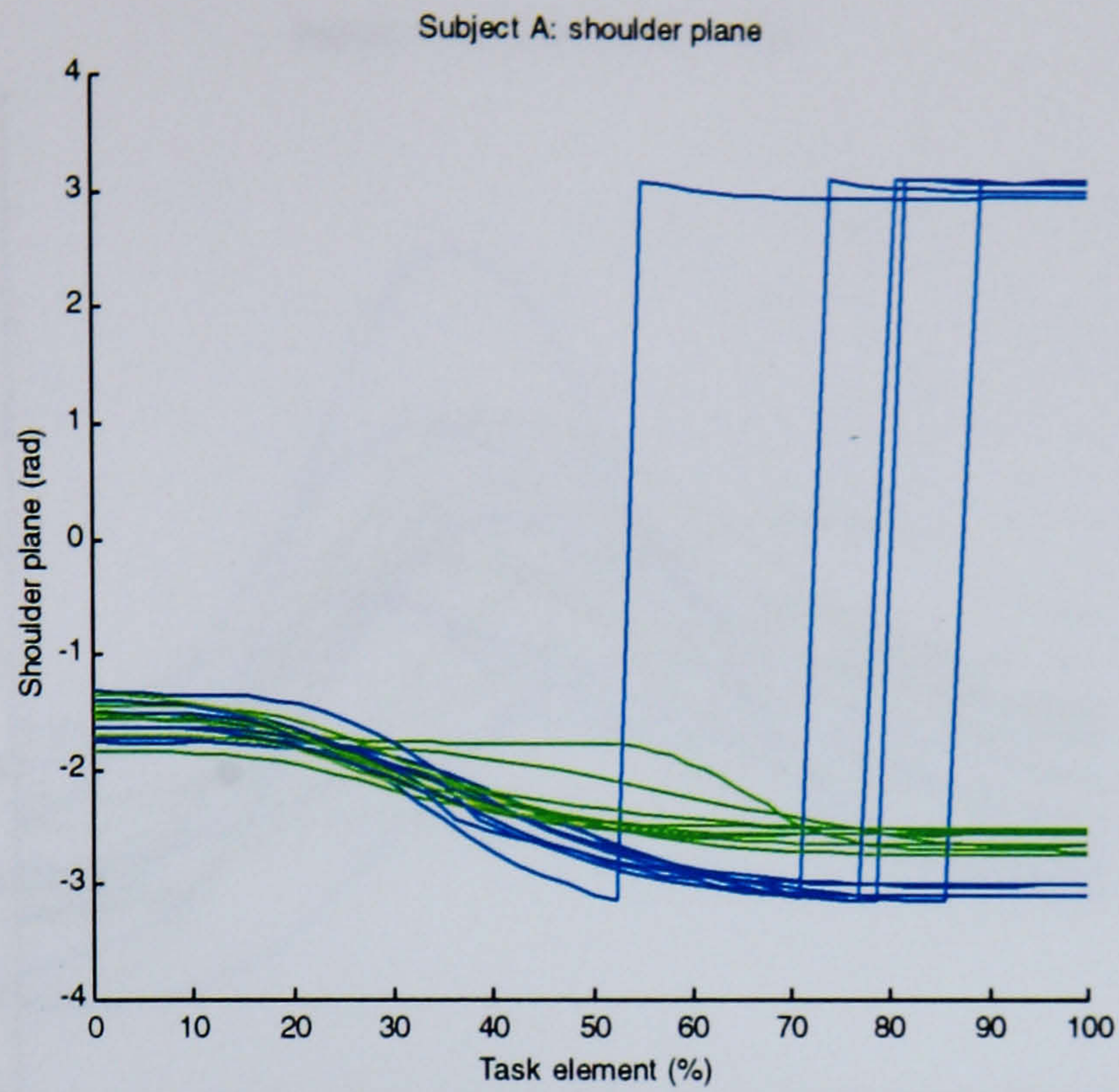


Figure 52 Shoulder plane of elevation

The sudden jumps in some of the shoulder plane measurements are caused by the fact the shoulder plane of elevation is calculated for values of $\pm\pi$. When the angle goes beyond $-\pi$ its value immediately jumps to $+\pi$. In general the angle of shoulder plane ranged from $-\pi/2$ at the beginning of the task element to $\pm\pi$ at the end.

3.3.12.3 Shoulder elevation angle

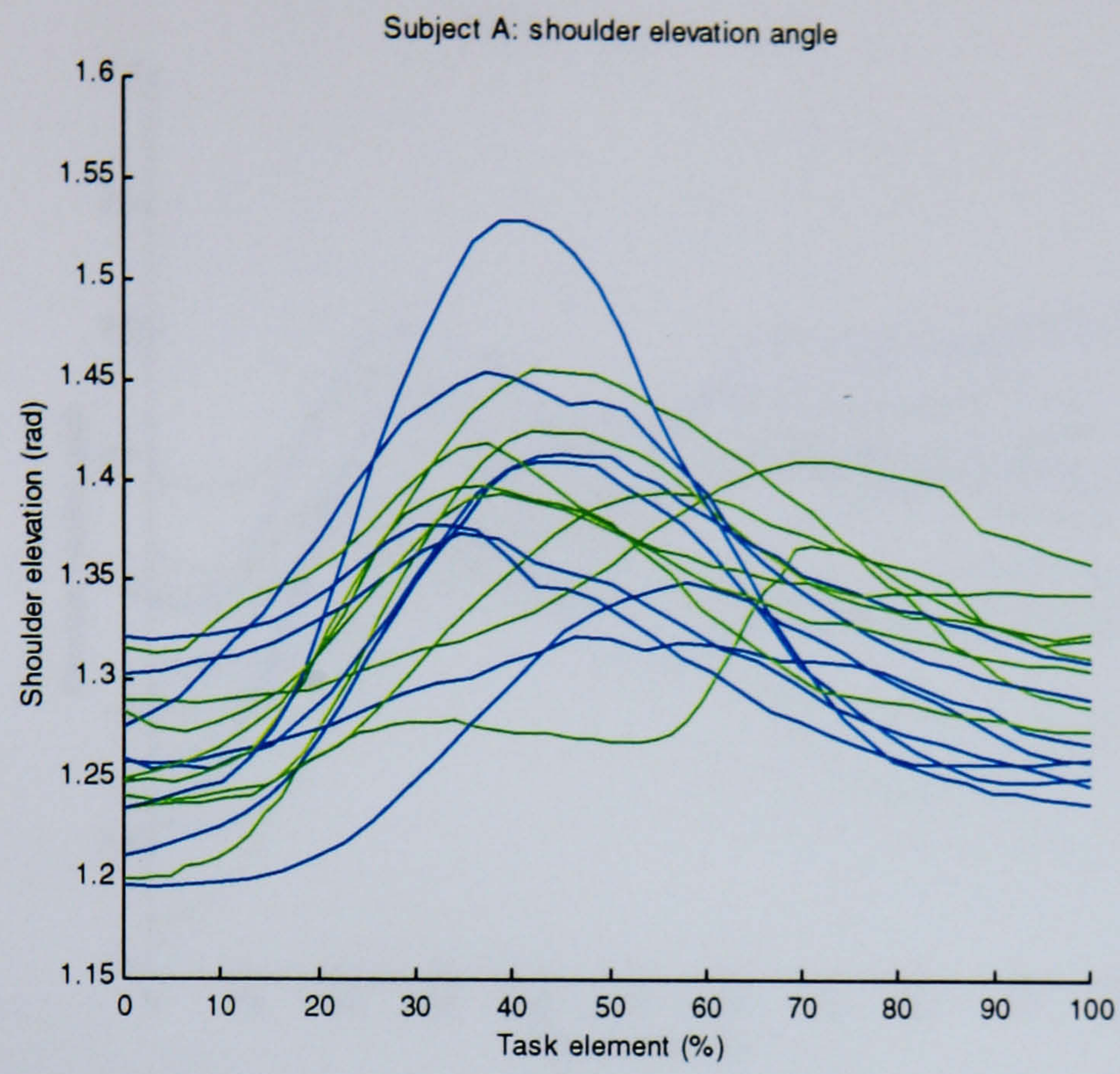


Figure 53 Shoulder elevation angle

Shoulder elevation typically reached its lowest value at the moment a block was picked up, this was followed by an increase to a maximum value after approximately 40% of the total task element time had elapsed, and then a decrease to the point at which the block was put down.

3.3.12.4 Upper arm rotation

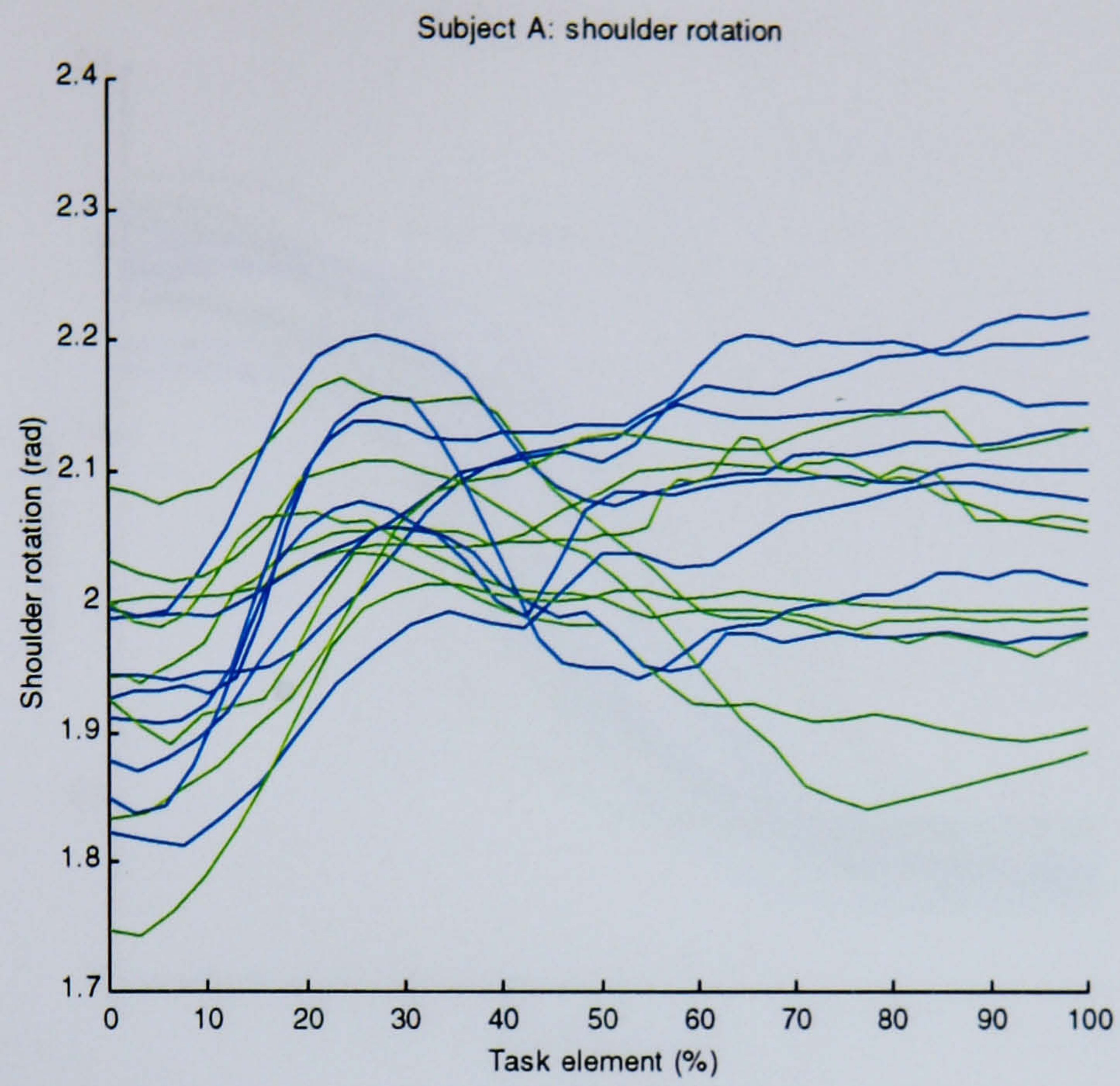


Figure 54: shoulder rotation angle

Upper arm rotation tended to vary by about 0.2rad (11°) through the task, with a dip occurring at the point of block pick-up, a peak shortly afterwards and little change in rotation angle during the final 60% of the motion.

3.3.12.5 Elbow bend

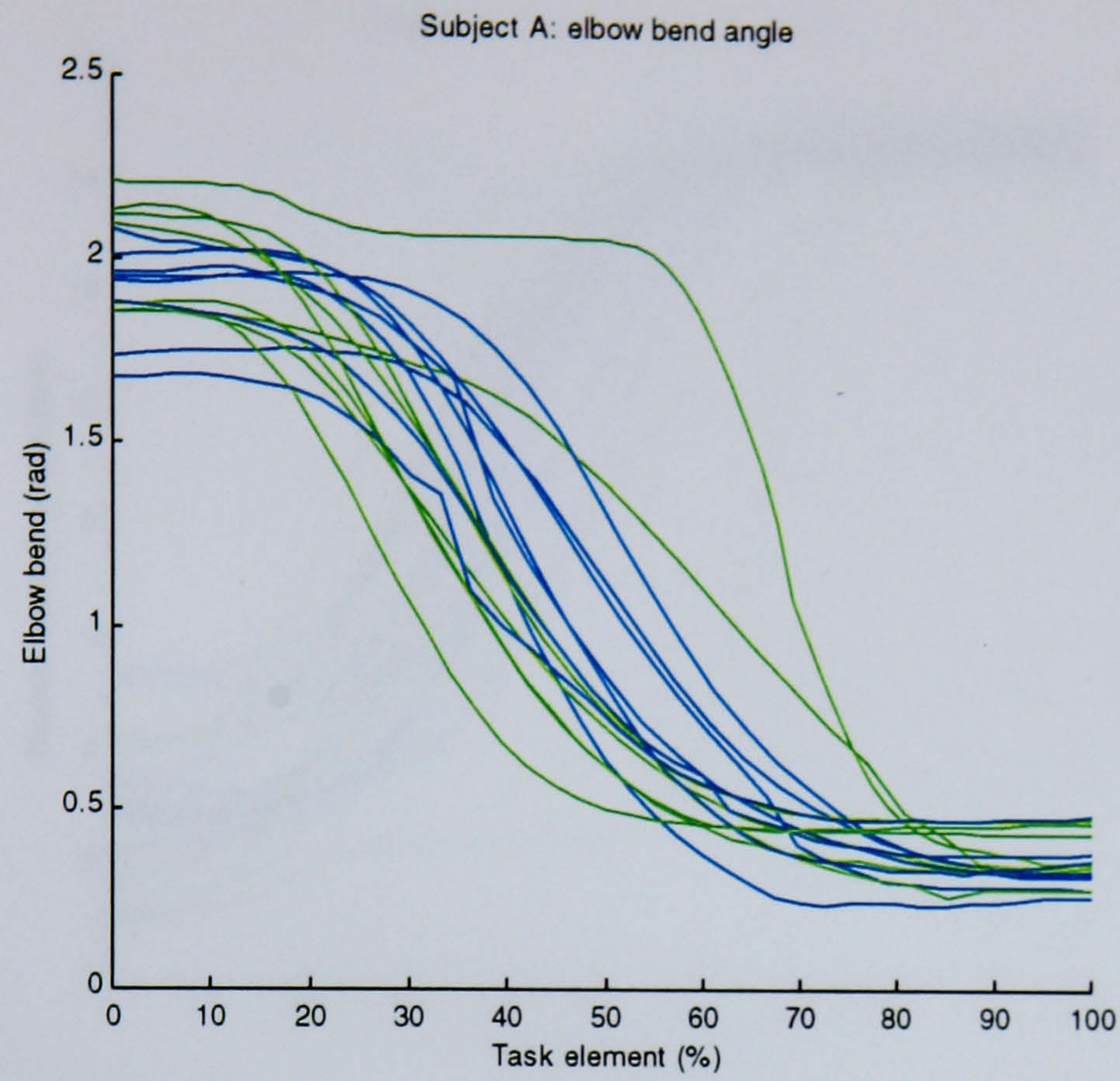


Figure 55: Elbow bend

The elbow bend value was at its greatest at the moment the blocks were picked up. Most motions were characterised by a continuous extension of the elbow throughout the motion, with the bend angle reaching a minimum at the point of placement. That the right-most line stands out from the others is an anomaly of the time normalisation process: for this particular task element there was a longer period without elbow extension at the beginning of the task, thus the line does not sit with the others.

3.3.12.6 Shoulder elevation torque

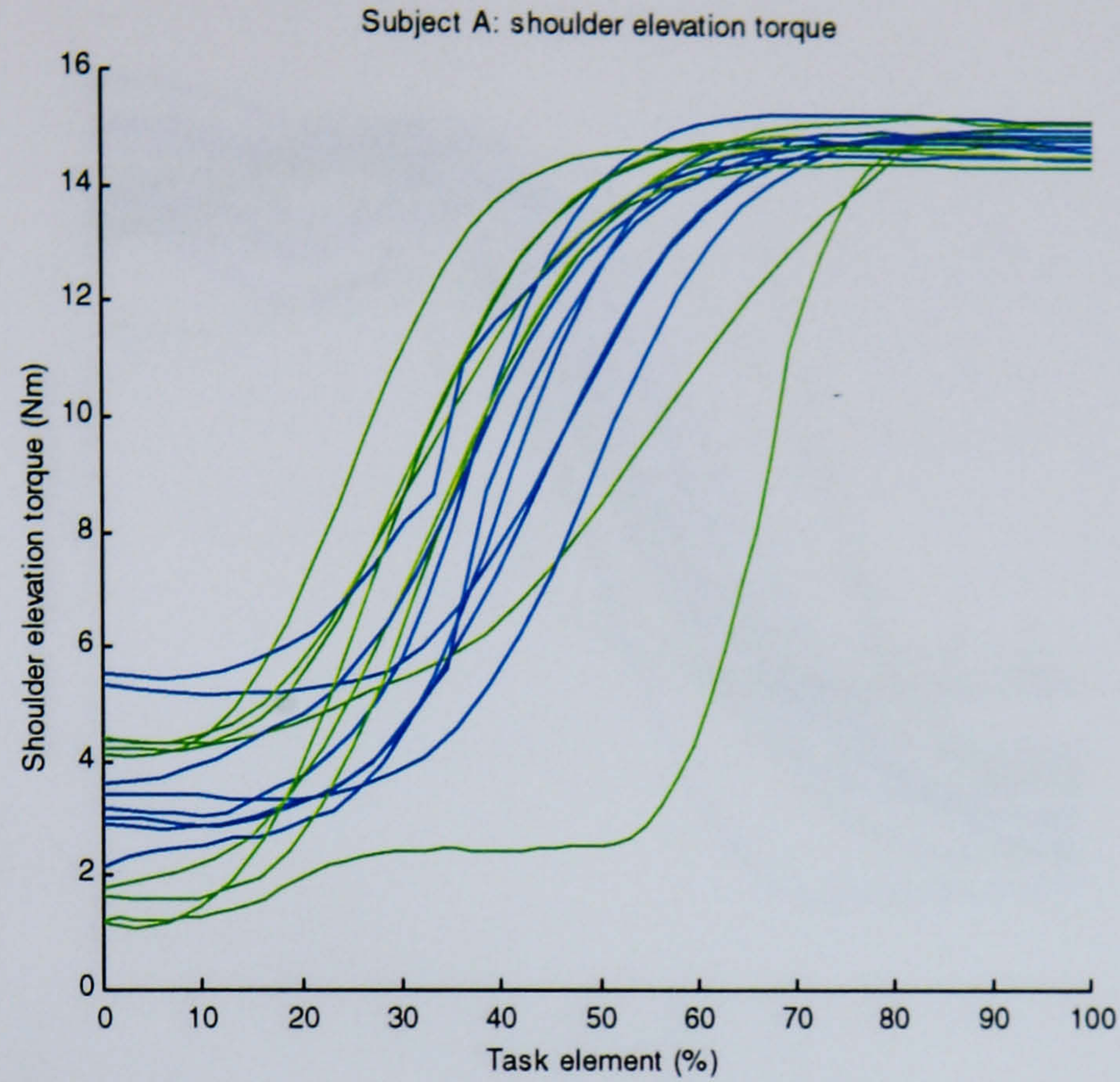


Figure 56: Shoulder elevation Torque

Shoulder elevation torque was at a minimum at the point of block pickup, it rose continuously to reach a maximum just before the block placement point. This rise was clearly associated with the increasing horizontal distance between the shoulder joint and the limb segment centres of mass as the task progressed.

3.3.12.7 Shoulder rotation torque

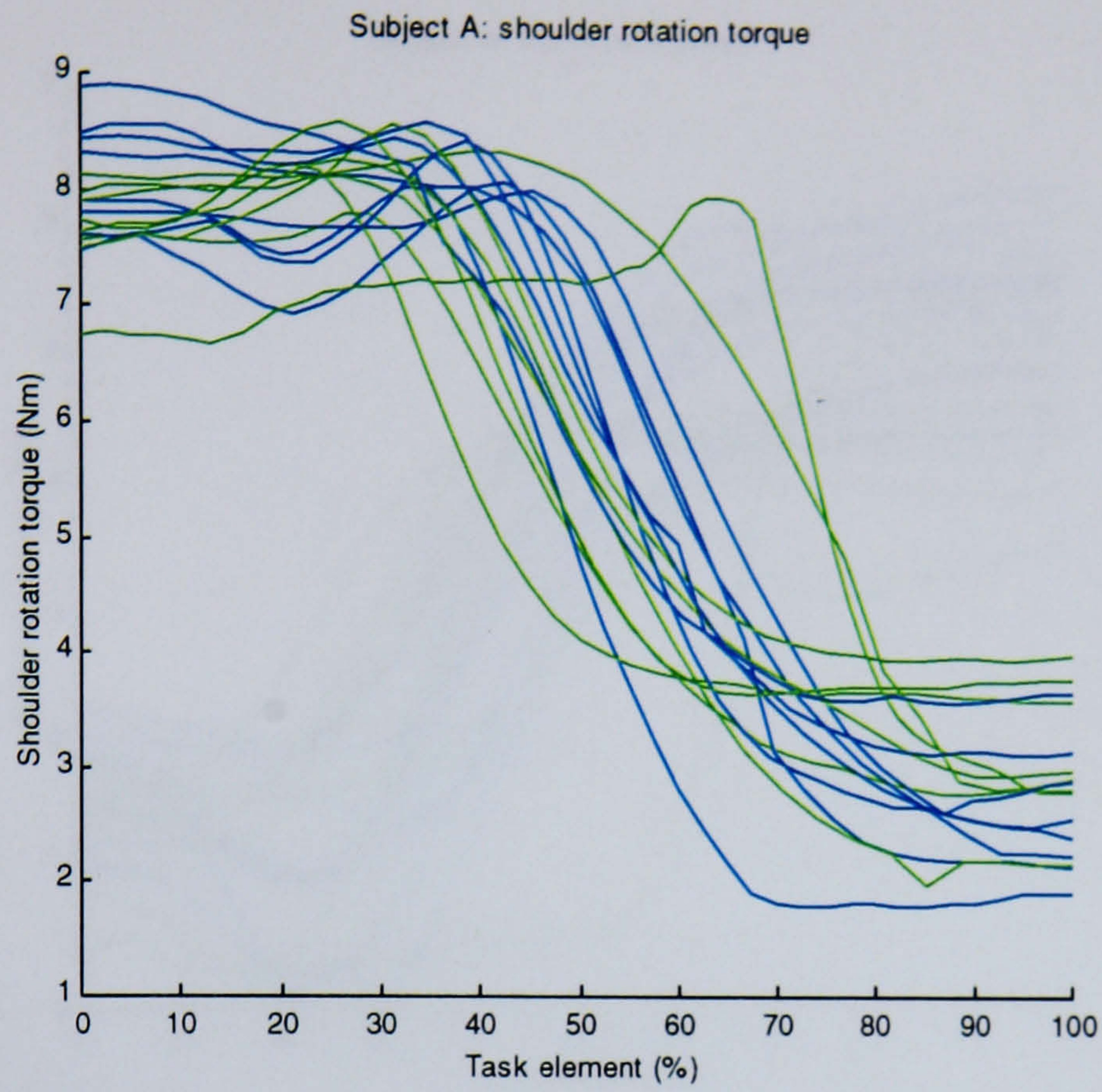


Figure 57: Shoulder rotation torque

Shoulder rotation torque values were, at their maximum, approximately half the elevation torque values. Maximum shoulder rotation torque occurred at the point of block pick up, with torque declining throughout the motion. This effect can be attributed to the relative alignment of the z axis of the upper arm segment and the forearm segment centre of mass during the task. At the beginning of the task the forearm centre of mass was at its furthest distance from the vertical plane in which the upper arm segment lay, but as the motion progressed so the forearm segment mass moved closer to this plane, thereby reducing the moment of the forearm around the longitudinal axis of the upper arm.

3.3.12.8 Elbow bend torque

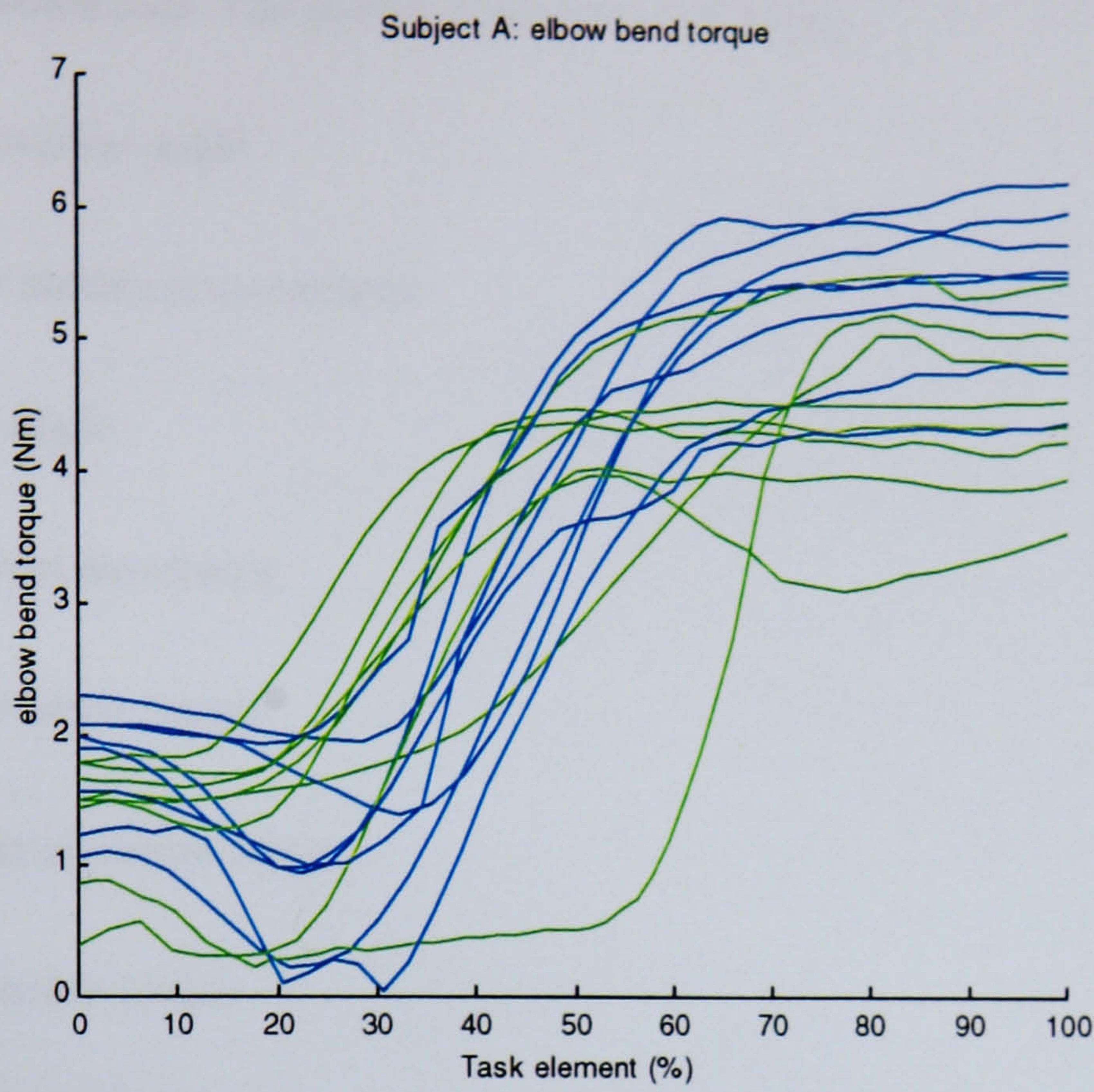


Figure 58: Elbow bend torque

Elbow bend torque values were similar in value to those of shoulder rotation, but they rose from a minimum at, or just after, the point of block pick up to a maximum at the point of placement. This effect can be attributed to the increasingly horizontal attitude of the forearm resulting in a greater horizontal distance from the elbow to the forearm centre of mass and therefore greater elbow torque.

3.3.12.9 Subject variability

In order to assess the variability attributable to the experimental subjects, an Analysis of Variance (ANOVA) process was used.

Two factors were established as independent variables in the ANOVA model:

1. Differences between the experimental subjects
2. Differences caused by the differing product configurations

The remaining differences caused by subjects differing in their motion patterns from one lifting task to another, and by noise in the sensor system were considered to make up the residual variance.

In order to assess these differences, the model was constructed using various quality characteristics derived from the collected data. The quality measures used were:

1. Mean shoulder elevation angle
2. Range of shoulder elevation movement
3. Mean elbow bend angle
4. Range of elbow bend movement
5. Mean shoulder elevation torque
6. Maximum shoulder elevation torque
7. Mean Shoulder rotation torque
8. Maximum shoulder rotation torque
9. Mean elbow bend torque
10. Maximum elbow bend torque.

The mean angular measures were designed to provide a measure of the overall posture required by the task. The "range of angular motion" measures were considered to be one possible measure of the stressfulness of a task, in cases where people have limited joint mobility, movement outside a narrow range can be painful or impossible. The mean and peak torques were also considered good measures of the overall stressfulness of a task, and thus might provide ideal joint-specific quality measures.

Only two angular measurements were analysed in order to avoid the additional difficulty of decoupling the interactions that occur between plane and rotation angles in the Euler convention

The selected measures were calculated for each individual block lifting action, a total of 128 separate measures. The measures were then analysed using the ANOVA function of the SPSS statistical analysis package. The ANOVA model attributes variation in a quality measure to each of the three factors described above. The full results are presented in Section 7.2, but summary data are tabulated below.

The summary data show the mean square deviation attributed to differences between subjects and differences within subjects (the residual) according to the ANOVA model. The square roots of these values are also shown, which correspond to the standard deviation values. expressed in the relevant units of measurement (radians or Nm).

It should be noted that the evaluation of mean angle and torque values relies on motion being continuous throughout the task element being measured. If a particular task element features a long period at its beginning or end during which the limb is stationary, these values will tend to affect the mean level of the factor under analysis.

Measure	Between subject MSD	Between subject Standard dev. Rads(degrees)	Within subject MSD	Within subject Standard dev. Rads(degrees)
Mean Shoulder elevation	0.069	0.263(15)	0.002	0.045(3)
Range of shoulder elevation	0.047	0.217(12)	0.006	0.077(4)
Mean Elbow bend	0.466	0.683(39)	0.020	0.141(8)
Range of elbow bend	0.898	0.948(54)	0.045	0.212(12)

Figure 59: Inter- and intra- subject deviations for various angular measures.

Measure	Between subject MSD	Between subject Standard dev. Nm	Within subject MSD	Within subject Standard dev. Nm
Mean shoulder elevation	140.3	11.84	0.992	1.0
Max. shoulder elevation	226.8	15.05	0.828	0.91
Mean shoulder rotation	49.5	7.03	0.375	0.61
Max shoulder rotation	95.9	9.79	0.111	0.33
Mean elbow bend	22.43	4.73	0.288	0.53
Max. elbow bend	19.49	4.41	0.491	0.7

Figure 60: Inter- and intra- subject deviations for various torque measures.

It can be seen that for both angular and torque measures, variability between subjects was considerably greater than variability within them. In the case of angular measurements the inter-subject variability was typically 3 to 5 times higher than the intra-subject variability, while in the case of torque measures, inter-subject variability was typically 10 times higher. This difference in magnitude is to be expected since angular measures are likely to vary linearly with respect to variations in linear anthropometry, such as segment length: while torque values can be expected to vary in proportion to segment mass values, which in turn are related to the cube of segment length.

3.3.12.10 Effect of product configuration changes

The third factor analysed in the ANOVA process was the variation attributable to the differences in product configuration, represented in this case by the different block landing areas. If the biomechanical analysis technique proposed here is to be useful in a product design context then it is crucial that this element of the analysis provides some useful data.

In order to identify the principal effects of the product differences, two techniques were used:

1. The F-test
2. Pie charts of mean square deviations.

Both methods rely on the ANOVA process.

In the F-test method, the mean square deviations attributed to the various sources of variation under analysis are each divided by the mean square of the residual. The resulting values are known as F-values, and represent the ratio of variations of known cause to variations due to random or uncontrollable fluctuations. The higher the F-value, the more likely that a particular source of variation is having a real effect, and the less likely that the observed effects are due to random sampling differences. The exact value of F needed to determine with a given degree of confidence that a particular effect is statistically significant depends on the number of degrees of freedom in the experiment: the more degrees of freedom, the lower the F-value need be before an effect is considered significant.

The use of pie charts is a cruder version of the F-test process that is very useful for the rapid identification of interesting effects. The relative size of the variance effects can be plotted and any effects that appear to be considerably larger than the "residual" pie-slice are probably significant.

In this experiment there were only three effects to be plotted: subject, product configuration, and residual. Subject effects were likely to be highly significant for all measures, so the main are of interest was those measures which showed a significant effect attributable to product variation.

Inspection of the ANOVA tables and pie charts in Section 7.2 reveals that 5 of the tested variables appeared to be affected significantly by the changes in product configuration. These were:

1. Mean elbow angle
2. Range of elbow movement
3. Mean shoulder elevation torque
4. Maximum shoulder elevation torque
5. Mean shoulder rotation torque

These factors all had F-values greater than 10, and so could be described as being significant at the $\alpha=0.001$ level. This means that there is a 0.2% chance that the observed effects were due to random fluctuations.

Once the most significantly affected factors had been identified, the mean values for each product group could be examined to identify the direction and physical magnitude of the effect. A summary of the mean effects is shown in Figure 61.

Factor	**Near value**	**Far value**	**Far-Near**
Mean elbow angle	1.1	0.98	-0.12rad (7°)
Range of elbow movement	1.411	1.486	+0.075rad (4°)
Mean shoulder elevation torque	9.566	10.199	+0.633Nm
Maximum shoulder elevation torque	13.056	14.008	+0.952Nm
Mean shoulder rotation torque	6.008	5.565	-0.443Nm

Figure 61: Principal mean factor effects due to variation in placement position.

This table shows that none of the mean factor effects was greater than 0.12 rad or 1 Nm. The "far" product configuration would be expected to be the more stressful, since it required subjects to stretch further, increasing the distance of the limb segment centres of mass form the torso. In practice, this proved to be the case. Mean and range of elbow angle were lower for the far position, indicating greater elbow extension (elbow bend is zero at maximum extension), and both mean and maximum shoulder elevation torques were higher. Interestingly, the effect of the far position on mean shoulder rotation torque was to lower it slightly, a fact probably explained by the reasoning given in Section 3.3.12.7.

3.3.13 The use of quasi-static calculation

The first set of user data offered the opportunity to evaluate the assumption made prior to the commencement of the work (Section 2.3.6) that inertial terms could be ignored for tasks involving low limb velocity. The only acceleration considered in the model was acceleration due to gravity, which has a value of $9.81 ms^{-2}$. If the other accelerations occurring during the task were substantially less than this value then the static mode of analysis would be adequate.

To test this theory the movements of the wrist-mounted sensor were examined, since the wrist would be the fastest moving part of the arm during the test. The acceleration of the wrist sensor was calculated for each subject and its maximum value noted. The differentiation required to obtain acceleration from position data has a tendency to exaggerate outlying values. So in addition to the raw calculated data a plot was made using data that had been smoothed using a cubic spline averaging technique. Typical results are shown in Figure 62.

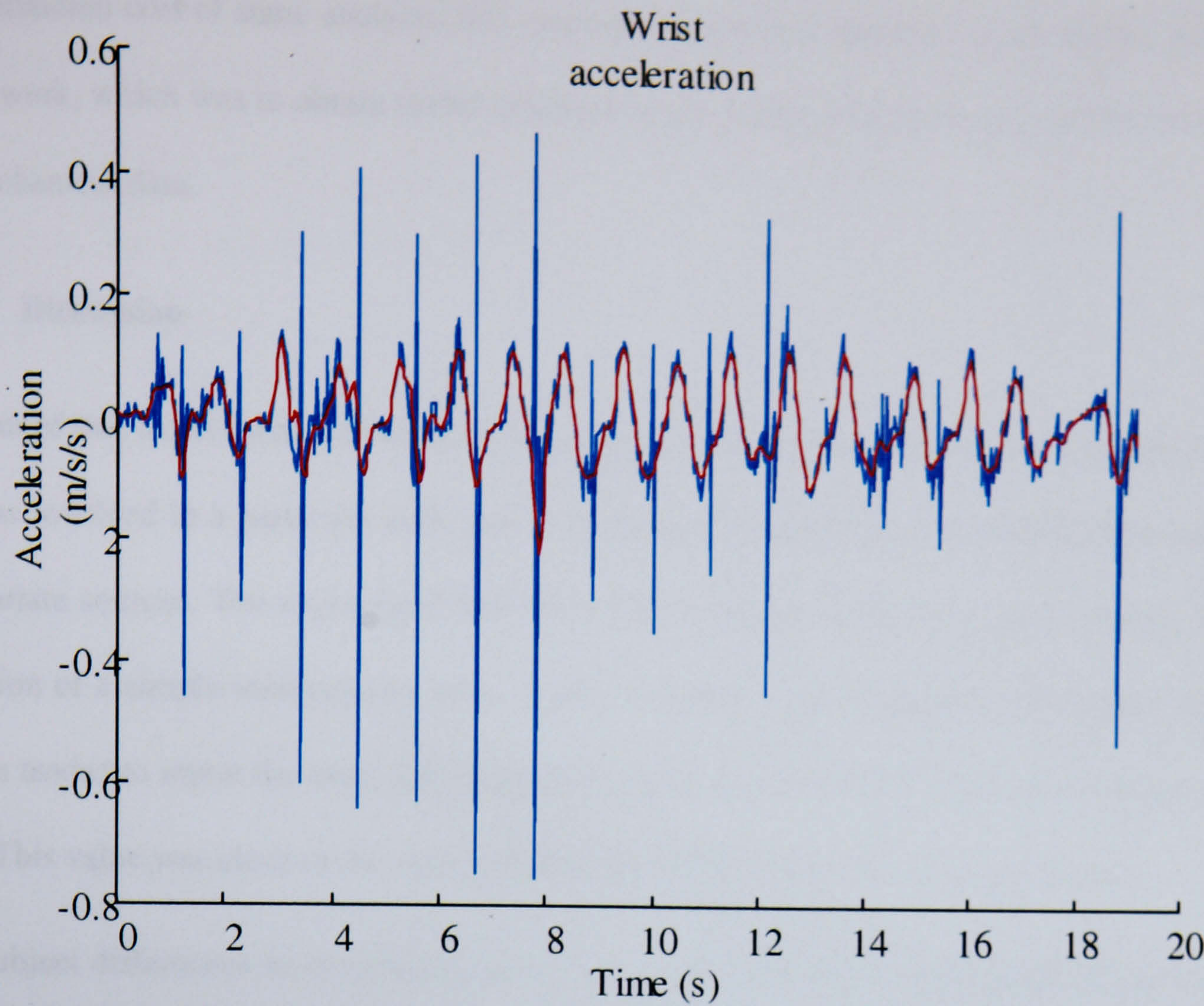


Figure 62: Wrist acceleration data for a sample subject during the block-placing task. The blue line smoothed raw acceleration values, the red line shows smoothed values

The highest values recorded in the raw data were under 0.8ms^{-2}, while those in the smoothed data were less than 0.3ms^{-2}. It might reasonably be assumed, therefore, that the effects on the limb resulting from inertia were less than 5% of those resulting from gravity.

Jäger and Luttman [Jäger and Luttman, 1998], in an evaluation of static and dynamic biomechanical models report that:

> dynamic and static analyses of materials handling tasks may reveal large differences in the stress values. The conclusion can be drawn from this that static analyses are insufficient in cases involving high working speed. The working speed at which the effects of inertia should not be neglected must be clarified for each individual case.

It was felt that, in the light of the results obtained above, and since the fundamental aim of this work is the evaluation of situations relating the use of products in a domestic environment rather than a sporting or manufacturing production line context, the differences in values obtained through the use of static and dynamic analyses could be ignored. Bearing in mind the considerably lower computational cost of static analysis. this assumption was also expected to benefit the eventual aim of the work, which was to obtain useful information as quickly and easily as possible from recorded biomechanical data.

3.3.14 Discussion

The aim of this experiment was to examine various measures that might be used to characterise the motions involved in a particular task, and to attribute the variability revealed in these measures to appropriate sources. The experiment did reveal clear patterns in the motions produced during the execution of a simple manipulation task. It also revealed a high degree of intra-subject consistency: subjects tended to repeat the same task using joint angles that were within five or so degrees of each other. This value was close to the expected accuracy limits of the measurement system.

Inter-subject differences in movements and torques, the result of a combination of anthropometric and performance factors, were much higher, between 15 and 50 degrees difference in angular measures and 4 and 12N in torque measures.

The differences in biomechanical parameters attributable to changes in product configuration in this trial were of a similar scale to the intra-subject differences, this means that while they were detectable using the modelling system they were much smaller than the differences between subjects. This information has important ramifications for the use of the motion analysis process as a design tool, since it means that relatively sophisticated analysis techniques and careful experimental design are required in order to detect differences in product configuration.

An important point emerging from this result is that a variety of subjects is much more important for the collection of reliable data than a large number of repetitions or replications involving a single subject. This finding was probably to be expected, but is unfortunate from the perspective of experimental cost reduction as finding subjects and preparing them for the measurement process is a far more expensive process than is collecting multiple data sets from a single subject.

A statistical power analysis approach (Section 6.5) can be adopted to select an optimum number of subjects. This method was used in the product comparison experiments (Section 3.5).

The limitations of the modelling approach in this product context are well worth emphasising here. The measures adopted to characterise the task took no account of movements around the axes of the wrist, or spatial movement of the shoulder complex. The size and layout of the task was such that some subjects, particularly those with shorter limb segment lengths had a tendency to move from the waist, meaning that the joints of the torso made a large contribution to the final position of the hand. Typical shoulder centre movements are shown in Figure 63.

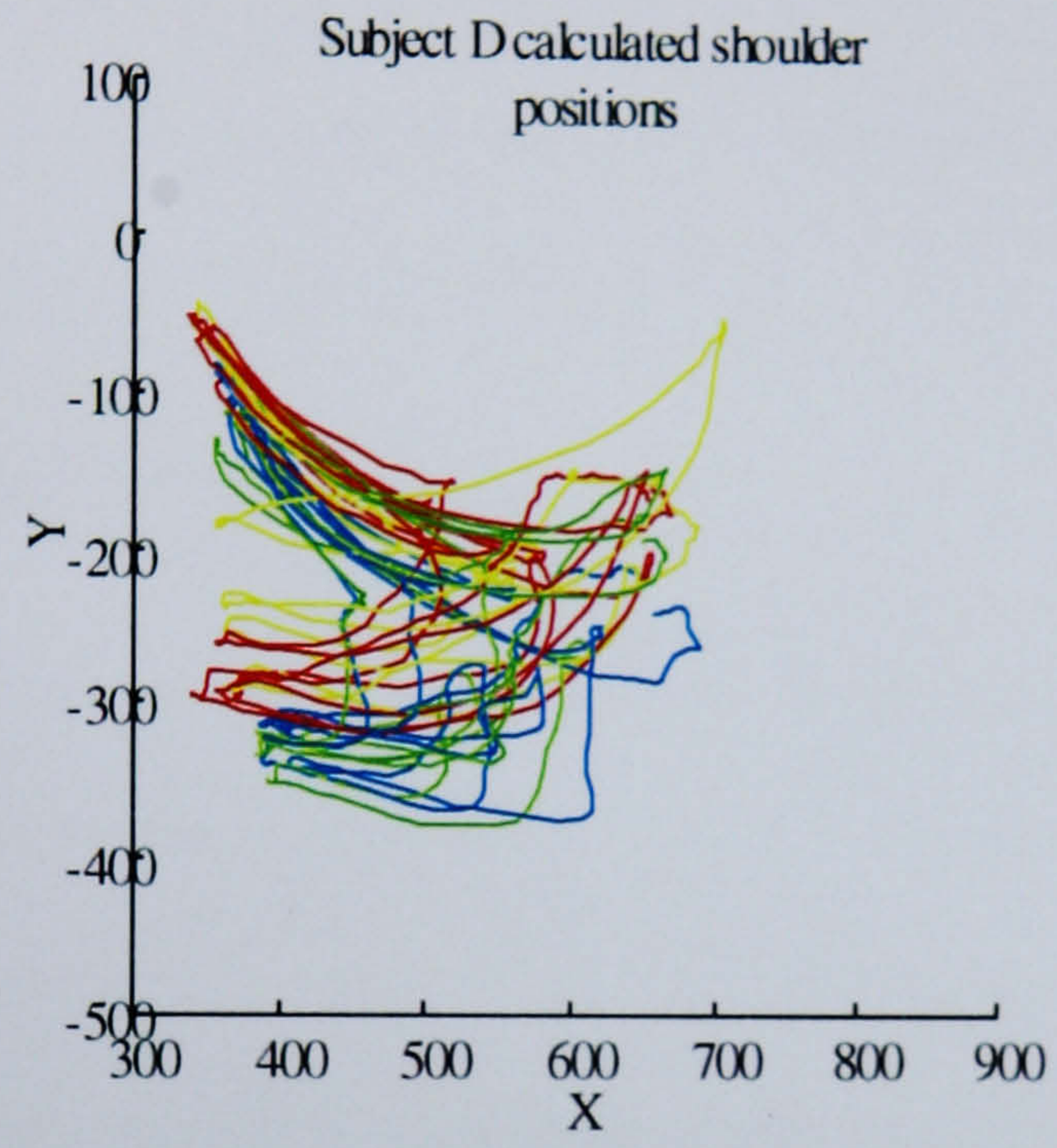


Figure 63: Typical shoulder-centre movements during the block manipulation task.

The experimenter is faced with something of a dilemma here. The aim of the experimental process is to gather data on body movements that will be transferable to real world situations, but the experiments must be designed in such a way as to make quantitative comparisons between subjects and tasks reasonable. By restricting upper body position, it might be argued that the task is being made unrealistic, but in this case it was felt to be necessary in order to allow straightforward inter and intra-subject comparisons. During the subsequent experimental phases different approaches have been adopted to try and eliminate these problems, ranging from linking overall body position to anthropometric variables and so reduce its effects to allowing the subjects complete freedom to position themselves as they see fit.

A final point that should be emphasised here is great difficulty involved in drawing conclusions from biomechanical data presented in the forms that were chosen for this experiment. Whilst statistical analyses of this type are effective in providing quantitative information on the relative sizes of different sources of variability, the effort required to draw conclusions from them was considerable. It is an important feature of any design analysis tool that while the effort involved in data collection and reduction may be great, the eventual result should be a presentation of data in a form that allows key issues to be readily identified.

3.4 Simulated impairment experiment

3.4.1 Context

The previous experiment had examined the variability that occurs when a single subject repeats the same and similar tasks and the variability that occurs between subjects performing the same task. The next stage was to attempt to examine the effects of a physical impairment in isolation from other factors. The only practical way to do this was to simulate an impairment by restricting the motions available to otherwise healthy subjects.

3.4.2 Aims and objectives

The extensive difficulties involved in conducting an extensive survey of disabled people are discussed by [Institute for Consumer Ergonomics, 1981]. The assessment of people with disabilities is not merely a challenge for technological development. To intrude further into the lives of people for whom basic daily tasks present a significant challenge, and whose reliance on others for assistance in these tasks often leaves them with very limited privacy, is asking a lot. The designers of assessment studies and those who seek to develop such methods must ensure that the approaches adopted allow the extraction of the maximum amount of reliable, significant data with the minimum additional inconvenience to the subjects.

As an overall goal of the work is to investigate methods that improve the design of products for people with disabilities and impairments, the second series of experiments was designed to investigate the effect of a minor impairment on product use. This was achieved through the use of artificial restriction on unimpaired subjects in order to allow direct comparison between subjects with and without impairments.

It was recognised that this approach cannot hope to provide information that would have direct transferability to a group of subjects with real upper limb impairments. However, as a precursor to the analysis of such a group it does have several advantages, most notably the ability to remove and apply the impairments at will, and so compare impaired and unimpaired movements without interference from other anthropometric effects.

3.4.3 Background

Electromagnetic motion analysis techniques have been used [O'Neill et al, 1992] to investigate the availability of compensatory motion in the upper limb to cope with elbow arthrodeses. The experimental work was similar to that undertaken here in that subjects were asked to complete a number of simple tasks involving the use of domestic products with the motion of on joint, in this case the elbow, restricted. The overall objective, however, was different from that of the current work in that the experimenters were attempting to identify a fixed elbow position that would maximise the subjects' ability to operate existing products rather than attempting to identify product configurations that allowed subjects with limited mobility to maximise their use. Interestingly, the authors note that for many limb joints, excluding the elbow, full compensatory motion can take place using other joints. This comment has useful repercussions for this work in which the nature of that compensatory motion is being investigated.

3.4.4 Wrist immobilisation

The impairment was supplied using a wrist splint of the type used to combat certain types of cumulative trauma disorder. The splint consisted of a rigid aluminium plate within a fabric and leather sheath that was held against the palm of the hand and the palmar surface of the forearm with a number of Velcro straps. The item is shown in Figure 64. The effect of the wrist splint was to immobilise the wrist completely, preventing all flexion and deviation movement.

It had been observed that the block manipulation task tended to cause considerable wrist motion, particularly palmar flexion, although the measurement methods used did not quantify the degree of this motion. It was hypothesised that if this motion were prevented then subjects would tend to compensate by altering their patterns of motion at the elbow and shoulder. The aim of the experiment was to quantify the nature and magnitude of these compensatory effects. Such effects are interesting as they could serve to indicate the potential magnitude of differences in performance, as opposed to anthropometry, between subjects.

Figure 64: The splint used to immobilise the wrist

3.4.5 Subjects

Five subjects were used in the experiment, four male and one female. All subjects were right hand dominant and all used their right hand during the experimental process.

3.4.6 Method

The experimental method was identical to that used in the previous experiment (Section 3.3) with the exception that each subject completed each set of block movements four times, the first two replications were completed without the wrist splint, the splint was then added and the second two replications were carried out.

The fitting of the wrist strap necessitated the removal of the wrist sensor. Once the sensor had been replaced, software alignment was repeated in order to compensate for the fact that the sensor was unlikely to have been replaced in exactly the same orientation as that used for the first two repetitions.

3.4.7 Data treatment

The data treatment process was identical to that used in the previous experiment:

1. Data validity checks

2. Biomechanical angle calculation

3. Torque calculation

4. Task element separation.

3.4.8 Results

As discussed previously, the simulated impairment experiment had two principal objectives:

1. To examine and quantify the effects of restricted wrist motion on the block moving task

2. To confirm the results of the previous experiment.

To carry out this process, a three way ANOVA model was established, with Subject, Block Placement Position and Impairment State as factors. The same quality measures used in Section 3.3.12.9 were again analysed during the process. The results are presented in Section 7.3, and a summary is presented in Figure 65. The table shows the various quality measures, notes whether or not they were significant at the α=0.01 level, and if they were significant, records the mean physical effect size. The table is sorted according to the F value for the effects of the splint so the strongest effects are presented first.

Quality Characteristic	Subject effects	Destination effects		Impairment effects		
	Significant ?	Significant?	Effect of "Far"	Significant ?	F level	Effect of splint
Mean elbow bend torque	Yes	Yes	+0.247Nm	Yes	122.89	-0.943Nm
Mean shoulder elevation angle	Yes	Yes	-0.037rad	Yes	115.9	+0.123rad
Mean shoulder rotation torque	Yes	No	-	Yes	114.533	+0.834Nm
Maximum shoulder rotation torque	Yes	No	-	Yes	100.32	-0.68Nm
Maximum elbow bend torque	Yes	Yes	+0.591Nm	Yes	57.39	-0.741Nm
Maximum shoulder elevation torque	Yes	No	-	Yes	48.68	-0.466Nm
Mean shoulder elevation torque	Yes	No	-	Yes	24.93	-0.565Nm
Elbow bend angular range	Yes	No	-	Yes	15.72	-0.101rad
Mean elbow bend angle	Yes	No	-	Yes	9.96	+0.052rad
Shoulder elev. angular range	Yes	Yes	+0.056rad	No	2.55	-

Figure 65: Summary of the Analysis of variance process for the simulated impairment experiment (significance at α=0.01).

It can be seen from the table that the inter-subject variation was significant in all factors, this was to be expected given the results discussed in the previous experiment. The table also shows that the addition of the wrist splint had a strong effect, being significant in all but one measure. By comparison, the product configuration changes had a relatively small, or relatively specific, effect overall, achieving statistical significance in only four out of the ten measures.

The physical effects of the addition of the wrist splint can be summarised as follows: again, the results are presented in descending order of effect significance:

1. A decrease in mean elbow torque.

2. An increase in mean shoulder elevation angle.

3. An increase in shoulder rotation torque

4. An increase in mean elbow bend angle, but a reduction in elbow bend angular range

5. A decrease in shoulder elevation torque

It may be construed from this that subjects make up for the loss of wrist flexion capability by increasing the elevation of the shoulder and the bend of the elbow, and then rotating the upper arm to position the hand. The main effect of this alteration in posture is to increase rotational torque at the upper arm, whilst slightly reducing the other torques. As discussed in Section 3.5.10, it is desirable to minimise shoulder rotation torques and to allow forces to be transferred through the shoulder by elevation.

3.4.8.1 Effect of block placement position

By comparison of Figure 61 and Figure 65, it may be seen that none of the significant effects detected in the first experiment were detected in the second. This result suggests two possibilities: -

1. The experimental method was invalid
2. There were strong interactions taking place between the factors under analysis, and these interactions prevented the successful de-coupling of product configuration effects from the effect of the simulated impairment.

In order to investigate the second theory, the ANOVA process was repeated, but on the second occasion, two-way interactions between factors were included in the analysis. The results of this analysis are summarised in Figure 66.

Quality characteristic	Significance of interactions		
	Subject/Destination	Subject/Impairment	Destination/Impairment
Mean shoulder elevation angle	-	Yes	-
Shoulder elev. angular range	Yes	-	Yes
Mean elbow bend angle	-	Yes	-
Elbow bend angular range	-	-	-
Mean shoulder elevation torque	-	Yes	-
Maximum shoulder elevation torque	-	Yes	Yes
Mean shoulder rotation torque	-	Yes	-
Maximum shoulder rotation torque	-	Yes	-
Mean elbow bend torque	-	Yes	-
Maximum elbow bend torque	-	Yes	Yes

Figure 66: Significance of two-way interactions in the simulated impairment experiment at the a=0.01 level.

It can bee seen in the table that while there was very little detectable interaction between the effects of subject variations and differences in block destination, there were interactions detectable between subject and impairment in nearly all the measures. This result suggested that the wrist splint was having a far from consistent effect on subjects' movements and that compensatory behaviour varied between subjects.

3.4.9 Discussion

This experiment demonstrated clearly how differences in user capabilities can have a very powerful effect on the motion patterns generated during task execution. It is likely however, that some of the effects of the wrist splint were caused by its unfamiliarity for the subjects. During the experimental process subjects were not given any time to become used to the splint's effects: it is therefore highly likely that a familiarisation process was occurring as the measurements were being made, with subjects exploring either consciously or otherwise those movements still available to them. In subjects with a genuine impairment this compensatory process would occur over a period of time and they would be likely to have optimised their movements to a high degree.

A second cause of variation in the effects is the possibility that splint itself provided slightly differing degrees of restriction to subjects during the experiment. A single size of adjustable splint was used to immobilise the wrist and, while every attempt was made to ensure that restriction was consistent, it is possible that, particularly with the smaller subjects, some movement remained possible. In particular the splint design used might restrict radial and ulnar deviation less severely for subjects with smaller hands. In any future work, it would be recommended that individual ranges of motion be measured with and without splint use to quantify such variation. However, the experiment as conducted still serves as a reasonable model of the effects of impairment since genuine impairments could be expected to have similarly varying effects on subjects – it is unlikely that any disorder would constrict the range of motion in a particular joint to exactly the same degree in every person affected.

While this experiment appeared to demonstrate some consistent effects arising as a result of the inclusion of a wrist splint during the block manipulation task it also demonstrated vividly the complexity of analysing biomechanical data like this in order to draw conclusions about the tasks being undertaken. It became clear during the process that strong interactions between design elements are likely, which would be likely to have a negative effect on the overall performance of the analysis process.

3.5 Product evaluation experiment

3.5.1 Context

The previous two experiments had looked at a deliberately simple task with the aim of investigating variability rather than measuring design performance. The next stage was to apply the techniques under study to more realistic tasks and, with the knowledge gained already of expected levels of variation, to attempt to draw useful information on the performance of different designs from the collected data.

3.5.2 Aims and objectives.

The aim of the product evaluation experiment was to apply the techniques of biomechanical analysis under development in this work to a more realistic product design context. The work described in Section 3.3 had demonstrated that it was possible to identify consistent effects on biomechanical variables and attribute them to changes in product configuration, but the product context used was deliberately a highly simplified one. The next logical step in the evaluation of the system was a trial involving the movements of a group of subjects undertaking a simple task which would be repeated using real products with different user interface characteristics. The products chosen were eating and drinking utensils, ideal because they have almost universal application and are available with a number of different physical user-interface designs. The intention was to use measures of joint torque as quality characteristics to compare the various products, and to place emphasis on the speedy evaluation of collected data and the ease at which design information could be drawn from the analysis.

3.5.3 The products

The block manipulation experiment demonstrated that the most time-consuming part of the biomechanical analysis work, apart from the analysis of the data itself, was the process of calibration and the collection of anthropometric data from the subjects. For this reason, it was decided to evaluate two types of product in the same experimental session, thus maximising the amount of information collected per subject. The selected products were:

1. Drinking Vessels
2. Spoons.

Both these products offered the following features that made them suitable for analysis using the biomechanical assessment techniques under discussion in this work.

1. They are products with a very wide potential user population.
2. Their use is an upper limb manipulation process with a large range of limb motion
3. The task of lifting a cup or spoon to the mouth is a simple and repeatable one.
4. Both cups and spoons have received considerable attention in the past from designers attempting to make products more accessible for disabled people. The solutions offered present a variety of user interface characteristics.

It should be noted that the intention was not to undertake a critique of the disability-specific designs under evaluation. Most of the designs tested were intended to reduce grip strength and finger mobility demands, neither of which are measured by the analysis system used here. Rather, interest was focused on the effects of the different grasp types and hand postures further up the limb segment chain. It should also be noted that the subject context was not appropriate for thorough analysis of an assistive technology product since none of the subjects under evaluation were impaired, either naturally or artificially, by the conditions that the products had been designed to tackle.

The selected products are described in detail below.

3.5.3.1 Spoons

Figure 67: The spoons used in the product evaluation experiment

The three types of spoon used in the experiment are illustrated in Figure 67. The particular interface characteristics are summarised below:

1. Spoon 1 was a conventional stainless steel dessert spoon, it was held in a precision grip, with the exact grip type left up to the individual subject. (Object ID 1)

2. Spoon 2 was part of a modular cutlery system designed for use by people with poor finger mobility or low grip strength. The system consists of a range of large handles, designed to be held using a power grip, combined with various spoon and fork ends which are connected to the handle using an interference fit. Spoon 2 was a conventional straight-shafted spoon. (Object ID 2)

3. Spoon 3 was also part of the modular cutlery system, but rather than using a straight shaft the spoon bowl was twisted at an angle of 30° to the handle. This alteration was designed to reduce the wrist movement required to bring the spoon bowl into the mouth. The handle was held using the same power grip used on spoon 2. (Object ID 3)

The grip styles adopted by the subjects are shown in Figure 68.

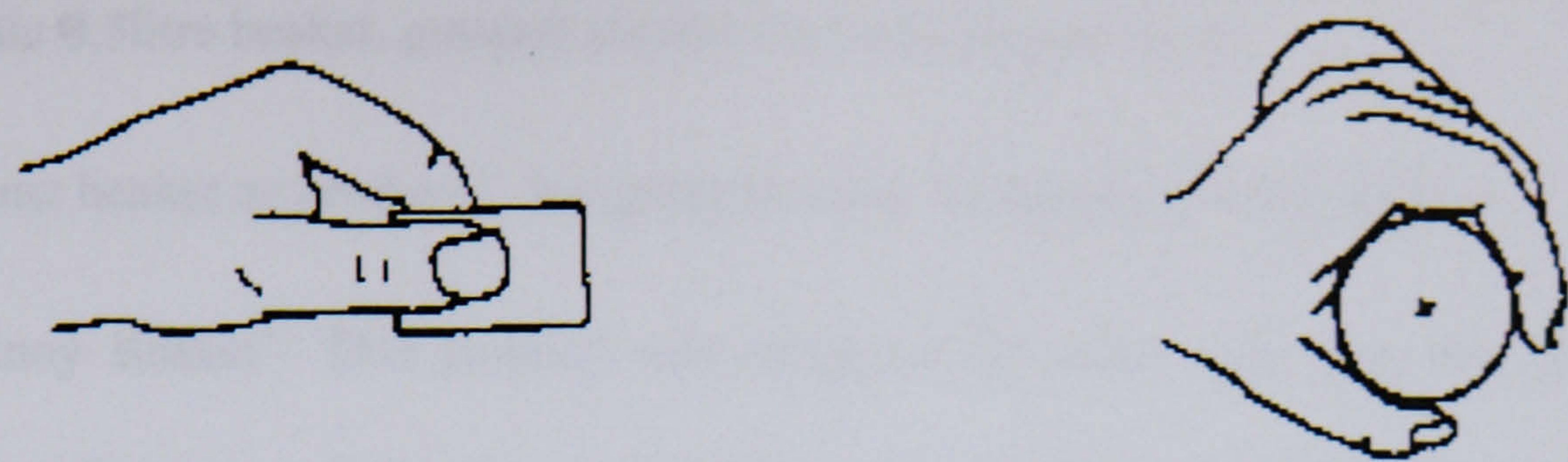


Figure 68: The two basic grip patterns used to hold the spoons

The task under analysis for the spoons was designed to simulate the consumption of soup or some similar liquid food product. Water was used as the actual food product under analysis. The water was placed in a plastic beaker with a diameter at the brim of 70mm. A small diameter container was used in preference to a larger bowl to reduce the inter-subject differences arising from different methods of collecting liquid in the bowl of the spoon. For analysis purposes a single task element was considered to be the action of lifting a spoonful of liquid from the beaker to the mouth, sipping it, and returning the spoon to the beaker.

3.5.3.2 Drinking vessels

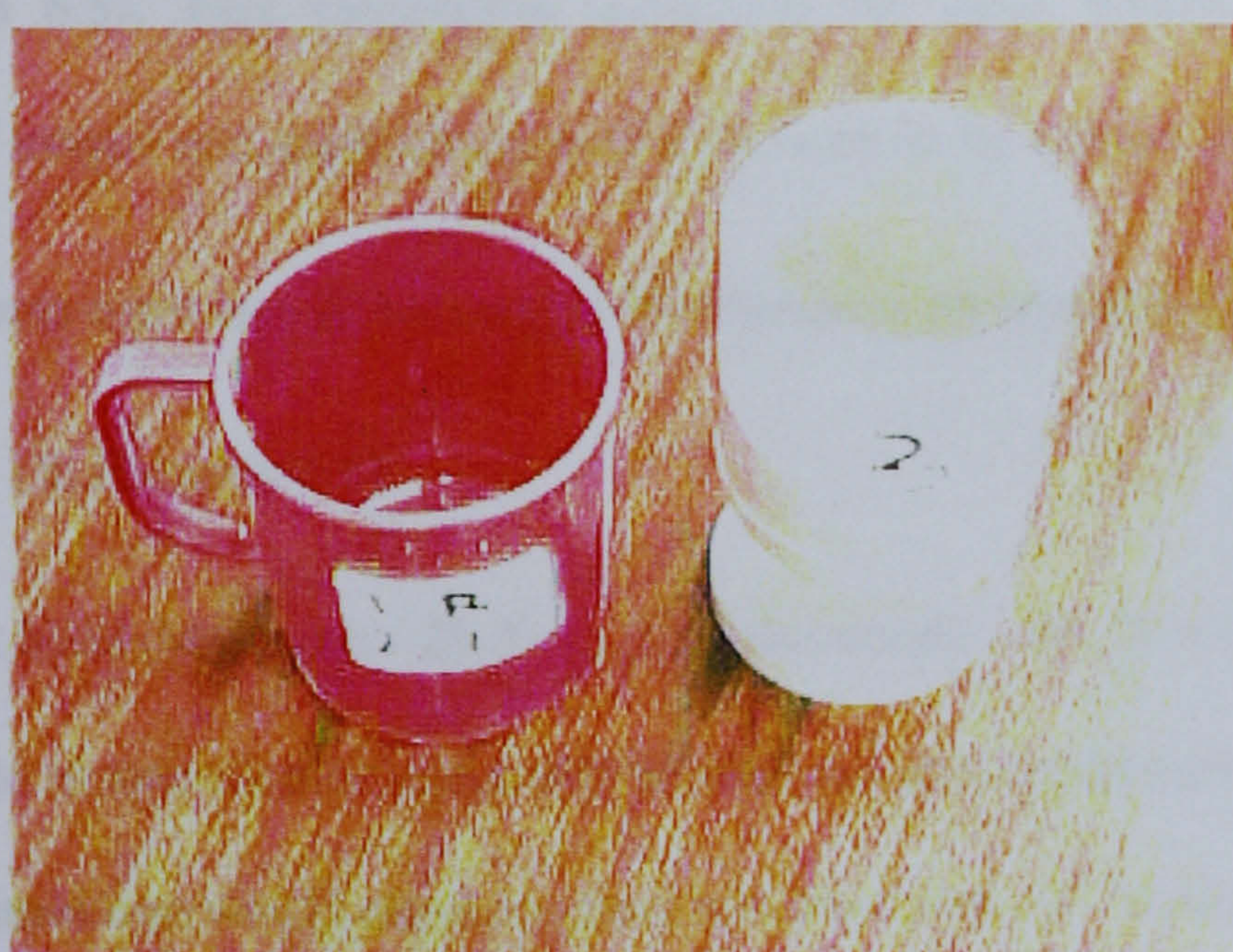


Figure 69: The drinking vessels used in the product evaluation experiment

The drinking vessels used in the experiment were again tested in three configurations. The containers used are shown in Figure 69, the different configurations are described below:

1. A plastic 0.3litre beaker, grasped around the body (Object ID 4)
2. The same beaker as product 1, but grasped using the handle (Object ID 5)
3. A "Minoy Beaker". This product was designed for users with very low grip strength. The container features a large slot in the base into which the first two fingers of the hand are inserted. The thumb is then wrapped around the outside of the beaker base to provide support and control. (Object ID 6)

The task under analysis for the drinking vessels was the action of lifting the vessel from a pre-determined location on the work surface, sipping a small quantity of water from it and then returning the container to the same point from which it was collected.

3.5.4 Subjects

A larger number of subjects was used for this experiment than the previous block manipulation work, although all subjects were selected from a relatively homogeneous population: the staff and student bodies of the University of Wales Institute, Cardiff.

A simple statistical power calculation was used to suggest an appropriate number of subjects for the experiment (Section 6.5). This calculation suggested the ideal number of subjects would be approximately 33, if torque and angle changes of 15% were to be reliably detected.

In practice, **35 subjects** were tested; summary information is presented below:

1. Gender: .Males:- 18, Females :- 17
2. Handiness: Right hand dominant: - 25, Left Hand dominant: - 10. (It is interesting to note that no attempt was made to specifically select left handers for this experiment, although in the overall population of Britain one would expect to find less than 10% left handers, rather than the nearly 30% found here.)
3. Height (self-estimates collected): Overall mean height 1708mm (std 97mm). Mean for males 1768mm (std 85mm), mean for females 1644mm (std 63mm).

3.5.5 Method

All subjects completed a task using each of the six different product configurations (three mugs and three spoons). The order in which the tests were carried out was randomised, although subjects completed all the tests using the same type of product (mug or spoon) consecutively. Experimental details were recorded on a specially designed database.

Subjects were presented with the following introductory information:

> Introduction
>
> The purpose of this experiment is to analyse the motion of your arm as you use a variety of simple domestic items. Some of these items have been specially designed for use by people with physical disabilities.
>
> Your movements will be monitored using an electromagnetic motion tracking device. The device consists of two sensors that will be attached to your arm with elastic straps, and a magnetic field generator, which is the grey cube on the desk in front of you.
>
> The experimenter will first collect some personal details from you. He will then make some measurements of your arm and fit the two sensors, one to your wrist and one to your upper arm.
>
> The system will be calibrated and you will be asked to perform two experiments.
>
> The whole process should take approximately 20 minutes.
>
> After the experiment you will be given the opportunity to comment on the items you use during the experiments and the experimental process itself.

Personal details including age, estimated standing height and history of upper limb injury were collected, and the usual selection of anthropometric measures was obtained (Section 2.3.11) The sensors were then fitted and calibrated (Section 2.3.17).

The laboratory area was set up as shown in Figure 70. The location of the chair was fixed, and a graduated tape measure was attached to the desk in such a manner as to indicate the distance from the back of the chair at desk height. The starting and finishing locations for the mugs and the location of the container from which spooning was to take place were shown by positioning a clear acrylic square over the tape. This position was set to a distance of three times the subject's radial length from the back of the chair. In this way it was hoped that the effect of any interaction between the experimental environment and subjects' anthropometric parameters would be eliminated, leaving the differences in product configuration as the main experimental variable.

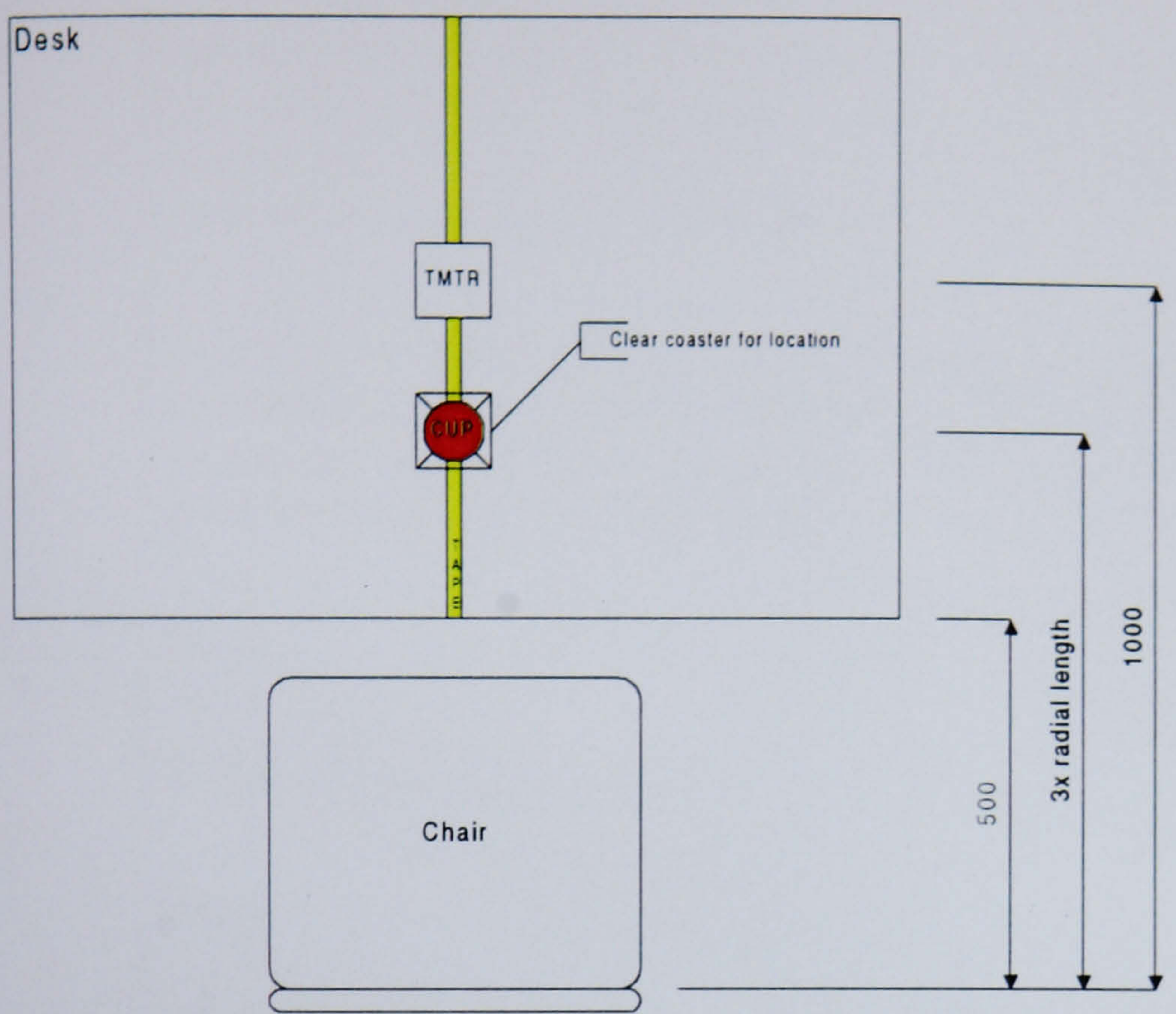


Figure 70: Plan view of the laboratory environment used in the product comparison experiments.

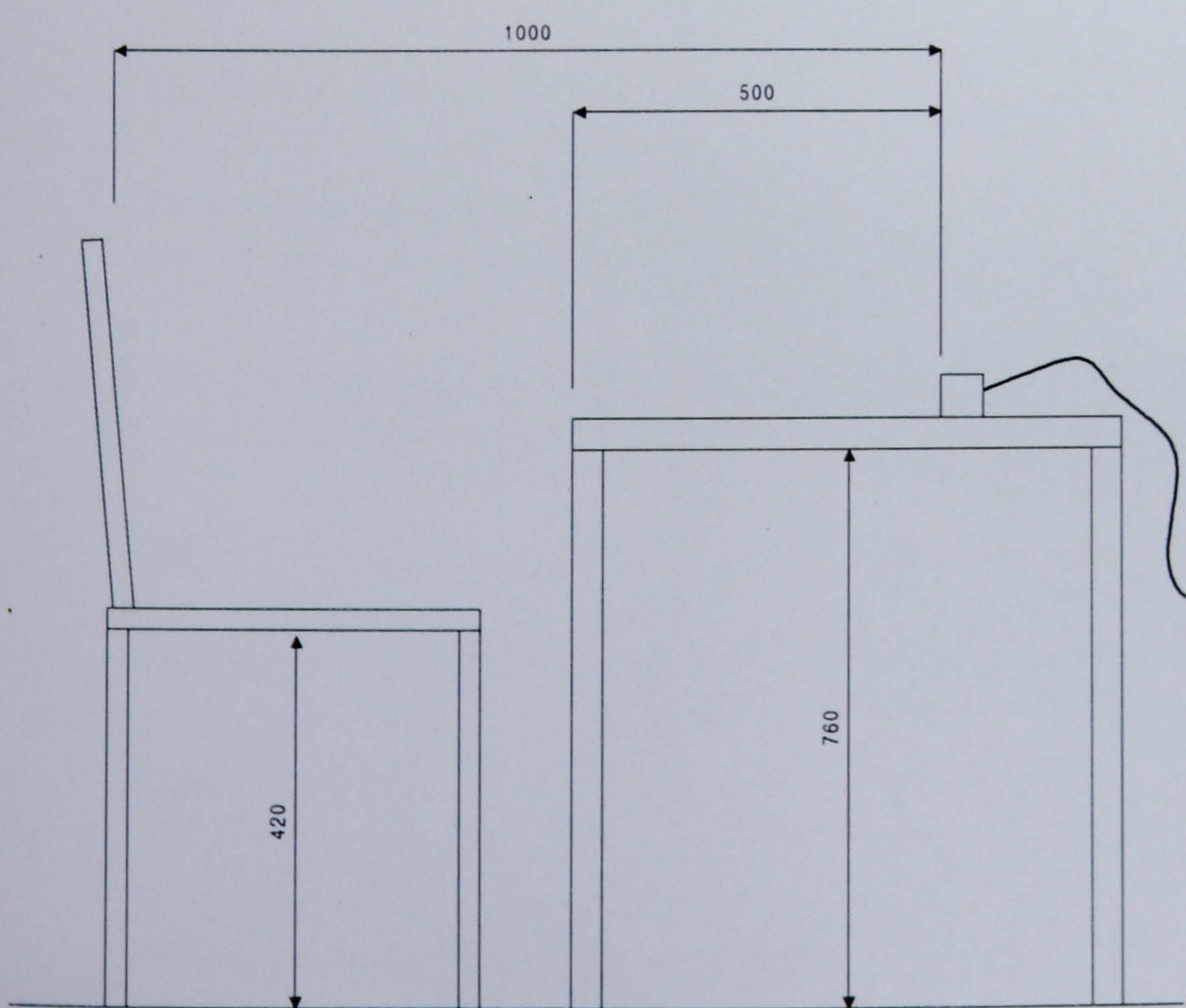


Figure 71: Side view of the laboratory environment used in the product comparison experiments

The experimental instructions were then given to each subject:

Spoons

In this experiment a bowl of water will be placed on the desk in front of you. the experimenter will ask you to drink 6 spoonfuls of water from the bowl. The experimenter will count the repetitions out loud. The speed of your actions is not a factor in this experiment. The process will be repeated with 3 different designs of spoon. You should not move the bowl during the experiments.

To ensure consistency in these experiments it is important that you hold each spoon in the way its designers intended, these ways are described below. The spoons are labelled with the appropriate numbers, but the order of their use will be randomised. If you have any questions please ask the experimenter.

Spoon 1

Should be held as you would normally hold a spoon for eating breakfast cereal, etc.

Spoons 2 & 3

Should be gripped in the fist.

Cups

In this experiment a cup of water will be placed on the desk in front of you, the experimenter will ask you to drink 6 sips of water from the cup. Between sips you should replace the cup in its original position and release it momentarily. The experimenter will count the repetitions out loud. The speed of your actions is not a factor in this experiment. The process will be repeated with 3 different designs of cup.

To ensure consistency in these experiments it is important that you hold each cup in the way its designers intended, these ways are described below.

The cups are labelled with the appropriate numbers, but the order of their use will be randomised. If you have any questions please ask the experimenter.

Cup 1

Should be held without using its handle, by grasping around the body.

Cup 2

Is the same vessel as cup 1, but should be held by the handle, as you would normally hold such a vessel's handle for the purpose of drinking from it.

Cup 3

Should be held by placing the thumb in the large recess at the bottom of the cup and wrapping the other fingers around the outside.

Six repetitions of the sipping task for each product was judged the maximum number that would be comfortable for the subjects, any more than 36 sips each might become unpalatable and difficult. Between experimental runs the water levels in the cups and in the bowl from which water was spooned were replenished. The level in the cups was set at 40mm below the rim (approximately half-full) and the water level in the bowl was set at 10mm below the brim.

After the experiment, subjects were given the opportunity to comment in writing on the products. In particular they were asked to specify their favourite or least favourite product configurations.

Figure 72: A subject taking part in the product comparison experiment

3.5.6 Data manipulation

Once the motion data had been collected, it was converted into angular and torque values in the manner described in section 3.3.7.

3.5.6.1 Task element separation

Task element separation was a major problem, firstly because the large number of subjects, products and repetitions meant that a total of 1260 separate lifting actions had to be identified, requiring the location of 2520 start and finish points; and secondly because the requirement that subjects release the mugs momentarily between sips (This was included in the experimental method as it became clear that the action of grasping the Minoy beaker was a cause of significant difficulty, and therefore a likely site of peak torque or angle values) resulted in large variation in hand sensor position at this point in the task.

The algorithm adopted to separate the task elements utilised the fact that the point at which the product was brought to the lips was always the highest hand position. These points could be identified using the techniques described in section 3.3.9 and used as the end points of the task elements. Element start points were then identified by moving backwards (temporally) through the sensor files, following the descent of the hand sensor until the first inflexion in the z-coordinate prior to the upper hand position was located. This point was assumed to be the start of the task.

The new task separation algorithm had a success rate of approximately 80%, graphical display of the results and the start and finish points identified by the system allowed erroneous readings to be rapidly identified and manually corrected. However one of the subjects had generated motion patterns that could not be reliably separated visually, because they elected to carry out nearly all movement with their upper torso, keeping the arm virtually stationary throughout the task.

3.5.7 Results

The very large amount of data produced during the experiment (66 Mb) made the ability to rapidly summarise the results crucial. Therefore the data was visualised and analysed in two stages:

1. Graphs of individual subjects' angular and torque data were generated, in which task elements were normalised with respect to time and then superimposed on the same axes. This approach allowed and assessment of the general motion patterns generated by the tasks and gave visual feedback on the degree of intra- and inter-subject variability.

2. Attempts were made to fit curves of various types to the collected data in order to smooth, simplify and characterise the results.

3. A form of analysis commonly used in Taguchi Methods for robust design was adopted to examine the relative effects of the different products on a variety of quality measures.

3.5.7.1 Data visualisation

The graphs below show the patterns of the angle and torque variables that have been analysed throughout this work. Typical results for a single subject and a single product are shown. In practice the basic similarity of all the products tested resulted in similar overall motion patterns. A single task element was considered to consist of the action of lifting the product from the work surface to the mouth and then returning it to the work surface. The graphs additionally separate lifting from descending task elements by colour, although in practice the transition point usually occurred at or around the half-way reading.

3.5.7.2 Shoulder elevation angle

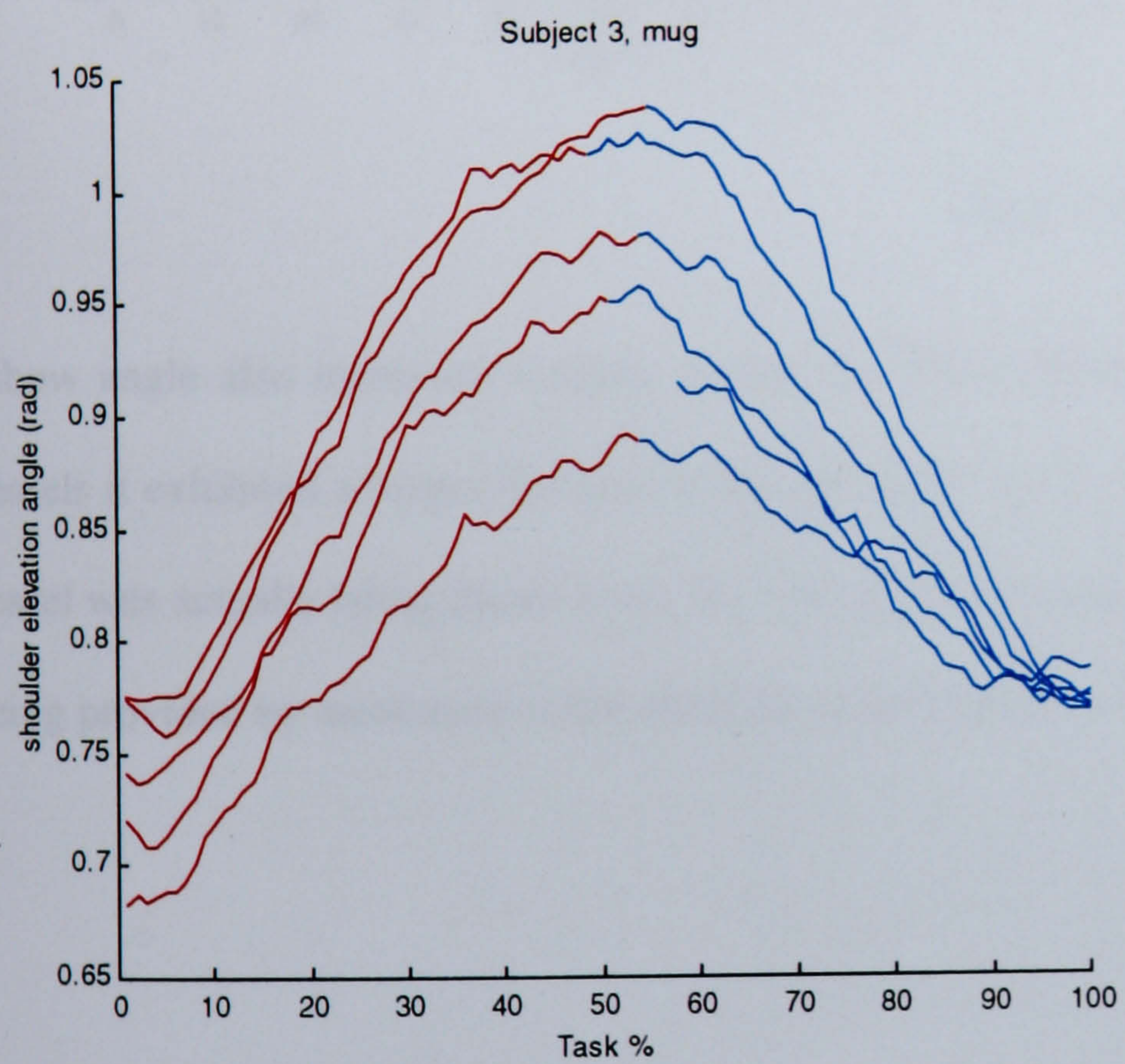


Figure 73: Shoulder elevation angle variation for a single subject/product combination.

Shoulder elevation rose steadily from a minimum at the point of pickup to a maximum as the product reached the mouth.

3.5.7.3 Elbow angle

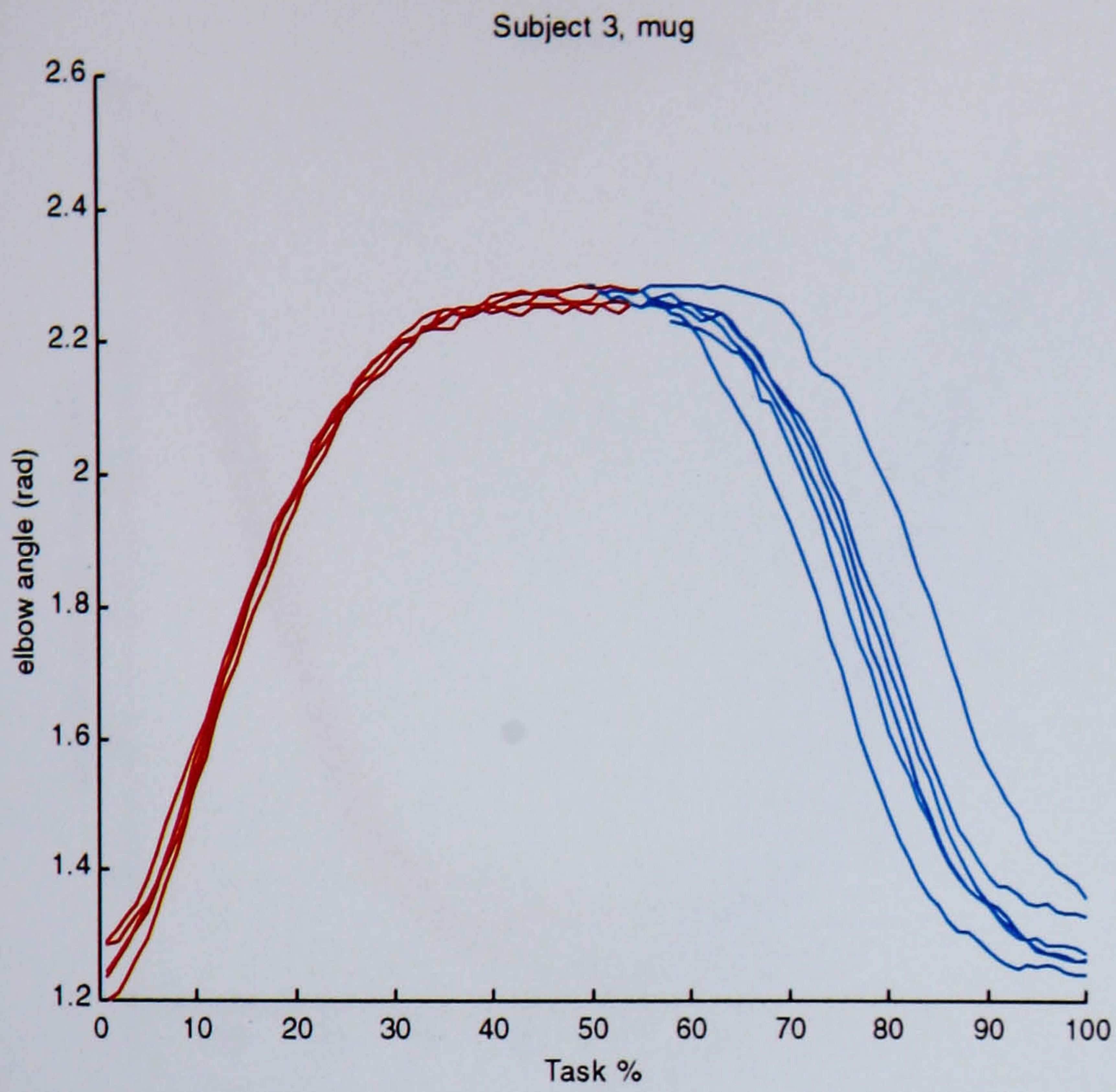


Figure 74: Elbow angle variation for a single subject/product combination.

Elbow angle also increased steadily during the lifting phase of the motion, but for the drinking vessels it exhibited a longer flat area at the top of the curve. This corresponded to the time that the vessel was actually being drunk from, the tipping motion required to pour liquid from the container being provided by movement at the shoulder rather than the elbow.

3.5.7.4 Shoulder elevation torque

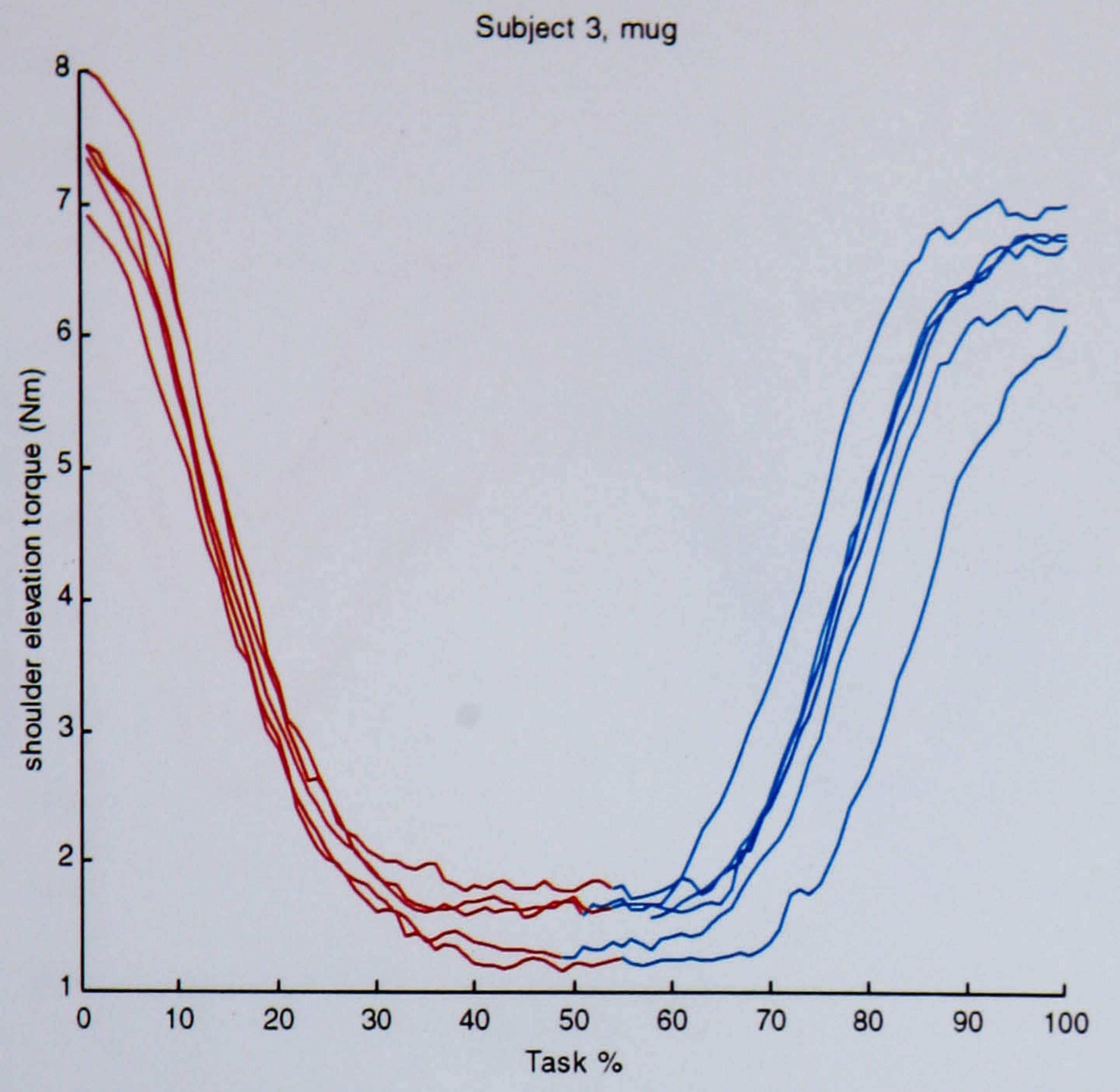


Figure 75: Shoulder elevation torque variation for a single subject/product combination

Shoulder elevation torque reached a minimum at the point at which liquid was sipped, despite the overall increase in elevation. This was associated with increasing elbow angle bringing the mass of the forearm and hand proximal of the elbow joint and therefore reducing the overall moment on the shoulder

3.5.7.5 Shoulder rotation torque

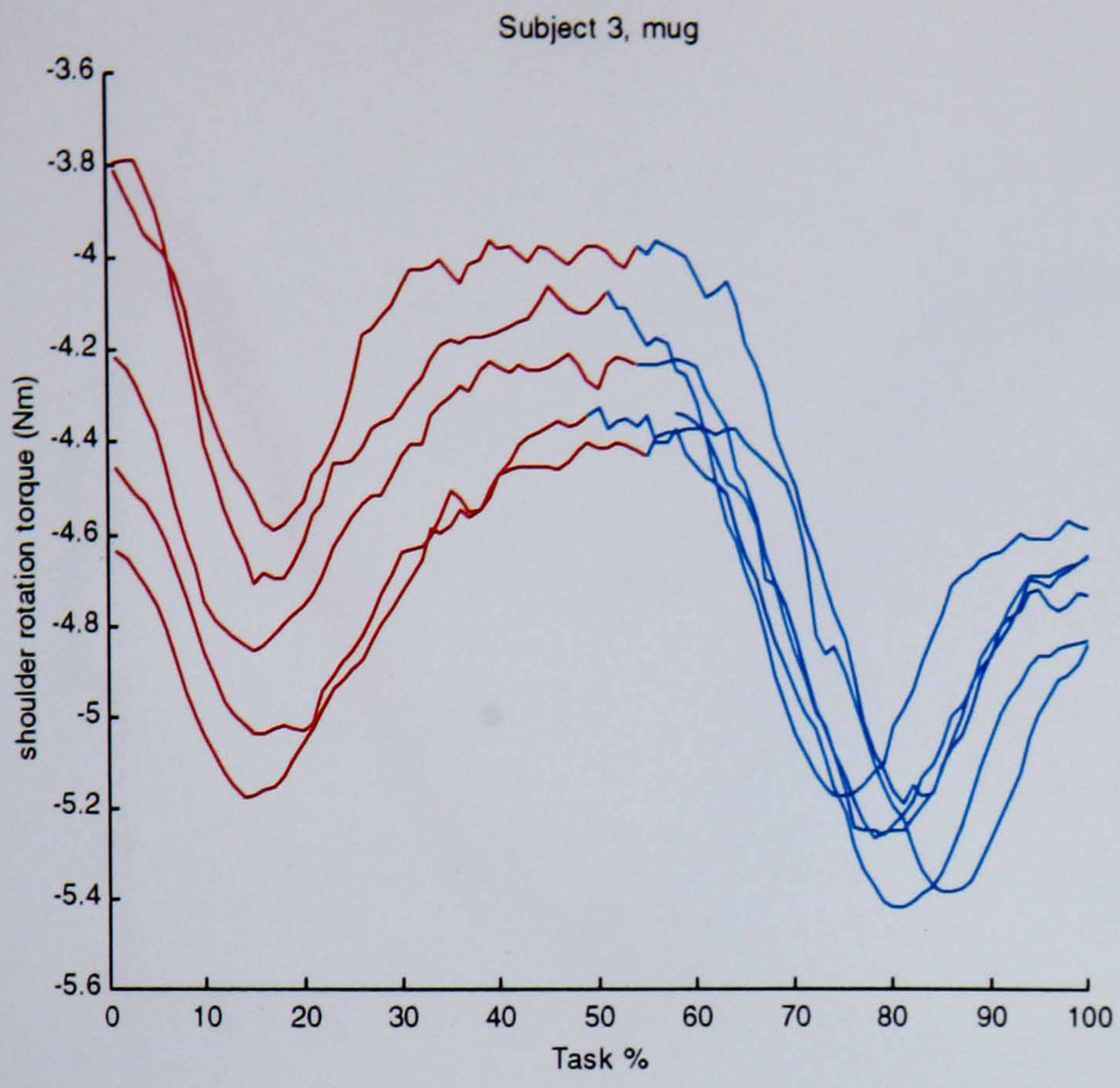


Figure 76: Shoulder rotation torque variation for a single subject/product combination.

Shoulder rotation torque dropped during the first stages of the lifting process and then increased again as the container was brought to the mouth. This effect can probably be attributed to interactions between shoulder elevation, rotation and elbow bend that first brought the centre of mass of the forearm and hand closer to the vertical plane of the upper arm and then moved it further away. This process was reversed during the descent phase of the motion.

3.5.7.6 Elbow torque

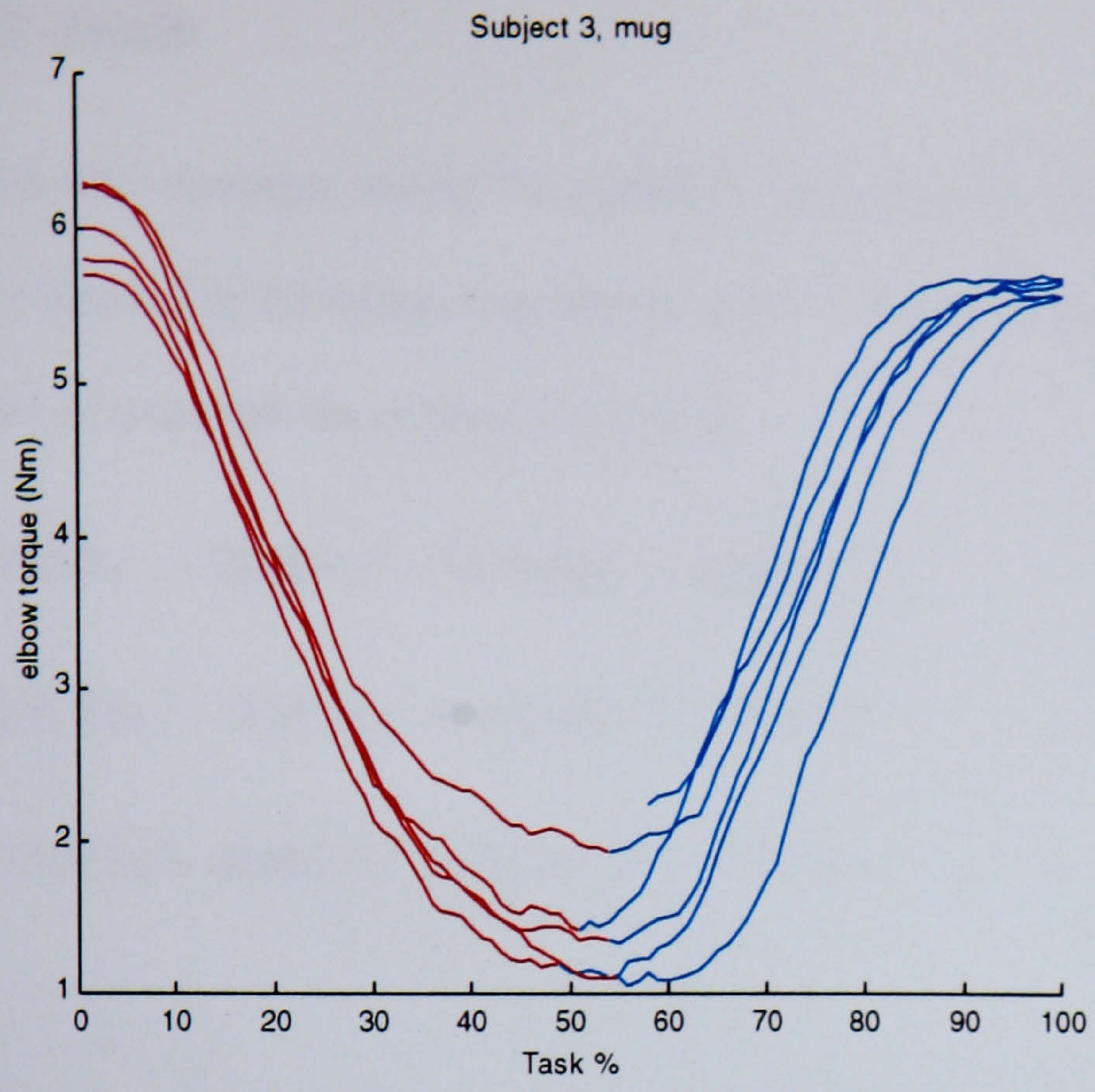


Figure 77: Elbow torque variation for a single subject/product combination.

Elbow torque reduced consistently during the lifting phase as the angle of the forearm approached the vertical.

3.5.8 Polynomial curve fitting

One possible gateway to the further analysis of the limb angle and torque data was considered to be the fitting of some form of curve to the measured values. Initial evaluations were carried out on a single data set using the polynomial curve fitting functions available in the MATLAB system.

3.5.8.1 Data used

Subject 20, was selected for the curve fitting process and object 1, the conventional spoon, was used as the trial object. Torque values were evaluated.

3.5.8.2 Method.

An attempt was made to fit a simple polynomial to the data describing a single task element: the action of lift the vessel, sipping from it and the replacing it the starting position.

Attempts were made to fit 4th, 5th, 6th and 8th order polynomial functions to the data using.

3.5.8.3 Results

For Shoulder elevation torque the equations generated for 4th, 5th and 6th order polynomials are shown below. *T* is the torque experienced and *x* is the time elapse during the task element expressed in 30ths of a second (the reading frequency).

$$T = 0.002x \quad - 0.0029x^2 - 0.2146x^3 + 4.8092x^4$$

$$T = 0.0023x^2 - 0.0612x^3 + 0.4188x^4 + 3.0978x^5$$

$$T = 0.0013x^3 - 0.0421x^4 + 0.2716x^5 + 3.3926x^6$$

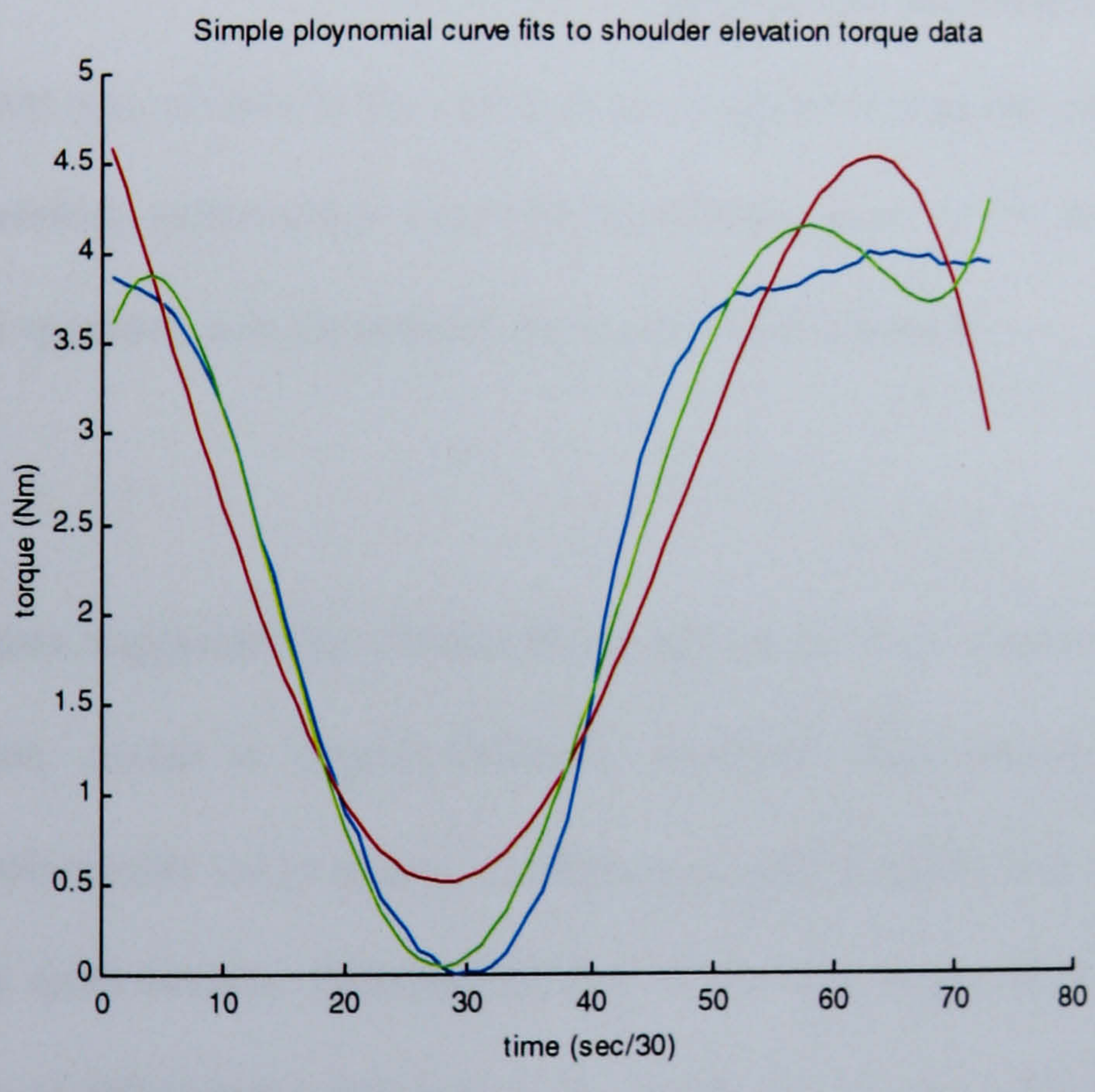


Figure 78: Shoulder elevation torque data (blue), together with 4th order polynomial fit (red) and 6th order polynomial (magenta).

Figure 78 shows the original data plotted along with the 4th and 6th order polynomial fits. By inspection it was judged that the polynomial approach offered a poor fit the collected data. This assumption was checked by plotting the differences between the 6th order polynomial and the original data.

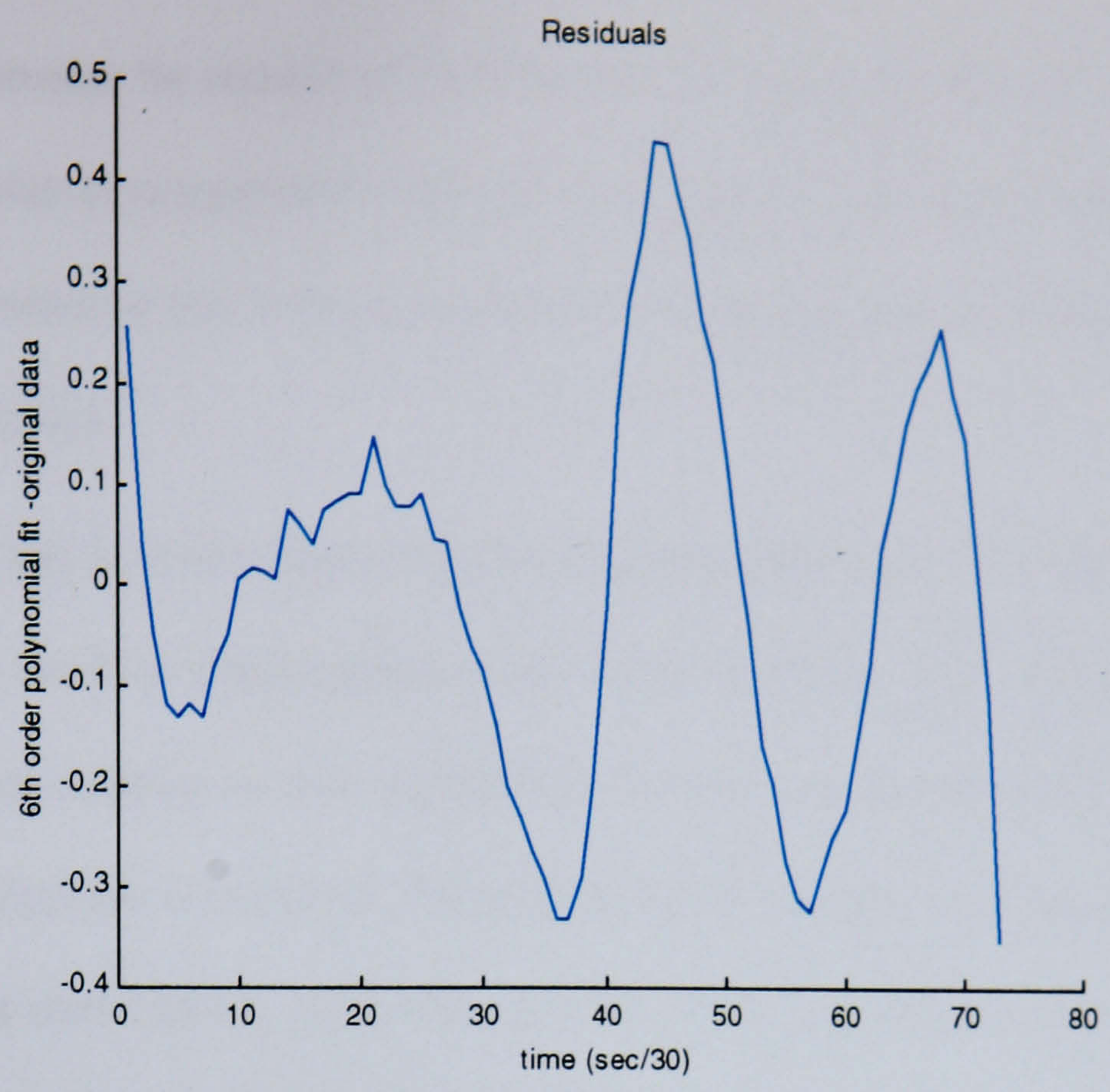


Figure 79: Plot of difference between polynomial data and original values.

The strong pattern that was evident in the residual data suggested that the error occurring was not random and that, therefore, polynomials were not providing a good fit for the torque data. At this point the polynomial approach was abandoned and an alternative sought.

3.5.9 Conclusion

Examination of the data suggested that a better functional model than a polynomial might be found in the form of a sine, cosine or tangent function. However, after consideration of the results obtained from the polynomial curve fitting procedures it was decided that the usefulness of the process was actually quite limited. Parameterisation of the data might be a useful technique for reducing the volume of information that had to be stored and manipulated during the modelling process and might also be helpful in analysis requiring differentiation of the data, when the smoothing process inherent in curve fitting would improve the output of velocity and acceleration information, but the curve coefficients themselves were not considered to be directly useful in the comparison of different tasks, users, or objects which was the overriding goal of the work.

In future work, where it might be useful to have a library of typical motion styles for simulation purposes a parameterised approach would be a flexible and effective way of storing such a library, but such developments lie outside of the scope of this work. It was felt that the used of means, maxima and minima as comparative measures was more effective for the problem under discussion here: the identification of key differences between the biomechanical stresses produced by different product configurations.

Typical of what has now become a widely accepted approach to curve fitting in biomechanical modelling is the work of [McLaughlin et al, 1977] is which cubic spline curves were fitted to biomechanical data relating to limb segment position before time derivatives were taken to obtain velocity and acceleration information. The emergence of numerous computer software packages for data analysis and curve fitting since that time has made the process of curve fitting much more straightforward, whilst advances in CAD modelling techniques has resulted in the availability of more complex curve description techniques.

3.5.9.1 Taguchi analysis

One important part of the Taguchi approach to robust design is the use of *signal to noise ratios*. Taguchi argued that every design had an ideal state that could be measured using some form of *quality metric*, in this work the quality metrics used have typically been torque levels or required ranges of motion. This approach differs in philosophy from other design for quality approaches, which typically impose tolerance limits on a design, and so measure deviations from acceptable rather than ideal performance. He went on to state the cost of deviation from the target state was a quadratic function: twice the deviation from the target would cost four times as much in terms of the probable costs of product malfunction or the requirement for corrective work. Taguchi's measures of quality are thus based on the *mean square deviation from target*. Taguchi went on to refine his measures further by taking logarithms of quality measures. This has the effect of compressing widely varying data into a form that can be rapidly assessed. If one is comparing a range of products, for example, the same graph of quality functions can show the entire range of product performance from the best to the very worst, while still allowing slight differences between the performance of the best designs to be identified.

An important factor in the application of Taguchi methods is the identification of the target values. In the work covered here the chief concern is to minimise stress. This implies an ideal, but unachievable value of zero for the quality functions, and encourages the use of what is known as the *smaller-the-better* signal to noise ratio (S/N-STB).

Figure 80 shows the equation used to calculate the S/N-STB. In the equation y_i is the quality value obtained in each of i=1...n experimental runs. The -10 multiplier is designed to scale the data and to ensure that a larger value represents a better condition, thus making the approach psychologically more appealing.

$$S / N_{STB} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right]$$

Figure 80: The "smaller-the-better" signal to noise ratio

The S/N-STB was calculated for the mean and maximum torque measures used in the previous experiments. The results for the spoons are shown graphically in Figure 81 and Figure 82 and for the mugs in Figure 83 and Figure 84.

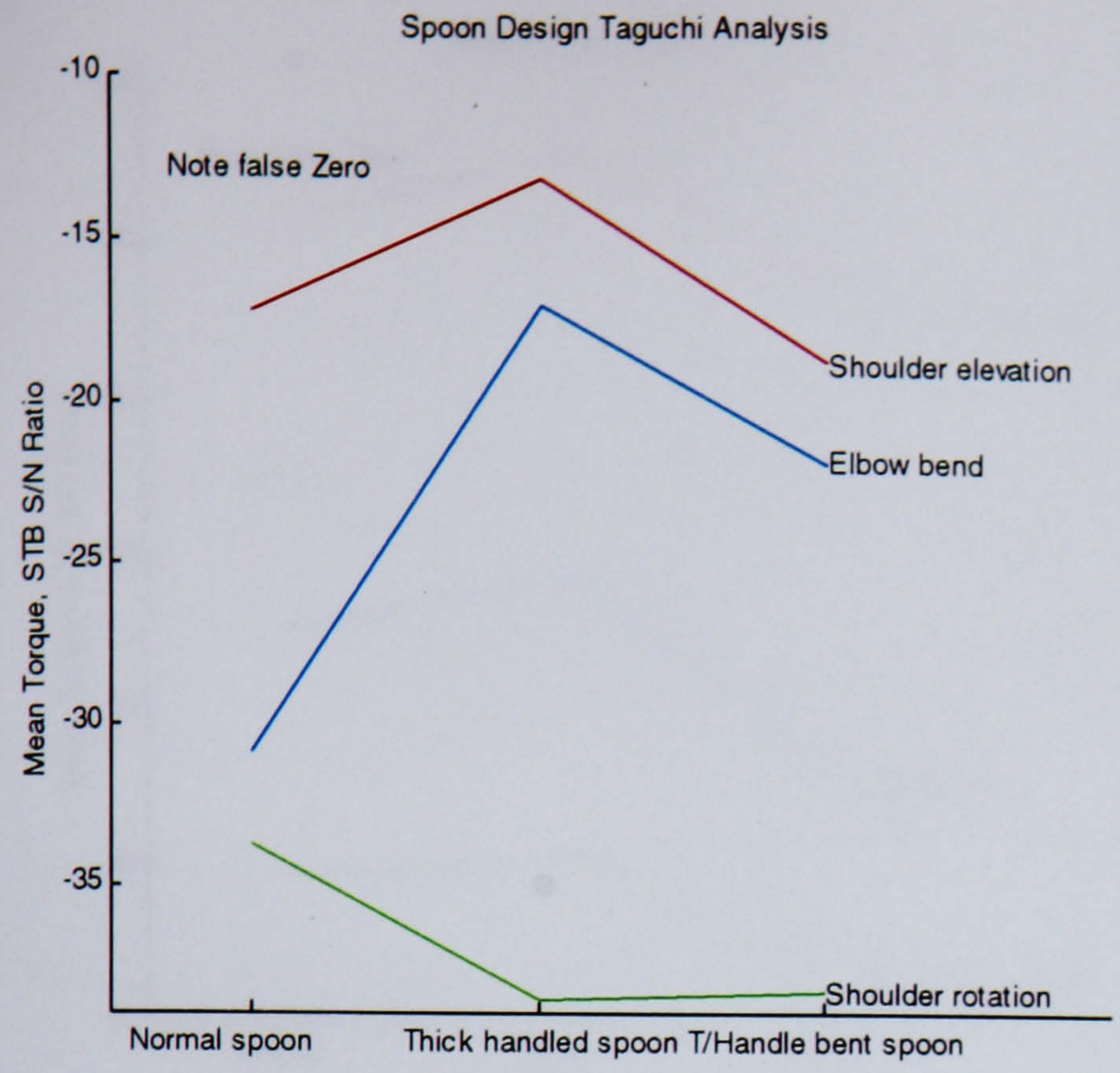


Figure 81: S/N-STB values for the spoons using mean torque as the quality measure.

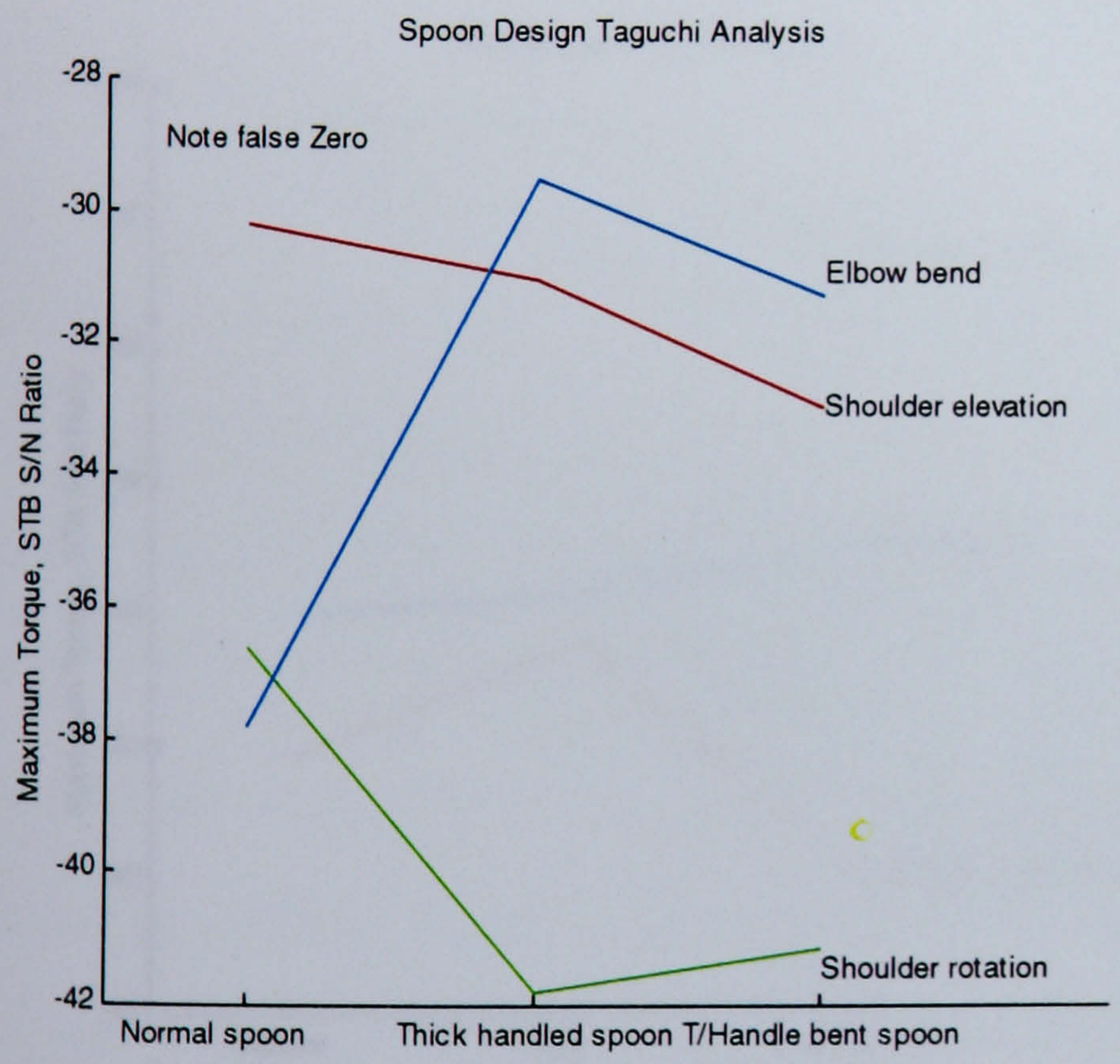


Figure 82: S/N-STB values for the spoons using maximum torque as the quality measure.

The normal spoon offered the least humeral rotation torque, but more elbow bend torque than either of the thick handled spoons, and a poorer maximum shoulder elevation value than either of the thick handled spoons. The thick handled spoon showed the best performance in both mean elbow bend and shoulder elevation torque categories,

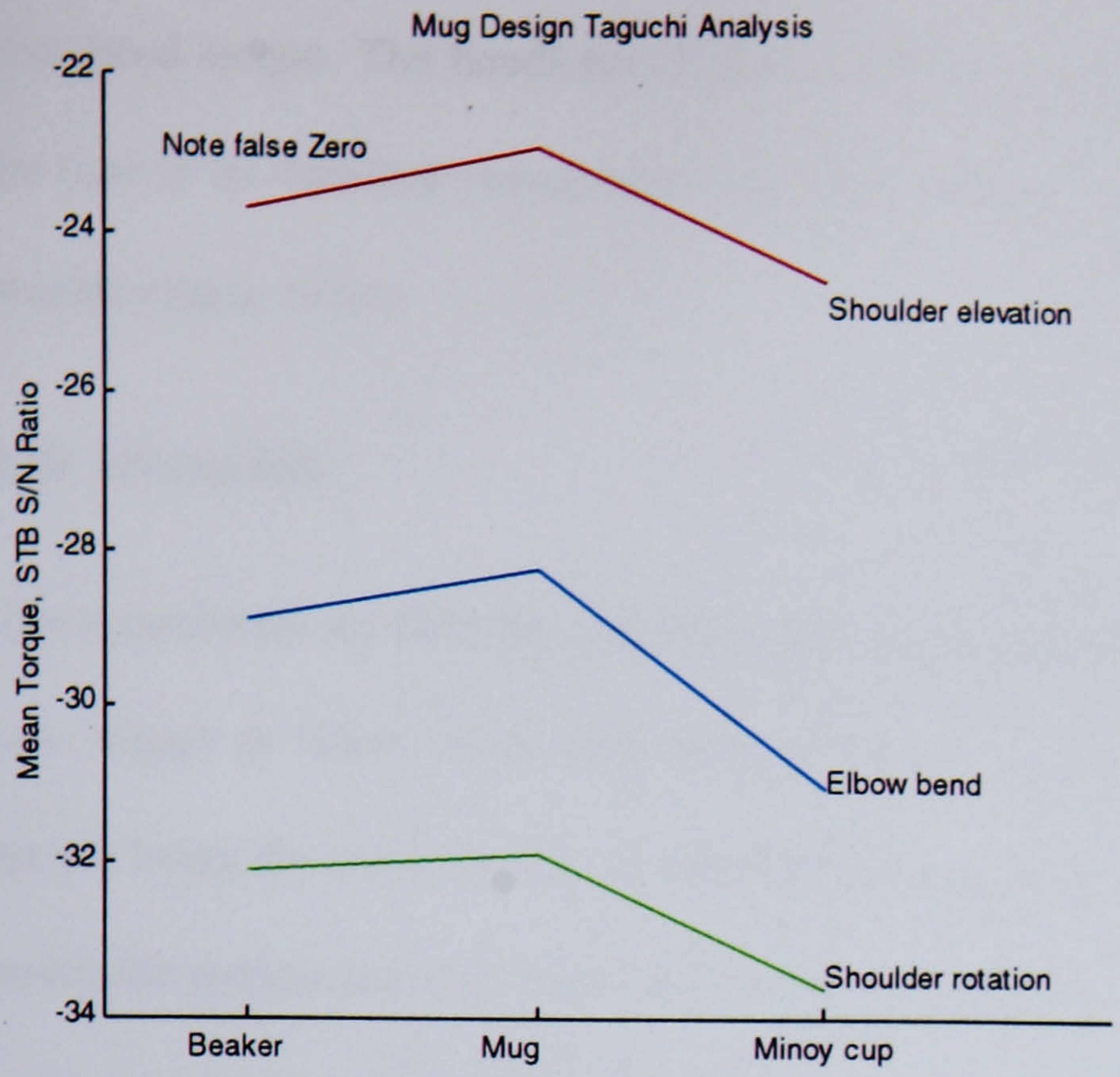


Figure 83: S/N-STB values for the mugs using mean torque as the quality measure.

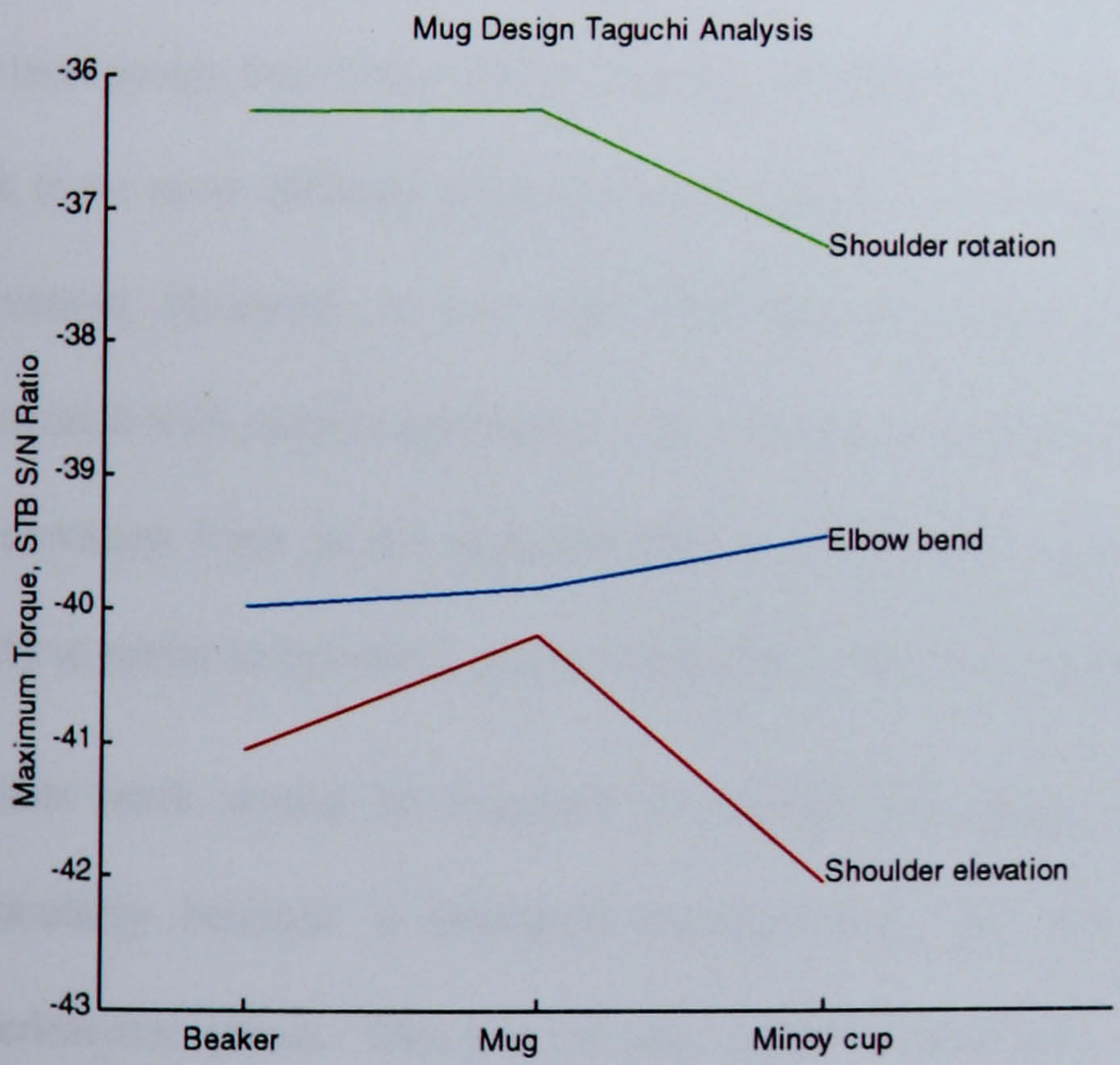


Figure 84: S/N-STB values for the mugs using maximum torque as the quality measure.

Performance differences between the mug categories were much smaller than were those between the spoons. The mug with the side-positioned handle exhibited better performance in all the mean torque categories, and in all the maximum torque categories with the exception of elbow bend. The Minoy cup exhibited the poorest performance in all categories with the exception of maximum elbow bend torque. The handleless beaker exhibited performance that was virtually indiscernible from that of its handled counterpart with the exception of noticeably higher maximum shoulder elevation torque values.

3.5.10 Discussion

In this experiment six different products were compared, three drinking vessels and three types of spoon. Signal to Noise ratios were used as a rapid quality evaluation measure, with the quality objective being the minimisation of individual joint torques. The results indicated clear differences between the spoons, but only small differences between the mugs.

Interestingly, the two thick handled spoons demonstrated higher scores in all mean torque measures except shoulder rotation, but qualitative assessments by subjects rated spoons of this design well below the normal spoon in terms of ease of use. This may be put down to unfamiliarity on behalf of the user group, but it may also be true the subjects found the fine movements required in a spooning task to be more difficult when the hand adopts a power grip and manipulation with the fingers is prevented. However, it was also clear that the minimisation of shoulder rotation torque was associated with subject preference. This finding makes anatomical sense since it is easier to provide an elevation force at the shoulder than a longitudinal rotation force, therefore subjects would be likely to prefer to operate a product that allows forces to applied in the former manner.

Further work would be required to confirm this result but it is a highly appealing finding, particularly because it emerged strongly from the simple analysis carried out during this experimental phase. The use of the Taguchi approach is a highly promising technique for information extraction in this context. The key advantage of the method being that it generates very simple results, the thousands of data points collected during the experimental process were reduced to only six for each product under analysis. Data reduction of this nature can be considered to one of the overriding aims of this work.

3.6 Product design experiment

3.6.1 Context

The previous experiments had provided some quite revealing insights into the way subjects interact with real products. The next stage was to apply the techniques used already, along with some new ones, in a pre-design context and to attempt to gain useful information that could aid designers in the selection of optimum interface parameters.

3.6.2 Aims and objectives

Section 3.5 describes the application of the task analysis and modelling process to commercial products, and demonstrated that it was possible to gain useful information on the way different designs are used. This type of evaluation has extensive potential in circumstances where a choice has to be made between a number of competing design options. However, during the design of a product, the problem of interface optimisation is unlikely to be one of simply choosing between two or three possible designs. It is likely that there will be a large number of interface parameters to consider, and that it will be possible to adopt different combinations of these parameters in a manner that effectively generates large numbers of different designs. The number of possible designs will rise geometrically with the number of interface parameters being examined and it therefore becomes highly undesirable to have to carry out a lengthy analysis process with every available possibility. This experiment was intended to explore efficient ways of evaluating a large interface design space, using the minimum possible number of experimental runs to obtain the maximum possible amount of useful information on the product's characteristics. This approach is an extension of the overall philosophy of maximising useful information reaped from an investment of effort in the interface evaluation process.

The key differences in method between this work and that of the previous section are:

1. Multiple factors were evaluated simultaneously.

2. Partial factorial experimental design was used to minimise the number of necessary experimental runs.

3. The subject group was deliberately selected to offer a large range of user variability from a small sample group.

The experiment was designed to simulate the sort of process a real design team might go through if they were to apply the techniques discussed in this work.

The experiment took place in two distinct phases:

1. An evaluation of the relative effect sizes of the design variables and uncontrollable user variability.

2. An experiment to select the optimum levels of design variables.

In the language of Robust Design these phases would be known as the *noise factor experiment* and the *parameter optimisation experiment* respectively [Fowlkes and Creveling, 1995].

3.6.3 Background

[Hsiang et al, 1997] applied Taguchi methods directly to an industrial design context using a variety of different parameters to optimise the design of a knife for use in repetitive cutting tasks. The quality response chosen by the group to measure knife performance was speed of task execution, which is straightforward to measure but issues of usage comfort were only tackled using psychophysical methods: subjects were asked to operate the knife "without causing any discomfort". This focus in the measurement of task quality does not put the same emphasis on injury potential or usage discomfort, as does the present work. Interestingly the authors chose to treat increased variation in cutting speed during the experiment as an indicator of potentially increased risk of injury, since the variation in the task would be caused by pauses, or moments of difficulty during the cutting process.

[Imrhan and Jenkins, 1990] carried out a study on maximum available wrist twisting torques. Subjects were asked to rotate a number of instrumented handles with their arms held in different positions. The study revealed that maximum available wrist torque was not altered by arm position. However, no attempt was made to model torque in other limb joints or estimate efficiency or comfort for the motions tested.

3.6.4 The product

The first stage in the experimental design was to select a product for evaluation. To ensure that the product selected was likely to respond well to the proposed analysis a number of factors needed to be considered:

1. The product must involve large upper limb movements, and relatively high loads
2. It must be possible to alter a number of design variables, all of which would be expected to have an effect on biomechanical parameters.
3. It must be possible to build a physical model of the product upon which the design variables under examination can be altered.

After careful consideration of these requirements a product was selected. Since only the interface parameters are of interest in the current work, the product chosen was a simplified interface representation of **any hypothetical device that required a lever to apply a certain force**. Some design examples of such a product might be:

1. A bottle opener
2. An aluminium can crusher to assist domestic recycling.
3. A hole punch or heavy duty stapler
4. An embossing device
5. A guillotine or wire cutter
6. A one-armed bandit gaming machine
7. A door opening device
8. A beer pump.

3.6.5 Design variables

Five design variables were selected for analysis. To improve the robustness of the analysis it was decided to evaluate each factor at only two different levels [Pignatiello and Ramberg, 1991] The factors chosen and their selected levels are described below:

3.6.5.1 Lever axis

The lever axis could lie in any direction. For design concept evaluation the choice of axes was restricted to the global x, y or z directions, as shown in Figure 85. These axes represent the three "most different" possible axis configurations, although it would be quite possible to evaluate intermediate axis positions, should the direction of the axis prove to be a major design factor.

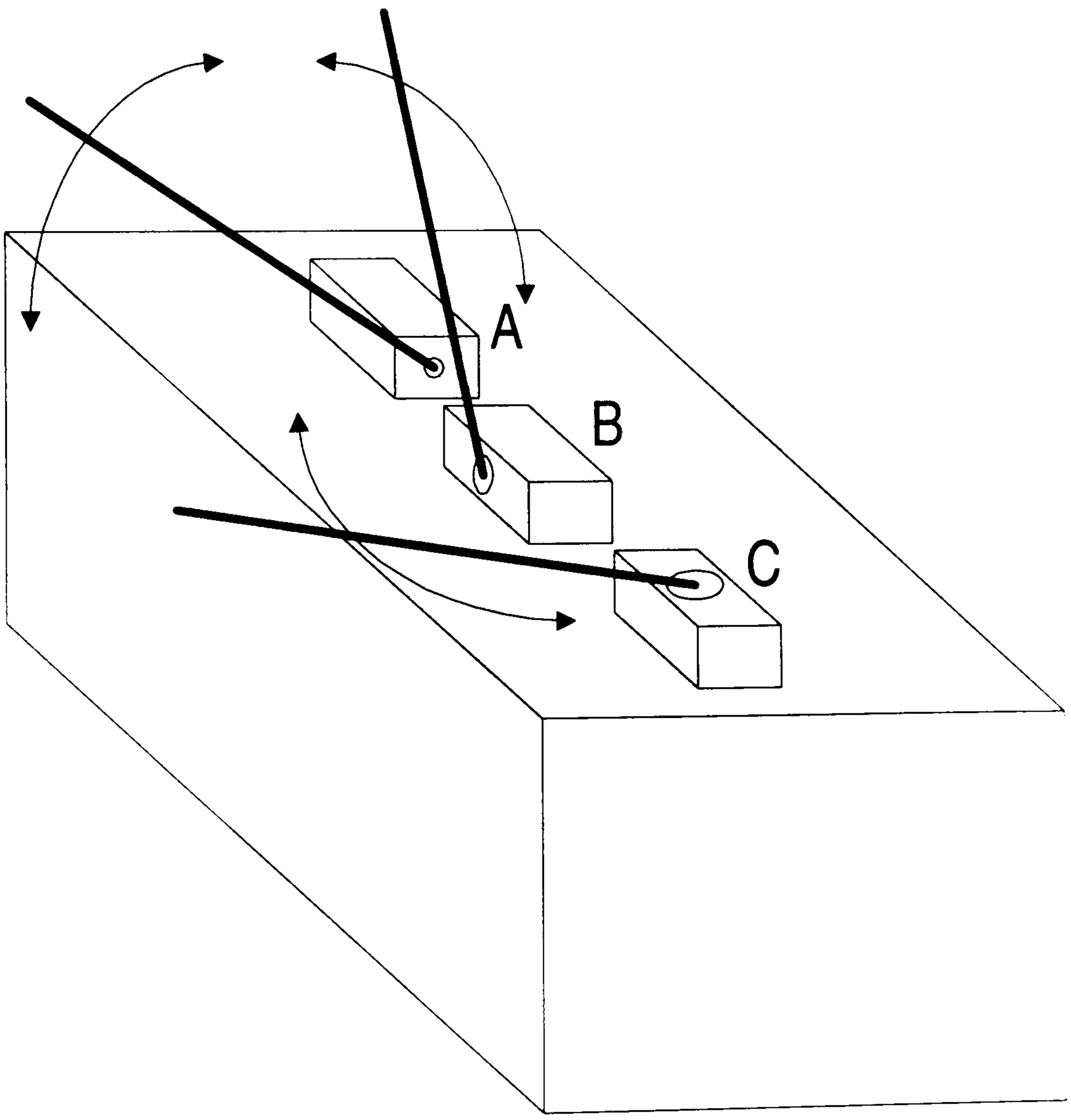


Figure 85: Three possible lever axes.

Of these three options C. was rejected, as it would entail the user loosing the advantage of gravitational assistance. The selected levels were therefore:

1. Lever axis in the sagittal plane, lever motion occurring in the frontal plane. (Lever transverse)

2. Lever axis in the frontal plane, lever motion occurring in the sagittal plane. (Lever sagittal)

3.6.5.2 Handle configuration

The design of the handle will influence the orientation of the hand and wrist, and therefore, as has been observed in previous experiments, would also affect the position of the elbow and the orientation of the shoulder. It would be quite possible to select a handle that would allow users considerable freedom to orient their hands as they felt fit; for example a spherical handle might offer this facility. Whilst there were strong arguments from the perspective of universal design and the facilitation of compensatory behaviours to adopt such a design, it was valuable to evaluate the effects of a more highly constrained hand position. Figure 86 shows a number of possible handle configurations.

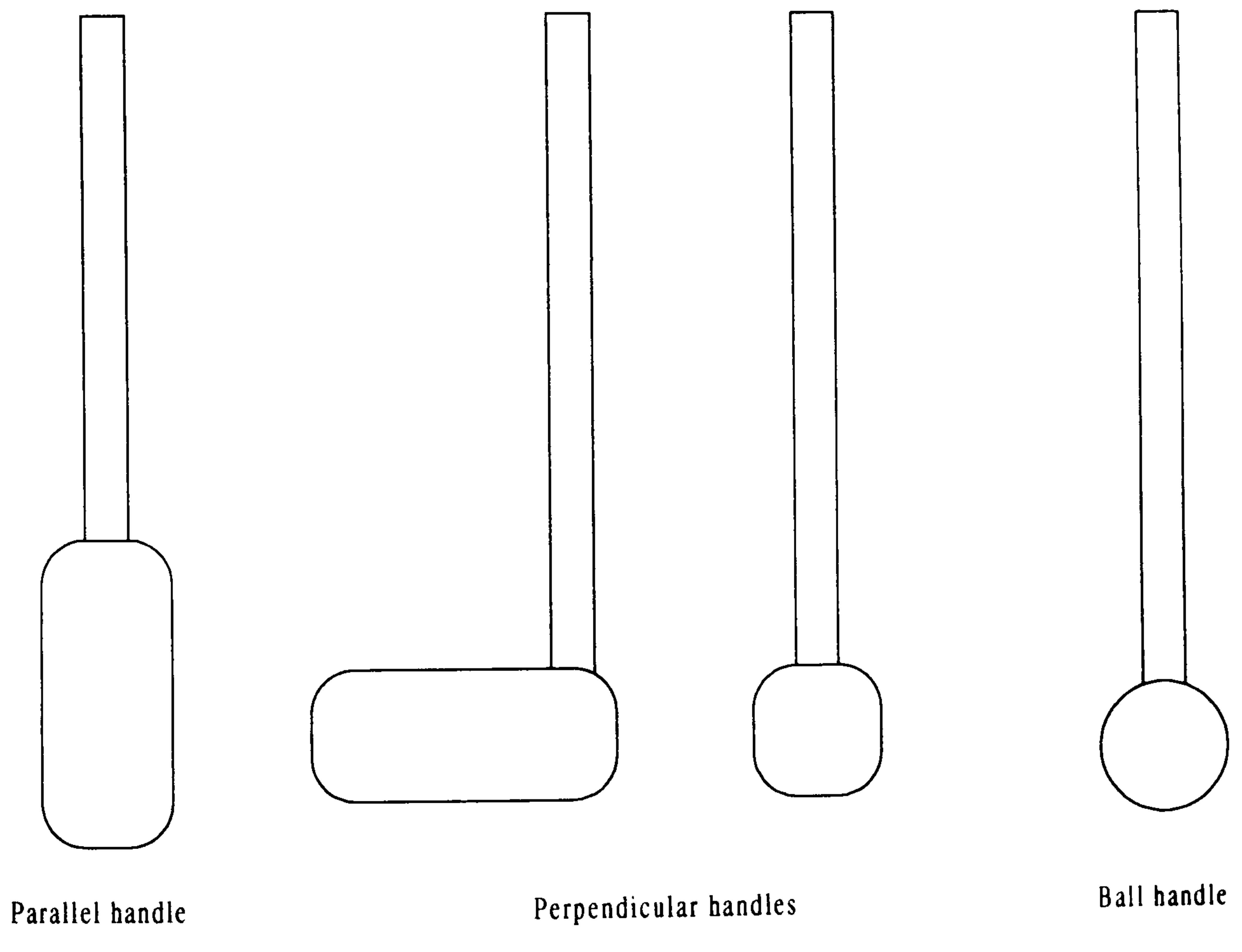


Figure 86: Possible handle configurations.

Care had to be taken to ensure that the handle orientation was expressed in terms of its angle relative to the user rather than relative to the lever arm. This would minimise the interaction between the choice of lever axis and the orientation of the handle. Therefore the following handle orientations were selected (handle directions were defined with the lever arm itself in a horizontal position):

1. Handle in a vertical position.

2. Handle in a horizontal position in the frontal plane. This meant that with the lever moving in the sagittal plane the handle would be perpendicular to it, but with the lever moving in the frontal plane handle and lever would be parallel.

3.6.5.3 Axis height

It was assumed that the product would normally be operated at work-surface height, and that there would be a requirement to minimise its overall size. However, even within a design envelope of some 300mm vertically there was considerable choice available as to the positioning of the lever axis. Two axis heights were selected for evaluation:

1. A low position, 135mm above the work surface plane.

2. A high position, 235mm above the work surface plane.

3.6.5.4 Lever length

Lever length was expected to have a strong effect on biomechanical parameters. If a constant torque was assumed, then variations in lever length effected a trade off between high torque and small displacement of the limb and low torque combined with large limb displacement. The two lever lengths chosen for analysis were:

1. A short length of 160mm.

2. A long length of 260mm.

3.6.5.5 Position of maximum mechanical advantage.

Assuming a gravitationally assisted lever action, the maximum mechanical advantage would occur when the lever passed through the horizontal. It was possible that the point at which this occurred during the task would have an effect on the limb loadings. It was decided to evaluate lever action through a 45° arc with the horizontal lever position occurring either at the beginning or at the end of the motion.

In practice, all subjects were asked to move the lever through a 90° arc and their recorded motion data were separated at the lever's horizontal point to produce data sets for the two possible levels. This factor was expected to interact quite strongly with axis height, since both had an effect on the vertical position of the handle. The selected levels were:

1. Lever horizontal at the start of the task.

2. Lever horizontal at the end of the task.

3.6.6 Design of apparatus

With the design variables selected, a suitable apparatus had to be built that allowed all the variables to be rapidly and conveniently altered during the experimental process. In order to minimise the risk of magnetic field distortion by metallic objects the apparatus was constructed using medium density fibre board and softwood dowel. Figure 87, Figure 88 and Figure 89 are dimensioned drawings of the apparatus, while Figure 90 and Figure 91 show the completed device in various configurations

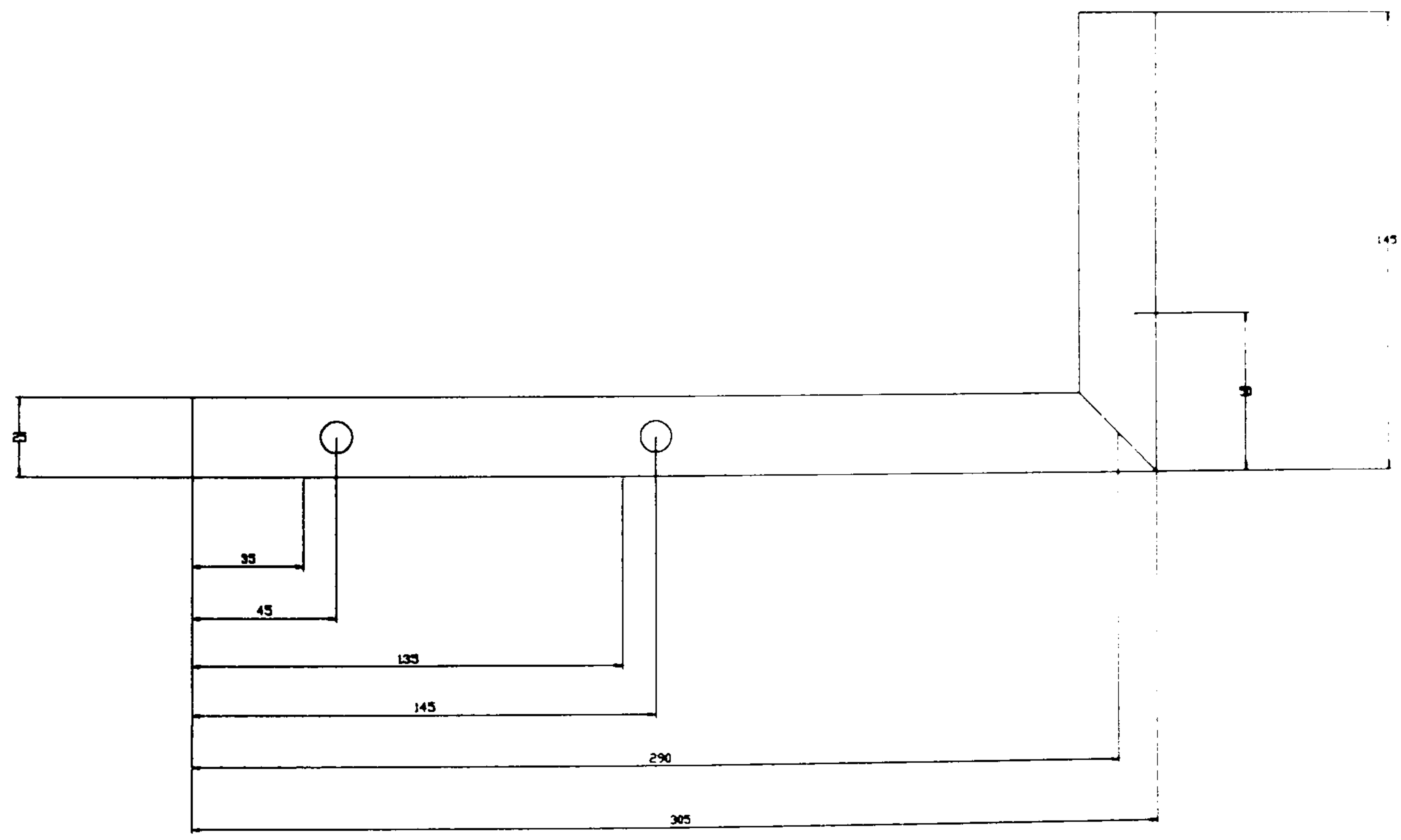


Figure 87: The lever

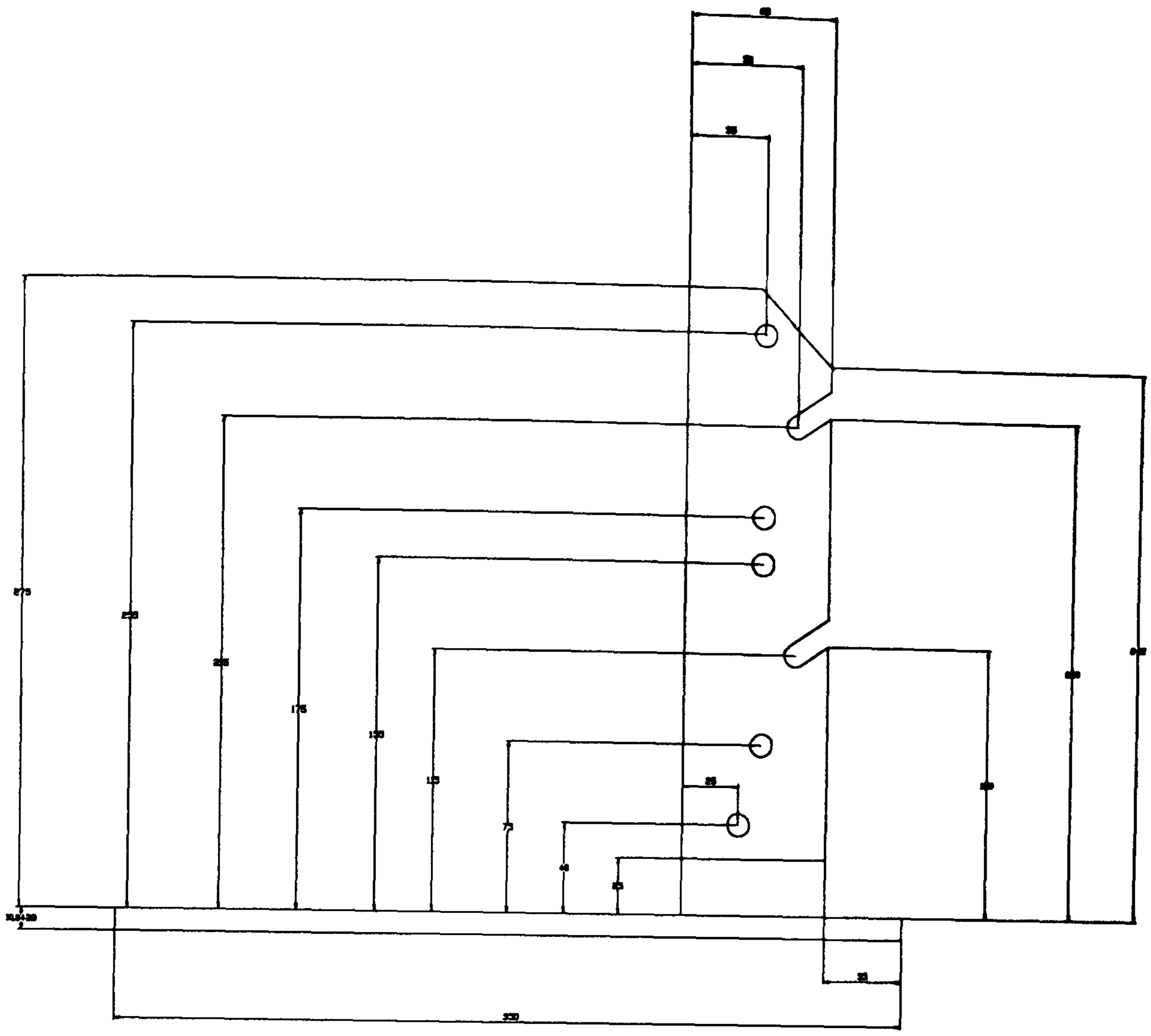


Figure 88: Side view of the lever apparatus.

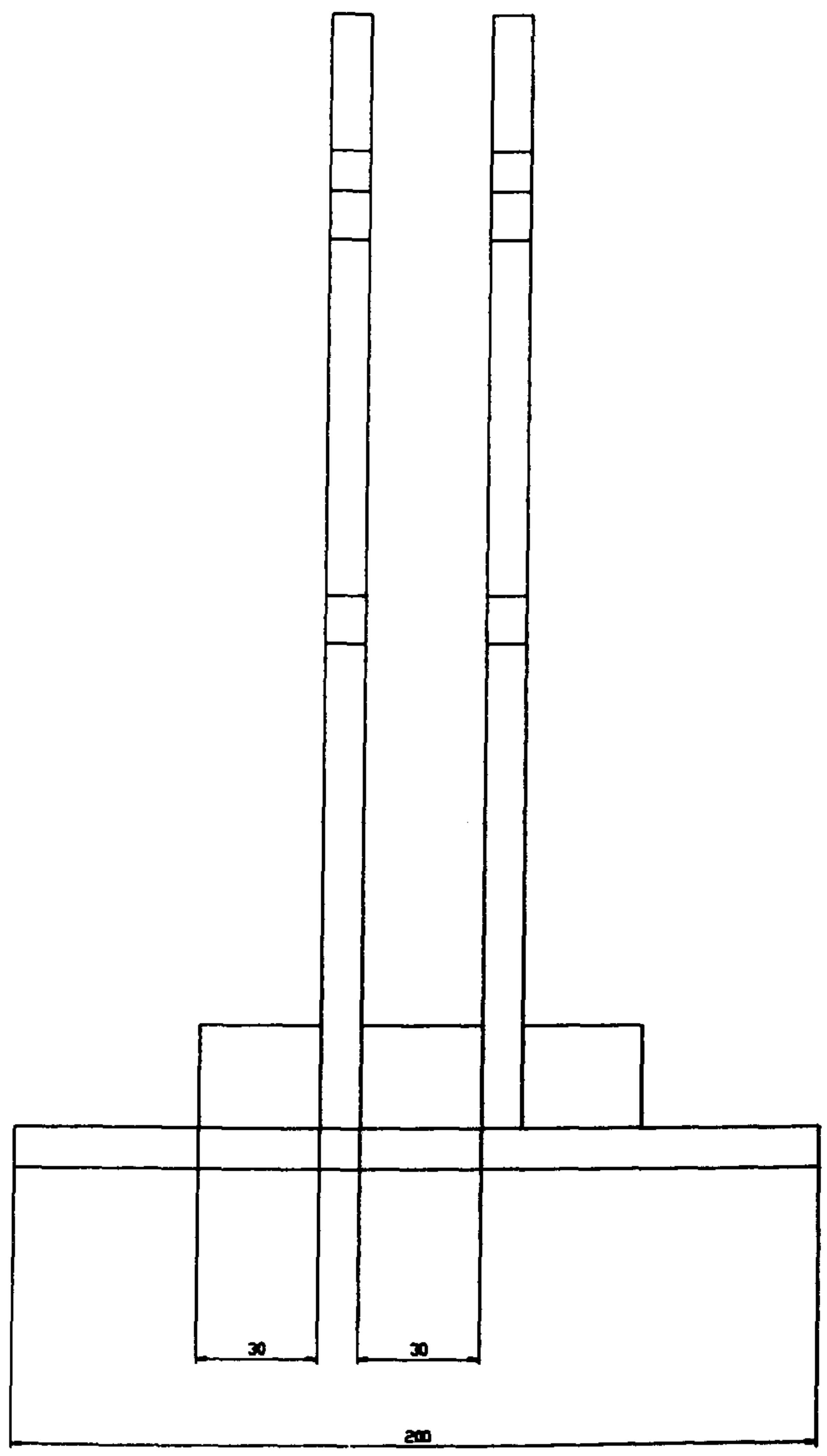


Figure 89: Front view of the lever apparatus.

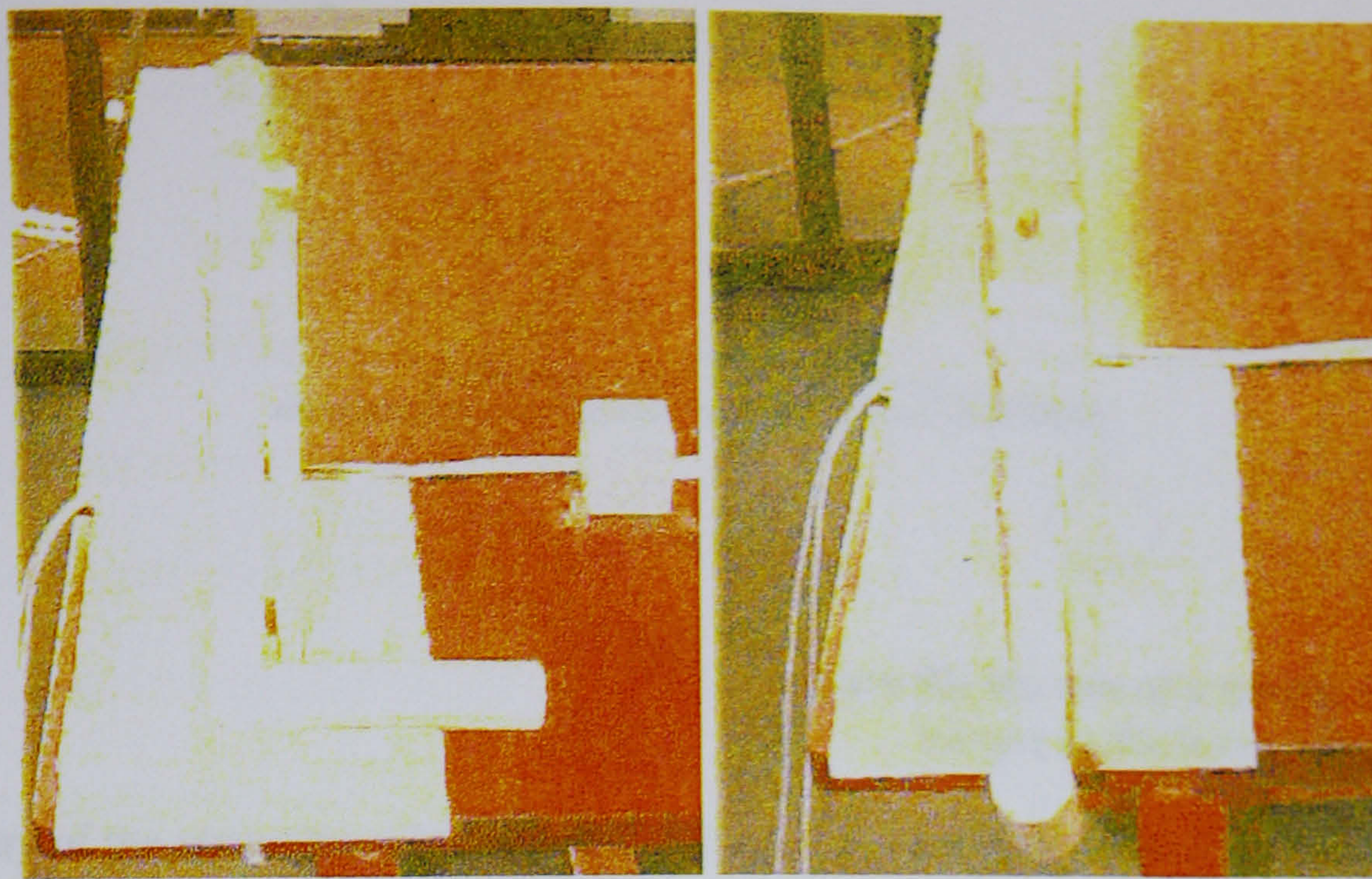


Figure 90: Views of the lever apparatus with the handles in different orientations.

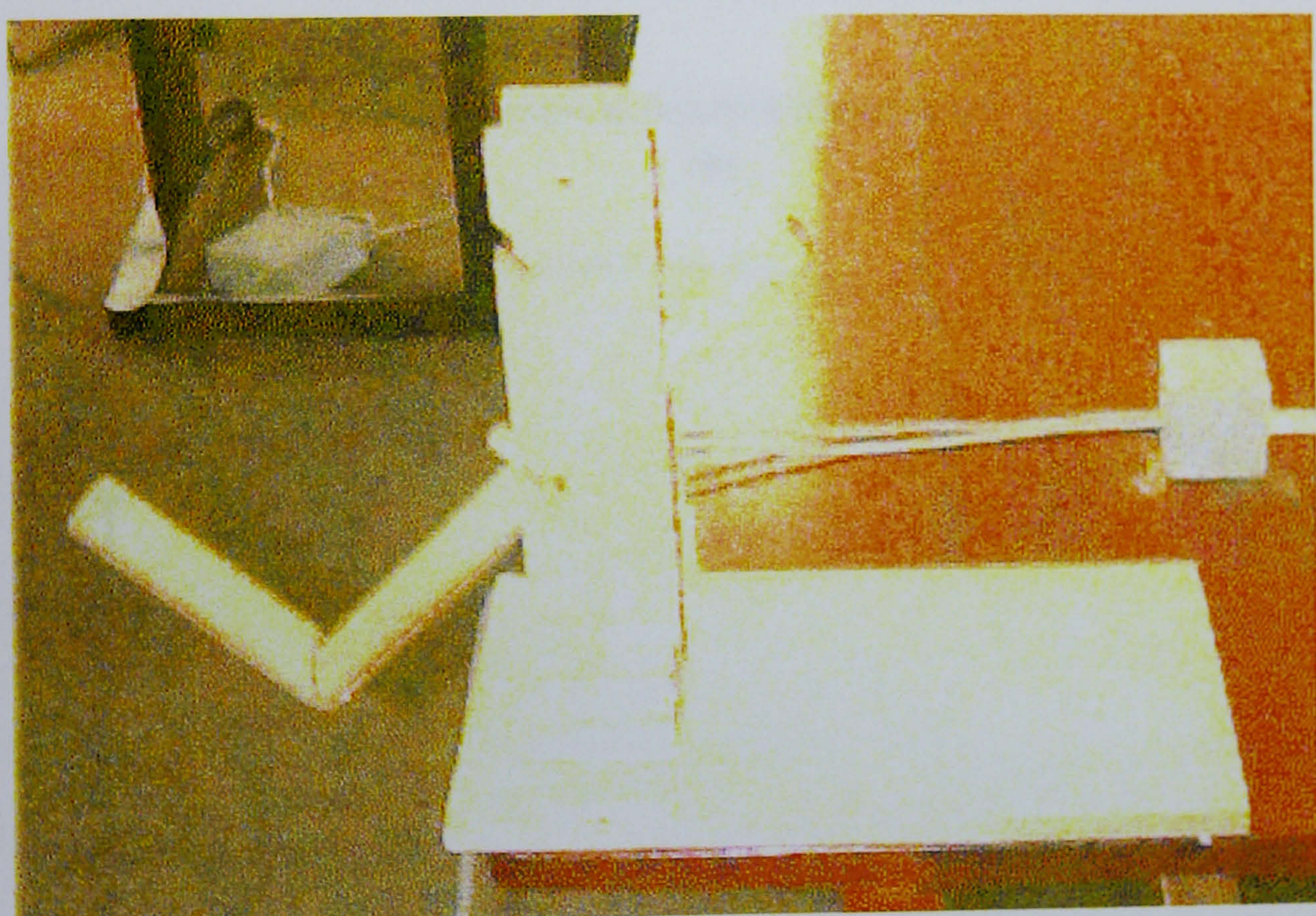


Figure 91: Side view of the lever apparatus with the handle vertical and the lever in its low axis, short position.

In use, a constant torque was introduced at the lever by suspending a weight on a length of polypropylene cord over the edge of the work surface. The weight acted to produce a torque in an upward direction at the handle, as shown in Figure 92.

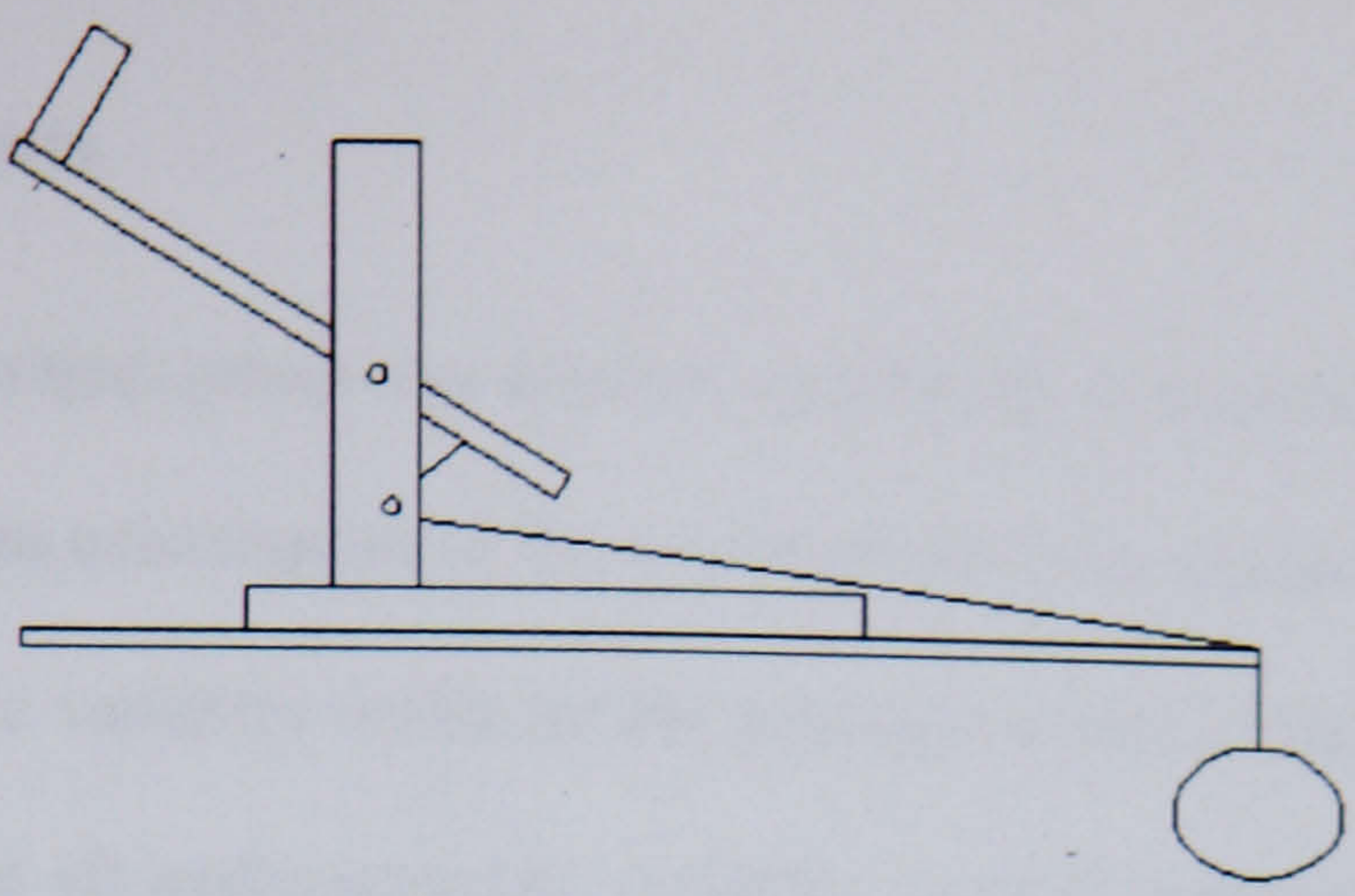


Figure 92: the use of a weight to generate torque at the lever handle.

The geometry of the apparatus was such that the load was not applied in a constant perpendicular direction relative to the lever and thus the torque applied to the lever would vary by some degree as the lever moved. The variation in effective lever arm is shown in Figure 93.

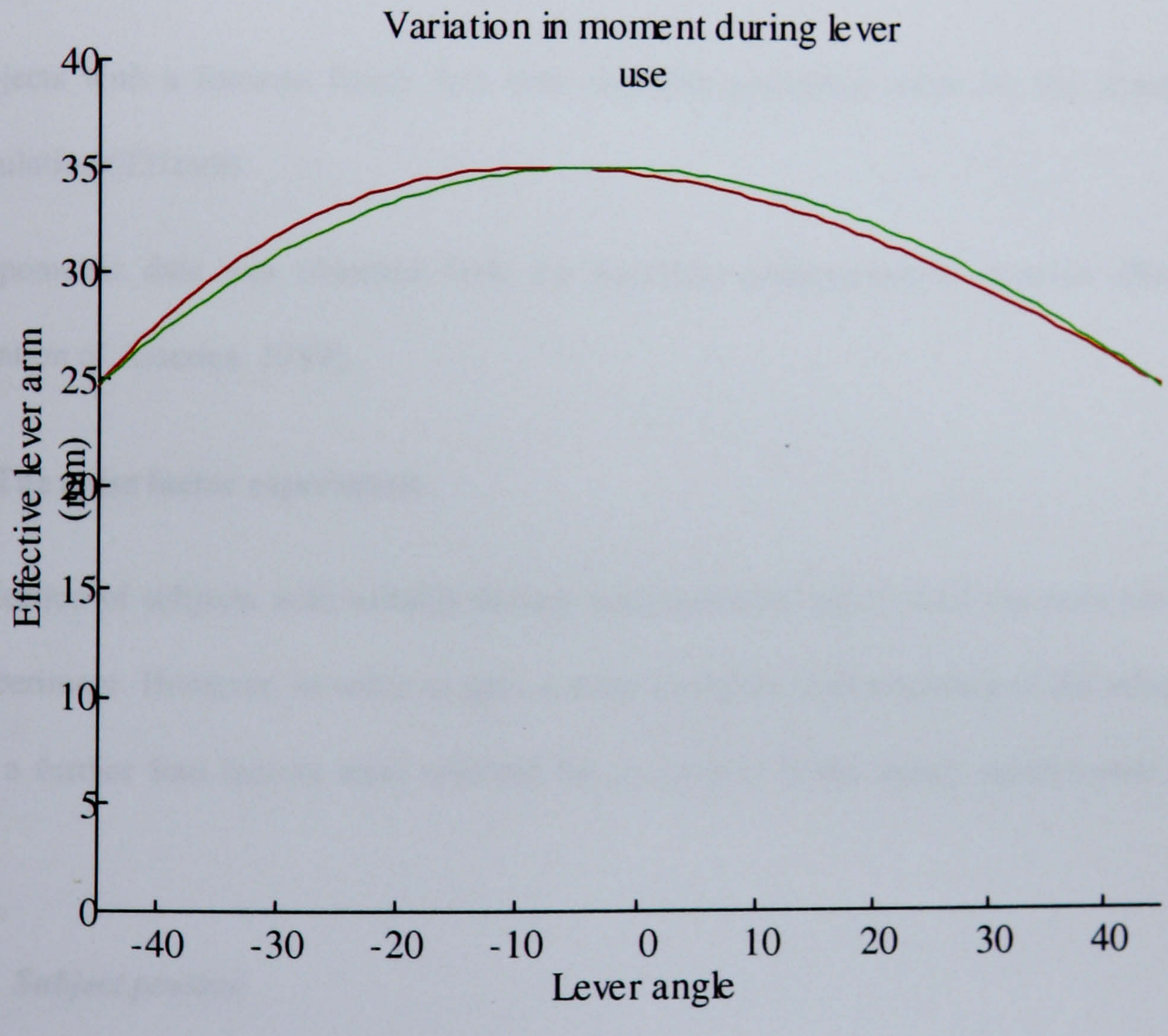


Figure 93: Variation in effective lever arm during movement. The red line indicates values for the lever in its low position. The green line indicates values for the lever in its high position.

This variation was accounted for in the calculation of lever torque as discussed in Section 3.6.11.

3.6.7 Selection of subjects.

In this experiment, the subject group was selected specifically to maximise result variability from a small subject group. From examination of the results of previous experiments, the assumption was made that anthropometric variables would be the principal source of inter-subject variation, and it was further assumed that all anthropometric variables could be assessed by pooling subjects into two basic groups. To do this, forearm length was used as the deciding variable. This value was chosen as it is a directly measurable factor that is closely correlated to the overall size and mass of all upper limb segments. The groups were therefore:

1. Subjects with a forearm length greater than the 75th percentile value for the standard British population (262mm)
2. Subjects with a forearm length less than the 25th percentile value for the standard British population (231mm)

Anthropometric data was obtained from the Ergobase anthropometric database [Biomechanics Corporation of America, 1989].

3.6.8 The noise factor experiment

The selection of subjects with suitably diverse anthropometry represented the main noise factor in this experiment. However, in order to gain a more complete understanding of the effects of noise factors a further four factors were selected for evaluation in the initial experimental run. These were:

3.6.8.1 Subject posture

Subjects were evaluated in two basic postures:

1. Standing
2. Seated.

This was a further attempt to examine the effect of restricting body position on overall task measures, as discussed in Section 3.3.14.

3.6.8.2 Distance from lever

The distance a subject positioned themselves from the lever would be likely to have a strong effect on the position of their arm during the task. In order to try and separate the effect of distance from anthropometric variables, the starting distance was defined in terms of the position of the subject's arm at the beginning of the task, when the hand was placed on the lever handle. The positions were:

1. Elbow fully extended.

2. Elbow flexed at 90°.

3.6.8.3 Wrist restriction

The wrist splint that has been used in earlier trials was reintroduced as a further noise factor, the factor levels were:

1. No restriction of wrist motion

2. Wrist held by splint.

3.6.8.4 Load

The torque that would have to be overcome in order to move the lever might be a design variable or a noise variable depending on the specific product application. It was introduced into the noise factor experiment as a further variable. The factors were:

1. A load of 2Kg, generating a torque range from 1.0 to 1.4Nm at the lever

2. A load of 4Kg, generating a torque of 2.0 to 2.8Nm at the lever

3.6.9 Noise experiment array design

The initial noise factor experiment was designed to assess all the factors listed above in the smallest possible number of experimental runs. An orthogonal array was used to carry out this process. The array chosen was the L12 Array. This array allows the evaluation of eleven factors in twelve experiments, with two levels being tested for each factor. The array design is shown in Figure 94. Only ten factors were analysed in this experiment, the eleventh column was left blank, allowing its use as an estimate of residual variation if required. Each experimental condition was repeated five times by each subject, so the collected data had a total of 59 degrees of freedom. This facilitated the use of the redundant degrees of freedom as an alternative measure of residual.

Expt.	Factor										
	1	2	3	4	5	6	7	8	9	10	11
1	Sub 1	No Splint	Standing	Close	Lever T'verse	Heavy	Handle VERT	Axis Low	Lever Short	Mech Adv. Start	1
2	Sub 1	No Splint	Standing	Close	Lever T'verse	Light	Handle HORIZ	Axis High	Lever Long	Mech Adv. End	2
3	Sub 1	No Splint	Seated	Far	Lever Sagit.	Heavy	Handle VERT	Axis Low	Lever Long	Mech Adv. End	2
4	Sub 1	Splint	Standing	Far	Lever Sagit.	Heavy	Handle HORIZ	Axis High	Lever Short	Mech Adv. Start	2
5	Sub 1	Splint	Seated	Close	Lever Sagit.	Light	Handle VERT	Axis High	Lever Short	Mech Adv. End	1
6	Sub 1	Splint	Seated	Far	Lever T'verse	Light	Handle HORIZ	Axis Low	Lever Long	Mech Adv. Start	1
7	Sub 2	No Splint	Seated	Far	Lever T'verse	Heavy	Handle HORIZ	Axis High	Lever Short	Mech Adv. End	1
8	Sub 2	No Splint	Seated	Close	Lever Sagit.	Light	Handle HORIZ	Axis Low	Lever Short	Mech Adv. Start	2
9	Sub 2	No Splint	Standing	Far	Lever Sagit.	Light	Handle VERT	Axis High	Lever Long	Mech Adv. Start	1
10	Sub 2	Splint	Seated	Close	Lever T'verse	Heavy	Handle VERT	Axis High	Lever Long	Mech Adv. Start	2
11	Sub 2	Splint	Standing	Far	Lever T'verse	Light	Handle VERT	Axis Low	Lever Short	Mech Adv. End	2
12	Sub 2	Splint	Standing	Close	Lever Sagit.	Heavy	Handle HORIZ	Axis Low	Lever Long	Mech Adv. End	1

Figure 94: The L12 Array used for the product design noise factor experiment.

3.6.10 Method

Anthropometric measurements were collected from subjects in the same manner as the previous experiments. Sensors were fitted and the subjects were given the following instructions:

This experiment is designed to analyse the movement of your arm as you operate a simple lever. The measurements will be made using an electromagnetic tracking device. The device consists of two sensors which will be strapped to your upper arm and to your wrist. Once the experimenter has fitted the sensors to your arm a short calibration procedure will be performed. Your movements will then be measured with the lever arranged in **8** slightly different configurations. Once the lever has been configured you should grasp it in the manner indicated to you by the experimenter and, when instructed to do so, you should pull the lever down to its fullest extent and then raise it again **5** times.

The collected data was saved to disc.

3.6.11 Data manipulation

As in previous work, the recursive Newton Euler method was used to obtain torque values at each joint in the model. The first and second differentials of joint position were set to zero to provide a quasi-static estimate of torque values, and the values for limb segment length, mass and centre of gravity were obtained by the methods described previously.

An important difference in this experiment was that the lever provided an external load that worked against gravity, tending to push the end-effector of the model in a direction tangential to the lever arm. The Robotics Toolbox routines for torque estimation allowed an external force to be modelled as a force and torque vector expressed in the coordinate system of the model's end-effector. In the noise factor experiment therefore, three factors would affect the value and direction of the applied external force:

1. The orientation of the lever handle.

Since the model used in the analysis of this experiment did not have a separate hand segment the assumption was made that the alignment between the hand and forearm segment was good enough to allow the external force to be expressed in the forearm coordinate frame. it then followed that in situations where the handle was horizontal the external force acted in the -x direction of the end effector coordinate frame and when the handle was vertical the force acted in the +y direction. Figure 95 illustrates this.

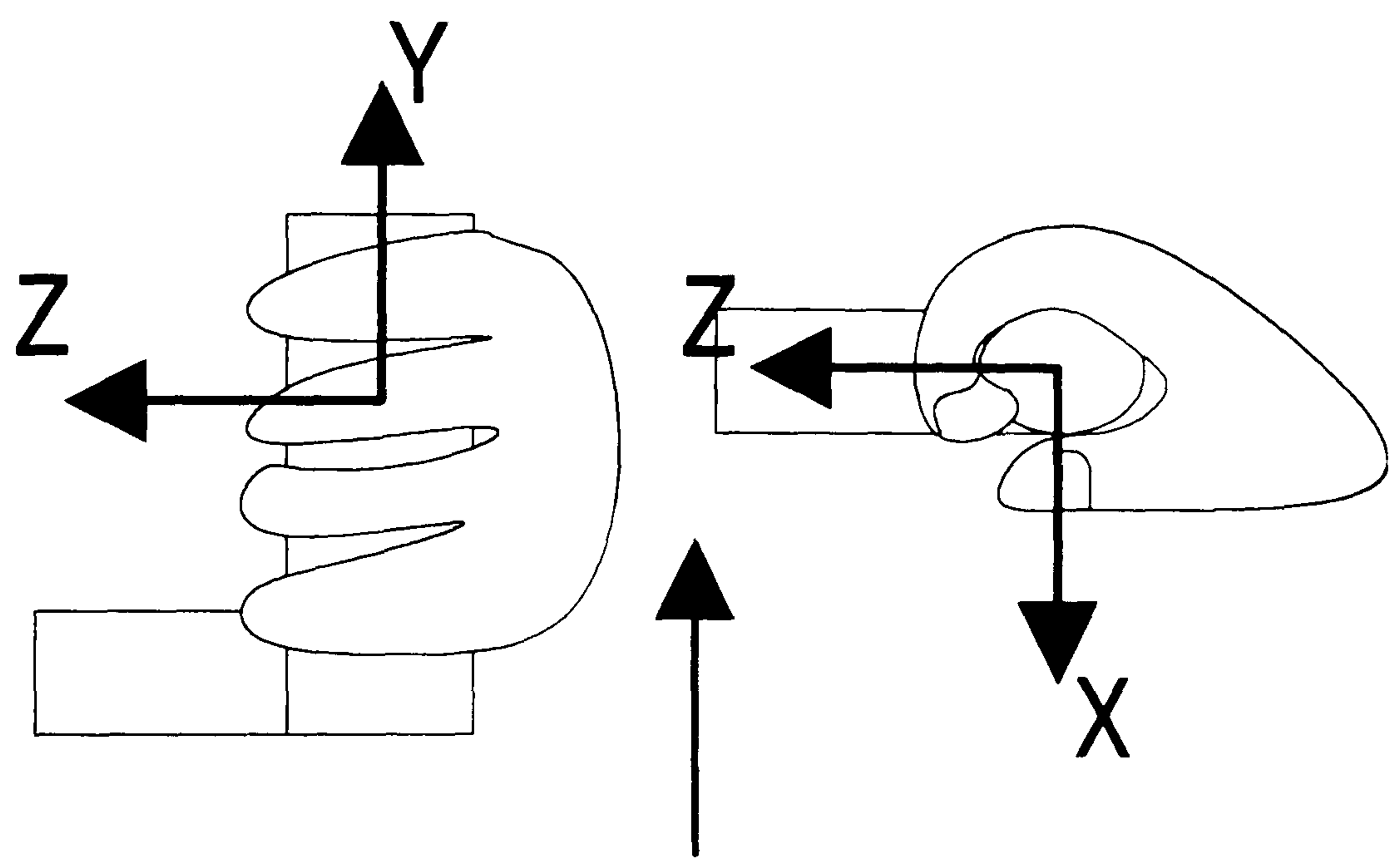


Figure 95: The direction of the external force applied to the model end-effector

It is likely that this assumption was more accurate in the experimental cases where wrist movement was restricted with an external splint than when it was not, and it is also likely that in configurations where the lever handle was in a horizontal position. rotation of the hand around the handle may have altered the angle between the forearm coordinate frame and the tangent to the lever.

1. The magnitude of the applied load affected the torque experienced at the lever axis. which in turn effected the tangential force on the hand at the lever end.
2. The lever length had an effect on the tangential force experienced by the hand for a given level of torque.

Figure 96 shows the base values of the externally applied load used in the torque estimation calculations. These values represent the torque applied when the weight acted in a line perpendicular to the lever. At other points during its motion, the external force was multiplied by an appropriate amount to create the effect of a varying lever arm as shown in Figure 93.

Experiment	Load	Handle Direction	Lever Length	External force x (N)	External force y (N)
1	Heavy	Handle VERT	Lever Short	0.00	9.33
2	Light	Handle HORIZ	Lever Long	-2.80	0.00
3	Heavy	Handle VERT	Lever Long	0.00	5.60
4	Heavy	Handle HORIZ	Lever Short	-9.33	0.00
5	Light	Handle VERT	Lever Short	0.00	4.67
6	Light	Handle HORIZ	Lever Long	-2.80	0.00
7	Heavy	Handle HORIZ	Lever Short	-9.33	0.00
8	Light	Handle HORIZ	Lever Short	-4.67	0.00
9	Light	Handle VERT	Lever Long	0.00	2.80
10	Heavy	Handle VERT	Lever Long	0.00	5.60
11	Light	Handle VERT	Lever Short	0.00	4.67
12	Heavy	Handle HORIZ	Lever Long	-5.60	0.00

Figure 96: The external loads applied to the end effector in the Product Design Noise Factor experiment model.

3.6.11.1 Task element separation

The algorithm used to separate the task elements in this experiment was similar to that used previously. A single task element was considered to be one pull of the lever from the top to the bottom of its stroke. The endpoints were identified by examining the z coordinate of the wrist-mounted sensor. The z data was passed directly to the low-point finding routine to identify the ends of the task motions and passed again after being inverted (z'→-z) to identify the high points.

A key additional factor that had to be identified was the lever horizontal point, since this defined the start and end points for the analysed sections of motion data, according to the position of maximum mechanical advantage being assessed in each run. A separate analysis routine was written that located the hand sensor reading whose z value was closest to the half way point between maximum and minimum recorded z values. This reading was then taken to indicate the lever horizontal position. Typical results are shown in Figure 97.

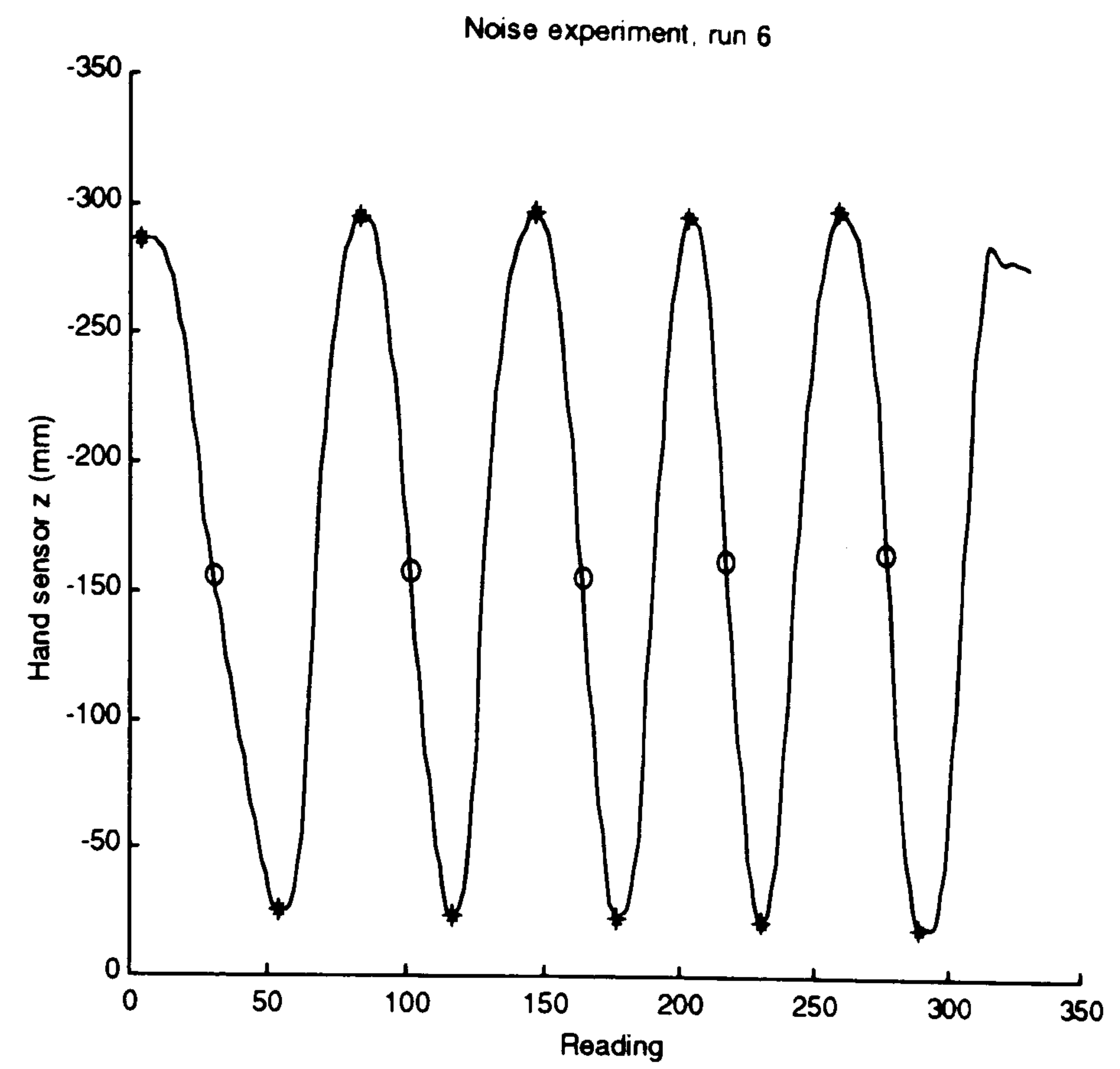


Figure 97: Typical output from the noise experiment task element separation process. Asterisks indicate the start and finish points of the motion; circles indicate the estimated lever horizontal position.

3.6.12 Results

In a partial factorial experiment such as this one, plots of the raw data are of little use to the experimenter, because it is impossible to attribute variations to a single cause. The first action in the analysis of the data was therefore. to construct Analysis of Means and Analysis of Variance models for a variety of quality measures.

3.6.12.1 Effect significance

The ANOVA models constructed for the parameter optimisation experiment results revealed very high confidence intervals for the effects of nearly all the factors (>99.9%) such an effect size might tempt one to ascribe 'significance' to all such results. However this idea needs careful consideration. The large number of degrees of freedom in the experiment (399) has the tendency of reducing the F-ratio required to achieve purely statistical significance to a very low level.

In order to make sensible attributions of significance therefore: the physical effect size corresponding to a significant difference between two designs must be decided. For the purpose of the discussion in this section it might be useful to define a threshold level above which factor effect sizes are considered sufficiently interesting to merit discussion. Such a threshold might be expressed as a physical quantity: a number of radians or Newton-meters, or as a percentage change in a particular measure. In the discussion that follows, angular effects of less than 0.1rad and torque effects of less than 1Nm are not discussed. These numbers are close to the expected accuracy limits of the analysis system (Section 3.2) and also seem intuitively reasonable.

Signal to noise ratios were not used in the analysis of this experiment. It was judged that most of the advantages of their use could also be obtained by applying the same graphical techniques to the data in its original units.

3.6.12.2 Angular measures

Two angular quality factors were examined:

1. The mean angle. This was intended to serve as a measure of the overall posture that a particular design factor required the user to adopt, and as an alternate measure of factor effect size.
2. The angular range: maximum angle minus minimum angle. This was intended to provide an assessment of the range of motion required to operate the product, which might be an effective quality measure.

Only the elevations at the shoulder and elbow were analysed using these methods. As discussed previously, the high probability of interactions between the plane and rotation angles, coupled with difficulty in correlating variations in these measures with anatomical characteristics, made their analysis unrevealing. The full results and graphs are given in Section 7.3. The main effects are tabulated on a factor by factor basis below (Figure 98).

Factor	Measure	Effect size rad (deg)	Effect direction	Comments
Subject	Mean shoulder elevation	0.13 (7.5)	Smaller subject higher	This might be expected by the fact that subject 2 s shoulder joint was lower in relation to the lever handle
Splint	Mean shoulder elevation	0.1 (5.7)	With splint higher	
Splint	Range of elbow bend	0.12 (7)	No splint higher	
Posture	Mean shoulder elevation	0.68 (39)	Seated higher	All posture effects attributable to lower shoulder-centre position relative to handle when seated
Posture	Range of shoulder elevation	0.1 (5)	Seated higher	Posture had the largest effect on all angular measures
Posture	Mean elbow bend	0.13 (7)	Seated higher	
Posture	Range of elbow bend	0.2 (10)	Standing higher	
Distance	Mean shoulder elevation	0.14 (8)	Far higher	Probably a consequence of the higher elbow position when subjects were far
Distance	Mean elbow bend	0.55 (31)	Near higher	Elbow bend was used to set near/far distance in the first place, so this result should be no surprise

Factor	Measure	Effect size rad (deg)	Effect direction	Comments
Lever axis	Mean elbow bend	0.23 (13)	Sagittal higher	
Lever axis	Range of elbow bend	0.18 (9)	Sagittal higher	Lever axis effects possibly caused by horizontal handle movement relative to torso when in sagittal plane
Load	Range of shoulder elevation	0.1 (5)	Heavy higher	
Load	Range of elbow bend	0.14 (8)	Heavy higher	Load effects may be a consequence of a transfer of effort from the elbow to the shoulder
Handle direction	No strong effects			
Axis height	Mean shoulder elevation	0.12 (7)	High position higher	
Axis height	Mean elbow bend	0.12 (15)	High position higher	Probably a result of the high handle position relative to the shoulder
Axis height	Range of elbow bend	0.2 (11)	Low position higher	The low handle position probably means she shoulder reaches its lowest point near the bottom of the stroke, so requiring more elbow motion to complete the task
Lever length	Range of elbow movement	0.2 (11)	Long lever higher	Hand must move through a greater distance
Lever length	mean elbow bend	0.13 (6)	Short lever higher	
Lever length	Range of shoulder elevation	0.16 (9)	Long lever higher	
Max mech. adv. pos.	Mean shoulder elevation	0.17 (10)	MMA end higher	
Max mech. adv. pos.	Range of elbow bend	0.16 (9)	MMA end higher	Higher position of handle in MMA end position is the probable cause of these effects

Figure 98: Factor effects on angle measures

3.6.12.3 Torque measures.

Two basic torque measures were used in this analysis:

1. Mean joint torque

2. Maximum joint torque.

The results obtained are summarised in Section 7.5.3. In practice, the same effects were demonstrated by the mean and maximum torque measures in most cases. The direction of factor effects remained the same, but the relative size of some effects differed slightly between the two types of analysis. The main effects are discussed below on a factor by factor basis (Figure 99):

Factor	Measure	Effect size Nm	Effect direction	Comments
Subject	All mean torques	3.36 (mean shoulder elevation) 4.29 (max shoulder elevation)	Subject one always higher	Limb self-weight increases torques for larger subject
Splint	Mean shoulder elevation torque	2.31	Splint higher	
Splint	Max shoulder elevation torque	2.13	Splint higher	
Posture	Mean Shoulder elevation torque	6.09	Seated higher	Higher angle value increases moment at shoulder
Distance	Mean Shoulder elevation torque	10.03	Far higher	Increased moment, as for posture effects
Distance	Mean Elbow torque	3.34	Far higher	As above
Distance	Mean Shoulder rotation torque	3.24	Near higher	Elbow more bent in near position increases distance from upper arm long axis to forearm centre of mass, increasing moment
Lever axis	Shoulder elevation	1.16	Transverse higher	
Lever axis	Mean Elbow bend	1.40	Transverse higher	
Load	Mean Shoulder elevation	2.64	Heavy higher	
Load	Mean Elbow bend	1.05	Heavy higher	
Load	Mean Shoulder rotation	2.37	Light higher	Heavy load may cause users to pull more directly from shoulder, reducing shoulder rotation torque
Handle direction	Mean shoulder elevation	1.17	Vertical higher	
Axis height	Mean Shoulder elevation	1.69	Low position higher	
Axis height	Mean Shoulder rotation	3.76	High position higher	
Max mech. adv. pos.	Mean shoulder rotation	2.65	Max at end, higher	Higher shoulder elevation through motion increases torque

Figure 99: Summary of parameter effects on torque measures

3.6.13 The parameter optimisation experiment

The noise factor experiment demonstrated statistically detectable effects emerging from many of the controlled factors. However, the results also indicated that the effect of noise factors tended to be much higher than that of the signal factors. The purpose of the second experiment was to investigate more thoroughly the signal factor effects.

It will be remembered that the noise factors under analysis in the first experiment came from two basic sources:

1. Anthropometric factors
2. Control of user posture.

Neither a product's designers, nor its users can have any control over anthropometric variables, but in the normal use of products, users are free to optimise their own posture. The assumption was made therefore, that in normal use people do carry out such an optimisation process unconsciously, and they will tend to adopt a posture that minimises biomechanical stress. In the design of the signal factor experiment, an anthropometrically diverse range of subjects was assessed, and subjects were allowed to select their own posture by practising lever movements a few times before measurements commenced.

3.6.14 Parameter optimisation array design

With all the noise factors removed from the analysis of the second experiment, the five signal factors remained:

1. Lever axis
2. Handle direction
3. Axis height
4. Lever length
5. Maximum mechanical advantage position.

An L8 orthogonal array was used for the parameter optimisation experiment. This array allows the evaluation of seven factors at two levels each, in eight experiments, and also has the property that certain factor interactions can be investigated if some columns are left blank. The allocation of factors to columns is shown in Figure 100.

	Factor						
Expt.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	Lever axis	**Handle Direct.**	**Noise 1**	**Axis Height**	**Lever Length**	**Mech. Adv. Pos.**	**Noise 2**
1	Transverse	Vertical	1	Low	Short	Start	1
2	Transverse	Vertical	1	High	Long	End	2
3	Transverse	Horiz.	2	Low	Short	End	2
4	Transverse	Horiz.	2	High	Long	Start	1
5	Sagittal	Vertical	2	Low	Long	Start	2
6	Sagittal	Vertical	2	High	Short	End	1
7	Sagittal	Horiz.	1	Low	Long	End	1
8	Sagittal	Horiz.	1	High	Short	Start	2

Figure 100: The experimental array used in the parameter optimisation experiment.

3.6.15 Parameter optimisation method

Ten subjects were assessed in the parameter optimisation experiment, five each from the two anthropometric groups described in Section 3.6.7. The experimental procedure was identical to that used in the noise experiment, with the following exceptions:

1. Subjects all assumed a standing position, but no further restriction was placed upon their posture.

2. Subjects carried out the task on eight separate lever configurations instead of six.

3.6.16 Data manipulation

The data manipulation process was identical to that used in the Section 3.6.11. The larger number of subjects and experimental repetitions per subject resulted in a total of 400 separate task elements for analysis. Figure 101 shows the external forces used in the modelling process. These forces were calculated in the same manner as those applied previously and altered in the same way to account for the variation in torque during the l.

Experiment	**Handle Direction**	**Lever length**	**External force x (N)**	**External force y (N)**
1	Vertical	Short	0	9.3
2	Vertical	Long	0	5.6
3	Horiz.	Short	-9.3	0
4	Horiz.	Long	-5.6	0
5	Vertical	Long	0	5.6
6	Vertical	Short	0	9.3
7	Horiz.	Long	-5.6	0
8	Horiz.	Short	-9.3	0

Figure 101: The external forces applied to the end-effector in the modelling of the parameter optimisation experiment.

3.6.17 Results

As in the noise factor experiment, Analysis of Means and Analysis of Variance models were used to examine the data. The ANOVA model included the subjects as a factor with nine degrees of freedom. The full analysis results are given in Section 7.6. The main factor effects are described below:

3.6.17.1 Angular measures

Factor	**Measure**	**Effect size rad (deg)**	**Effect direction**	**Comments**
Lever axis	Mean elbow bend	0.1 (5)	Sagittal higher	
Handle direction	Mean shoulder elevation	0.1 (5)	Horizontal higher	
Axis height	No significant effects			
Lever length	Mean elbow bend	0.11 (5)	Long higher	
Max mech. adv. pos.	Mean shoulder elevation	0.14 (8)	MMA end higher	
Max mech. adv. pos.	Mean elbow bend	0.4 (23)	MMA end higher	High handle position probable cause of these effects
Max. mech. adv. pos.	Range of elbow bend	0.23 (13)	MMA start higher	Lower handle position takes shoulder to bottom of useful movement, requiring further elbow extension to compensate

Figure 102: Summary of signal experiment angle effects

3.6.17.2 Torque measures

Factor	**Measure**	**Effect size Nm**	**Effect direction**	**Comments**
Lever axis	No significant effects			
Handle direction	Shoulder elevation torque	3	Vertical higher	
Handle direction	Shoulder rotation torque	2	Horizontal higher	Vertical position allows more direct pull at the shoulder
Axis height	Shoulder elevation torque	1	High position higher	Higher handle position causes greater moment at shoulder
Lever length	Maximum elbow torque	1	Short length higher	
Mac mech. adv. pos.	No significant effects			

Figure 103: Summary of signal experiment torque effects

3.6.17.3 Signal and noise experiment correlation

If the assumption of additivity is correct, then one would expect a match between the effects of the control factors in the parameter selection experiment and the same factors in the noise factor experiment. Figure 104 lists the factors and the direction of their effects on various quality measures under assessment in both experiments:

Factor	Level	Shoulder elevation range		Elbow bend range		Maximum shoulder elevation torque		Maximum shoulder rotation torque		Maximum elbow bend torque	
		Noise	Signal	Noise	Signal	Noise	Signal	Noise	Signal	Noise	Signal
Lever axis	Transverse	-	-	-	-	+	0	-	-	+	-
	Sagittal	+	+	+	+	-	0	+	+	-	+
Handle dir.	Vertical	-	+	+	+	+	+	-	-	-	+
	Horizontal	+	-	-	-	-	-	+	+	+	-
Axis height	Low	+	-	+	-	+	-	-	+	+	-
	High	-	+	-	+	-	+	+	-	-	+
Lever length	Short	-	-	-	-	+	+	+	+	-	+
	Long	+	+	+	+	-	-	-	-	+	-
MMA position	Start	0	-	-	+	+	-	-	-	+	-
	End	0	+	+	-	-	+	+	+	-	+

Figure 104: Comparative effect directions for factors in the noise factor and parameter design experiments.

It can be seen that out of a total of 25 possible combinations of parameter effect and quality measure, only eleven had the same effect in both experiments. Such a result suggests that interaction between factors, and particularly between the signal and noise factors in the first experiment was high. However, considering the widely differing number of subjects between the experiments and the fact that the noise factors in the first experiment had a much stronger effect than the signal factors, this result might suggest a satisfactory degree of consistency between the two experimental sets.

3.6.18 Discussion

Several clear conclusions can be drawn from the lever evaluation experiment. The first conclusion is that the effects of noise factors were considerably higher than those of signal factors in the experimental configuration used. While this result is unsurprising it does emphasise a key difficulty in any attempt to optimise design through biomechanical analysis: the designer has comparatively little leverage with which to effect the desired outcome. With a subject group that exhibited true population variability it is quite conceivable that control factor effects would simply be too small to make any noticeable difference to the overall performance of the product.

The second important conclusion, again a confirmation of the findings of earlier experiments, is that strong interactions do exist between the various control factors and between control and noise factors. It is part of the nature of the Taguchi analysis process that it is difficult or impossible to evaluate the nature of such interactions, and it is part of the philosophy of the process that such interactions should be designed out before experimental work begins. Whether this can truly be done in the case of an interface optimisation problem remains to be seen.

With these points having been made however, it was certainly clear from the analysis that the effects of most interface parameters were fairly consistent, and that certain design conclusions might be drawn from them. These factors are discussed below.

3.6.18.1 Parameter set selection

The torque and angular quality measures suggest that two key factors affect the biomechanical loads involved in the use of the lever mechanism:

1. The vertical handle position allows most of the arm pulling force to be provided by elevation of the shoulder. This configuration is likely to recruit more muscle mass to the task than configurations that require most of the force to be generated by shoulder rotation and elbow bend.
2. The higher the overall handle position, the higher generated shoulder torque was likely to be. Two of the design variables under analysis in this experiment contributed to overall handle height: axis height and the section of lever arc under analysis. With the parameter range used here, the effect of altering the arc segment under analysis was much stronger than that of axis height. This effect can probably be attributed to two separate causes. Firstly, a higher handle tends to cause the perpendicular distance from the lines of force cause by limb segment mass and lever force to the shoulder axis to increase, and secondly, the lower handle positions under analysis here tended to cause the shoulder's angle of elevation to be reduced to a point where the shoulder could provide no more effective force. After this point elbow movement had to take over to provide the rest of the motion.

This evidence would suggest that the lever design could be optimised by selecting a configuration that allowed the hand to be held in a vertical position and a combination of lever length and axis height that allowed the shoulder to provide the majority of lever motion. Figure 105 shows such an arrangement. The selection of lever axis height is an operating window selection process. too high a handle would tend to increase shoulder torque unnecessarily, whilst too low a position would have the effect of preventing effective use of the shoulder in part of the task.

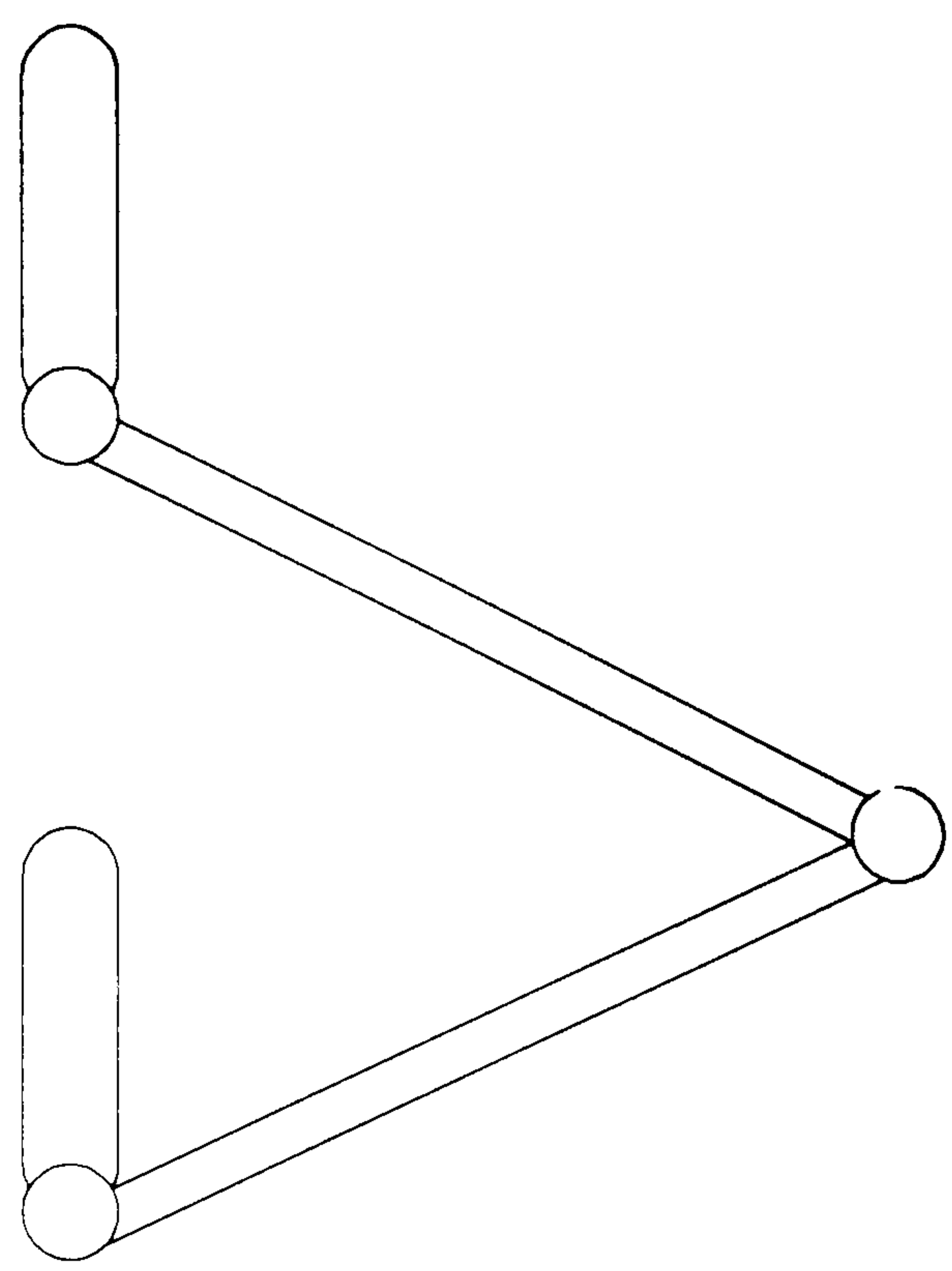


Figure 105: A possible configuration for the lever mechanism, the pivoting handle allows the wrist to be held straight, whilst still maximising direct pull from the shoulder.

3.6.18.2 Limitations

It is important to note that the biomechanical variables analysed in this experiment are unlikely to tell the whole story. Observation of subjects during the experimental process suggested that, particularly for taller subjects, the lower handle positions tended to require movement of the entire shoulder complex. The motion was normally provided by bending at the waist. This sort of motion can be expected to have a profound effect on the overall biomechanical stress of the task.

Secondly, the analysis of wrist motion was not included in this work. While the horizontal handle configuration allowed the hand to be rotated about the handle during use, letting the wrist remain straight at all times, the rigid vertical handle provided no such freedom. In order to complete the task, subjects had either to deviate the wrist or alter their grip on the handle. Wrist deviation is highly undesirable from an ergonomics perspective as it has been associated with cumulative trauma disorders [Schoenmarklin et al. 1994]. Alteration of grip type would also be undesirable in a task like this where power transfer is important. The power grip normally adopted by subjects reduced forces on the fingers to a minimum, which is another highly desirable situation.

An important limitation of any parameter optimisation experiment such as this is that the experimental process only allows exploration of the problem space as it was analysed in the experiment. While there is no need to ensure that the optimum design configuration is actually one of the experimental configurations, the approach will only predict the performance of combinations of those factor levels under analysis. It is quite possible that a better solution to the lever design problem lies outside the range of parameters tested here.

3.7 Experimental section summary

The experimental section of this work is summarised in the following points.

3.7.1 System Error Level

The magnetic tracker system used in the work was found to achieve a spatial accuracy of ±7mm and an angular accuracy of ±3.2°. When combined with the errors caused by the fitting of a simplified model to natural limb motion, this resulted in an expected error in modelled end-effector position of some 60mm. This in turn corresponds to errors in the calculation of limb segment angles of 10°

3.7.2 Intra-user variability

Subjects were found to repeat the same task in a very similar manner, with individual variations of less than 5° or 1Nm recorded.

3.7.3 Inter-user variability

When different subjects completed the same task variations in joint angle of up to 50° were observed along with torque variations of up to 12Nm. A combination of anthropometric factors and performance differences was considered to be the cause of these effects.

When subjects had the motion of the wrist artificially impaired, differences in joint angle of up to 7° were observed during the same task compared to the unimpaired state. Strong interactions were found to exist between subject and impairment: the impairment did not affect subjects in a predictable way.

3.7.4 Design information

The power grip used by subjects to operate the thick handled spoons designed for users with low grip strength tended to increase shoulder rotation torque and user discomfort.

The difference in drinking vessel designs had a much smaller effect on user performance than did the spoons. The mug with a side handle produced the lowest mean torques; the Minoy adapted beaker produced the highest.

In the lever design experiment, hand height relative to the shoulder during operation was found to be the key factor, with higher hand positions producing higher torques. The design of the experiment meant several factors interacted to have an effect on the overall height of the handle. Putting the handle too low required taller subjects to move their entire upper body, however, which would be likely to place additional loads on the spine and shoulder complex.

4. Discussion

This work has examined ways of improving the evaluation of consumer product usability. The ageing population and the need to cater for users with a range of physical impairments has created new demands for designers who seek to make products accessible to a large user population. The difficulties involved in the evaluation of products with a large number of potential users are compounded by shortening product development cycles, which reduce the opportunities for testing, and feedback.

It has been proposed that these difficulties can be overcome by simulating users electronically and carrying out ergonomic analysis within a computer aided design system [Taha et al, 1996]. However, it is argued here that the diverse and unpredictable nature of human-product interactions makes it impossible for current modelling systems to produce a sufficiently accurate or reliable simulation of human performance. As an alternative, this work proposes that the maximum benefit may be obtained from ergonomic analysis by combining a conventional user-testing approach with a biomechanical computer model that provides information on the forces and motions experienced in a user's limbs during the operation of a product.

In order to evaluate this approach, a prototype system has been implemented that makes use of an alternating current electromagnetic tracking system to detect upper limb motion data and a two-segment biomechanical limb model to produce information on torques and joint angles. The principal challenge in the successful implementation of a such a system is not the collection of data, but rather the interpretation of such data in a product design context and the generalisation of the information obtained from the sample group to the more full user population.

The main objective of the experimental phase of this work has been an investigation of the likely effectiveness of the modelling approach in producing generaliseable results and an evaluation of various graphical and statistical methods for the conversion of biomechanical data into design information. These elements are discussed below.

1. **Generalisability of results.** All user evaluation relies on the data collected from a sample group being applicable to the general population of intended users. The sample size needed to represent a given population effectively depends upon the variability found in that population. In the context of biomechanical data collection this variability is caused by anthropometric and performance factors. The data available to estimate anthropometric variability is quite limited, while data on performance variability is virtually non-existent. The first 3 experiments undertaken during this work were designed to investigate the amount of variability in biomechanical data collected from samples of potential users undertaking various simple tasks.

   These experiments demonstrated that, while individuals tended to repeat the same task in a very similar fashion, variability between subjects was high. In certain cases alterations in product parameters had effects that differed in direction as well as magnitude: a factor that tended to increase shoulder torque with one subject, might reduce it with another. This effect shows firstly the difficulty faced by any designer hoping to achieve truly universal product improvements, and secondly the risks involved in extrapolating from a very small sample group to a wider population, although human interface design experiments necessarily have to use small samples in their design as the testing process is inherently so expensive.

2. **Collection of design information.** The use of biomechanical analysis as a support to the user evaluation process would be of no benefit if the interpretation of the resulting data was so time consuming and difficult that it resulted in a considerable increase in the expense of the evaluation process. In order to avoid this, the team carrying out the analysis must have available a range of measures which allow them to quickly assess the relative performance of different designs. The approach adopted to tackle this problem in this work was the selection of quality characteristics: summary measures that were used to define the performance of a particular design. These measures were typically the mean or maximum joint torque values obtained from a particular task element. In the final experimental sequences these were modified using the Taguchi signal to noise ratio transformation. The use of statistical significance tests, either T

tests or analysis of variance, allowed the most significant design parameters to be rapidly identified.

Useful results were generated by these experiments, but the more data the process produced, the more it revealed that different experimental designs would be required to make best use of the collected information. The principal weakness of the Taguchi approach used here was the large number of interactions identified in the results. Interface parameters tend to interact strongly, while coping with interactions is a known weakness of Taguchi's methods [Pignatiello and Ramberg, 1991]. Further refinement of either experimental design, or analysis techniques, or both, are required here.

Beyond the technical aspects of experimental design and data collection there are further questions that must be asked about the use of the techniques described in this work. A fundamental question about this sort of biomechanical modelling is the breadth of its usefulness in the modern product context. Computers, electric motors and disposable packaging may well come to dominate domestic life and the age of the simple hand tool could be over. When looking for products to evaluate during the experimental part of this work it was actually quite difficult to select items that seemed likely to benefit from fine-tuning through biomechanical analysis, in many cases the item can simply be replaced with a high-technology solution if needed, or even a low technology one: a drinking straw removes the need to lift a cup or use a spoon to consume soup. More significant challenges for the ergonomist may lie in the realm of human-computer interaction design and the study of how the next generation of highly sophisticated electronic products will actually be controlled.

Universal design itself, which is fundamental to this work, is also a concept that may have limited scope. While there is no doubt that items for general public use need to be as accessible as possible, in an age where flexible manufacturing technology allows the idea of mass customisation to become a realistic one it is quite conceivable that every product will soon be tailored to the needs of its eventual end user. Indeed many cars and computers are already made in this way. It is not difficult to imagine therefore, a situation where a simple product is made available with a number of different user-interfaces, or with their user interface customised. There would be opportunities for biomechanical modelling in this context too, with individual users being measured and modelled during a "fitting session". Such an approach would require very different optimisation techniques from those explored in this work.

There are other fields however, outside the world of product design, in which the techniques discussed in this work might have considerable application. There are opportunities for the use of motion analysis combined with some form of quality measure or characterising process in the medical field. Just as much motion analysis technology evolved to carry out gait analysis, the measurement of lower limb motion, so might the same techniques be applied to upper limb motion to assess recovery after surgery, for example. Historically the fact that upper limbs do not naturally adopt consistent, repetitive patterns of movement has made analysis of their motion for diagnostic and assessment purposes difficult, but by involving the limbs in interaction with a product or task of some kind, the normal motions of which had already been extensively studied, this problem might be circumvented.

The process of product design has moved forward dramatically in recent years, driven primarily by the explosive growth in the power of computers. Computer systems allow the use of sophisticated design techniques requiring the completion of many thousands of calculations: models have increased in sophistication and design refinement through the automated analysis of hundreds of different "what-if" scenarios is now possible. Designers have the opportunity to try many more alternative solutions before committing themselves to any particular course of action.

Ergonomic design, having entered the design vocabulary fairly late, still lags considerably behind other fields. The reason for this is perhaps the enormous difficulty involved in creating a reasonable model of the human being. Virtually without exception, other design variables can be reduced to some system of equations, allowing them to be represented in the strict logical terms needed by a digital processor. No such system exists for the human body.

The complexity and unpredictability of human nature has another effect on the development models for machine interface design. People can and do learn to adapt to the most unusual circumstances and this adaptability takes away much of the most pressing need to optimise the interface between people and their tools. An electric motor will simply fail if the gearbox connected to it demands too much torque, or if the supplied current is insufficient to operate it, but people have always found ways to cope with ill-fitting devices, sometimes adapting them to their own needs, more often adapting themselves in an appropriate fashion. In an environment like this, expending effort looking for a possibly non-existent "ideal interface" may seem to be an unaffordable luxury.

The demands on product designers are changing, however, and what was once perceived as luxury often becomes necessity with a short period of time. If people with limited physical capabilities are to be allowed to take a full role in society, then society must give them the tools with which to do so. It must not ask them to adapt in ways that exceed their strength or mobility.

This work has sought to find one means by which this can be achieved. By basing itself on the idea of design improvement through the observation of users, but attempting to reduce those observations to terms that might be used comfortably within a computer model, the intention has been to open up a way of evaluating human performance in the same way that an electric motor or a robot might be evaluated. By its very nature analysis of this type cannot take into account the many emotional and social factors that contribute to the way a product is used. The fundamental question that must be asked of this approach is, how much vital information on the way we really use things will be lost in the process?

4.1 Recommendations for further work

The work up to this point has established that biomechanical modelling is capable of providing useful design information, and it has tested some promising methods for turning this theory into practice. However, it is clear that many elements of this work should be improved, extended or replicated to confirm its validity.

In particular the following deserve special attention:

1. Data collected in the experiments during this work could be analysed in numerous other ways. One of the most noticeable omissions was the dimension of time. The examination of velocity and acceleration measures from the model has the potential to produce further significant insights into product use and opens the possibility of a range of alternative measures of interface quality.

2. Time was also ignored in an important second respect in this work. All the tasks completed during the experimental phase were of short duration and no attempt was made to measure the effects of muscle fatigue on subjects' performance. Repetition of even a moderately strenuous task for an extended period of time will result in considerable changes to performance, and while few domestic tasks involve extended repetition, there are many industrial activities that do. If the methods discussed here are to be use in the analysis and prevention of cumulative trauma injuries then some examination of these longer term effects would be necessary.

3. The experimental costs involved in the analysis must be significantly reduced. The time needed to manipulate, process and analyse the data, even discounting that used in the exploration of alternative but eventually unfruitful quality measures, was much too great for sensible application outside the research laboratory. In its current form, very few manufacturers will have the resources to adopt this sort of biomechanical analysis in a real product development period.

4. The use of more sophisticated models could contribute significantly to the usefulness of the analysis. The inclusion of a wrist joint into the analysis would seem to be vital, while modelling of the finger joints and movement in the upper torso would be useful if the data reduction

process was advanced to such point where this would not result in an excessively high data processing load.

5. The testing of more types of product and, most importantly, a wider range of abilities is a vital development. The more prior knowledge that ergonomists have of the problem domain, i.e. the range of anthropometry and performance characteristics in their target populations, the more closely they can select representative users for product testing and ensure that the results obtained during trials are likely to reflect real outcomes.

6. The testing of as many new products as possible will also help in the quest for a set of truly useful quality measures. Which will in turn increase the speed of the analysis process, since most of the analysis effort in this work was focused on searching for useful measures, work that was rejected once the best measures had been found. A large quantity of such information would also begin to produce more feedback on the product parameters that tended to produce improvements in the user interface: handle types that minimise shoulder torque in use, for example.

Beyond the considerable data collection effort required to bring the methods described in this work to a point where they might be easily and practically applied, The extension of the same techniques into numerous different domains is a realistic long-term goal. As discussed above, modelling and measurement of the quality of the quality of a user's interactions with a product, when combined with the ability to manufacture unique products quickly and cheaply offers opportunities for the creation of individually customised interfaces. Outside the field of product design, the ability to use sophisticated quantitative measures of upper limb performance may have uses for the diagnosis of impairments and the assessment of therapies.

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6. Appendices

6.1 Hardware Selection

6.1.1 Introduction

The following sections describe a formal selection process for the choice of an appropriate human movement measurement system. Sections 6.1.2-6.1.13 describe the criteria that were considered in the selection process. Possible systems were then rated according to the various selection criteria (Section 6.1.14) and the criteria themselves given weightings according to their particular importance in the work under discussion here (Section 6.1.15).

6.1.2 Selection criteria

The following criteria are the main factors that would need to be considered in the selection of a motion analysis system for application in any context. Weightings will then be given to the criteria according to their specific relevance to the problem under discussion here.

6.1.3 Image storage

Some sensor systems record an image of the subject as they operate. This can be very useful during the interpretation of the data since it allows the experimenter to rapidly and easily correlate the recorded results with the observed elements of a task. Without synchronised image storage. interpretation of the recorded motion data (even if graphical methods are used to reconstruct an animated model) can be problematic.

6.1.4 Real time data collection

Systems that require extensive post-processing (either manual or automatic) before motion data can be viewed make it difficult to check data validity during an experiment This can result in the potential for extensive data loss if problems are not detected until the end of a large experimental

6.1.5 Line of sight dependence

Several motion analysis systems that use cameras, or other light-based sensor devices, require that markers placed on the subject be in view of at least two cameras at all times. During the measurement of complex movements this can be difficult to achieve and full data collection will require either expensive additional cameras or manual adjustment of the data to fill in gaps where sensors have fallen out of view.

6.1.6 Movement restriction

Most commercially available motion analysis systems require some form of sensor or marker to be attached to the subject under test. The exact nature and number of the sensors required varies from system to system, but all present a potential to restrict or alter the subject's movements in some way, and thus reduce the validity of the measurements taken. Some sensor types must be connected to the data collection hardware by an umbilical cable, a state of affairs that is highly undesirable in situations where a subject might be required to be ambulant, but probably not a significant problem in tests involving stationary seated or standing subjects. Some marker types are highly sensitive to the movement of flesh or clothing, flexible goniometers being a notable example; the geometry of the device can make it very difficult to find a stable mounting point for the ends of the goniometer on some joints and large limb movements can take place without corresponding movement being transferred to, or detected by the goniometer.

6.1.7 Number of markers

The number of markers or sensors that must be attached to the body can vary quite considerably between systems. Optical systems usually require several widely spaced markers to locate accurately the position of each body segment in three dimensional space, while electromagnetic tracking systems can provide spatial and angular information from a single marker.

6.1.8 Measurement rate

The frame rate or number of measurements that can be made per second by a system may be an important issue in the measurement of high speed motions, such as those in sporting activities. Frame rates that are too slow can lead to aliasing errors [Winter, 1990] where a periodic motion is misinterpreted through the failure of a system to sample enough points.

6.1.9 Automatic marker differentiation

Video camera based motion analysis systems that use reflective markers need each marker to be identified manually at the beginning of a recorded sequence, they then use algorithms to associate the position of a marker in one frame with the most likely position of the same marker in the next frame. It is possible for markers to cross over, or for a marker to disappear from view for a few frames and then not be relocated when it reappears. Experimental data suffering from these problems can be difficult and time-consuming to untangle.

6.1.10 Portability

A considerable usage restriction can be the sheer size of the measurement system hardware. Systems that use multiple cameras or sensor arrays are bulky to move around and time-consuming to set up if subjects cannot be brought to a ready made laboratory. Lack of portability can have the effect of restricting the potential subject pool, since only those who are willing and capable of coming to a laboratory can be studied.

6.1.11 Environmental restrictions

Very few motion analysis systems will work freely in any environment, however some are considerably more robust than others. Systems that rely on the transmission of visible or infrared light can be highly sensitive to background lighting levels and reflections from the environment, a problem that can be difficult to diagnose in the case of infra-red systems because the human eye is incapable of determining the reflectivity of surfaces at infrared wavelengths. Systems that use DC netic fields can be very sensitive to ferrous objects in their environment, while those using alternating fields are affected by all local conductors. The presence of such objects must be closely controlled, or their effect on the system can be carefully measured and calibration software then used to adjust the recorded data. [Kalawsky, 1993] warns however, "The computation required to undertake this mapping should not be underestimated".

6.1.12 Measurement limitations

Some measurement systems are limited in the way they can collect data: for example, inclinometer systems can only measure angles relative to a horizontal plane, and are prone to disturbance by sudden accelerations. Systems that collect only spatial or angular data require this data to be differentiated with respect to time if velocity or acceleration information is required. The differential process has the effect of exaggerating any noise in the data, so smoothing or filtering is usually required. Accelerometer systems collect acceleration data directly and require this data to be integrated to give velocity and position. Such data is usually fairly smooth, but the positional data can suffer from drift, i.e. poor repeatability over time.

6.1.13 Cost

Measurement systems can vary widely in cost, from a few hundred to more than a hundred thousand pounds. Research budgets, therefore, tend to impose severe limitations on capital expenditure.

6.1.14 Choice of measurement system

In attempt to reach an objective decision when choosing a system for the experimental phase of this work a selection matrix approach was adopted [Pugh, 1991]. A similar approach to the selection of motion analysis systems was used by Tyson and Das in their work. [Tyson and Das, 1990]. The features described above were given a rating ranging from 0 to 1, with 0 representing a total lack of performance in a category and 1 representing excellent performance. The requirements for each level in a particular category are given below: -

nage storage. Systems that provide such a facility were given 1, other systems 0.

2. **Real time data collection**. Systems that offer this feature were given 1, other systems 0.

3. **Line of sight dependence.** Systems that are fully dependent on line of sight were given zero, systems that have no line of sight requirement were given 1 and systems that rely on line of sight, but which can be manually overridden were given 0.5.

4. **Movement restriction.** Systems that require activity to be stopped while measurements were taken were given zero, those which use an exoskeletal assembly were given 0.25, those which require markers connected to flexible umbilical cables were given 0.5, those which use uncabled or telemetered markers 0.75, and those which need no markers at all 1.

5. **Cost.** Systems costing less than £100 were given 1, those costing in the region of £100 and £2000 were given 0.6, those costing between £2000 and £20000 0.3, and those costing more than £20000 were given zero.

6. **Accuracy.** As manufacturers' accuracy claims are expensive and difficult to substantiate, all automatic systems were assumed to offer similar levels of accuracy and were given 1. Manually measured systems were given 0.5 due to the risk of high inter-observer variability.

7. **Measurement Rate.** Systems that can collect data at more than 100Hz were given 1, those which can collect at 30-100Hz were given 0.6, those which operate at 1-29Hz were given 0.3, and those which require manual measurements to be made individually were given 0.

8. **Marker differentiation.** Systems that can automatically differentiate their markers were given 1; systems that can suffer from marker confusion were given 0.

9. **Portability.** Systems that require a fixed location were given 0.25, those which can be moved easily in a car and set up rapidly were given 0.5, those which can be carried in a small bag were given 0.75 and those which would fit in a pocket, 1.

10. **Environmental restrictions.** Systems that are only suitable for use in a highly controlled laboratory were given 0.3, those which could be used in most indoor environments were given 0.5, and those which could be used in virtually any environment were given 1.

11. **Availability.** Systems that are widely available and produced by a number of different manufacturers were given 1, those made by only a few specialist manufacturers were given 0.6, those made by a single manufacturer were given 0.3 and those which are not available commercially at the present time and which would need to be specially made were given 0.

12. **Measurement limitations.** Some attempt was made here to score the system-specific limitations of different measurement techniques on a single scale, this column might have been titled "other". The electromagnetic sensor systems were given 1 because of their ability to collect both position and orientation data from a single sensor, whilst 0 was given to the inclinometer systems because of their gravity dependence. Other systems were ranged between these extremes.

6.1.15 Weightings

It was the intention of the rating system described above to assess the available systems without regard to the specific application under study. The next stage in the selection process was to weight each factor according to its importance in this application. The selected weightings are given below:

Criteria	Weight
Image storage	0.5
Real time data collection	1
Line of sight dependence	1
Movment restriction	2
Accuracy	1
Measurement rate	1.3
Marker differentiation	0.5
Portability	1.3
Environmental restrictions	1.3
Availability	2
Measurement limitations	2
Cost	3

Figure 106: The weightings given the motion analysis system selection attributes.

The weightings for this work were:

1. **Image storage (0.5).** The widespread availability of video recording equipment was considered make the need for image storage an intrinsic part of the system redundant.

2. **Real time data collection (1).** This was considered important for visual verification purposes, but as any detailed analyses would have to take place at a later date, some degree of post-processing of the data was likely to be essential.

3. **Line of sight dependence (1).** The relatively simple movements under analysis mean that any problems with marker differentiation could probably be solved by careful positioning of cameras or sensor arrays.

4. **Movement restriction (2).** Unlike gait analysis, where movements are largely sub-conscious and the subject does not normally look at their legs during movement, there is a high risk that subjects will alter the motion patterns of their upper limbs according to any real or perceived movement restriction.

5. **Accuracy (1).** All commercially available systems were considered to be sufficiently accurate for this work

6. **Measurement Rate (1.3).** Repetitive limb movement tasks occur at a frequency of around 1Hz, so any measurement system with a data collection rate of above about 20Hz would be suitable.

7. **Marker differentiation (0.5).** Upper limb movements with a stationary torso are unlikely to cause significant crossing of markers.

8. **Portability (1.3).** See 9.

9. **Environmental restrictions (1.3).** For a system to be useful to designers and ergonomists working in a commercial situation it is desirable that it be operable in as wide a variety of environments as possible.

10. **Availability (2).** Project time constraints made the purchase or rental of an off-the-shelf system highly desirable.

11. **Measurement limitations (2).** The nature of upper limb movements is such that any of the measurement limitations discussed in this section would have serious consequences for data

collection. Full three dimensional recording of limb segment position would be essential for a system that intended to record arm movements with any degree of accuracy.

12.. **Cost (3).** Cost is likely to be a critical factor in the widespread acceptance of any biomechanical modelling system intended for use as a commercial ergonomic design tool.

System	Image storage	Real time data collection	Line of sight dependence	Movment restriction	Cost	Accuracy	Measurement rate	Marker differentiation	Portability	Environmental restrictions	Availability	Measurement limitations	Score
Fibre-optic goniometer	0	1	1	0.5	0.3	1	0.6	1	0.75	1	0.3	0.6	
Flexible conductive polymer goniometer	0	1	1	0.5	0.3	1	0.6	1	0.75	1	0.3	0.6	
Potentiometric goniometer	0	1	1	0.25	0.3	1	0.6	1	0.75	1	0.6	0.6	
Liquid filled inclinometer	0	0	1	0	1	1	0	1	1	1	1	0	
Mechanical inclinometer	0	0	1	0	1	1	0	1	1	1	1	0	
Flexible metallic goniometer	0	1	1	0.5	0.3	1	0.6	1	0.75	1	1	0.3	
Accelerometer	0	1	1	0.5	0.6	1	0.6	1	0.5	1	0.3	0.3	
Alternating current electromagnetic system	0	1	1	0.75	0.3	1	0.6	1	0.5	0.3	0.6	1	
Direct current electromagnetic system	0	1	1	0.75	0	1	0.6	1	0.5	0.6	0.6	1	
Polarised light goniometer	0	1	0	0.5	0.6	1	0.6	1	0.5	0.6	0	0.3	
CCD array spot locator	0	1	0	0.75	0	1	1	1	0.25	0.3	0.6	0.6	
Active marker, multiple camera infrared spot	1	1	0	0.75	0	1	1	1	0.25	0.3	0.6	0.6	
Passive marker, multiple camera infrared spot	1	1	0	1	0	1	1	1	0.25	0.3	0.6	0.6	
Manually digitised Video	1	0	0.5	1	0.3	0.5	0.6	0	0.5	1	0.6	0.3	
Stroboscopy	1	0	0.5	1	0.6	0.5	0.3	0	0.25	0.3	1	0.3	
Weightings	**0.5**	**1**	**1**	**2**	**3**	**1**	**1.3**	**0.5**	**1.3**	**1.3**	**2**	**2**	
Fibre-optic goniometer	0	1	1	1	0.9	1	0.78	0.5	0.975	1.3	0.6	1.2	10.255
Flexible conductive polymer goniometer	0	1	1	1	0.9	1	0.78	0.5	0.975	1.3	0.6	1.2	10.255
Potentiometric goniometer	0	1	1	0.5	0.9	1	0.78	0.5	0.975	1.3	1.2	1.2	10.355
Liquid filled inclinometer	0	0	1	0	3	1	0	0.5	1.3	1.3	2	0	10.1
Mechanical inclinometer	0	0	1	0	3	1	0	0.5	1.3	1.3	2	0	10.1
Flexible metallic goniometer	0	1	1	1	0.9	1	0.78	0.5	0.975	1.3	2	0.6	11.055
Accelerometer	0	1	1	1	1.8	1	0.78	0.5	0.65	1.3	0.6	0.6	10.23
Alternating current electromagnetic system	0	1	1	1.5	0.9	1	0.78	0.5	0.65	0.39	1.2	2	10.92
Direct current electromagnetic system	0	1	1	1.5	0	1	0.78	0.5	0.65	0.78	1.2	2	10.41
Polarised light goniometer	0	1	0	1	1.8	1	0.78	0.5	0.65	0.78	0	0.6	8.11
CCD array spot locator	0	1	0	1.5	0	1	1.3	0.5	0.325	0.39	1.2	1.2	8.415
Active marker, multiple camera infrared spot	0.5	1	0	1.5	0	1	1.3	0.5	0.325	0.39	1.2	1.2	8.915
Passive marker, multiple camera infrared spot	0.5	1	0	2	0	1	1.3	0.5	0.325	0.39	1.2	1.2	9.415
Manually digitised Video	0.5	0	0.5	2	0.9	0.5	0.78	0	0.65	1.3	1.2	0.6	8.93
Stroboscopy	0.5	0	0.5	2	1.8	0.5	0.39	0	0.325	0.39	2	0.6	9.005

Figure 107: The motion analysis system selection matrix.

The completed decision matrix is shown in

System	Image storage	Real time data collection	Line of sight dependence	Movement restriction	Cost	Accuracy	Measurement rate	Different lat[illegible] Marker	Portability	[illegible]
Fibre-optic goniometer	0	1	1	0.5	0.3	1	0.6	1	0.75	
Flexible conductive polymer goniometer	0	1	1	0.5	0.3	1	0.6	1	0.75	
Potentiometric goniometer	0	1	1	0.25	0.3	1	0.6	1	0.75	
Liquid filled inclinometer	0	0	1	0	1	1	0	1	1	
Mechanical inclinometer	0	0	1	0	1	1	0	1	1	
Flexible metallic goniometer	0	1	1	0.5	0.3	1	0.6	1	0.75	
Accelerometer	0	1	1	0.5	0.6	1	0.6	1	0.5	
Alternating current electromagnetic system	0	1	1	0.75	0.3	1	0.6	1	0.5	
Direct current electromagnetic system	0	1	1	0.75	0	1	0.6	1	0.5	[illegible]
Polarised light goniometer	0	1	0	0.5	0.6	1	0.6	1	0.5	
CCD array spot locator	0	1	0	0.75	0	1	1	1	0.25	
Active marker, multiple camera infrared spot	1	1	0	0.75	0	1	1	1	0.25	
Passive marker, multiple camera infrared spot	1	1	0	1	0	1	1	1	0.25	[illegible]
Manually digitised Video	1	0	0.5	1	0.3	0.5	0.6	0	0.5	
Stroboscopy	1	0	0.5	1	0.6	0.5	0.3	0	0.25	[illegible]
Weightings	**0.5**	**1**	**1**	**2**	**3**	**1**	**1.3**	**0.5**	**1.3**	**1**
Fibre-optic goniometer	0	1	1	1	0.9	1	0.78	0.5	0.975	[illegible]
Flexible conductive polymer goniometer	0	1	1	1	0.9	1	0.78	0.5	0.975	[illegible]
Potentiometric goniometer	0	1	1	0.5	0.9	1	0.78	0.5	0.975	[illegible]
Liquid filled inclinometer	0	0	1	0	3	1	0	0.5	1.3	[illegible]
Mechanical inclinometer	0	0	1	0	3	1	0	0.5	1.3	[illegible]
Flexible metallic goniometer	0	1	1	1	0.9	1	0.78	0.5	0.975	[illegible]
Accelerometer	0	1	1	1	1.8	1	0.78	0.5	0.65	[illegible]
Alternating current electromagnetic system	0	1	1	1.5	0.9	1	0.78	0.5	0.65	0.
Direct current electromagnetic system	0	1	1	1.5	0	1	0.78	0.5	0.65	0.
Polarised light goniometer	0	1	0	1	1.8	1	0.78	0.5	0.65	0
CCD array spot locator	0	1	0	1.5	0	1	1.3	0.5	0.325	[illegible]
Active marker, multiple camera infrared spot	0.5	1	0	1.5	0	1	1.3	0.5	0.325	0.
Passive marker, multiple camera infrared spot	0.5	1	0	2	0	1	1.3	0.5	0.325	0
Manually digitised Video	0.5	0	0.5	2	0.9	0.5	0.78	0	0.65	[illegible]
Stroboscopy	0.5	0	0.5	2	1.8	0.5	0.39	0	0.325	[illegible]

Figure 107. It is a tendency of any decision matrix structured like this one to produce outcomes with relatively small variations. The large number of similarly weighted fields tend to cancel each other out and reduce overall differences. However, in the results matrix (summarised in

System	Score
Fibre-optic goniometer	10.26
Flexible conductive polymer goniometer	10.26
Potentiometric goniometer	10.36
Liquid filled inclinometer	10.10
Mechanical inclinometer	10.10
Flexible metallic goniometer	11.06
Accelerometer	10.23
Alternating current electromagnetic system	10.92
Direct current electromagnetic system	10.41
Polarised light goniometer	8.11
CCD array spot locator	8.42
Active marker, multiple camera infrared spot locator	8.92
Passive marker, multiple camera infrared spot locator	9.42
Manually digitised Video	8.93

Figure 14) it can be seen that of the 15 systems under examination, only two have a score of more than 10.5. These systems were the flexible metallic goniometer and the alternating current electromagnetic tracking system.

System	Score
Fibre-optic goniometer	10.26
Flexible conductive polymer goniometer	10.26
Potentiometric goniometer	10.36
Liquid filled inclinometer	10.10
Mechanical inclinometer	10.10
Flexible metallic goniometer	11.06
Accelerometer	10.23
Alternating current electromagnetic system	10.92
Direct current electromagnetic system	10.41
Polarised light goniometer	8.11
CCD array spot locator	8.42
Active marker, multiple camera infrared spot locator	8.92
Passive marker, multiple camera infrared spot locator	9.42
Manually digitised Video	8.93

6.2 Upper limb anatomy

In order to discuss the construction of a model of the upper limb it is important to consider the actual anatomy of the arm. The brief description given here is based on that of [MacKenzie and Iberall, 1994].

6.2.1 Bones

Five major bones contribute to the structure and mobility if the arm, with a further twenty seven making up the hand. The anatomy of the hand will not be discussed here, as hand movements were not considered in the model developed for this work.

The bones of the arm are connected at three main joint complexes: the shoulder, the elbow and the wrist. Figure 108 illustrates the bones and joints that make up these areas, and the main joint groups are discussed below.

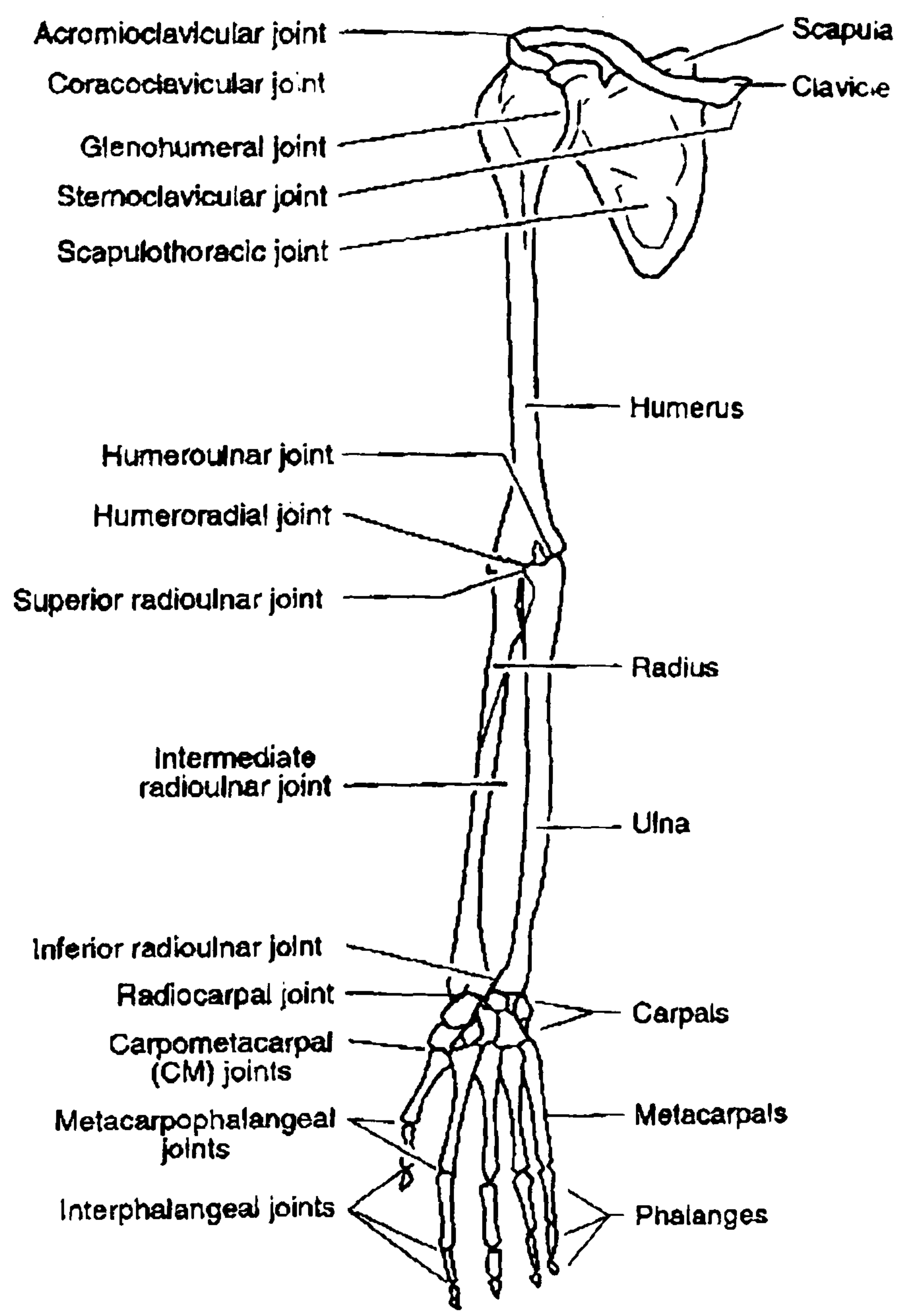


Figure 108: The skeletal structure of the upper limb.

1. The shoulder

The shoulder is the most mobile joint in the body. The shoulder complex is connected to the *sternum* (breast bone) by the *clavicle* (collar bone). The clavicle allows the *scapula* (shoulder blade) considerable movement, allowing the shoulders to be shrugged and moved in an anterior-posterior direction. The ***humerus*** (upper arm bone, or funny bone) rotates at the *glenohumeral joint* providing most of the movement at the shoulder for the arm itself. The glenohumeral joint is normally considered to be a spherical or ball and socket joint, allowing three degrees of rotational freedom.

2. The elbow

At the elbow, the humerus is joined to the two bones of the forearm: the *radius* (on the thumb side) and the *ulna* (on the little finger side). The *humeroradial joint* and *humeroulnar joint* allow the elbow to be bent, while three *radioulnar joints* allow *pronation* and *supination* (rotation of the forearm) to take place. The elbow joint also allows a certain degree of ulna and radial abduction, although this is often ignored in the design of models.

3. The wrist

At the wrist, the *radiocarpal joint* allows most of the wrist movements to take place, although movement is often combined with motion in the many joints between the small bones of the hand. The wrist is free to move in two planes, a flexion/extension movement sometimes described as *plamarflexion* and *dorsiflexion* and an abduction/adduction movement, sometimes described as *radial and ulnar deviation.*

6.2.2 Muscles

The muscular arrangement in the upper limb is a good example of the complexity that can be encountered in an attempt to model the arm accurately. There are close to sixty muscles in the arm and hand, many of which cross more than one joint and therefore have the potential to cause movement at any of these. Muscle action is not discussed in detail here, but describes the principal actions of the main muscles operating the arm.

	Shoulder						Elbow		Forearam		Wrist			
	flexion	extension	abduction	adduction	internal rotation	external rotation	flexion	extension	pronation	supination	flexion	extension	radial deviation	ulna deviation
Pectoralis major														
deltoid														
coracbrachialis														
biceps														
supraspinatus														
latissimus dorsi														
teres major														
triceps														
subscapularis														
infraspinatus														
teres minor														
brachialis														
brachioradialis														
pronator teres														
anconeus														
pronator quadratus														
flexor carpi radialis														
abductor pollicis longus														
extensor pollicis longus														
flexor carpi radialis														
flexor carpi ulnaris														
palmaris longus														
extensor carpi radialis longus														
extensor carpi radialis brevis														
extensor carpi ulnaris														

Figure 109: Principal actions of major upper limb muscles.

5.2.3 Anatomical description of motion

Clinical professions have developed a system for the description of joint motion. The system describes deviation of the of the joints from a neutral position known as the *anatomical position*. In

; position the arms hang vertically by the sides with the palms of the hands facing forwards. All : anatomical motion terms used in this work are described in the glossary (Section 6.6), and will t be repeated here. It is worth noting however, that anatomical descriptions were designed as a ethod for describing single joint movements. Their use as a system for the description of complex ovements is fraught with difficulty, and while the more rigorous mathematical techniques scribed in Section 6 can be designed to correlate quite closely with anatomical methods, their use to be preferred in a biomechanical modelling context.

6.3 Matrix geometry

As it was decided to use three dimensional modelling techniques for the work in this work, the first stage in the mathematical description of motion has to be the representation of the position and orientation of limb segments in three dimensional space.

6.3.1 Position

The usual method adopted to represent three dimensional position is the *Cartesian coordinate system*. In this system three mutually perpendicular axes are defined, and normally given the names x, y and z. There are two ways of establishing such an axis set, or *coordinate frame*. If the x axis is drawn horizontally from left to right on a piece of paper and the y axis is drawn vertically from bottom to top, then the z axis may either rise up from the plane of the paper or descend below it, these two options are known as *right hand* and *left hand* sets respectively. The normal convention is to use a right handed axis set. Position is then defined by the movement required along vectors parallel to each of these axes to travel from the origin to point of interest. This movement is not sequence-dependent: travelling in the direction of the axes in any order will lead to the same position. For use in matrix calculations (Section 6.3.3) it is normal to express position as a column vector (Figure 110).

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

Figure 110: Cartesian position coordinates expressed as a column vector.

6.3.2 Orientation

While three coordinates are sufficient to locate a point in space, any solid object can lie in a variety of orientations. The description of the rotations required for an object to move from a "neutral" orientation to a particular one of interest is a somewhat more complex matter. Just as position can be defined in terms of three *degrees of freedom*, expressed by the three Cartesian co-ordinates, so ıere are three theoretical degrees of freedom for the description of rotation. The complication ccurs because simply specifying three rotations is not sufficient to describe orientation. Rotations equire an axis of reference, rather than just a point, and one rotation will have the effect of altering he relative orientation of any axes required for further rotations. Thus the rotations are sequence lependent, and the concept of *global* and *local* axes becomes important. Global axes are the basic ;, y and z axis used for the definition of position, while local axes are a set of axes attached to an ›bject and which rotate with it.

A variety of rotation conventions exist [Nikravesh, 1988] The most commonly used in ›iomechanics being the *Euler angle* convention or similar conventions suggested by the slightly more general International Society of Biomechanics recommendations [Wu and Cavanagh, 1995] The Euler angle convention entails the following sequence of rotations:

1. A rotation about the global Z axis: the plane of elevation (ψ)

2. A rotation about the (now rotated once) local X axis: the angle of elevation (θ)

3. A final rotation around the new local Z axis: the angle of rotation. (σ)

These rotations are shown graphically in Figure 111.

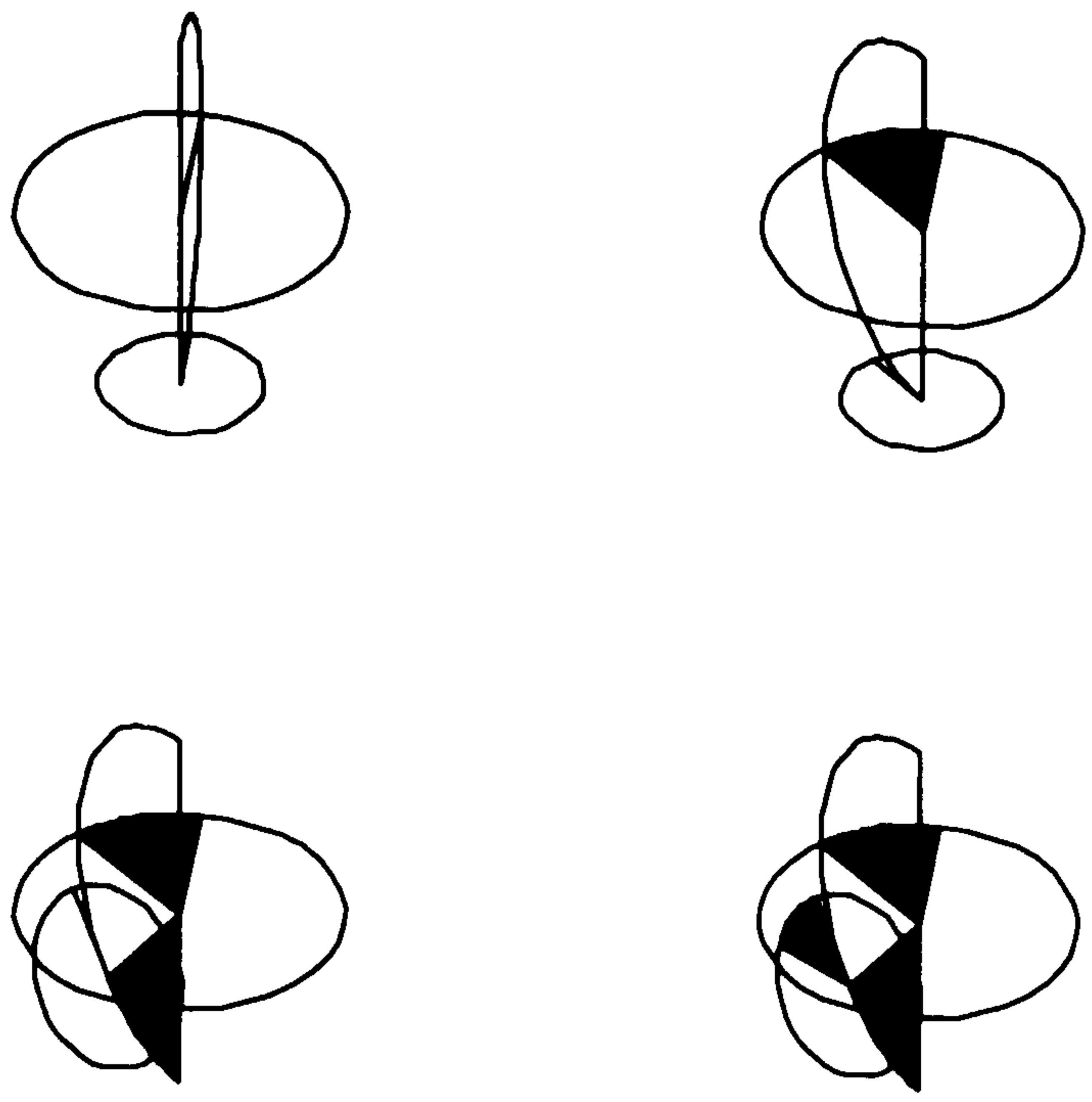


Figure 111: The three sequential rotations that make up the Euler angle convention

ıe International Society of Biomechanics recommendations for angular description are based on ɜ need to express the relative angles between two limb segments. They require that a coordinate ıme is defined in each segment, initially these two frames will be aligned with each other. The ree rotation angles are then defined as follows:

The first rotation occurs around one of the axes fixed in the first segment.

The **third** rotation occurs around one of the axes fixed in the second segment.

The second rotation takes place around an axis that is mutually perpendicular to the other two axes of rotation.

can be seen in Figure 112, that this convention is a generalisation of the Euler convention. though the ISB recommends that rotations are chosen to match the Euler conventions where ssible, other orders and axes of rotation are quite permissible. The rotation shown in the diagram ı z-x-y convention, but if the coordinate frame of the distal segment was redefined to exchange z and y axes then the Euler convention would result.

ıblems can occur with any sequential rotation set in situations where the first and third axes are ɟned. Under these conditions it becomes impossible to differentiate between the rotations about the first and third axes, and as long as their sum is constant, the actual values of each rotation can vary widely. This situation is sometimes described as *gymbal lock* after a similar failure that can occur with gymbal mounted gyroscope systems when two of their axes align.

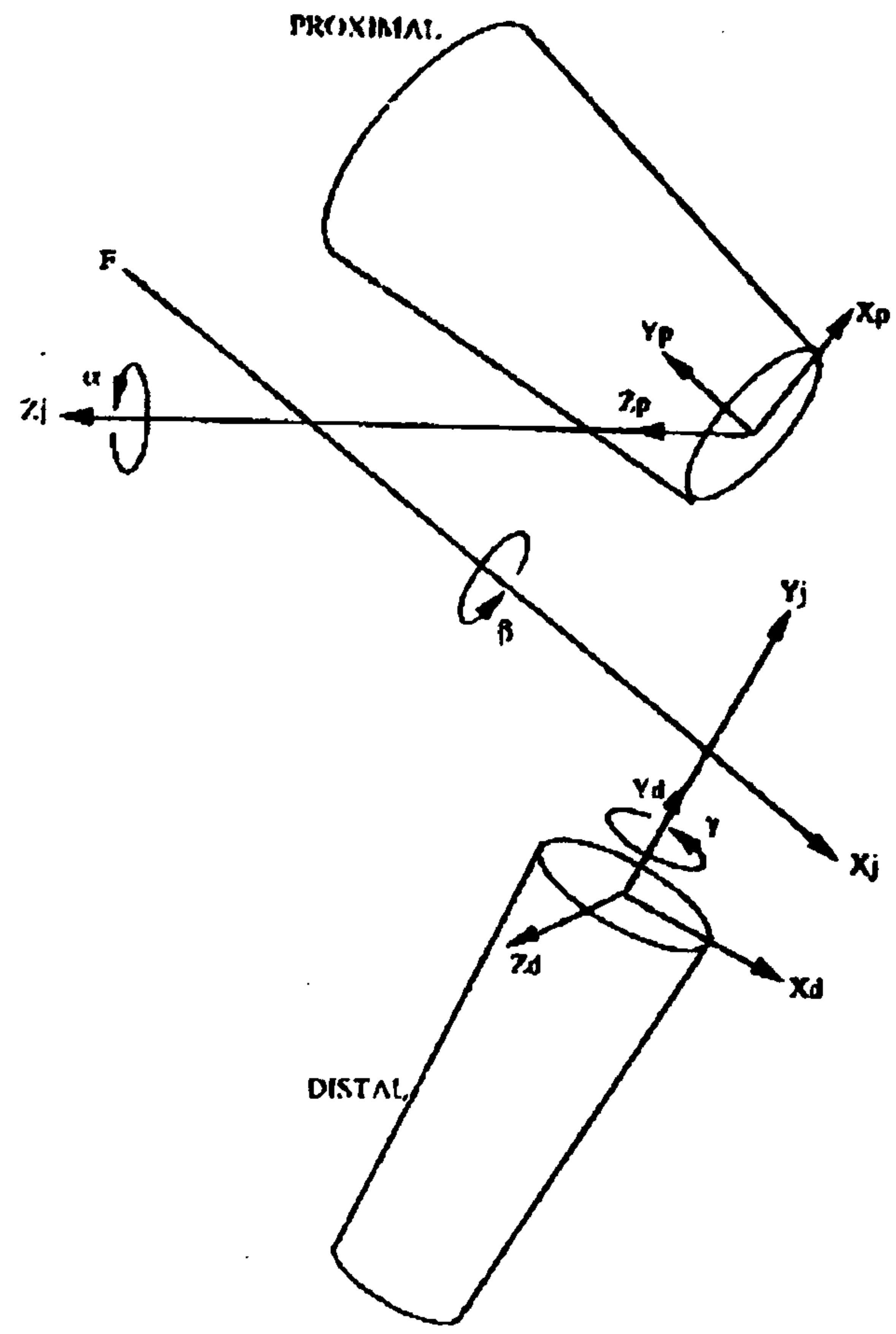


Figure 112: An example of ISB joint angle description conventions. (From [Wu and Cavanagh, 1995])

5.3.3 Matrix Transformations.

Most computational geometry is done using matrix mathematics. At its most basic level matrix arithmetic follows the rules below:

1. A matrix consists of a square or rectangular grid of elements; these elements can be numbers, variables or expressions.

2. the elements of a matrix are addressed as $\mathbf{A}_{rc}$ where a is a matrix of **M** rows and **N** columns, **r** is row number, from 1 to **M** and **c** is the column number, from 1 to **N**

3. To multiply two matrices together there must be the same number of columns in the first as rows in the second. The multiplication process **A.B** consists of multiplying the elements in the first row of **A** with the corresponding elements in the first column of **B** and summing the products.

The process is continued with the second row of **A** and the second column of **B** and so on. The resulting matrix has the same number of rows as **A** and columns as **B**.

4. Matrix multiplication is dependent on the order of the terms A.B≠B.A

5. A.B.C=A.(B.C)

6.3.4 Matrix Geometry

Any geometrical transformation can be carried out on a coordinate vector by either of the two approaches shown in Figure 113:

$$\begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \bullet \begin{bmatrix} x \\ y \\ z \end{bmatrix} \qquad \begin{bmatrix} x+l \\ y+m \\ z+n \end{bmatrix}$$

Figure 113: The matrix representation of rotation (left) and translation (right).

Where the first equation carries out rotations (where the co-ordinates are mutually dependent) and the second caries out translations (where they are not.)

6.3.5 The Translation Matrix

The translation matrix is relatively simple; l, m and n represent the difference in the X, Y and Z co-ordinates respectively between where an object is now and where one would like it to be.

6.3.6 The Rotation Matrix

The rotation matrix is somewhat more complex. It does follow some basic rules, however:

1. It is an *Orthogonal* matrix, i.e. its transpose (exchanging of rows and columns) is the same as its *inverse* (used for matrix division $A.A^{-1}=I$, where I is a matrix with all elements zero except the leading diagonal: - r1c1, r2c2 etc.)

2. The *determinant* of the matrix is always 1

3. The column vectors are of unit length (the sum of the squares of their elements is one)

Basic rotation matrices are given in Figure 114.

Rotation about the X axis by the angle θ: $\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}$

Rotation about the Y axis by the angle θ: $\begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}$

Rotation about the Z axis by the angle θ: $\begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$

Figure 114: Matrices for rotation about the global axes.

6.3.7 Direction Cosines.

The columns of the rotation matrix are described as direction cosines, they represent the cosines of the angles between the original axes (XYZ rows 1,2,3) and the transformed axes (XYZ cols. 1,2,3).

6.3.8 Homogenous Coordinates

Ideally one would like to have a single type of transformation to carry out both rotations and translations, such an approach can be achieved by the use of *Homogeneous Coordinates*.

By adding an extra element **h** to the bottom of the Cartesian co-ordinate vector, it becomes possible to create a 4x4 matrix of the form shown in Figure 115.

$$\begin{bmatrix} \mathbf{a} & b & c & l \\ d & e & f & m \\ g & h & i & n \\ 0 & 0 & 0 & 1 \end{bmatrix} \bullet \begin{bmatrix} x \\ y \\ z \\ h \end{bmatrix}$$

Figure 115: The elements of a homogeneous transformation matrix.

Translational elements are placed in the first three rows of the fourth column. Thus the matrix in figure *xx would apply a translation of 1 unit in the x direction, 2 units in the y and 3 in the z.

$$\begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 2 \\ 0 & 0 & 1 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 116: A homogeneous transformation matrix that would cause translation without rotation.

The case for a Euler angle rotational transformation is shown in Figure 117 Where ψ is the initial z rotation, θ is the subsequent x rotation and σ is the final rotation around the local z axis.

$$\begin{bmatrix} \cos(\psi)\cos(\sigma) - \sin(\psi)\cos(\theta)\sin(\sigma) & -\cos(\psi)\sin(\sigma) - \sin(\psi)\cos(\theta)\cos(\sigma) & \sin(\psi)\sin(\theta) & 0 \\ \sin(\psi)\cos(\sigma) + \cos(\psi)\cos(\theta)\sin(\sigma) & -\sin(\psi)\sin(\sigma) + \cos(\psi)\cos(\theta)\cos(\sigma) & -\cos(\psi)\sin(\theta) & 0 \\ \sin(\psi)\sin(\sigma) & \sin(\psi)\cos(\sigma) & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 117: The 4 by4 homogeneous transformation matrix for Euler Rotations

6.3.9 Serial link manipulators

When studying limb motions it is intuitive to think of the position of the hand as the cumulative result of the positions of various joints, typically the shoulder, the elbow and the wrist. Mathematically, however, this creates some difficulty. If the angle of the elbow is defined carefully in global space using Euler angles or an appropriate transformation matrix, and the angle of the shoulder joint is then altered, new angles and matrices would need to be calculated despite the fact that the elbow joint has not itself been altered. To avoid this inconvenience it is possible to construct matrices in which the position of each joint is expressed relative to the previous segment in a chain leading from the hand (or *end-effector*) back to whatever part of the body is firmly rooted to the environment.

Joints between segments can have up to six degrees of freedom, but typically, they have far less. As with the general description of motion there are two basic types of movement possible between segments: rotation and translation. A joint that allows rotation around a single axis is called a *revolute joint* and one that allows translation along a single axis is called a *translational joint*.

One of the most common conventions for the description of such *kinematic chains* was developed for the analysis of robot arms, or *serial link manipulators* as they are known to the robotics community, this method is known as the *Denavit-Hartenberg convention* and it is described below. A full explanation of the Denavit-Hartenberg system can be found in [Corke, 1996; Spong and Vidyasagar, 1989] or any textbook on robotics.

Denavit-Hartenberg models consist of a sequence of links connected by joints. Each joint can only have a single degree of freedom (one axis of movement), but more complex joints can be modelled by connecting various simple joints using links with zero length. As each joint only has one degree of freedom its position can be specified using a single *joint variable*. Each link in a Denavit-Hartenberg model has it's own local coordinate system, and the z axis of this coordinate frame is always positioned such that the next link in the chain rotates about it (in the case of a revolute joint) or slides along it (in the case of a translational joint). The global coordinate system is therefore always defined so that its z axis corresponds with the first joint in the sequence. The Denavit-Hartenberg convention then requires that the other two axes are positioned so that two assumptions are satisfied:

1. The x axis of one coordinate frame has to be perpendicular to the z axis of the previous frame.

2. The x axis of one coordinate frame must intersect the z axis of the previous frame.

The transformation between one axis and the next can then be expressed by the combination of four transformations:

1. A rotation around the z axis, called the *rotation* and usually given the symbol $\boldsymbol{\theta}$.

2. A translation along this z axis, called the *offset* and usually given the symbol **d**.

3. A translation along the x axis, called the *length* and usually given the symbol **a**.

4. A rotation around this x axis called the *twist* and usually given the symbol **α**.

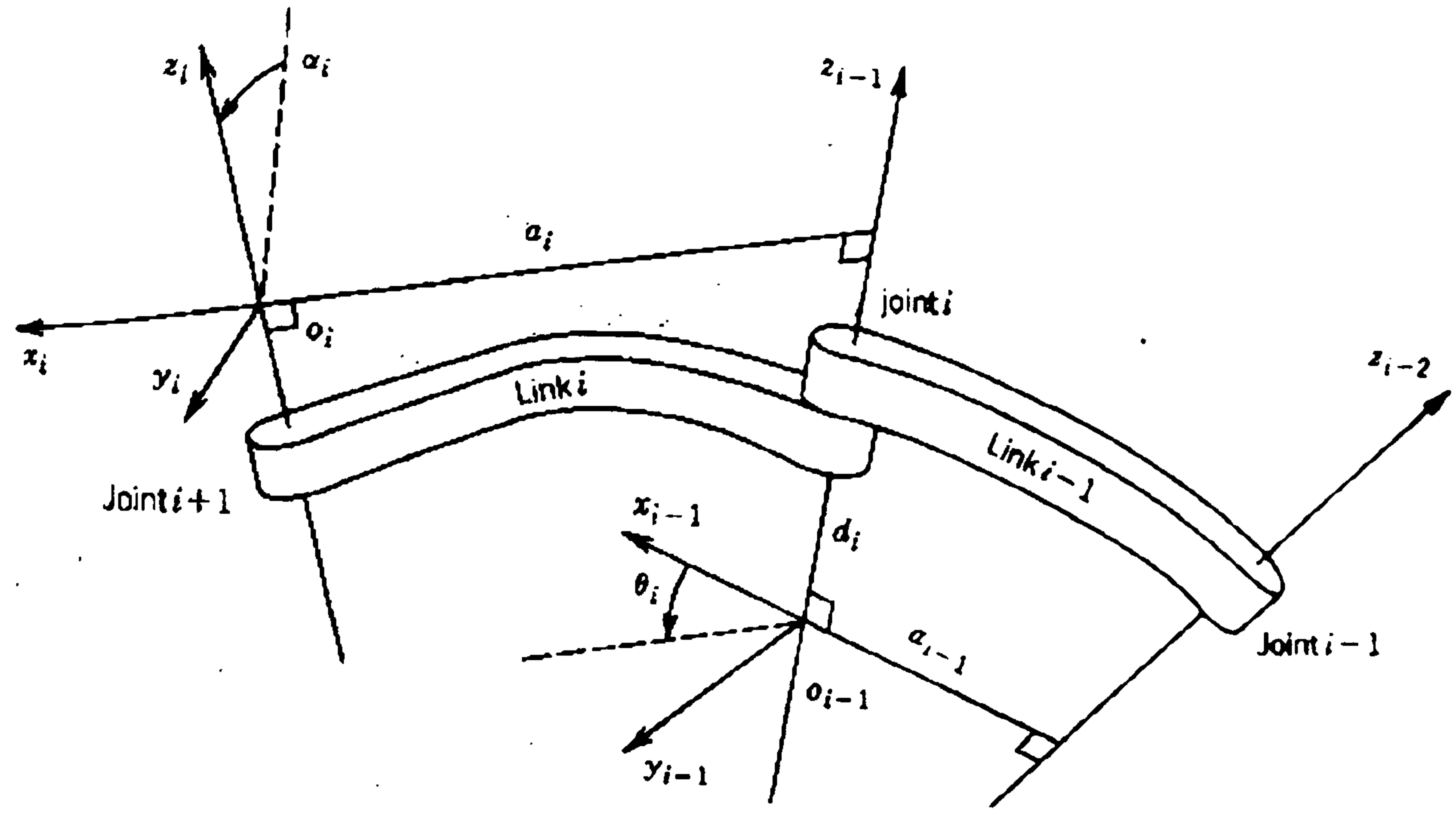


Figure 118: Denavit-Hartenberg coordinate assignment. (From [Spong and Vidyasagar, 1989])

An example of Denavit-Hartenberg axis assignment is shown in Figure 118. It should be noted that the origin of a link's coordinate system may not lie on the link itself. If the local axes are set up in this consistent manner, then the transformation can be expressed as follows: [Spong and Vidyasagar, 1989]

$$\begin{bmatrix} \cos(\theta) & -\sin(\theta)\cos(\alpha) & \sin(\theta)\sin(\alpha) & a\cdot\cos(\theta) \\ \sin(\theta) & \cos(\theta)\cos(\alpha) & -\cos(\theta)\sin(\alpha) & a\cdot\sin(\theta) \\ 0 & \sin(\alpha) & \cos(\alpha) & d \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 119: Denavit-Hartenberg transformation matrix.

When a model is run, all the parameters remain fixed with the exception of the joint variables (**θ** in the case of a revolute joint and **d** in the case of a translational joint). Once the Denavit-Hartenberg parameters have been established, only the joint variables have to be entered into the equation to determine the position of the entire structure.

A variety of computer programs are available for the simulation of robots and other serial link mechanisms, all such activity in this work was carried out using the Robotics Toolbox [Corke, 1996], an extension of the MATLAB matrix manipulation and numerical analysis package.

6.3.10 Torque estimation

The key advantage of a biomechanical modelling system is its ability to provide estimates of the forces and torques being transmitted through the limb segments and joints. These forces are virtually impossible to measure or estimate any other way. In the field of robotics there are several methods available for the modelling of forces [Spong and Vidyasagar, 1989]. The method used for torque estimation in this work is known as the *recursive Newton-Euler* method. Detailed derivation of the method used is not given here, but the basis of the method is described below:

The Newton-Euler method is based upon Newton's laws of motion: Every action has an equal and opposite reaction, The total force applied to a body equals the rate of change of linear momentum and the total torque applied to a body equals the rate of change of angular momentum.

To calculate the forces and torques each link in the model is treated in turn. Starting at the root of the model, the forces and torques caused by the mass and motion of each link on itself are calculated. Once the individual forces have been calculated, the recursion is repeated backward from the end-effector to the root, with forces transferred from each link to the next most proximal being calculated. At the end of this second series of calculations the total torques acting on the model are available. Thus the process is one of *forwards-backwards recursion.*

The Recursive Newton-Euler method is a general technique that can be used for dynamic calculations, however if the first and second differential terms of the joint angles are set to zero, then a quasi-static calculation will take place. In the majority of the torque estimation activity in this work the quasi-static approach was adopted. The calculations were carried out using the RNE routines of the MATLAB Robotics toolbox [Corke, 1996].

6.4 Sensor data processing

6.4.1 Introduction

The Data collected by the ETALOT program underwent a series of transformations in order to produce biomechanical data. The section demonstrates that process using a small sample of data.

6.4.2 Raw data

The ETALOT program produced ASCII data files of the following format:

Sensor0_X	Sensor0_y	Sensor0_z
$R0_{11}$	$R0_{12}$	$R0_{13}$
$R0_{21}$	$R0_{22}$	$R0_{23}$
$R0_{31}$	$R0_{32}$	$R0_{33}$
Sensor1_X	Sensor1_y	Sensor1_z
$R1_{11}$	$R1_{12}$	$R1_{13}$
$R1_{21}$	$R1_{22}$	$R1_{23}$
$R1_{31}$	$R1_{32}$	$R1_{33}$

Where Rn_{rc} is an element of the rotation matrix for sensor n.

Typical output is shown below:

```
602.4354 -394.6959 -466.9332
0.8842 0.4368 -0.1655
-0.4668 0.8402 -0.2760
0.0185 0.3213 0.9468
299.4781 -389.6603 -331.1564
0.9507 -0.0844 0.2985
0.0497 0.9913 0.1220
-0.3062 -0.1011 0.9466
```

In a full data file this pattern would be repeated through file for each sensor reading.

6.4.3 Conversion to homogeneous form

The first stage in the processing of the data was the conversion of the ETALOT output file into two sets of homogeneous matrices, representing the position and orientation of each sensor throughout the measurement process. As the MATLAB program with which the processing was done could only operate on two dimensional matrices (this has since changed) the homogeneous matrices were reshaped and into a 1 by 16 row vector, and each vector was stored as a row in a large 2D matrix.

```
s0 =

 Columns 1 through 7

 0.8842 -0.4668 0.0185 0 0.4368 0.8402 0.3213

 Columns 8 through 14

 0 -0.1655 -0.2760 0.9468 0 602.4354 -394.6959

 Columns 15 through 16

 -466.9332 1.0000

s1 =

 Columns 1 through 7

 0.9507 0.0497 -0.3062 0 -0.0844 0.9913 -0.1011

 Columns 8 through 14

 0 0.2985 0.1220 0.9466 0 299.4781 -389.6603

 Columns 15 through 16

 -331.1564 1.0000
```

The MATLAB "reshape" command can then be used to convert rows back into 4 x 4 homogeneous matrices:

```
» reshape(s0,4,4)

ans =

 0.8842 0.4368 -0.1655 602.4354
 -0.4668 0.8402 -0.2760 -394.6959
 0.0185 0.3213 0.9468 -466.9332
 0 0 0 1.0000


» reshape(s1,4,4)
```

```
ans =

0.2985 -0.0844 -0.9507 299.4781
0.1220 0.9913 -0.0497 -389.6603
0.9466 -0.1011 0.3062 -331.1564
0 0 0 1.0000
```

However, all processing routines were designed to operate on n x 16 flattened matrices.

6.4.4 Axis exchange

The peculiarities in the calibration process discussed in Section 2.3.17 required the swapping of certain axis in the forearm sensor (sensor 1). This process was completed by swapping columns of the flattened matrix:

```
» s1=touswap(s1)

s1 =

 Columns 1 through 7

 0.2985 0.1220 0.9466 0 -0.0844 0.9913 -0.1011

 Columns 8 through 14

 0 -0.9507 -0.0497 0.3062 0 299.4781 -389.6603

 Columns 15 through 16

 -331.1564 1.0000
```

6.4.5 Biomechanical angles

The data was now ready to be converted into biomechanical angles using the sensor-model fitting process. The output from the routine was an n x 5 matrix of angles that could then be used to drive the Denavit-Hartenberg limb model (Section 2.3.10)

```
» q=toucan(s0,s1)

q =

 -2.1109 0.3277 -1.0974 1.0917 -2.7295
```

6.4.6 Denavit-Hartenberg parameters

The TOUCAN routine produced a list of joint variables that were applicable to a Denavit-Hartenberg model. In order to reconstruct the model with the computer, the other parameters of the model had to be specified (Section 2.3.12). The MATLAB Robotics Toolbox [Corke, 1996] which was used for all the kinematics and dynamics activity in this project required an *m* x 20 input matrix, where *m* was the number of degrees of freedom in the model, and the columns are specified below:

1	alpha	link twist angle
2	A	link length
3	theta	link rotation angle
4	D	link offset distance
5	sigma	joint type, 0 for revolute, non-zero for prismatic
6	mass	mass of the link
7	rx	link COG with respect to the link coordinate frame
8	ry	
9	rz	
10	Ixx	elements of link inertia tensor about the link COG
11	Iyy	
12	Izz	
13	Ixy	
14	Iyz	
15	Ixz	
16	Jm	armature inertia
17	G	reduction gear ratio. joint speed/link speed
18	B	viscous friction, motor referred
19	Tc+	coulomb friction (positive rotation), motor referred
20	Tc-	coulomb friction (negative rotation), motor refereed

As inertial terms were ignored in this work, and there are obviously no motor-friction terms to be considered in a human limb, all columns after column 9 were set to zero. A typical input matrix is shown below:

```
dhmat =

 Columns 1 through 7

 -1.5708 0 0 0 0 0 0
 1.5708 0 0 0 0 0 0
 -1.5708 0 0 0.2615 0 2.5929 0
 1.5708 0 0 0 0 0 0
```

```
0 0 0 0.3750 0 2.4132 0

Columns 8 through 14

0 0 0 0 0 0 0
0 0 0 0 0 0 0
0.1475 0 0 0 0 0 0
0 0 0 0 0 0 0
0 0.1968 0 0 0 0 0

Columns 15 through 20

0 0 0 0 0 0
0 0 0 0 0 0
0 0 0 0 0 0
0 0 0 0 0 0
0 0 0 0 0 0
```

6.4.7 Torque Calculation

The Robotics Toolbox function "gravload" was used to calculate joint torques. This function simply calls the recursive Newton-Euler function "rne" with velocity and acceleration terms set to zero. It was, however, an extremely time-consuming routine to run. On a 66MHz PC the routine took approximately 0.75 seconds to process each sensor frame. This is 25 times slower than the recording rate of the sensors themselves, and resulted in processing times of up to 36 hours for the large experimental data sets used in this work. The torque output from the angle and Denavit-Hartenberg data used above is shown here.

```
» t=gravload(dhmat,q,)

t =

 0.0000 -10.1202 -3.4412 -12.2897 0
```

Note that the first and last joints always experience zero torque. The first because the joint axis is always parallel to the direction of gravity, and the last because all the mass of the forearm and hand segment always produces zero moment about the long axis of the forearm.

6.4.8 MATLAB codes

The functions used to carry out the processes described above were written using the MATLAB language [The Math Works, 1996]. Those routines not taken directly from the Robotics Toolbox [Corke, 1996] are listed below.

```
function [s0,s1]=getsens(filename)
% GETSENS reads an INSIDETRAK data file
%
%       [s0,s1]=GETSENS(filename)
%
%       The file format must be:-
%
%       2 sensors running
%
%       Data included:-
%
%       X,Y,Z in mm
%       X direction cosines
%       Y direction cosines
%       Z direction cosines
%
%       12 pieces of data per sensor.
%

file=fopen(filename);
data=fscanf(file,'%f',[24,inf]);
s0=data(1:12,:);
s1=data(13:24,:);
» type s2f

function m=s2f(s)
% S2F converts sensor data into a flattened homogeneous matrix
%
%       [m]=S2F(s)
%
%       the sensor data is a matrix in ETALOT format.
%       m is an n x 16 matrix, whereby each row may be
%       RESHAPEd (n,4,4) into a homogeneous transform.
%
%       if a single record is supplied the ouput matrix is homogeneous
%
%       n.b at the moment this file will ruin any 12 reading data sets
%       by inverting them.

%check that the input arguments are ETALOT data
if numrows(s)~=12&numcols(s)~=12
       error('Bad data');
end;

%put data in row order
if numcols(s)==12
       s=s';
end;

o=zeros(numcols(s),1);
i=o+1;

       m=[     s(4,:)' s(7,:)' s(10,:)' o,...
               s(5,:)' s(8,:)' s(11,:)' o,...
               s(6,:)' s(9,:)' s(12,:)' o,...
               s(1,:)' s(2,:)' s(3,:)' i];

if numrows(m)==1
       m=reshape(m,4,4);
```

```
function out=touswap(in)
% TOUSWAP alters some axes for Toucan purposes
%
%       out=touswap(in)
```

```
%
%       In the calibration process for the toucan test
%       The forearm is calibrated in the wrong position
%       this routine swaps axes in the following way:-
%
%       X becomes Z
%       Y becomes -Y
%       Z becomes X
%
%       This process sets the arm zero orientation in the
%       anatomical position, segments hanging down,
%       palm facing forwards.
%
%       The routine works with both normal and flattened
%       homogeneous matrices

if size(in)==[4 4],
        out=[in(:,3) in(:,2) -in(:,1) in(:,4)];
elseif numcols(in)==16,
        out=[in(:,9:12) in(:,5:8) -in(:,1:4) in(:,13:16)];
else
        error('Bad data');
end;



function dhs=toucan(arm,fore)
% TOUCAN obtains dh parameters a two sensor process
%
%       dhs=TOUCAN(arm,fore)
%
%       arm and fore are flattened homogeneous transform matrices,
%       the assumption being that the z axes of each are aligned
%       along the long axes of the limb segments, that the elbow is
%       a simple hinge joint, and that in the limb's zero position
%       all axes align with the global axes.
%
%       The dh parameters produced are for a five d.o.f. manipulator
%       with a spherical shoulder joint, a hinged elbow and forearm
%       rotation.
%
%       n.b also works with single matrices, flat or 4x4

if size(arm)==[4 4]
        arm=reshape(arm,1,16);
end;
if size(fore)==[4 4]
        fore=reshape(fore,1,16);
end;

if numcols(arm)~=16|numcols(fore)~=16|numrows(arm)~=numrows(fore)
        error('Bad data');
end;

for i=1:numrows(arm)


        % pull the matrices back to squares
        a=reshape(arm(i,:),4,4);
        f=reshape(fore(i,:),4,4);

        % get euler angles from a
        aeul=tr2eul(a);

        % obtain relative transformation
        e=a'*f;

        % get euler angles from e
        eul=tr2eul(e);
        dhs(i,:)=[aeul eul];

end;

% combine rotations
dhs=[dhs(:,1:2) dhs(:,3)+dhs(:,4) dhs(:,5:6)];
```

6.5 Statistical power calculation

Power calculation is a statistical technique that is used to relate levels of statistical significance to the physical size of the expected effect.

In most statistical tests, there are 2 hypotheses: -

1. The Experimental Hypothesis: The hypothesis that the factors under analysis have some measurable effect on the dependent variable(s).
2. The Null Hypothesis: The hypothesis that the dependent variables are not actually affected by the experimental factors, and that any differences observed are merely random effects.

Most statistical tests indicate the probability of false rejection of the null hypothesis; this is called the *Alpha* error. There is also, however, a probability that the experimental hypothesis was rejected falsely, this is called the *Beta* error. Statistical power is defined as 1-Beta, so a power of 0.9 indicates 10% probability that the experimental hypothesis was falsely rejected, i.e. the experiment was not sensitive enough to detect differences that actually exist. Power is closely related to the number of subjects or cases under analysis; typical experimental work seeks to produce powers in the range from 0.7 to 0.9. To estimate power one must know two things: -

1. The likely variability of the statistic under analysis within cases for which the experimental conditions are the same.
2. The expected difference in means between different experimental groups if the experimental hypothesis is proved to be true.

Expected difference is then divided by expected variability to give a *Critical Effect Size*. Once the critical effect size is known, tables can be consulted to suggest the appropriate number of subjects to give the required statistical power.

Power calculations therefore allow experimental designers to ensure that they have enough subjects to detect effects at a level that they consider interesting.

6.6 Glossary

Abduction elevation of a limb segment away from the centre line of the body in the frontal plane.

Additivity A characteristic of certain sets of design parameters in which the state of any one factor will not affect the state of any other: no *interaction* occurs.

Adduction movement of a limb segment towards the centre line of the body in the frontal plane.

Affordance the ability of a design to allow a certain style of use: A flat panel on a door affords pushing but not pulling.

Aliasing error A type of error that can occur in motion analysis when a motion is sampled at too low a frame rate, leading to the appearance of false motion patterns in the data.

Anatomical position The neutral position of the body when all joint angles are considered to be zero. For the upper limbs the arms hang vertically by the sides with the palms facing forwards.

Anterior near the front of the body.

Distal away from the trunk.

Drift The tendency of some sensor systems to slowly change the values they record even when the input signal remains constant.

Extension movement of a limb segment towards the centre line of the body in the sagittal plane.

Flexion movement of a limb segment away from the centre line of the body in the sagittal plane.

Frame rate The number of measurement cycles a motion analysis system is capable of making each second.

Frontal plane a vertical plane which divides the body into front and back parts.

Humerus The long bone in the upper arm

Lag The time taken between an event occurring and its being reported by a sensor system.

Lateral away from the midline of the body.

Medial near the midline of the body.

Noise factor In robust design: a factor which would not normally be within the control of the design team, but which is artificially controlled for experimental purposes

Noise variation in a signal that cannot be attributed to any particular cause.

Posterior near the rear of the body.

Pronation rotation of the forearm that turns the palm downwards.

Proximal near the trunk.

Quality characteristic Any measurable value that can be used to judge the quality of a design.

Radius The long bone in the forearm that joins the hand on the thumb side.

Reach envelope A space within which all controls must be placed if they are to be immediately accessible.

Rigid body model A biomechanical model in which all elements are assumed to have constant size and shape.

Robust design A design optimisation technique in which the aim is to make a product insensitive to external variability.

Sagittal plane a vertical plane which divides the body into left and right parts.

Signal factor in robust design: a design parameter that is adjusted by the design team in order to improve the performance of a product

Signal to noise ratio a transformation applied to quality characteristics in Taguchi's methods in order to more rapidly draw out the important results.

Stereolithography A technique for the production of prototype plastic parts in which a laser is used to cure successive layers of epoxy resin.

Supination rotation of the forearm that turns the palm upwards.

Taguchi methods A series of methods for *robust design* developed by Dr. Genichi Taguchi.

Transverse plane a horizontal plane which divides the body into top and bottom parts.

Ulna The long bone in the forearm that joins the hand on the little finger side.

7. Results

7.1 Units

In all the following results, torque is given in Nm and angles in radians.

7.2 Quantification of user variability: results.

7.2.1 Angular Measures

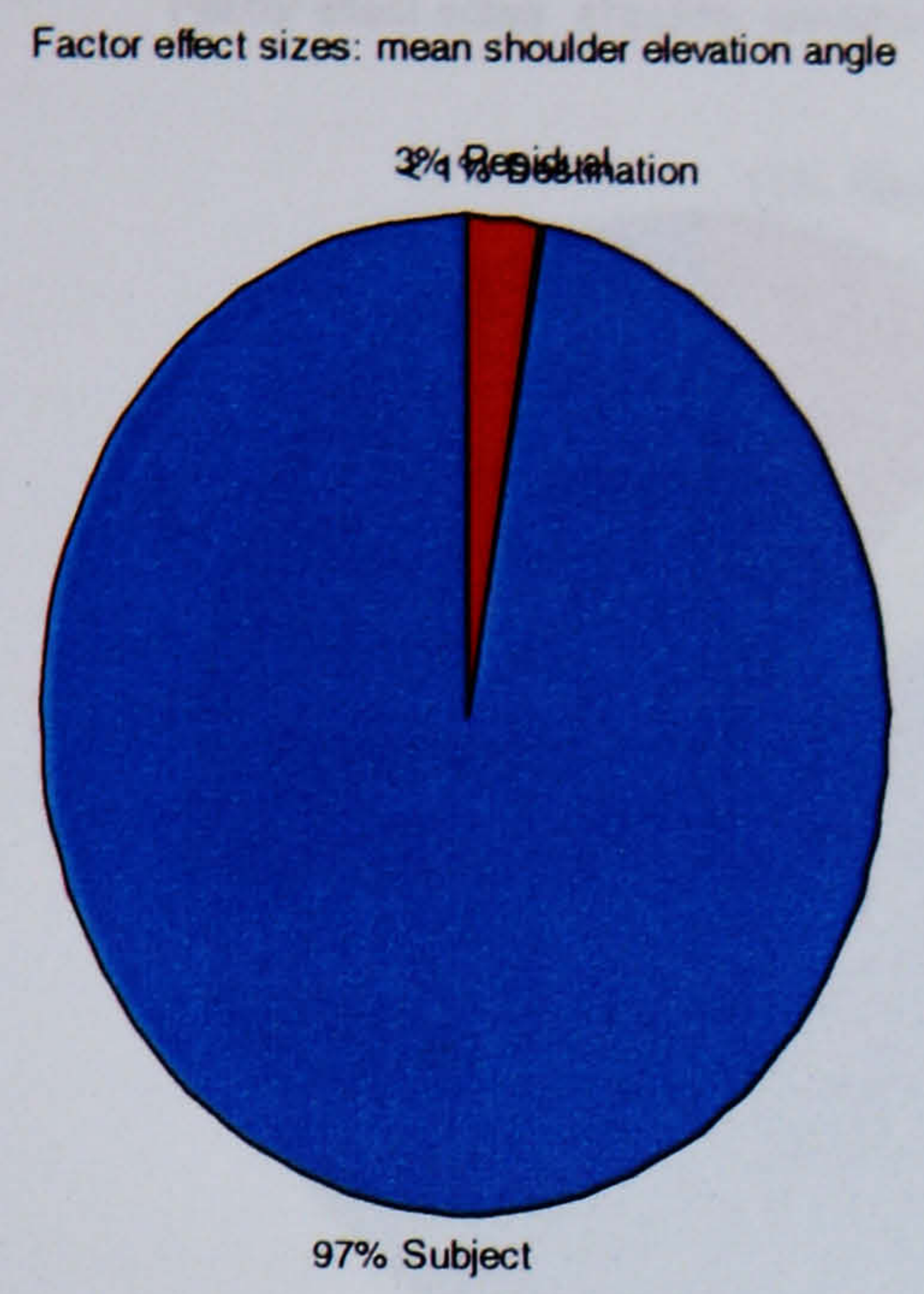
7.2.1.1 Shoulder elevation mean : summary table

	Mean shoulder elevation angle										
	All	**Near**	**Far**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**	**Sub 6**	**Sub 7**	**Sub 8**
Mean	1.275	1.274	1.276	1.327	1.227	1.251	1.330	1.327	1.345	1.224	1.168
std	0.078	0.092	0.061	0.026	0.079	0.053	0.030	0.041	0.070	0.040	0.023
Min	1.040	1.040	1.156	1.276	1.040	1.138	1.288	1.258	1.169	1.156	1.138
Max	1.451	1.451	1.386	1.363	1.314	1.300	1.390	1.406	1.451	1.297	1.229
Range	0.411	0.411	0.231	0.087	0.274	0.162	0.102	0.149	0.282	0.141	0.091
% of mean											
STDEV	6.12%	7.25%	4.78%	1.94%	6.41%	4.25%	2.28%	3.09%	5.19%	3.25%	1.94%
Range	32.24%	32.26%	18.08%	6.53%	22.34%	12.95%	7.70%	11.21%	20.95%	11.53%	7.79%

7.2.1.2 Shoulder elevation mean Value:- ANOVA

```
 Sum of Mean Sig
Source of Variation Squares DF Square F of F

Main Effects .483 8 .060 24.894 .000
 SUBJECT .483 7 .069 28.443 .000
 DESTINAT .000 1 .000 .048 .827

Explained .483 8 .060 24.894 .000

Residual .289 119 .002

Total .772 127 .006
```

7.2.1.3 Shoulder elevation mean Value: Relative effect sizes



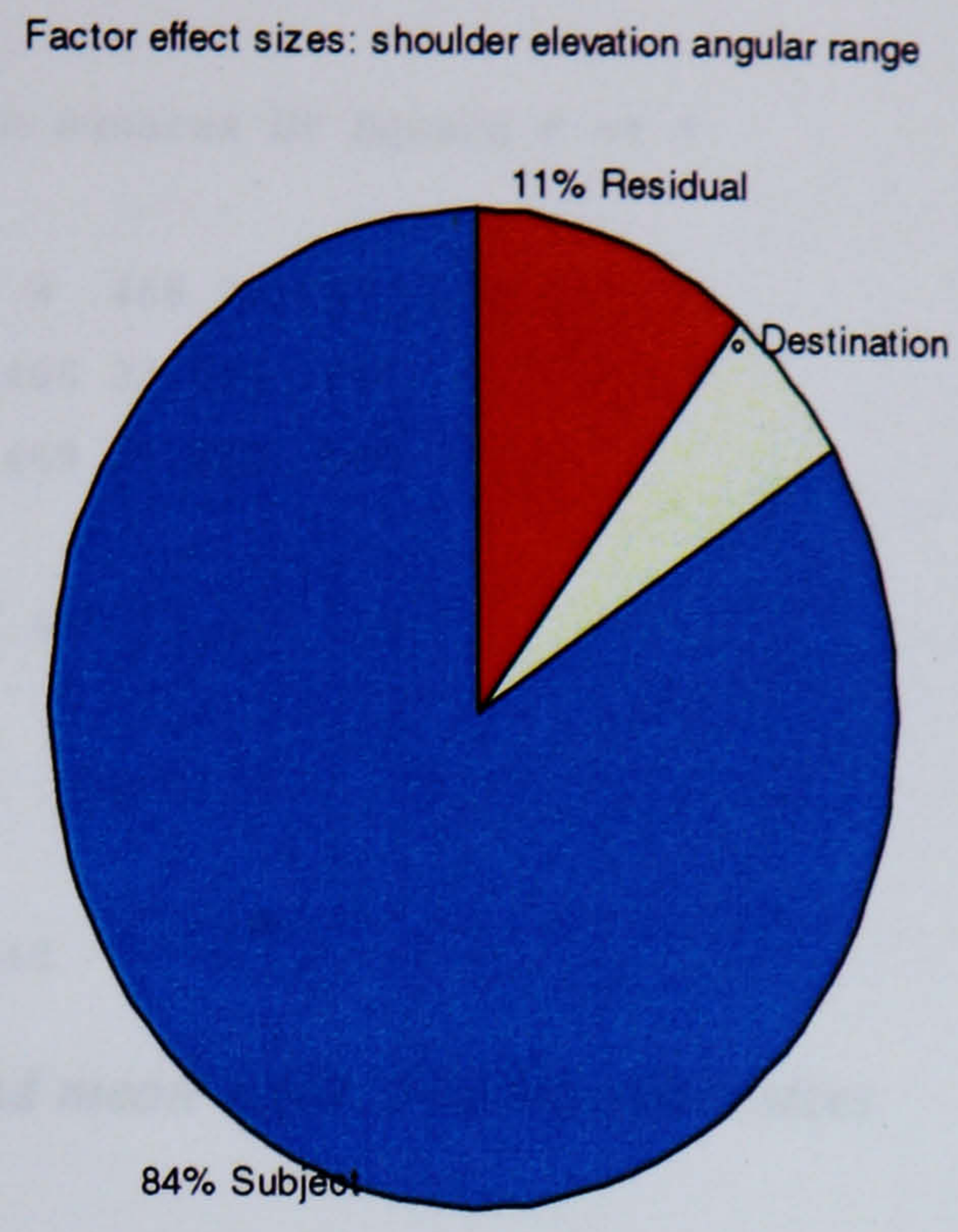
7.2.1.4 Shoulder elevation range: summary table

	Shoulder elevation angular range										
	All	**Near**	**Far**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**	**Sub 6**	**Sub 7**	**Sub 8**
Mean	0.203	0.198	0.208	0.160	0.237	0.183	0.120	0.221	0.260	0.277	0.167
std	0.093	0.077	0.108	0.051	0.087	0.035	0.071	0.132	0.093	0.076	0.059
Min	0.017	0.095	0.017	0.064	0.087	0.134	0.017	0.096	0.136	0.125	0.094
Max	0.577	0.414	0.577	0.295	0.418	0.247	0.274	0.577	0.443	0.395	0.298
Range	0.560	0.319	0.560	0.231	0.331	0.112	0.258	0.481	0.307	0.270	0.204
% of mean											
STDEV	45.94%	38.70%	51.84%	32.02%	36.84%	18.93%	58.95%	59.69%	35.75%	27.30%	35.56%
Range	275.7%	160.9%	269.3%	144.7%	139.9%	61.3%	214.1%	217.8%	117.9%	97.4%	122.5%

7.2.1.5 Shoulder elevation range: ANOVA

```
 Sum of Mean Sig
Source of Variation Squares DF Square F of F

Main Effects .333 8 .042 6.413 .000
 SUBJECT .330 7 .047 7.264 .000
 DESTINAT .003 1 .003 .457 .500

Explained .333 8 .042 6.413 .000

Residual .773 119 .006

Total 1.106 127 .009
```

7.2.1.6 *Shoulder elevation range: relative factor effects*



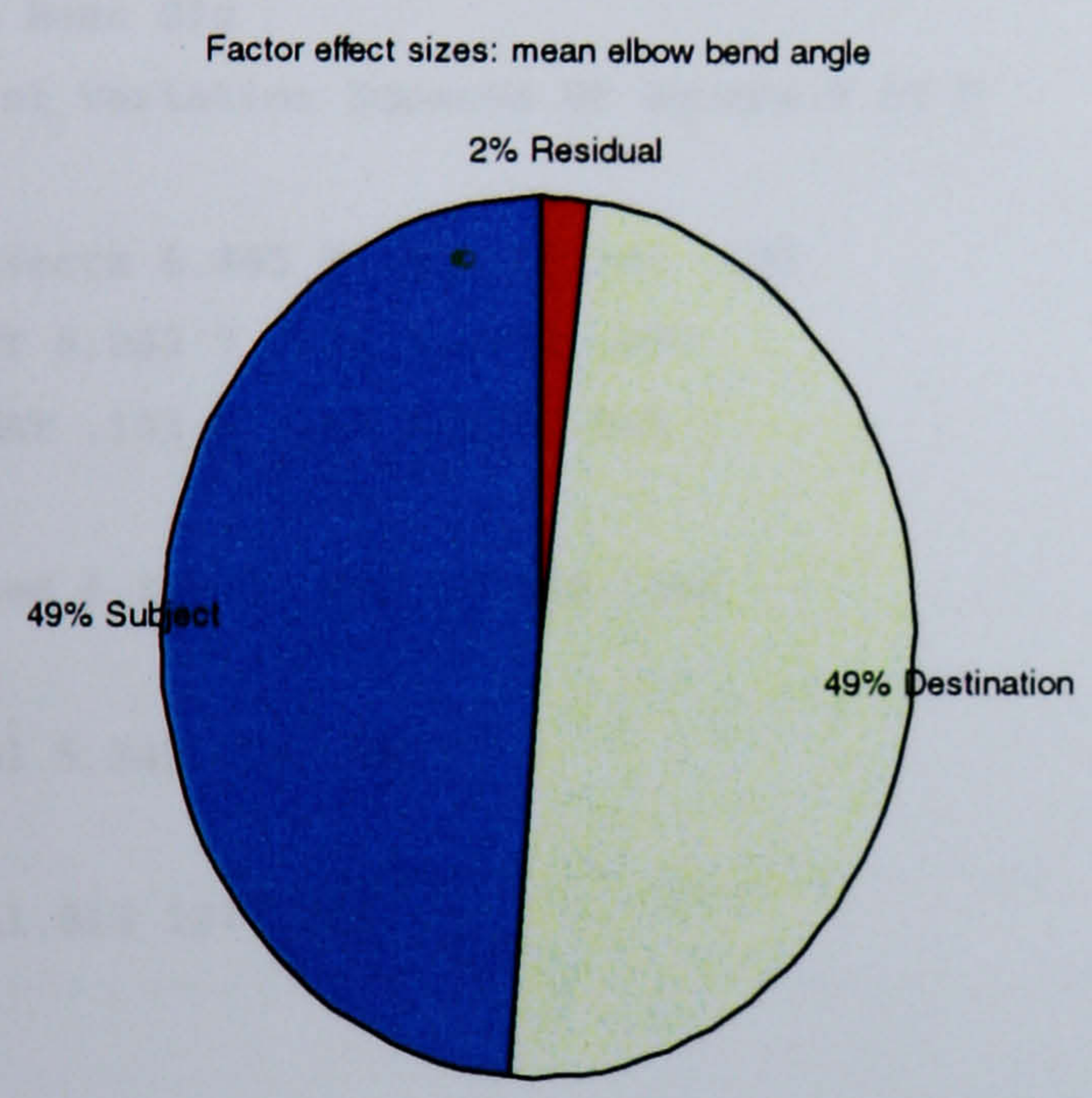
7.2.1.7 *Elbow bend mean : summary table*

	Mean elbow bend angle										
	All	**Near**	**Far**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**	**Sub 6**	**Sub 7**	**Sub 8**
Mean	1.040	1.100	0.979	1.072	1.304	1.166	0.831	1.067	0.829	0.907	1.141
std	0.219	0.253	0.158	0.163	0.234	0.079	0.067	0.227	0.130	0.142	0.080
Min	0.625	0.670	0.625	0.865	0.973	1.076	0.721	0.756	0.625	0.680	1.014
Max	1.757	1.757	1.327	1.555	1.757	1.280	0.915	1.560	1.086	1.148	1.325
Range	1.131	1.087	0.702	0.690	0.784	0.204	0.194	0.804	0.460	0.468	0.311
% of mean											
STDEV	21.03%	22.99%	16.14%	15.22%	17.96%	6.77%	8.03%	21.29%	15.68%	15.71%	7.03%
Range	108.8%	98.8%	71.7%	64.4%	60.1%	17.5%	23.4%	75.3%	55.5%	51.6%	27.2%

7.2.1.8 Elbow bend mean value: ANOVA

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	3.732	8	.466	23.697	.000
SUBJECT	3.262	7	.466	23.676	.000
DESTINAT	.469	1	.469	23.850	.000
Explained	3.732	8	.466	23.697	.000
Residual	2.342	119	.020		
Total	6.074	127	.048		

7.2.1.9 Elbow bend mean value: relative effect sizes



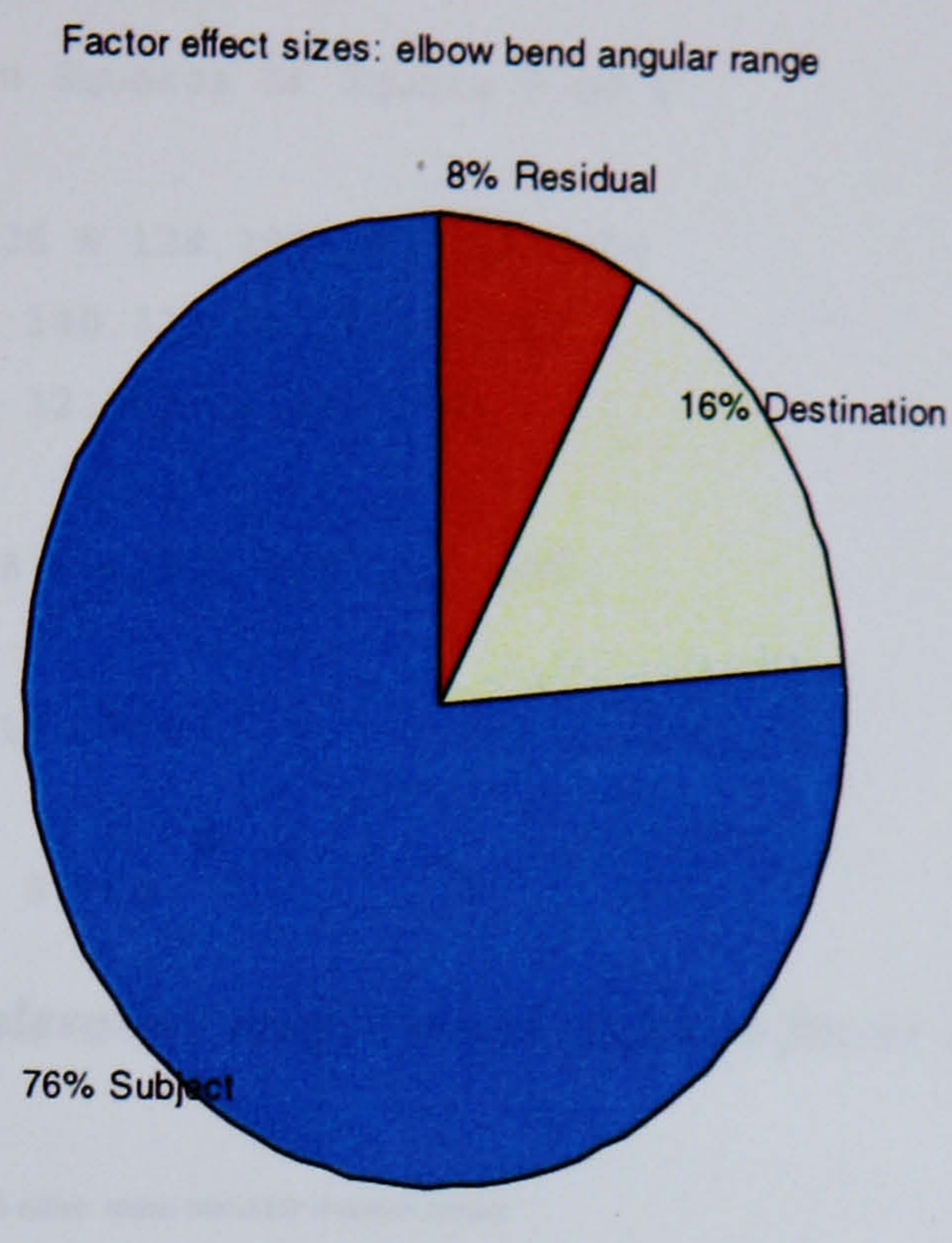
7.2.1.10 Elbow bend range: summary table

	Elbow bend angular range										
	All	Near	Far	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5	Sub 6	Sub 7	Sub 8
Mean	1.449	1.411	1.486	1.613	1.292	1.243	1.414	1.072	1.507	1.711	1.738
std	0.305	0.340	0.263	0.168	0.265	0.064	0.226	0.351	0.205	0.207	0.083
Min	0.484	0.484	0.866	1.219	0.760	1.174	1.085	0.484	1.194	1.403	1.571
Max	2.112	2.010	2.112	1.862	1.600	1.330	1.961	1.715	1.940	2.112	1.9[illegible]
Range	1.629	1.526	1.247	0.643	0.840	0.156	0.876	1.231	0.746	0.709	0.330
% of mean											
STDEV	21.05%	24.10%	17.67%	10.44%	20.53%	5.18%	15.96%	32.75%	13.58%	12.10%	4.8[illegible]%
Range	112.4%	108.2%	83.9%	39.9%	65.0%	12.6%	62.0%	114.9%	49.5%	41.5%	19.0%

7.2.1.11 Elbow bend range: ANOVA

```
 Sum of Mean Sig
Source of Variation Squares DF Square F of F

Main Effects 6.465 8 .808 17.984 .000
 SUBJECT 6.283 7 .898 19.972 .000
 DESTINAT .183 1 .183 4.062 .046

Explained 6.465 8 .808 17.984 .000

Residual 5.348 119 .045

Total 11.813 127 .093
```

7.2.1.12 *Elbow bend range: relative factor effects*



7.2.2 Torque measures

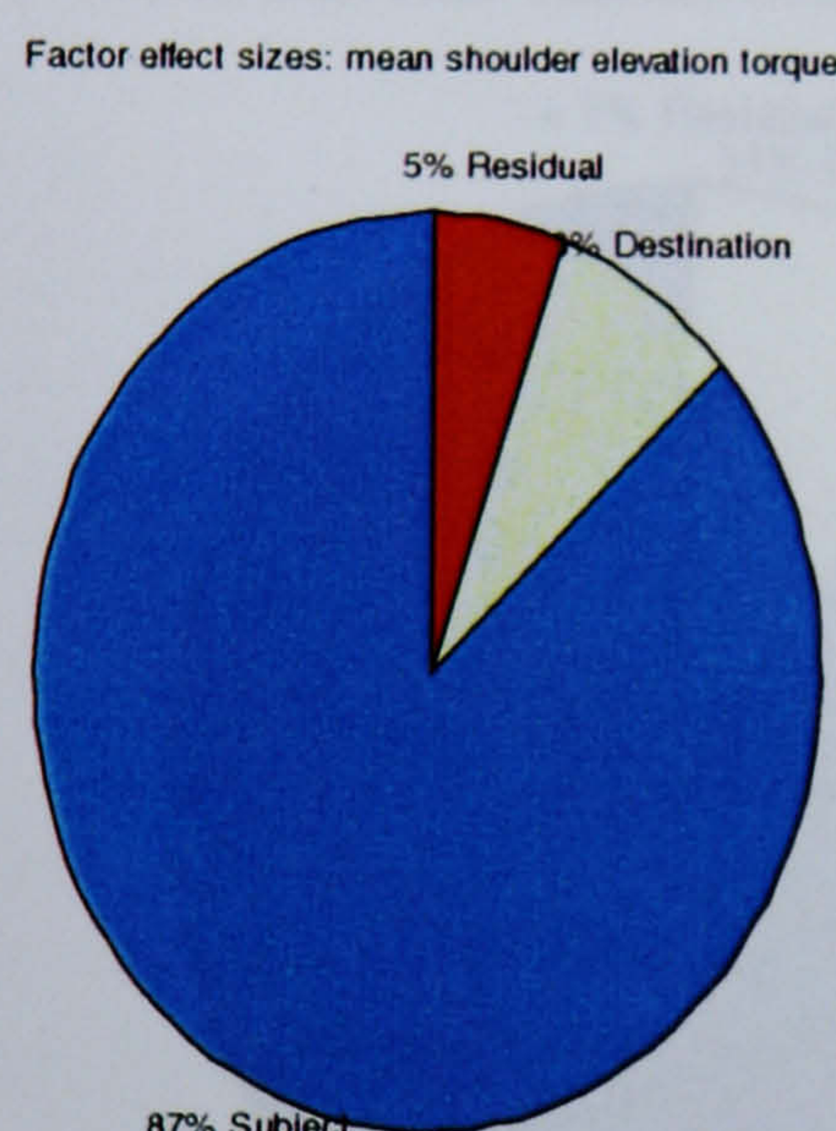
7.2.2.1 *Shoulder elevation torque mean : summary table*

	Mean shoulder elevation torque										
	All	**Near**	**Far**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**	**Sub 6**	**Sub 7**	**Sub 8**
Mean	9.883	9.566	10.199	10.165	4.249	11.560	12.919	10.664	12.571	6.779	10.154
std	2.961	3.088	2.816	1.256	1.029	0.532	0.493	1.973	0.999	0.620	0.539
Min	2.183	2.183	3.988	6.436	2.183	10.547	12.324	5.960	10.251	5.547	9.127
Max	14.079	14.079	14.019	11.874	5.788	12.129	13.694	13.506	14.079	7.699	11.132
Range	11.895	11.895	10.030	5.438	3.605	1.582	1.371	7.546	3.828	2.152	2.005
% of mean											
STDEV	29.96%	32.28%	27.61%	12.35%	24.21%	4.60%	3.82%	18.50%	7.94%	9.14%	5.31%
Range	120.4%	124.3%	98.4%	53.5%	84.8%	13.7%	10.6%	70.8%	30.4%	31.7%	19.7%

7.2.2.2 *Shoulder elevation torque mean: ANOVA*

```
 Sum of Mean Sig
Source of Variation Squares DF Square F of F

Main Effects 995.126 8 124.391 125.352 .000
 SUBJECT 982.331 7 140.333 141.417 .000
 DESTINAT 12.795 1 12.795 12.894 .000

Explained 995.126 8 124.391 125.352 .000

Residual 118.088 119 .992

Total 1113.214 127 8.765
```

7.2.2.3 *Shoulder elevation torque mean: relative factor effects*



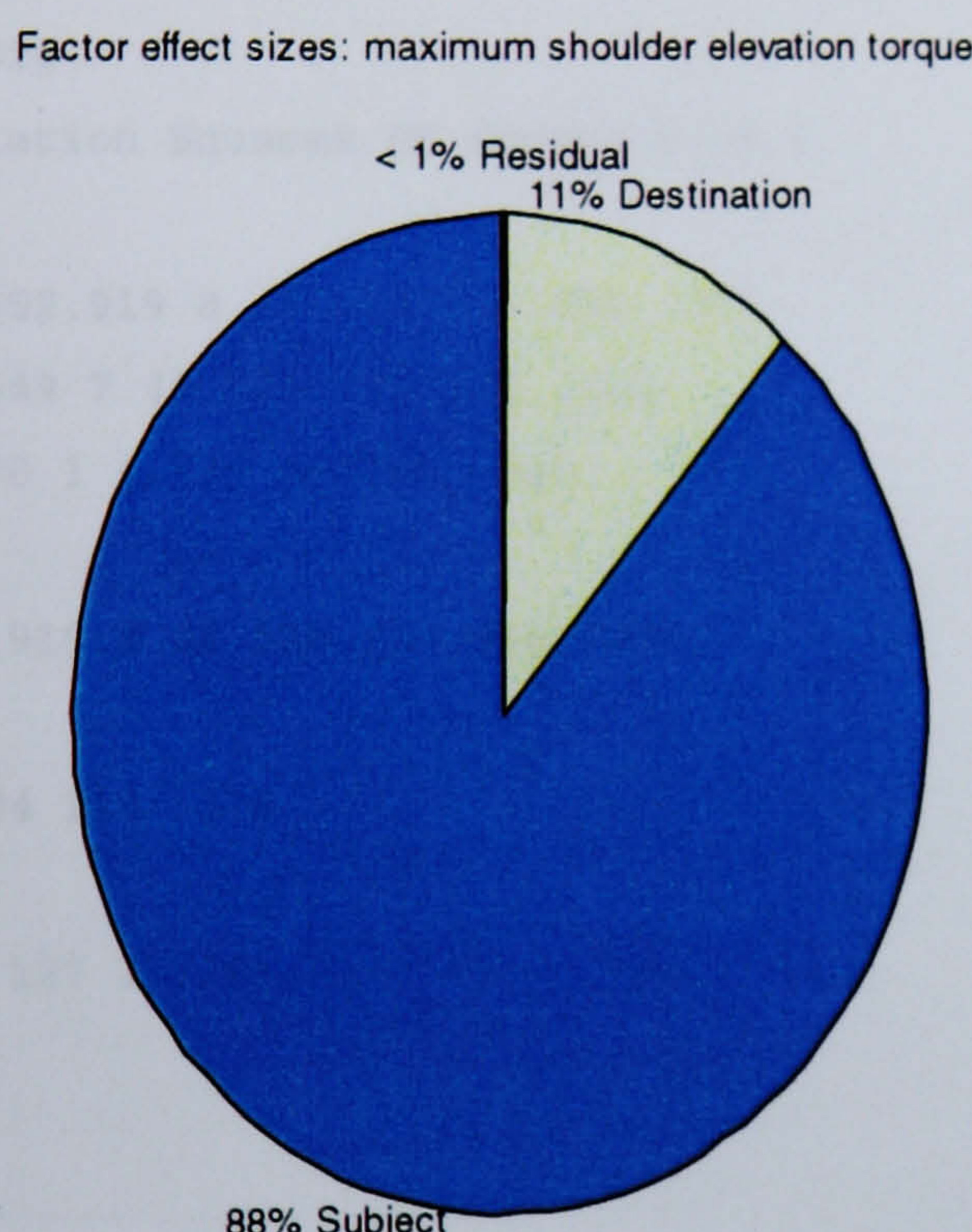
7.2.2.4 *Shoulder elevation torque maximum: summary table*

	Maximum shoulder elevation torque										
	All	**Near**	**Far**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**	**Sub 6**	**Sub 7**	**Sub 8**
Mean	13.532	13.056	14.008	14.922	6.419	15.490	16.662	13.935	16.472	8.969	15.383
std	3.675	3.860	3.444	0.221	1.507	0.467	0.145	2.346	0.541	0.053	0.378
Min	3.340	3.340	6.178	14.446	3.340	14.812	16.454	9.071	15.002	8.879	14.887
Max	17.148	17.011	17.148	15.316	8.587	16.091	17.011	16.624	17.148	9.046	16.054
Range	13.808	13.671	10.970	0.870	5.247	1.279	0.557	7.553	2.147	0.167	1.167
% of mean											
STDEV	27.16%	29.56%	24.59%	1.48%	23.48%	3.02%	0.87%	16.84%	3.29%	0.59%	2.45%
Range	102.0%	104.7%	78.3%	5.8%	81.7%	8.3%	3.3%	54.2%	13.0%	1.9%	7.6%

7.2.2.5 Shoulder elevation torque maximum: ANOVA

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	1616.318	8	202.040	243.994	.000
SUBJECT	1587.307	7	226.758	273.845	.000
DESTINAT	29.011	1	29.011	35.035	.000
Explained	1616.318	8	202.040	243.994	.000
Residual	98.538	119	.828		
Total	1714.856	127	13.503		

7.2.2.6 Shoulder elevation torque maximum: relative factor effects



7.2.2.7 Shoulder rotation torque mean : summary table

	Mean shoulder rotation torque										
	All	**Near**	**Far**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**	**Sub 6**	**Sub 7**	**Sub 8**
Mean	5.787	6.008	5.565	5.749	4.131	7.020	5.879	8.211	6.132	2.523	6.648
std	1.769	1.940	1.564	0.427	0.448	0.429	0.548	1.232	0.933	0.287	0.231
Min	2.026	2.341	2.026	4.863	3.464	6.027	4.872	6.735	4.390	2.026	6.256
Max	9.695	9.695	7.379	6.634	5.036	7.460	6.574	9.695	7.866	3.228	7.009
Range	7.668	7.354	5.352	1.770	1.572	1.433	1.701	2.960	3.476	1.201	0.753
% of mean											
STDEV	30.57%	32.29%	28.10%	7.43%	10.85%	6.11%	9.31%	15.01%	15.21%	11.38%	3.47%
Range	132.5%	122.4%	96.2%	30.8%	38.1%	20.4%	28.9%	36.0%	56.7%	47.6%	11.3%

7.2.2.8 Shoulder rotation torque mean: ANOVA

Sum of Mean Sig

Source of Variation Squares DF Square F of F

Main Effects 352.919 8 44.115 117.696 .000

SUBJECT 346.649 7 49.521 132.120 .000

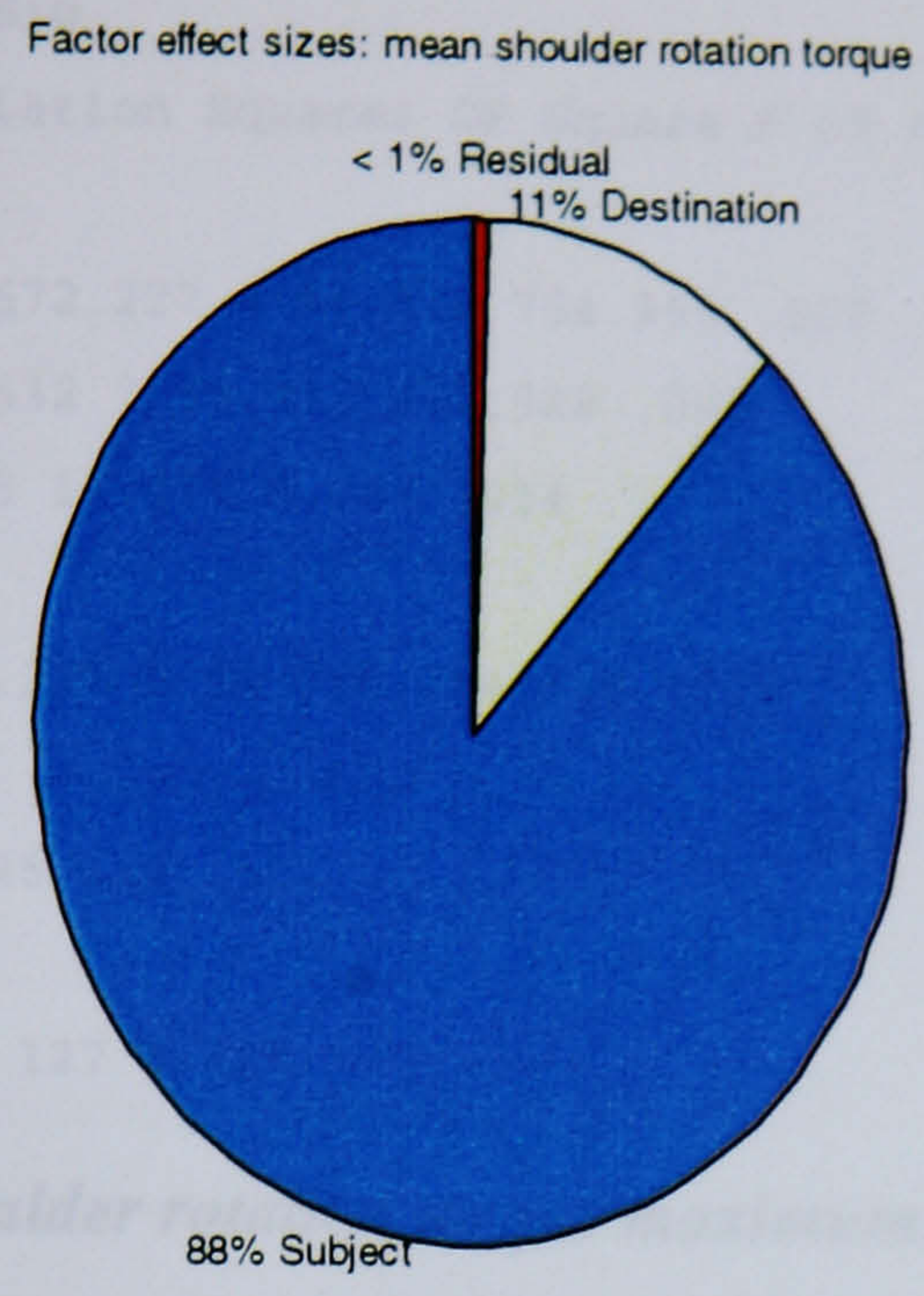
DESTINAT 6.270 1 6.270 16.728 .000

Explained 352.919 8 44.115 117.696 .000

Residual 44.604 119 .375

Total 397.523 127 3.130

7.2.2.9 *Shoulder rotation torque mean: relative factor effects*



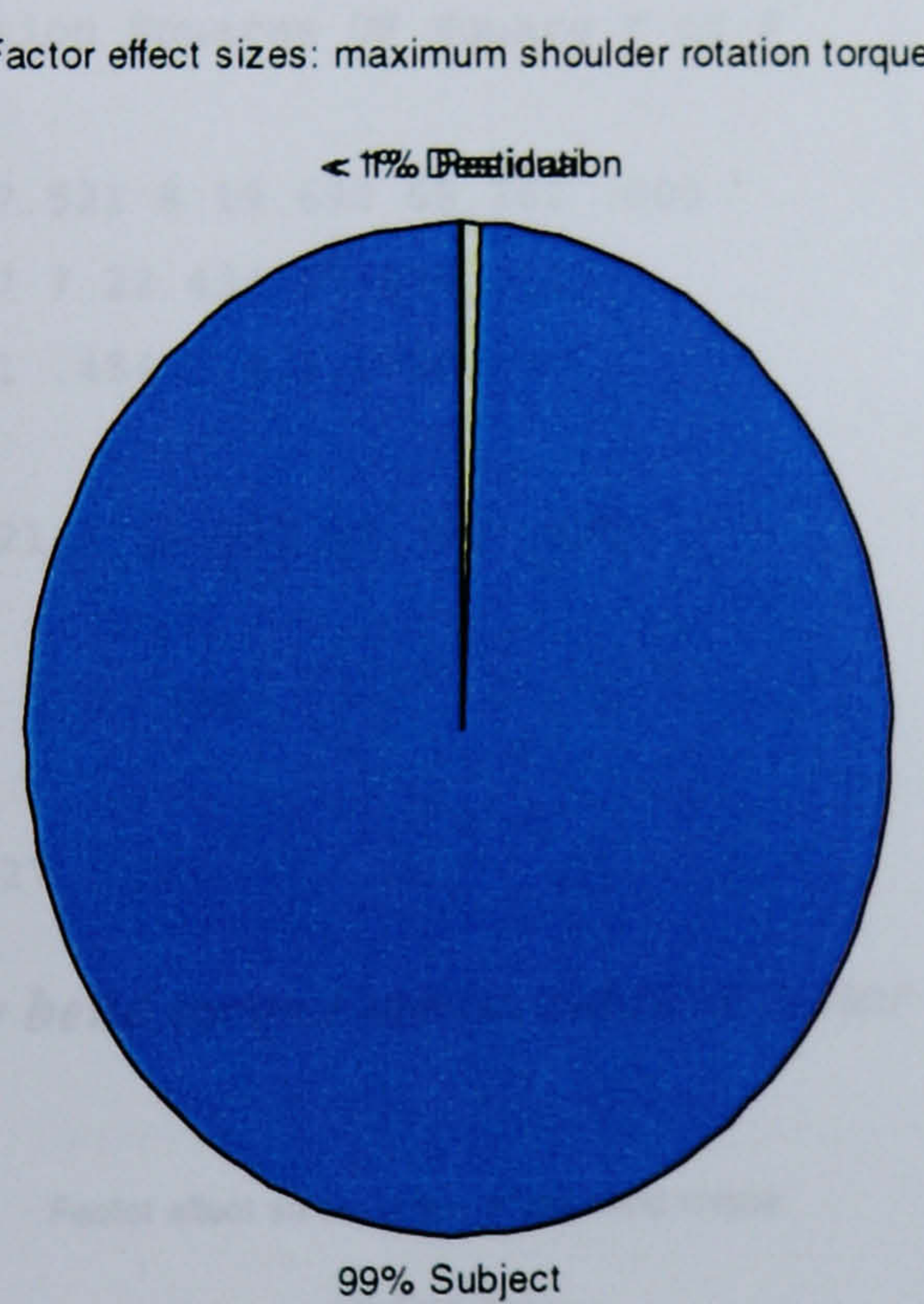
7.2.2.10 *Shoulder rotation torque maximum: summary table*

	Maximum shoulder rotation torque										
	All	**Near**	**Far**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**	**Sub 6**	**Sub 7**	**Sub 8**
Mean	8.267	8.193	8.341	8.306	4.828	8.622	9.551	10.396	10.531	4.190	9.713
std	2.323	2.297	2.365	0.294	0.289	0.693	0.219	0.218	0.250	0.283	0.203
Min	3.664	3.903	3.664	7.800	4.359	7.487	9.049	9.803	9.869	3.664	9.444
Max	10.811	10.776	10.811	8.906	5.458	9.572	9.842	10.743	10.811	4.741	10.161
Range	7.147	6.873	7.147	1.107	1.099	2.085	0.793	0.940	0.942	1.078	0.716
% of mean											
STDEV	28.10%	28.04%	28.35%	3.54%	5.99%	8.04%	2.29%	2.09%	2.37%	6.76%	2.09%
Range	86.5%	83.9%	85.7%	13.3%	22.8%	24.2%	8.3%	9.0%	8.9%	25.7%	7.4%

7.2.2.11 Shoulder rotation torque maximum: ANOVA

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	672.227	8	84.028	754.968	.000
SUBJECT	671.532	7	95.933	861.928	.000
DESTINAT	.695	1	.695	6.247	.014
Explained	672.227	8	84.028	754.968	.000
Residual	13.245	119	.111		
Total	685.472	127	5.397		

7.2.2.12 Shoulder rotation torque maximum: relative factor effects



7.2.2.13 Elbow bend torque mean : summary table

	Mean elbow bend torque										
	All	Near	Far	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5	Sub 6	Sub 7	Sub 8
Mean	2.979	3.040	2.918	3.357	1.451	4.577	4.042	1.905	1.775	2.747	3.977
std	1.229	1.176	1.286	0.565	0.508	0.645	0.454	0.500	0.773	0.244	0.459
Min	0.763	1.118	0.763	2.097	0.763	3.348	3.103	1.183	0.874	2.247	3.113
Max	5.629	5.629	4.790	4.102	2.546	5.629	4.611	2.994	3.798	3.121	4.790
Range	4.866	4.510	4.027	2.005	1.784	2.281	1.508	1.811	2.924	0.874	1.677
% of mean											
STDEV	41.25%	38.69%	44.07%	16.83%	35.01%	14.10%	11.24%	26.23%	43.55%	8.88%	11.53%
Range	163.3%	148.3%	138.0%	59.7%	122.9%	49.8%	37.3%	95.0%	164.7%	31.8%	42.2%

7.2.2.14 Elbow bend torque mean: ANOVA

Sum of Mean Sig

Source of Variation Squares DF Square F of F

Main Effects 157.521 8 19.690 68.362 .000

SUBJECT 157.037 7 22.434 77.888 .000

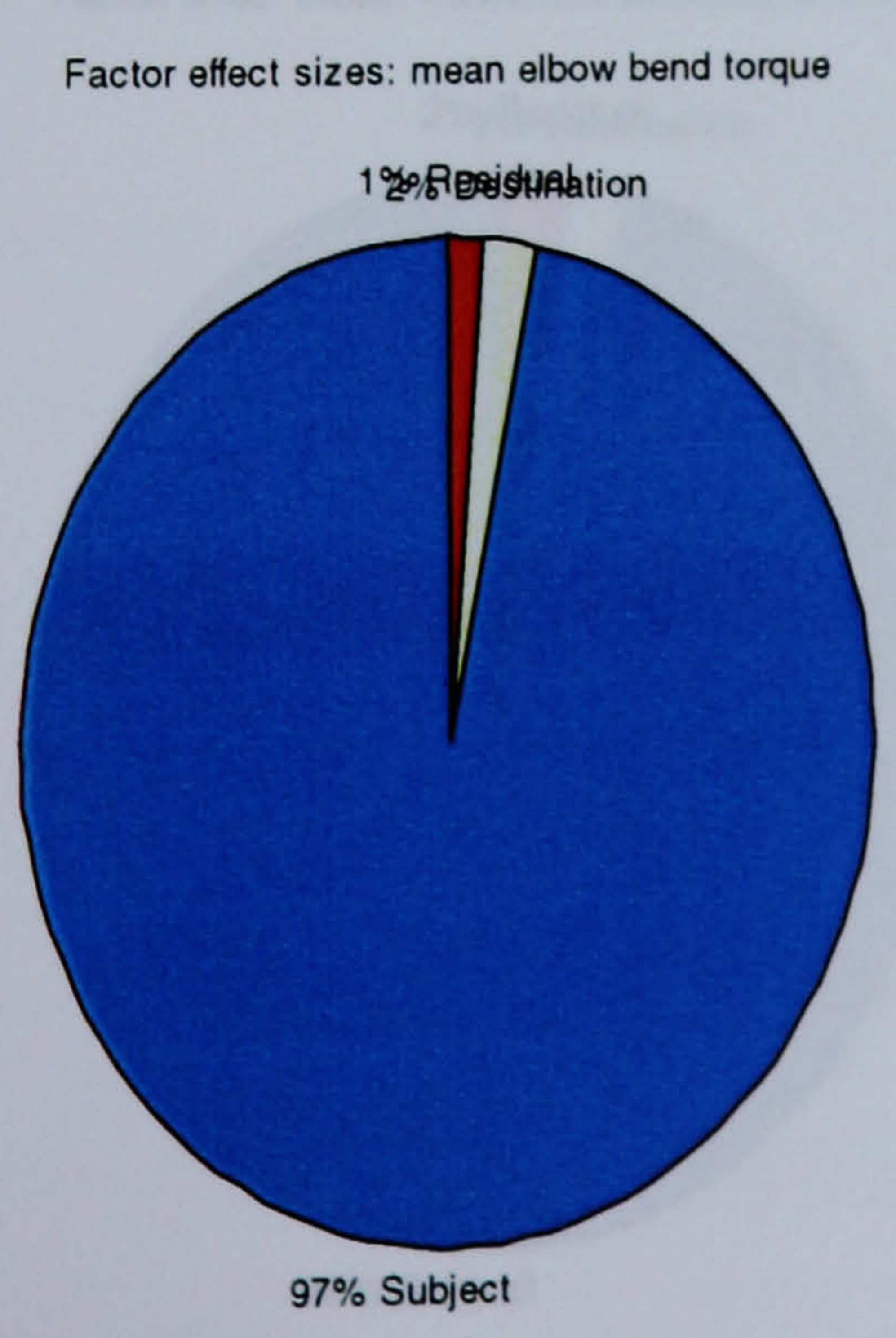
DESTINAT .484 1 .484 1.679 .198

Explained 157.521 8 19.690 68.362 .000

Residual 34.275 119 .288

Total 191.796 127 1.510

7.2.2.15 Elbow bend torque mean: relative factor effects



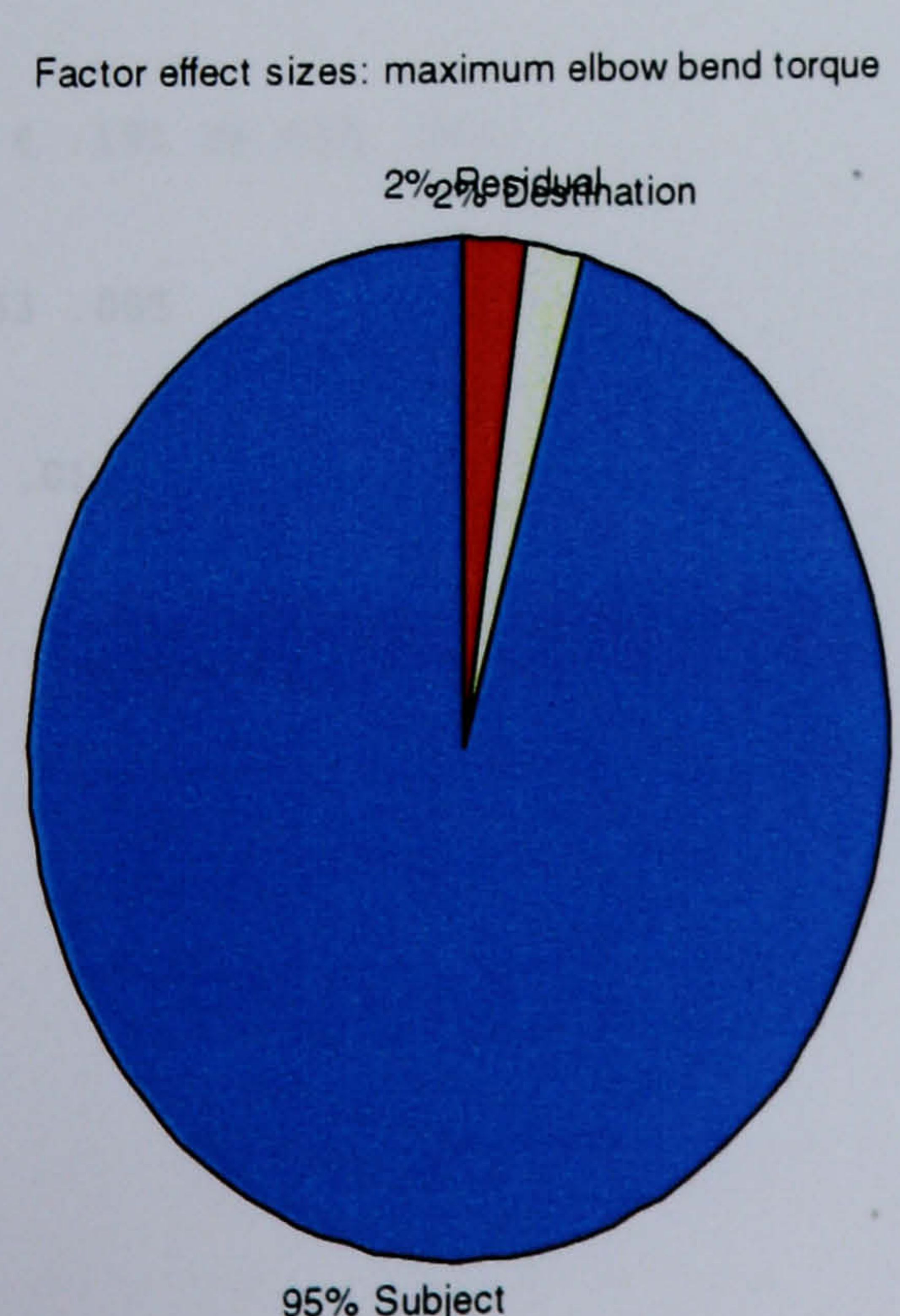
7.2.2.16 *Elbow bend torque maximum: summary table*

	Maximum elbow bend torque										
	All	**Near**	**Far**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**	**Sub 6**	**Sub 7**	**Sub 8**
Mean	4.356	4.296	4.415	5.072	2.896	6.284	4.820	3.402	4.242	3.410	4.719
std	1.240	1.145	1.335	0.699	0.611	0.694	0.526	0.605	1.304	0.183	0.453
Min	2.051	2.250	2.051	3.975	2.051	5.129	3.877	2.143	2.459	2.992	3.942
Max	7.633	7.633	6.602	6.236	3.965	7.633	5.564	4.540	6.272	3.702	5.337
Range	5.582	5.383	4.551	2.260	1.914	2.504	1.686	2.396	3.813	0.710	1.395
% of mean											
STDEV	28.47%	26.64%	30.25%	13.78%	21.08%	11.05%	10.91%	17.78%	30.75%	5.37%	9.61%
Range	128.2%	125.3%	103.1%	44.6%	66.1%	39.9%	35.0%	70.5%	89.9%	20.8%	29.6%

7.2.2.17 *Elbow bend torque maximum: ANOVA*

```
 Sum of Mean Sig
Source of Variation Squares DF Square F of F

Main Effects 136.887 8 17.111 34.842 .000
 SUBJECT 136.438 7 19.491 39.689 .000
 DESTINAT .449 1 .449 .914 .341

Explained 136.887 8 17.111 34.842 .000

Residual 58.440 119 .491

Total 195.327 127 1.538
```

7.2.2.18 *Elbow bend torque maximum: relative factor effects*



7.3 *Simulated impairment experiment: results*

7.3.1 Angular measures

7.3.1.1 Shoulder elevation mean: summary table

	Mean shoulder elevation angle									
	All	**Near**	**Far**	**No imp**	**Imp**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**
Mean	1.044	1.062	1.025	0.982	1.105	1.040	1.029	0.980	1.025	1.145
STDEV	0.111	0.103	0.116	0.086	0.098	0.100	0.113	0.061	0.122	0.080
Min	0.712	0.846	0.712	0.712	0.841	0.841	0.821	0.884	0.712	0.956
Max	1.319	1.319	1.228	1.202	1.319	1.213	1.319	1.103	1.217	1.272
Range	0.607	0.473	0.516	0.490	0.478	0.372	0.498	0.220	0.505	0.316
% of Mean										
STDEV	10.63%	9.72%	11.29%	8.79%	8.83%	9.58%	10.98%	6.25%	11.89%	7.03%
Range	58.16%	44.53%	50.36%	49.90%	43.20%	35.76%	48.37%	22.42%	49.30%	27.57%

7.3.1.2 Shoulder elevation mean: ANOVA

```
 Sum of Mean Sig
Source of Variation Squares DF Square F of F

Main Effects 1.145 6 .191 36.025 .000
 SUBJECT .475 4 .119 22.403 .00
 DESTINAT .057 1 .057 10.714 .001
 IMPAIRME .613 1 .613 115.826 .000

Explained 1.145 6 .191 36.025 .000

Residual .810 153 .005

Total 1.955 159 .012
```

7.3.1.3 *Shoulder elevation range: summary table*

	Shoulder elevation angular range									
	All	**Near**	**Far**	**No imp**	**Imp**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**
Mean	0.204	0.176	0.232	0.190	0.217	0.194	0.165	0.172	0.197	0.290
STDEV	0.119	0.120	0.112	0.126	0.111	0.133	0.072	0.084	0.101	0.149
Min	0.032	0.032	0.049	0.033	0.032	0.032	0.074	0.049	0.068	0.125
Max	0.974	0.974	0.562	0.974	0.562	0.562	0.377	0.420	0.532	0.974
Range	0.942	0.942	0.513	0.941	0.529	0.529	0.303	0.371	0.464	0.850
% of Mean										
STDEV	58.5%	68.3%	48.3%	66.4%	50.9%	68.4%	43.7%	49.0%	51.2%	51.2%
Range	462.5%	535.9%	221.4%	495.4%	243.7%	272.8%	184.0%	216.1%	234.9%	292.7%

7.3.1.4 *Shoulder elevation range: ANOVA*

```
 Sum of Mean Sig
Source of Variation Squares DF Square F of F

Main Effects .479 6 .080 6.893 .000
 SUBJECT .325 4 .081 7.016 .000
 DESTINAT .125 1 .125 10.744 .001
 IMPAIRME .030 1 .030 2.550 .112

Explained .479 6 .080 6.893 .000

Residual 1.773 153 .012

Total 2.253 159 .014
```

7.3.1.5 Elbow bend mean: summary table

	Mean elbow bend angle									
	All	**Near**	**Far**	**No imp**	**Imp**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**
Mean	1.173	1.163	1.182	1.147	1.199	1.430	1.269	1.063	1.111	0.991
STDEV	0.191	0.207	0.174	0.149	0.223	0.157	0.113	0.072	0.075	0.102
Min	0.798	0.798	0.883	0.868	0.798	1.126	0.999	0.897	0.972	0.798
Max	1.738	1.738	1.655	1.505	1.738	1.738	1.589	1.235	1.258	1.234
Range	0.940	0.940	0.772	0.638	0.940	0.612	0.589	0.338	0.286	0.436
% of Mean										
STDEV	16.3%	17.8%	14.7%	13.0%	18.6%	11.0%	8.9%	6.8%	6.8%	10.2%
Range	80.1%	80.8%	65.3%	55.6%	78.4%	42.8%	46.4%	31.8%	25.8%	44.0%

7.3.1.6 Elbow bend mean: ANOVA

Sum of Mean Sig

Source of Variation Squares DF Square F of F

Main Effects 4.101 6 .683 61.759 .000

SUBJECT 3.976 4 .994 89.825 .000

DESTINAT .014 1 .014 1.300 .256

IMPAIRME .110 1 .110 9.955 .002

Explained 4.101 6 .683 61.759 .000

Residual 1.693 153 .011

Total 5.794 159 .036

7.3.1.7 Elbow bend range: summary table

	Elbow bend angular range									
	All	**Near**	**Far**	**No imp**	**Imp**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**
Mean	0.800	0.811	0.790	0.851	0.750	0.880	0.872	0.734	0.748	0.768
STDEV	0.179	0.157	0.199	0.151	0.191	0.156	0.149	0.132	0.201	0.200
Min	0.278	0.356	0.278	0.489	0.278	0.544	0.665	0.470	0.279	0.357
Max	1.249	1.249	1.244	1.249	1.176	1.176	1.189	0.928	1.244	1.249
Range	0.971	0.893	0.966	0.760	0.898	0.632	0.525	0.458	0.966	0.892
% of Mean										
STDEV	22.4%	19.3%	25.2%	17.7%	25.5%	17.7%	17.0%	18.0%	26.9%	26.0%
Range	121.3%	110.1%	122.3%	89.3%	119.8%	71.8%	60.1%	62.4%	129.1%	116.3%

7.3.1.8 Elbow bend range: ANOVA

Sum of Mean Sig

Source of Variation Squares DF Square F of F

Main Effects 1.065 6 .177 6.732 .000

SUBJECT .632 4 .158 5.995 .000

DESTINAT .018 1 .018 .699 .404

IMPAIRME .414 1 .414 15.717 .000

Explained 1.065 6 .177 6.732 .000

Residual 4.033 153 .026

Total 5.097 159 .032

7.3.2 Torque measures

7.3.2.1 Shoulder elevation mean: summary table

	Mean shoulder elevation torque									
	All	**Near**	**Far**	**No imp**	**Imp**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**
Mean	9.102	9.129	9.076	9.385	8.820	8.659	8.348	10.662	10.636	7.207
STDEV	1.554	1.537	1.579	1.534	1.530	1.321	0.787	0.493	0.476	0.331
Min	6.339	6.339	6.468	6.468	6.339	6.688	6.339	9.383	9.697	6.468
Max	11.581	11.508	11.581	11.581	11.408	11.468	10.401	11.581	11.486	7.937
Range	5.242	5.169	5.113	5.113	5.069	4.779	4.062	2.198	1.789	1.469
% of Mean										
STDEV	17.1%	16.8%	17.4%	16.3%	17.4%	15.3%	9.4%	4.6%	4.5%	4.6%
Range	57.6%	56.6%	56.3%	54.5%	57.5%	55.2%	48.7%	20.6%	16.8%	20.4%

7.3.2.2 Shoulder elevation mean: ANOVA

```
 Sum of Mean Sig
Source of Variation Squares DF Square F of F

Main Effects 305.400 6 50.900 99.335 .000
 SUBJECT 292.510 4 73.127 142.714 .000
 DESTINAT .114 1 .114 .223 .637
 IMPAIRME 12.775 1 12.775 24.932 .000

Explained 305.400 6 50.900 99.335 .000

Residual 78.398 153 .512

Total 383.798 159 2.414
```

7.3.2.3 Shoulder elevation maximum: summary table

	Maximum shoulder elevation torque									
	All	**Near**	**Far**	**No imp**	**Imp**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**
Mean	11.040	11.023	11.057	11.273	10.807	11.880	10.269	12.409	12.267	8.377
STDEV	1.611	1.611	1.621	1.702	1.489	0.731	0.544	0.251	0.450	0.260
Min	7.751	7.974	7.751	7.751	7.867	10.288	7.974	11.811	11.306	7.751
Max	13.280	13.280	12.958	13.280	12.829	12.962	11.087	12.829	13.280	8.833
Range	5.529	5.306	5.207	5.529	4.962	2.674	3.113	1.018	1.974	1.082
% of Mean										
STDEV	14.6%	14.6%	14.7%	15.1%	13.8%	6.2%	5.3%	2.0%	3.7%	3.1%
Range	50.1%	48.1%	47.1%	49.0%	45.9%	22.5%	30.3%	8.2%	16.1%	12.9%

7.3.2.4 Shoulder elevation maximum: ANOVA

Sum of Mean Sig

Source of Variation Squares DF Square F of F

Main Effects 385.325 6 64.221 359.664 .000

SUBJECT 376.588 4 94.147 527.263 .000

DESTINAT .045 1 .045 .252 .617

IMPAIRME 8.692 1 8.692 48.680 .000

Explained 385.325 6 64.221 359.664 .000

Residual 27.319 153 .179

Total 412.644 159 2.595

7.3.2.5 Shoulder rotation mean: summary table

	Mean shoulder rotation torque									
	All	**Near**	**Far**	**No imp**	**Imp**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**
Mean	4.367	4.459	4.275	3.950	4.784	5.972	4.736	3.604	4.269	3.195
STDEV	1.170	1.160	1.179	1.105	1.087	0.534	0.573	0.618	1.037	0.268
Min	1.387	2.661	1.387	1.387	2.915	5.029	3.522	2.596	1.387	2.658
Max	6.919	6.919	6.559	6.273	6.919	6.919	5.734	4.654	5.797	3.752
Range	5.533	4.259	5.172	4.886	4.005	1.890	2.213	2.059	4.410	1.094
% of Mean										
STDEV	26.8%	26.0%	27.6%	28.0%	22.7%	8.9%	11.9%	17.1%	24.3%	8.4%
Range	126.7%	95.5%	121.0%	123.7%	83.7%	31.6%	46.1%	57.1%	103.3%	34.2%

7.3.2.6 Shoulder rotation mean: ANOVA

Sum of Mean Sig

Source of Variation Squares DF Square F of F

Main Effects 180.416 6 30.069 123.759 .000

SUBJECT 151.220 4 37.805 155.598 .000

DESTINAT 1.368 1 1.368 5.632 .019

IMPAIRME 27.828 1 27.828 114.533 .000

Explained 180.416 6 30.069 123.759 .000

Residual 37.174 153 .243

Total 217.590 159 1.368

7.3.2.7 *Shoulder rotation maximum: summary table*

	Maximum shoulder rotation torque									
	All	**Near**	**Far**	**No imp**	**Imp**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**
Mean	5.587	5.589	5.585	5.247	5.927	6.915	5.596	5.103	6.041	4.280
STDEV	1.040	0.991	1.093	0.965	1.005	0.507	0.512	0.651	0.728	0.188
Min	3.809	4.039	3.809	3.809	4.055	5.884	4.337	4.112	3.880	3.809
Max	7.814	7.458	7.814	7.343	7.814	7.814	6.457	6.181	6.914	4.646
Range	4.004	3.419	4.004	3.533	3.758	1.929	2.120	2.069	3.035	0.837
% of Mean										
STDEV	18.6%	17.7%	19.6%	18.4%	17.0%	7.3%	9.1%	12.8%	12.0%	4.4%
Range	71.7%	61.2%	71.7%	67.3%	63.4%	27.9%	37.9%	40.5%	50.2%	19.6%

7.3.2.8 *Shoulder rotation maximum: ANOVA*

```
 Sum of Mean Sig
Source of Variation Squares DF Square F of F

Main Effects 143.684 6 23.947 129.741 .000
 SUBJECT 125.167 4 31.292 169.531 .000
 DESTINAT .001 1 .001 .004 .947
 IMPAIRME 18.516 1 18.516 100.317 .000

Explained 143.684 6 23.947 129.741 .000

Residual 28.240 153 .185

Total 171.924 159 1.081
```

7.3.2.9 Elbow bend mean: summary table

	Mean elbow bend torque									
	All	Near	Far	No imp	Imp	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5
Mean	3.960	3.837	4.084	4.432	3.489	4.227	3.660	5.072	4.688	2.154
STDEV	1.250	1.261	1.234	1.195	1.125	0.776	0.774	0.531	0.946	0.525
Min	1.351	1.385	1.351	1.385	1.351	2.880	1.566	4.031	2.657	1.351
Max	5.978	5.978	5.959	5.978	5.523	5.523	5.014	5.789	5.978	3.250
Range	4.626	4.593	4.608	4.593	4.172	2.643	3.448	1.758	3.321	1.898
% of Mean										
STDEV	31.6%	32.9%	30.2%	27.0%	32.2%	18.4%	21.2%	10.5%	20.2%	24.4%
Range	116.8%	119.7%	112.8%	103.6%	119.6%	62.5%	94.2%	34.7%	70.8%	88.1%

7.3.2.10 Elbow bend mean: ANOVA

```
Sum of Mean Sig
Source of Variation Squares DF Square F of F

Main Effects 204.070 6 34.012 117.551 .000
 SUBJECT 166.064 4 41.516 143.488 .000
 DESTINAT 2.449 1 2.449 8.465 .004
 IMPAIRME 35.557 1 35.557 122.891 .000

Explained 204.070 6 34.012 117.551 .000

Residual 44.268 153 .289

Total 248.338 159 1.562
```

7.3.2.11 Elbow bend maximum: summary table

	Maximum elbow bend torque									
	All	**Near**	**Far**	**No imp**	**Imp**	**Sub 1**	**Sub 2**	**Sub 3**	**Sub 4**	**Sub 5**
Mean	4.831	4.536	5.127	5.202	4.461	4.982	4.161	6.092	5.717	3.205
STDEV	1.304	1.274	1.273	1.268	1.238	0.800	0.811	0.582	0.979	0.674
Min	1.646	1.646	2.338	1.646	1.852	3.355	1.852	4.936	3.472	1.646
Max	7.357	6.973	7.357	7.098	7.357	7.357	5.584	6.836	7.098	4.464
Range	5.712	5.328	5.020	5.452	5.505	4.003	3.732	1.899	3.626	2.818
% of Mean										
STDEV	27.0%	28.1%	24.8%	24.4%	27.8%	16.1%	19.5%	9.6%	17.1%	21.0%
Range	118.2%	117.5%	97.9%	104.8%	123.4%	80.3%	89.7%	31.2%	63.4%	87.9%

7.3.2.12 Elbow bend maximum: ANOVA

Sum of Mean Sig

Source of Variation Squares DF Square F of F

Main Effects 211.650 6 35.275 92.207 .000

SUBJECT 175.705 4 43.926 114.821 .000

DESTINAT 13.991 1 13.991 36.570 .000

IMPAIRME 21.954 1 21.954 57.387 .000

Explained 211.650 6 35.275 92.207 .000

Residual 58.532 153 .383

Total 270.182 159 1.699

7.4 Product comparison experiment: results

35 subjects took part in this experiment. Even presented in summary form, the results data is very extensive. For reasons of brevity, sample data from the first 5 subjects is shown here. One table is used for each product group.

The main experimental description section describes each object and its corresponding number.

7.4.1 Spoons

			Shoulder elevation				Elbow bend				Shoulder el. torque				Should. ro. torque				Elbow bend torque			
Subject	Object	Rep.	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX
1	1	1	0.67	0.07	0.59	0.76	2.15	0.25	1.69	2.39	3.14	1.80	1.34	6.24	5.01	0.34	4.46	5.63	5.55	2.04	3.43	8.69
1	1	2	0.67	0.06	0.58	0.73	2.14	0.28	1.61	2.39	3.54	1.88	1.91	6.94	4.85	0.45	4.29	5.57	5.36	2.25	3.11	8.99
1	1	3	0.63	0.04	0.58	0.71	2.08	0.31	1.57	2.41	4.17	2.22	1.89	7.58	4.67	0.57	3.92	5.44	5.93	2.27	3.29	9.07
1	1	4	0.63	0.06	0.57	0.71	2.07	0.30	1.61	2.38	4.18	2.16	1.92	7.45	4.77	0.37	4.26	5.26	6.02	2.27	3.43	9.09
1	1	5	0.64	0.05	0.59	0.72	2.08	0.30	1.56	2.40	4.46	2.17	2.10	7.95	4.68	0.50	4.02	5.38	5.76	2.35	2.86	9.10
1	1	6	0.67	0.06	0.61	0.76	2.06	0.33	1.55	2.38	4.31	2.14	2.10	7.53	4.95	0.61	4.28	5.81	5.57	2.58	2.68	8.91
1	2	1	1.04	0.10	0.88	1.15	2.23	0.25	1.72	2.45	1.44	2.01	0.03	5.70	6.69	0.94	5.64	7.97	2.31	2.60	0.00	6.55
1	2	2	0.95	0.09	0.80	1.05	2.20	0.24	1.79	2.46	1.95	1.82	0.00	5.00	6.46	0.83	5.38	7.42	3.21	2.45	0.36	6.97
1	2	3	0.95	0.08	0.84	1.06	2.21	0.23	1.83	2.47	1.70	1.65	0.05	4.43	6.45	0.90	5.33	7.65	3.22	2.40	0.20	6.59
1	2	4	0.95	0.10	0.78	1.07	2.24	0.23	1.81	2.46	1.73	1.68	0.12	4.85	6.14	0.77	5.23	7.21	2.67	2.65	0.02	7.01
1	2	5	0.93	0.10	0.79	1.06	2.16	0.26	1.73	2.44	2.54	2.00	0.34	5.81	6.35	0.84	5.26	7.30	3.31	2.78	0.02	7.19
1	2	6	0.98	0.10	0.83	1.09	2.25	0.24	1.78	2.46	1.67	1.74	0.13	5.04	6.12	0.95	5.17	7.59	2.18	2.79	0.07	6.82
1	3	1	0.92	0.13	0.71	1.07	2.20	0.18	1.90	2.39	1.55	1.26	0.23	3.68	6.49	0.33	6.04	6.92	3.86	2.35	1.06	7.38
1	3	2	0.94	0.11	0.82	1.09	2.15	0.24	1.82	2.41	2.04	1.73	0.08	4.41	6.74	0.65	5.95	7.60	3.75	2.45	0.59	6.84
1	3	3	0.91	0.08	0.79	1.02	2.14	0.24	1.78	2.40	2.12	1.76	0.15	4.72	6.68	0.67	5.85	7.46	4.10	2.19	1.47	7.10
1	3	4	0.94	0.07	0.83	1.03	2.22	0.24	1.81	2.43	1.64	1.51	0.25	4.21	6.39	0.92	5.46	7.73	3.17	2.43	0.64	6.78
1	3	5	0.98	0.07	0.90	1.08	2.16	0.26	1.74	2.42	2.05	1.86	0.18	4.96	6.85	1.01	5.65	8.41	3.20	2.39	0.38	6.35
1	3	6	1.00	0.09	0.89	1.11	2.10	0.29	1.72	2.42	2.51	2.04	0.25	5.28	7.06	1.12	5.56	8.29	3.15	2.81	0.02	6.52
3	1	1	0.87	0.07	0.77	0.94	2.00	0.30	1.49	2.32	2.85	2.00	0.91	6.16	-4.62	0.27	4.21	5.00	3.52	1.33	1.90	5.54
3	1	2	0.99	0.07	0.89	1.08	1.98	0.35	1.44	2.33	2.59	2.17	0.50	5.93	-5.16	0.46	4.59	5.76	2.94	1.40	1.38	4.87
3	1	3	1.05	0.07	0.96	1.14	1.93	0.34	1.48	2.35	2.67	2.11	0.15	5.40	-5.57	0.52	4.75	6.06	2.95	1.23	1.27	4.36
3	1	4	1.08	0.07	1.00	1.18	1.99	0.31	1.57	2.38	2.11	1.81	0.01	4.52	-5.68	0.66	4.67	6.31	2.71	1.15	0.96	4.07
3	1	5	1.10	0.07	1.00	1.19	2.02	0.28	1.57	2.37	1.83	1.67	0.04	4.47	-5.71	0.58	4.80	6.31	2.63	1.01	1.20	4.07
3	1	6	1.10	0.08	1.00	1.20	2.01	0.27	1.59	2.35	1.84	1.65	0.03	4.38	-5.74	0.50	4.92	6.29	2.74	0.98	1.32	4.03
3	2	1	1.21	0.05	1.11	1.28	2.20	0.19	1.84	2.40	1.02	0.95	0.10	2.90	-5.30	0.73	4.35	6.44	0.94	1.29	0.02	3.01
3	2	2	1.25	0.05	1.17	1.32	2.09	0.25	1.66	2.38	1.53	1.43	0.00	4.08	-5.82	0.81	4.66	6.86	1.20	1.25	0.02	2.88

			Shoulder elevation				Elbow bend				Shoulder el. torque				Should. ro. torque				Elbow bend torque			
Subject	Object	Rep.	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX
3	2	3	1.31	0.05	1.22	1.38	2.17	0.26	1.70	2.42	1.00	1.44	0.00	3.78	-5.57	0.96	4.42	6.98	0.56	1.38	0.01	2.49
3	2	4	1.31	0.05	1.25	1.38	2.10	0.26	1.68	2.42	1.36	1.48	0.04	3.93	-5.92	0.90	4.59	7.07	0.92	1.16	0.01	2.33

3	2	5	1.34	0.05	1.26	1.41	2.05	0.27	1.65	2.40	1.64	1.62	0.03	4.17	-6.14	0.88	4.76	7.12	0.96	1.10	0.01	2.25
3	2	6	1.34	0.05	1.26	1.41	2.09	0.27	1.64	2.42	1.38	1.58	0.03	4.17	-6.01	0.90	4.66	7.12	0.82	1.13	0.11	2.26
3	3	1	1.19	0.08	1.08	1.27	2.08	0.30	1.57	2.38	1.82	1.89	0.01	4.98	-5.58	0.71	4.70	6.51	1.45	1.38	0.01	3.53
3	3	2	1.25	0.08	1.15	1.36	2.04	0.29	1.61	2.41	1.85	1.75	0.00	4.50	-5.90	0.86	4.54	6.81	1.28	1.44	0.08	3.00
3	3	3	1.29	0.08	1.15	1.37	2.15	0.29	1.61	2.42	1.19	1.67	0.01	4.43	-5.60	0.89	4.53	6.84	0.75	1.46	0.01	3.02
3	3	4	1.26	0.07	1.19	1.38	1.86	0.29	1.55	2.37	2.95	1.81	0.06	4.88	-6.47	0.67	4.88	6.97	1.76	1.09	0.05	2.77
3	3	5	1.31	0.06	1.21	1.39	2.11	0.31	1.57	2.42	1.42	1.89	0.01	4.78	-5.76	0.97	4.58	7.00	0.75	1.37	0.05	2.63
3	3	6	1.32	0.08	1.19	1.41	2.11	0.32	1.52	2.43	1.40	2.01	0.00	5.14	-5.69	0.93	4.54	6.95	0.58	1.47	0.06	2.81
4	1	1	1.21	0.12	1.03	1.36	2.18	0.17	1.93	2.37	0.83	0.91	0.01	2.11	-4.78	0.48	4.14	5.32	0.90	1.46	0.00	2.90
4	1	2	1.27	0.09	1.15	1.40	2.19	0.21	1.83	2.41	0.70	1.00	0.02	2.47	-4.82	0.74	3.90	5.89	0.47	1.52	0.08	2.52
4	1	3	1.31	0.11	1.18	1.48	2.21	0.18	1.84	2.41	0.55	0.92	0.02	2.33	-4.79	0.72	3.83	5.97	0.16	1.58	0.07	2.29
4	1	4	1.22	0.08	1.13	1.37	2.10	0.23	1.79	2.41	1.21	1.19	0.02	2.78	-5.06	0.72	3.97	5.89	1.09	1.35	0.08	2.62
4	1	5	1.33	0.09	1.24	1.48	2.23	0.20	1.88	2.45	0.40	0.98	0.01	2.10	-4.81	0.81	3.77	6.04	0.13	1.44	0.09	1.96
4	1	6	1.42	0.13	1.26	1.60	2.25	0.22	1.84	2.46	0.15	1.15	0.07	2.23	-4.73	0.93	3.62	6.14	-0.43	1.77	0.17	2.79
4	2	1	1.51	0.10	1.37	1.64	2.23	0.18	1.90	2.40	0.11	0.93	0.03	1.88	-5.06	0.71	4.17	6.17	-0.27	1.28	0.04	2.17
4	2	2	1.47	0.13	1.26	1.62	2.14	0.25	1.70	2.39	0.67	1.39	0.01	3.11	-5.29	0.79	4.30	6.31	0.00	1.45	0.04	2.02
4	2	3	1.47	0.10	1.31	1.59	2.15	0.26	1.68	2.42	0.62	1.47	0.05	3.35	-5.15	0.93	3.98	6.41	-0.30	1.50	0.01	2.31
4	2	4	1.46	0.09	1.34	1.60	2.17	0.26	1.74	2.44	0.57	1.43	0.04	3.00	-5.12	0.97	3.89	6.41	-0.29	1.43	0.05	2.33
4	2	5	1.42	0.12	1.27	1.58	2.15	0.27	1.71	2.45	0.71	1.54	0.13	3.20	-5.10	0.96	3.87	6.29	-0.10	1.63	0.03	2.38
4	2	6	1.38	0.13	1.19	1.54	2.17	0.25	1.71	2.43	0.66	1.42	0.07	3.24	-4.91	0.88	3.88	6.13	-0.13	1.76	0.02	2.40
4	3	1	0.89	0.05	0.83	0.99	2.21	0.15	1.99	2.42	0.25	0.52	0.04	1.00	-4.07	0.30	3.66	4.52	3.21	0.74	1.97	4.15
4	3	2	0.90	0.05	0.84	0.98	2.25	0.16	1.99	2.43	0.22	0.53	0.04	1.09	-3.96	0.37	3.55	4.69	2.89	0.81	1.80	3.96
4	3	3	0.93	0.08	0.85	1.08	2.25	0.17	1.97	2.46	0.25	0.58	0.02	1.19	-4.03	0.38	3.56	4.62	2.67	1.07	0.90	4.07
4	3	4	0.94	0.06	0.87	1.04	2.27	0.17	1.99	2.46	0.30	0.52	0.04	1.12	-3.99	0.43	3.49	4.67	2.44	1.02	1.01	3.92
			Shoulder elevation				Elbow bend				Shoulder el. torque				Should. ro. torque				Elbow bend torque			
Subject	Object	Rep.	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX
4	3	5	0.93	0.08	0.86	1.08	2.23	0.18	1.97	2.47	0.48	0.65	0.04	1.34	-4.10	0.42	3.55	4.67	2.64	1.10	0.81	3.96
4	3	6	0.99	0.10	0.89	1.16	2.27	0.18	1.99	2.47	0.26	0.58	0.00	1.15	-4.07	0.44	3.55	4.77	2.12	1.33	0.17	3.82
5	1	1	0.50	0.05	0.43	0.59	2.57	0.18	2.09	2.75	2.15	1.17	0.83	5.04	0.39	0.06	0.32	0.50	0.52	1.29	0.02	3.36
5	1	2	0.51	0.05	0.45	0.62	2.55	0.13	2.22	2.67	2.10	0.80	1.15	3.91	0.67	0.14	0.56	1.08	0.72	1.02	0.02	3.01
5	1	3	0.50	0.06	0.40	0.60	2.63	0.14	2.27	2.77	1.55	0.89	0.60	3.57	0.69	0.12	0.59	1.05	0.37	1.19	0.01	3.07
5	1	4	0.48	0.04	0.40	0.55	2.58	0.16	2.14	2.72	1.75	0.94	0.75	4.03	0.86	0.14	0.72	1.30	0.98	1.13	0.00	3.70

5	1	5	0.40	0.05	0.33	0.48	2.63	0.11	2.35	2.74	1.75	0.67	0.96	3.17	0.63	0.07	0.56	0.88	1.01	0.89	0.01	3.01
5	1	6	0.47	0.08	0.34	0.58	2.63	0.13	2.28	2.75	1.34	0.67	0.61	2.86	0.83	0.12	0.72	1.24	0.75	1.26	0.01	3.54
5	2	1	0.97	0.04	0.93	1.05	1.91	0.43	1.17	2.37	2.69	2.33	0.42	6.71	4.04	0.44	3.25	4.76	2.46	1.34	0.20	4.32
5	2	2	0.81	0.04	0.76	0.88	2.15	0.42	1.42	2.58	2.16	2.06	0.20	5.86	2.91	0.66	1.97	3.83	2.03	1.79	0.02	4.66
5	2	3	0.83	0.04	0.78	0.88	2.33	0.39	1.55	2.70	0.96	1.88	0.02	4.96	2.78	0.79	1.77	3.93	1.59	1.71	0.04	4.45
5	2	4	0.92	0.06	0.85	1.02	2.13	0.43	1.52	2.63	1.45	2.03	0.01	4.48	3.60	0.84	2.30	4.54	2.12	1.74	0.00	4.17
5	2	5	0.98	0.05	0.89	1.07	2.30	0.38	1.59	2.70	0.51	1.63	0.04	3.80	3.42	1.02	2.00	4.76	1.46	1.62	0.05	3.89
5	2	6	1.02	0.05	0.94	1.09	2.12	0.33	1.62	2.57	1.11	1.63	0.05	3.64	4.14	0.76	2.80	4.94	2.10	1.17	0.04	3.63
5	3	1	1.14	0.03	1.09	1.20	1.88	0.70	0.72	2.52	2.65	3.74	0.03	8.71	3.72	0.81	2.91	5.35	1.51	1.94	0.02	4.36
5	3	2	1.14	0.04	1.08	1.22	2.33	0.23	1.75	2.52	-0.11	1.03	0.09	2.77	3.96	0.70	3.28	5.48	1.25	0.82	0.19	2.55
5	3	3	1.13	0.06	1.02	1.21	2.10	0.56	1.10	2.63	1.18	3.10	0.13	6.81	3.98	0.91	2.84	5.44	1.97	1.16	0.10	3.81
5	3	4	0.90	0.06	0.80	1.02	1.96	0.55	1.08	2.63	2.52	2.81	0.01	7.01	3.58	0.86	2.20	4.61	2.62	1.40	0.15	4.13
5	3	5	0.94	0.02	0.90	0.98	2.05	0.56	1.17	2.65	1.88	2.88	0.00	6.64	3.58	0.97	2.28	4.96	2.27	1.58	0.04	4.36
5	3	6	0.83	0.03	0.77	0.89	1.94	0.51	1.22	2.65	3.01	2.63	0.05	6.82	3.30	0.72	1.88	4.06	2.88	1.67	0.02	4.85

7.4.2 Drinking vessels

			Shoulder elevation				Elbow bend				Shoulder el. torque				Shoulder rot. torque				Elbow bend torque			
Subject	Object	Rep.	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX
1	4	1	0.75	0.05	0.69	0.84	2.18	0.40	1.27	2.50	3.65	2.91	1.57	10.39	4.64	1.06	3.45	6.34	3.66	3.12	0.00	8.82
1	4	2	0.76	0.06	0.70	0.90	2.17	0.38	1.27	2.48	3.93	2.90	1.57	10.81	4.58	0.99	3.54	6.16	3.43	3.24	0.05	8.86
1	4	3	0.70	0.06	0.61	0.80	2.16	0.42	1.27	2.51	3.96	3.08	1.61	10.54	4.36	1.04	3.32	6.05	4.15	3.21	0.14	8.99
1	4	4	0.76	0.06	0.68	0.86	2.19	0.40	1.26	2.49	3.37	3.01	1.45	10.68	4.69	1.00	3.64	6.37	3.64	3.19	0.00	8.93
1	4	5	0.77	0.10	0.66	0.93	2.21	0.40	1.27	2.52	3.24	3.22	0.98	10.85	4.53	0.85	3.60	5.90	3.33	3.61	0.06	9.13
1	4	6	0.73	0.08	0.64	0.88	2.16	0.41	1.26	2.50	3.76	3.20	1.35	10.89	4.53	0.85	3.63	5.89	3.96	3.40	0.04	9.20
1	5	1	0.82	0.08	0.73	0.93	2.14	0.40	1.31	2.48	3.67	3.30	1.20	10.74	5.15	0.88	3.99	6.44	3.60	3.38	0.06	8.85
1	5	2	0.77	0.07	0.68	0.89	2.12	0.43	1.31	2.51	4.21	3.47	1.25	10.95	4.73	1.05	3.45	6.26	3.82	3.58	0.02	8.98
1	5	3	0.79	0.09	0.68	0.92	2.14	0.39	1.36	2.47	3.95	3.21	1.47	10.58	4.84	0.80	3.76	6.08	3.54	3.49	0.04	9.13
1	5	4	0.85	0.08	0.74	0.96	2.14	0.42	1.31	2.50	3.37	3.68	0.51	10.61	5.39	0.88	4.16	6.71	3.56	3.34	0.07	8.82
1	5	5	0.80	0.10	0.67	0.94	2.18	0.40	1.36	2.52	3.53	3.36	0.85	10.57	4.73	0.81	3.67	5.84	3.16	3.76	0.00	9.16
1	5	6	0.77	0.09	0.68	0.89	2.18	0.41	1.35	2.51	3.49	3.36	1.07	10.38	4.67	0.89	3.61	5.90	3.63	3.61	0.05	9.03
1	6	1	0.86	0.06	0.78	0.98	2.06	0.42	1.17	2.39	3.57	3.45	1.01	11.01	6.01	0.77	5.00	7.15	4.20	2.77	0.38	8.42
1	6	2	0.87	0.08	0.79	1.02	2.03	0.46	1.10	2.42	3.97	4.03	0.86	11.99	5.86	0.74	4.86	7.17	4.07	3.13	0.05	8.73
1	6	3	0.86	0.07	0.79	0.99	2.08	0.43	1.18	2.43	3.42	3.64	0.70	11.04	5.86	0.79	4.86	7.13	4.12	2.90	0.00	8.44
1	6	4	0.84	0.08	0.75	0.98	2.10	0.40	1.23	2.41	3.12	3.22	0.78	10.30	5.86	0.81	5.03	7.15	4.25	2.83	0.32	8.21
1	6	5	0.83	0.08	0.75	0.98	2.09	0.41	1.22	2.41	3.40	3.31	1.03	10.54	5.70	0.80	4.85	6.96	4.22	2.89	0.09	8.34
1	6	6	0.83	0.07	0.76	0.96	2.15	0.38	1.29	2.44	2.44	3.08	0.06	9.61	5.78	0.86	4.90	7.15	4.30	2.62	0.54	8.19
3	4	1	0.75	0.08	0.63	0.86	2.05	0.30	1.38	2.30	3.34	1.54	2.10	6.95	-3.62	0.18	3.36	3.89	3.42	1.74	1.45	6.31
3	4	2	0.80	0.08	0.68	0.90	1.99	0.37	1.24	2.30	3.67	2.19	1.79	7.88	-3.82	0.18	3.56	4.20	3.38	1.86	1.34	6.43
3	4	3	0.79	0.08	0.67	0.89	2.01	0.34	1.27	2.30	3.47	1.96	1.87	7.63	-3.85	0.17	3.63	4.18	3.33	1.79	1.41	6.34
3	4	4	0.80	0.09	0.67	0.90	2.03	0.35	1.28	2.30	3.25	1.92	1.74	7.35	-3.90	0.15	3.75	4.23	3.29	1.80	1.56	6.27
3	4	5	0.81	0.09	0.68	0.91	2.03	0.33	1.30	2.29	3.00	1.88	1.54	7.22	-4.08	0.13	3.91	4.35	3.41	1.66	1.70	6.24
3	4	6	0.79	0.09	0.67	0.90	2.03	0.33	1.34	2.30	3.01	1.80	1.52	6.76	-4.04	0.16	3.85	4.33	3.46	1.70	1.67	6.18
3	5	1	0.83	0.08	0.71	0.92	1.96	0.35	1.23	2.24	3.14	2.27	1.44	7.84	-4.42	0.24	3.86	4.83	3.80	1.46	2.18	6.23
3	5	2	0.80	0.07	0.68	0.89	1.97	0.34	1.28	2.26	3.40	2.01	1.77	7.45	-4.14	0.22	3.81	4.60	3.66	1.56	1.93	6.29

			Shoulder elevation				Elbow bend				Shoulder el. torque				Shoulder rot. torque				Elbow bend torque			
Subject	Object	Rep.	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX
3	5	3	0.85	0.08	0.71	0.95	1.97	0.36	1.20	2.28	3.45	2.25	1.56	8.00	-4.26	0.25	3.78	4.71	3.39	1.72	1.42	6.28
3	5	4	0.87	0.09	0.74	0.98	1.98	0.34	1.25	2.27	3.16	1.98	1.59	7.42	-4.45	0.23	4.20	4.86	3.20	1.70	1.34	6.00

3	5	5	0.91	0.10	0.76	1.02	1.96	0.35	1.24	2.29	3.10	2.08	1.25	7.34	-4.68	0.24	4.31	5.04	3.16	1.71	1.14	5.80
3	5	6	0.92	0.09	0.77	1.04	2.00	0.33	1.29	2.29	2.77	1.92	1.17	6.90	-4.72	0.27	4.37	5.18	3.01	1.65	1.04	5.70
3	6	1	0.64	0.07	0.54	0.77	1.94	0.26	1.39	2.15	2.46	0.69	1.59	4.12	-3.84	0.29	3.59	4.56	4.90	1.09	3.22	6.24
3	6	2	0.69	0.05	0.62	0.77	1.94	0.30	1.35	2.19	2.67	1.03	1.79	4.79	-4.07	0.26	3.80	4.58	4.59	1.03	3.25	6.00
3	6	3	0.77	0.05	0.69	0.85	1.87	0.46	1.00	2.25	3.98	2.49	1.93	8.59	-3.95	0.16	3.75	4.30	3.94	1.51	2.15	6.07
3	6	4	0.80	0.06	0.73	0.89	1.89	0.42	1.04	2.22	3.74	2.25	1.93	8.17	-4.21	0.20	3.98	4.62	3.83	1.48	2.01	5.93
3	6	5	0.78	0.05	0.72	0.88	1.92	0.41	1.08	2.27	3.60	2.13	1.93	7.94	-4.07	0.33	3.68	4.65	3.76	1.57	1.65	5.91
3	6	6	0.80	0.06	0.72	0.89	1.90	0.41	1.10	2.24	3.71	2.23	1.89	8.00	-4.19	0.19	3.95	4.57	3.84	1.54	1.95	6.05
4	4	1	1.15	0.11	0.99	1.31	2.24	0.28	1.71	2.50	0.21	1.04	0.11	2.26	-4.45	0.69	3.61	5.48	1.51	1.63	0.00	3.74
4	4	2	1.13	0.13	0.94	1.29	2.15	0.38	1.43	2.51	0.95	1.89	0.04	4.62	-4.45	0.75	3.52	5.43	1.44	1.79	0.04	4.01
4	4	3	1.14	0.12	0.95	1.31	2.13	0.44	1.28	2.50	1.09	2.32	0.02	5.83	-4.40	0.77	3.53	5.56	1.35	1.85	0.05	4.11
4	4	4	1.12	0.11	0.97	1.29	2.11	0.45	1.26	2.50	1.20	2.33	0.03	5.83	-4.43	0.79	3.49	5.53	1.59	1.72	0.00	3.94
4	4	5	1.15	0.13	0.95	1.34	2.11	0.46	1.24	2.52	1.27	2.46	0.08	6.07	-4.38	0.81	3.38	5.56	1.21	1.99	0.05	4.12
4	4	6	1.09	0.17	0.87	1.36	1.90	0.55	1.24	2.55	2.52	3.12	0.01	6.57	-4.44	0.74	3.30	5.56	2.19	2.23	0.05	4.78
4	5	1	1.15	0.14	0.92	1.35	2.26	0.35	1.48	2.55	0.29	1.73	0.05	4.37	-4.17	0.78	3.31	5.37	1.28	1.85	0.03	4.06
4	5	2	1.08	0.12	0.92	1.25	2.07	0.44	1.41	2.51	1.50	2.19	0.01	4.96	-4.45	0.78	3.33	5.40	1.79	1.93	0.01	4.15
4	5	3	0.98	0.11	0.87	1.17	1.93	0.50	1.23	2.50	2.48	2.85	0.02	6.66	-4.27	0.56	3.38	5.08	2.68	1.87	0.01	4.80
4	5	4	1.12	0.12	0.90	1.27	2.19	0.43	1.36	2.57	0.85	2.19	0.11	5.35	-4.20	0.88	3.18	5.44	1.38	1.85	0.00	4.31
4	5	5	1.12	0.12	0.94	1.28	2.14	0.45	1.32	2.54	1.13	2.33	0.06	5.63	-4.32	0.84	3.33	5.47	1.40	1.91	0.03	4.10
4	5	6	1.12	0.13	0.95	1.31	2.13	0.44	1.41	2.57	1.11	2.23	0.07	4.88	-4.36	0.92	3.20	5.51	1.47	1.91	0.03	3.95
4	6	1	0.95	0.10	0.77	1.12	2.33	0.13	2.01	2.44	-0.32	0.27	0.02	0.72	-3.82	0.20	3.53	4.20	2.58	1.18	0.63	4.66
4	6	2	1.12	0.10	0.97	1.27	2.22	0.30	1.47	2.45	0.29	1.42	0.09	4.24	-4.48	0.60	3.93	5.49	1.95	1.28	0.05	3.80
4	6	3	1.11	0.11	0.95	1.30	2.09	0.40	1.34	2.46	1.11	2.07	0.10	5.15	-4.65	0.67	3.91	5.55	2.08	1.35	0.03	3.94
4	6	4	1.18	0.11	1.02	1.34	2.16	0.35	1.44	2.46	0.58	1.76	0.07	4.38	-4.71	0.70	3.99	5.70	1.76	1.26	0.01	3.48

			Shoulder elevation				Elbow bend				Shoulder el. torque				Shoulder rot. torque				Elbow bend torque			
Subject	Object	Rep.	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX	AVE	STD	MIN	MAX
4	6	5	1.21	0.10	1.04	1.36	2.12	0.39	1.36	2.48	0.87	2.07	0.09	4.92	-4.82	0.77	3.93	5.93	1.63	1.19	0.02	3.39
4	6	6	1.25	0.13	1.04	1.41	2.15	0.37	1.44	2.47	0.58	1.86	0.03	4.31	-4.84	0.74	4.02	5.85	1.58	1.27	0.05	3.35
5	4	1	0.45	0.06	0.36	0.54	2.36	0.42	1.56	2.73	2.18	1.93	0.53	5.82	1.25	0.32	0.90	1.75	2.40	2.11	0.22	5.76
5	4	2	0.34	0.09	0.16	0.44	2.48	0.40	1.59	2.81	1.88	1.45	0.78	5.77	0.79	0.54	0.40	1.84	2.08	2.25	0.00	5.70
5	4	3	0.33	0.06	0.23	0.41	2.22	0.39	1.59	2.66	2.94	1.84	1.14	6.16	1.07	0.23	0.82	1.43	3.67	1.66	1.09	5.76
5	4	4	0.32	0.07	0.20	0.41	2.47	0.35	1.69	2.76	1.73	1.39	0.72	5.32	0.84	0.24	0.66	1.43	2.47	1.90	0.60	5.67

5	4	5	0.37	0.05	0.27	0.44	2.38	0.41	1.58	2.74	2.28	2.01	0.62	6.21	0.99	0.23	0.77	1.40	2.72	1.89	0.73	5.75
5	4	6	0.39	0.08	0.24	0.48	2.55	0.34	1.69	2.79	1.46	1.58	0.30	5.43	0.89	0.26	0.73	1.57	1.87	1.87	0.19	5.53
5	5	1	0.58	0.07	0.43	0.67	2.18	0.49	1.22	2.63	2.58	2.24	0.61	7.05	1.90	0.46	1.37	2.69	2.77	2.05	0.17	5.64
5	5	2	0.55	0.07	0.44	0.65	2.23	0.46	1.39	2.66	2.73	2.18	0.62	6.55	1.61	0.35	1.20	2.12	2.56	2.20	0.02	5.72
5	5	3	0.44	0.06	0.31	0.51	2.42	0.38	1.51	2.72	1.98	1.82	0.69	6.54	1.14	0.26	0.85	1.69	2.22	1.88	0.34	5.72
5	5	4	0.39	0.07	0.24	0.47	2.61	0.14	2.21	2.74	1.63	0.58	1.00	3.12	0.69	0.09	0.57	1.01	1.25	1.19	0.12	4.25
5	5	5	0.45	0.06	0.35	0.54	2.45	0.40	1.55	2.76	1.33	1.79	0.12	5.64	1.30	0.38	0.95	1.98	2.28	1.96	0.28	5.66
5	5	6	0.46	0.08	0.34	0.55	2.46	0.32	1.71	2.72	1.33	1.22	0.49	4.72	1.30	0.28	0.97	1.86	2.19	1.87	0.27	5.52
5	6	1	0.40	0.06	0.29	0.51	2.17	0.46	1.45	2.60	3.39	2.36	1.33	7.18	1.07	0.11	0.83	1.35	3.44	1.94	0.94	5.97
5	6	2	0.43	0.07	0.30	0.53	2.23	0.45	1.36	2.62	2.29	2.53	0.30	7.25	1.40	0.12	1.21	1.69	3.41	1.78	1.15	5.98
5	6	3	0.44	0.04	0.36	0.51	2.27	0.40	1.36	2.59	1.90	1.98	0.40	6.66	1.57	0.29	1.31	2.20	3.26	1.57	1.45	5.87
5	6	4	0.48	0.05	0.37	0.55	2.17	0.54	1.24	2.63	2.35	2.52	0.06	6.77	1.66	0.39	1.22	2.22	3.29	1.92	0.99	5.83
5	6	5	0.38	0.08	0.23	0.48	2.32	0.45	1.38	2.68	2.35	2.05	0.99	6.89	1.10	0.35	0.81	1.77	2.87	1.98	0.72	5.90
5	6	6	0.42	0.08	0.27	0.52	2.45	0.35	1.55	2.70	1.68	1.72	0.50	6.14	1.12	0.13	1.01	1.43	2.32	1.80	0.60	5.81

7.5 Product design, noise experiment: results

7.5.1 Averages

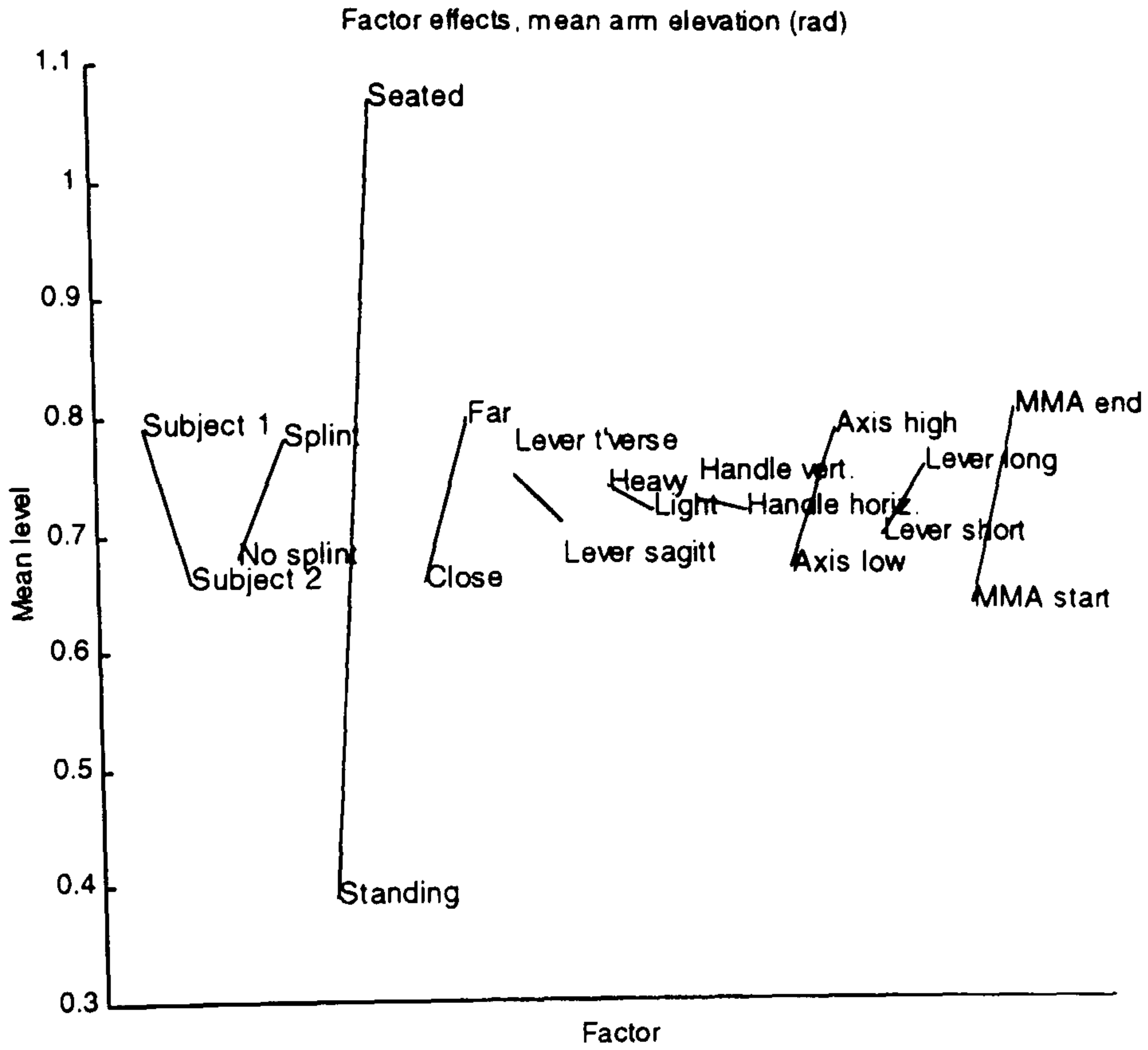
		Angular Measures				Torque measures					
		Shoulder elevation		Elbow bend		Shoulder elevation		Shoulder rotation		Elbow bend	
Factor	**Level**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Maximum**	**Mean**	**Maximum**	**Mean**	**Maximum**
Subject	Subject 1	0.79	0.22	1.03	0.32	15.09	17.22	5.06	5.91	12.98	13.84
	Subject 2	0.66	0.24	1.06	0.3	12.49	13.81	2.07	2.85	9.82	10.94
Splint	No splint	0.68	0.22	1.07	0.37	13.13	14.82	2.81	3.38	11.89	12.78
	Splint	0.78	0.24	1.02	0.25	14.46	16.21	4.32	5.39	10.91	12
Posture	Standing	0.39	0.18	0.98	0.42	10.55	12.76	3.25	4.05	11.77	12.76
	Seated	1.07	0.28	1.11	0.2	17.04	18.28	3.89	4.71	11.03	12.03
Distance	Close	0.66	0.24	1.32	0.36	8.33	11.04	5.03	5.87	9.59	11
	Far	0.8	0.22	0.77	0.26	19.25	19.99	2.1	2.9	13.22	13.79
Lever axi	Lever t've	0.75	0.2	0.93	0.22	14.37	16.03	2.86	3.74	12.22	13.24
	Lever sagi	0.71	0.26	1.16	0.4	13.21	15.01	4.27	5.03	10.59	11.54
Load	Heavy	0.74	0.28	0.83	0.38	15.58	18.03	2.06	2.94	12.27	13.63
	Light	0.72	0.18	1.26	0.24	12	13	5.08	5.83	10.53	11.16
Handle di	Handle ver	0.73	0.22	1.08	0.34	13.68	15.91	3.24	3.9	10.63	11.83
	Handle hor	0.72	0.24	1.01	0.28	13.9	15.12	3.9	4.87	12.17	12.96
Axis hei.	Axis low	0.67	0.24	0.91	0.41	14.51	16.52	2.14	3.02	11.58	12.71
	Axis high	0.79	0.22	1.18	0.21	13.08	14.51	5	5.75	11.23	12.08
Lever ler	Lever shor	0.7	0.15	1.11	0.2	14.07	15.99	4.26	4.65	11.37	12.08
	Lever long	0.76	0.31	0.98	0.42	13.51	15.05	2.87	4.12	11.43	12.71
MMA pos.	MMA start	0.64	0.23	1.05	0.23	14.56	16.54	3.02	3.87	11.51	12.77
	MMA end	0.81	0.23	1.04	0.39	13.02	14.49	4.12	4.9	11.29	12.01

7.5.2 Angular measures

7.5.2.1 Data

Factor												Shoulder elevation				Elbow bend			
Subject	Splint	Posture	Distance	Axis dir	Load	Handle dir	Axis height	Lever length	Mech adv pos	Noise	Rep	Mean	STD	Min	Max	Mean	STD	Min	Max
1	1	1	1	1	1	1	1	1	1	1	1	0.121	0.011	0.107	0.143	0.835	0.183	0.563	1.098
1	1	1	1	1	1	1	1	1	1	1	2	0.087	0.015	0.070	0.119	0.771	0.188	0.475	1.041
1	1	1	1	1	1	1	1	1	1	1	3	0.066	0.021	0.043	0.106	0.769	0.140	0.545	0.972
1	1	1	1	1	1	1	1	1	1	1	4	0.080	0.014	0.062	0.110	0.758	0.161	0.547	1.014
1	1	1	1	1	1	1	1	1	1	1	5	0.086	0.026	0.060	0.136	0.759	0.176	0.494	1.016
1	1	1	1	1	2	2	2	2	2	2	1	0.632	0.117	0.413	0.770	1.454	0.124	1.167	1.556
1	1	1	1	1	2	2	2	2	2	2	2	0.644	0.061	0.513	0.704	1.568	0.114	1.260	1.663
1	1	1	1	1	2	2	2	2	2	2	3	0.596	0.053	0.485	0.649	1.496	0.126	1.204	1.611
1	1	1	1	1	2	2	2	2	2	2	4	0.593	0.060	0.464	0.650	1.515	0.120	1.228	1.629
1	1	1	1	1	2	2	2	2	2	2	5	0.639	0.092	0.525	0.773	1.547	0.098	1.200	1.624
1	1	2	2	2	1	1	1	2	2	2	1	1.373	0.178	1.023	1.540	0.642	0.225	0.423	1.001
1	1	2	2	2	1	1	1	2	2	2	2	1.310	0.169	1.022	1.517	0.675	0.261	0.317	1.030
1	1	2	2	2	1	1	1	2	2	2	3	1.295	0.153	1.043	1.511	0.667	0.248	0.269	0.998
1	1	2	2	2	1	1	1	2	2	2	4	1.297	0.152	1.025	1.489	0.689	0.243	0.338	1.036
1	1	2	2	2	1	1	1	2	2	2	5	1.289	0.152	1.027	1.457	0.756	0.229	0.477	1.082
1	2	1	2	2	1	2	2	1	1	2	1	0.742	0.121	0.546	0.895	0.674	0.091	0.541	0.785
1	2	1	2	2	1	2	2	1	1	2	2	0.589	0.079	0.467	0.694	0.904	0.025	0.852	0.939
1	2	1	2	2	1	2	2	1	1	2	3	0.591	0.076	0.461	0.678	0.918	0.018	0.865	0.939
1	2	1	2	2	1	2	2	1	1	2	4	0.579	0.068	0.468	0.670	0.875	0.017	0.832	0.898
1	2	1	2	2	1	2	2	1	1	2	5	0.528	0.066	0.421	0.608	0.978	0.022	0.920	1.007
1	2	2	1	2	2	1	2	1	2	1	1	1.102	0.023	1.075	1.146	1.825	0.042	1.726	1.861
1	2	2	1	2	2	1	2	1	2	1	2	1.113	0.021	1.087	1.155	1.776	0.066	1.640	1.839
1	2	2	1	2	2	1	2	1	2	1	3	1.064	0.051	1.002	1.142	1.775	0.048	1.675	1.826
1	2	2	1	2	2	1	2	1	2	1	4	1.089	0.036	1.041	1.145	1.775	0.078	1.617	1.853
1	2	2	1	2	2	1	2	1	2	1	5	1.048	0.066	0.952	1.144	1.744	0.057	1.629	1.797
1	2	2	2	1	2	2	1	2	1	1	1	1.050	0.064	0.961	1.162	0.494	0.023	0.469	0.542
1	2	2	2	1	2	2	1	2	1	1	2	1.019	0.063	0.944	1.141	0.556	0.033	0.514	0.621
1	2	2	2	1	2	2	1	2	1	1	3	1.023	0.071	0.934	1.150	0.536	0.019	0.514	0.531
1	2	2	2	1	2	2	1	2	1	1	4	1.030	0.078	0.941	1.175	0.544	0.014	0.525	0.569
1	2	2	2	1	2	2	1	2	1	1	5	1.038	0.083	0.935	1.186	0.562	0.020	0.540	0.594
2	1	2	2	1	1	2	2	1	2	1	1	1.041	0.045	0.985	1.120	0.585	0.019	0.563	0.619
2	1	2	2	1	1	2	2	1	2	1	2	1.063	0.040	0.996	1.130	0.585	0.022	0.551	0.618
2	1	2	2	1	1	2	2	1	2	1	3	1.061	0.045	0.998	1.135	0.580	0.025	0.546	0.620
2	1	2	2	1	1	2	2	1	2	1	4	1.063	0.042	0.998	1.132	0.584	0.022	0.551	0.619
2	1	2	2	1	1	2	2	1	2	1	5	1.062	0.043	0.987	1.134	0.591	0.027	0.548	0.631
2	1	2	1	2	2	2	1	1	1	2	1	0.742	0.091	0.588	0.859	1.807	0.045	1.735	1.860
2	1	2	1	2	2	2	1	1	1	2	2	0.791	0.090	0.623	0.890	1.786	0.064	1.709	1.881
2	1	2	1	2	2	2	1	1	1	2	3	0.783	0.093	0.623	0.893	1.778	0.062	1.695	1.857
2	1	2	1	2	2	2	1	1	1	2	4	0.786	0.099	0.609	0.888	1.774	0.065	1.696	1.858
2	1	2	1	2	2	2	1	1	1	2	5	0.783	0.091	0.628	0.890	1.774	0.055	1.699	1.841
2	1	1	2	2	2	1	2	2	1	1	1	0.281	0.068	0.226	0.461	1.013	0.097	0.859	1.134
2	1	1	2	2	2	1	2	2	1	1	2	0.199	0.037	0.170	0.323	1.071	0.155	0.899	1.356
2	1	1	2	2	2	1	2	2	1	1	3	0.184	0.029	0.141	0.245	1.108	0.176	0.913	1.414
2	1	1	2	2	2	1	2	2	1	1	4	0.188	0.031	0.163	0.295	1.131	0.161	0.953	1.424
2	1	1	2	2	2	1	2	2	1	1	5	0.250	0.015	0.223	0.295	1.063	0.180	0.888	1.422
2	2	2	1	1	1	1	2	2	1	2	1	1.114	0.159	0.798	1.269	1.363	0.022	1.318	1.388
2	2	2	1	1	1	1	2	2	1	2	2	1.168	0.133	0.904	1.318	1.278	0.027	1.196	1.303
2	2	2	1	1	1	1	2	2	1	2	3	1.124	0.152	0.851	1.301	1.257	0.016	1.228	1.278
2	2	2	1	1	1	1	2	2	1	2	4	1.126	0.147	0.860	1.294	1.243	0.024	1.206	1.272
2	2	2	1	1	1	1	2	2	1	2	5	1.121	0.144	0.863	1.286	1.228	0.027	1.175	1.266
2	2	1	2	1	2	1	1	1	2	2	1	0.695	0.054	0.591	0.772	0.615	0.065	0.505	0.697
2	2	1	2	1	2	1	1	1	2	2	2	0.580	0.035	0.532	0.625	0.885	0.026	0.814	0.909
2	2	1	2	1	2	1	1	1	2	2	3	0.544	0.034	0.507	0.589	0.945	0.037	0.853	0.983
2	2	1	2	1	2	1	1	1	2	2	4	0.518	0.018	0.487	0.548	0.998	0.076	0.826	1.078
2	2	1	2	1	2	1	1	1	2	2	5	0.501	0.020	0.465	0.523	0.997	0.068	0.839	1.064
2	2	1	1	2	1	2	1	2	2	1	1	0.230	0.080	0.136	0.396	0.613	0.225	0.445	1.157
2	2	1	1	2	1	2	1	2	2	1	2	0.231	0.102	0.113	0.435	0.729	0.285	0.456	1.311
2	2	1	1	2	1	2	1	2	2	1	3	0.232	0.123	0.090	0.469	0.796	0.284	0.481	1.383
2	2	1	1	2	1	2	1	2	2	1	4	0.247	0.139	0.090	0.506	0.876	0.307	0.522	1.457
2	2	1	1	2	1	2	1	2	2	1	5	0.223	0.117	0.092	0.435	0.865	0.286	0.516	1.420

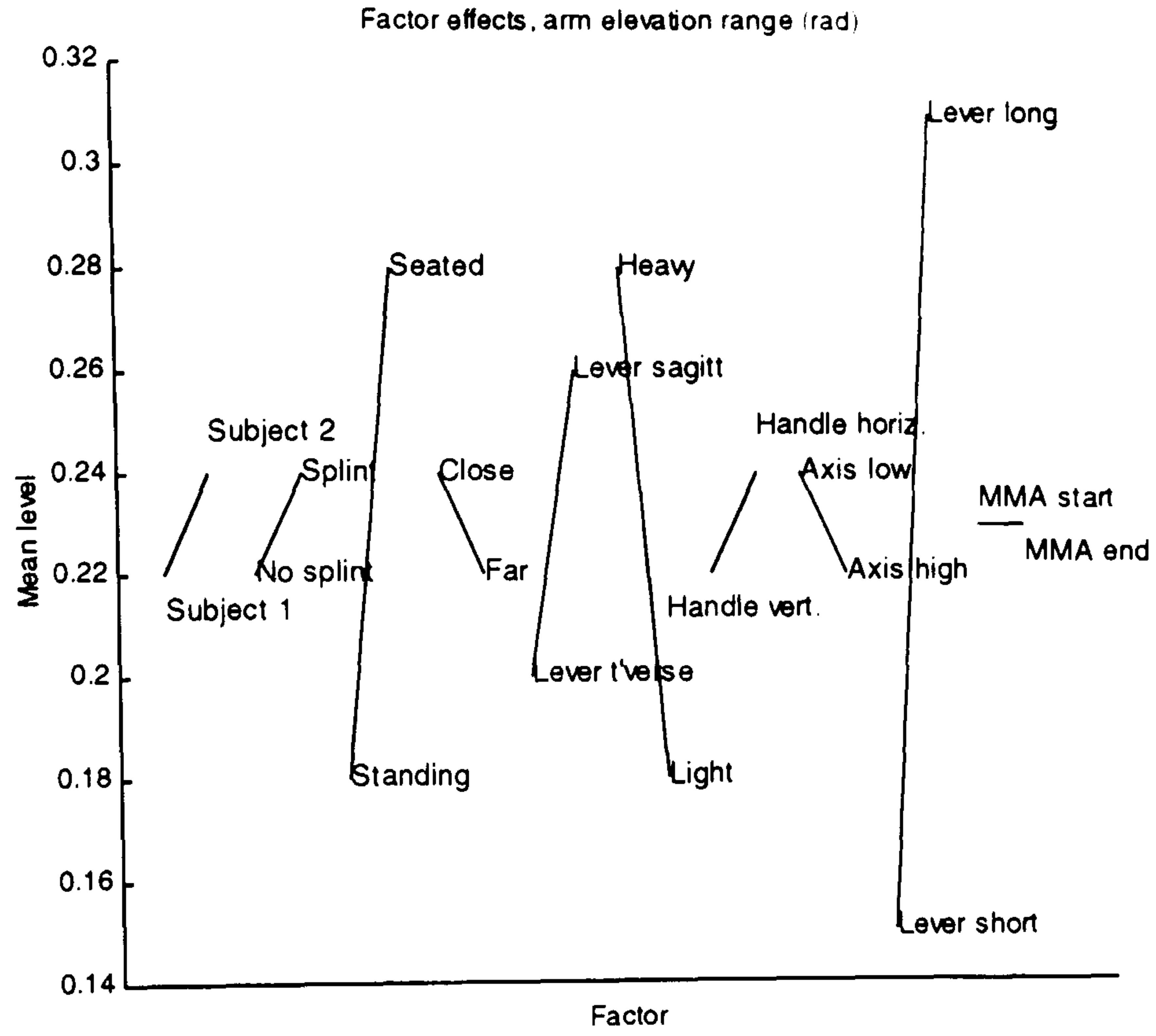
7.5.2.2 Shoulder elevation factor effects plot: mean values



7.5.2.3 *Shoulder elevation ANOVA : mean values*

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	8.288	10	.829	52.140	.000
SUBJECT	.239	1	.239	15.017	.000
SPLINT	.138	1	.138	8.662	.005
POSTURE	6.861	1	6.861	431.630	.000
DISTANCE	.312	1	.312	19.599	.000
AXIS_DIR	.029	1	.029	1.848	.180
LOAD	.007	1	.007	.424	.518
HANDLE_D	.002	1	.002	.155	.695
AXIS_HEI	.209	1	.209	13.177	.001
LEVER_LE	.057	1	.057	3.591	.064
MECH_ADV	.434	1	.434	27.301	.000
Explained	8.288	10	.829	52.140	.000
Residual	.779	49	.016		
Total	9.067	59	.154		

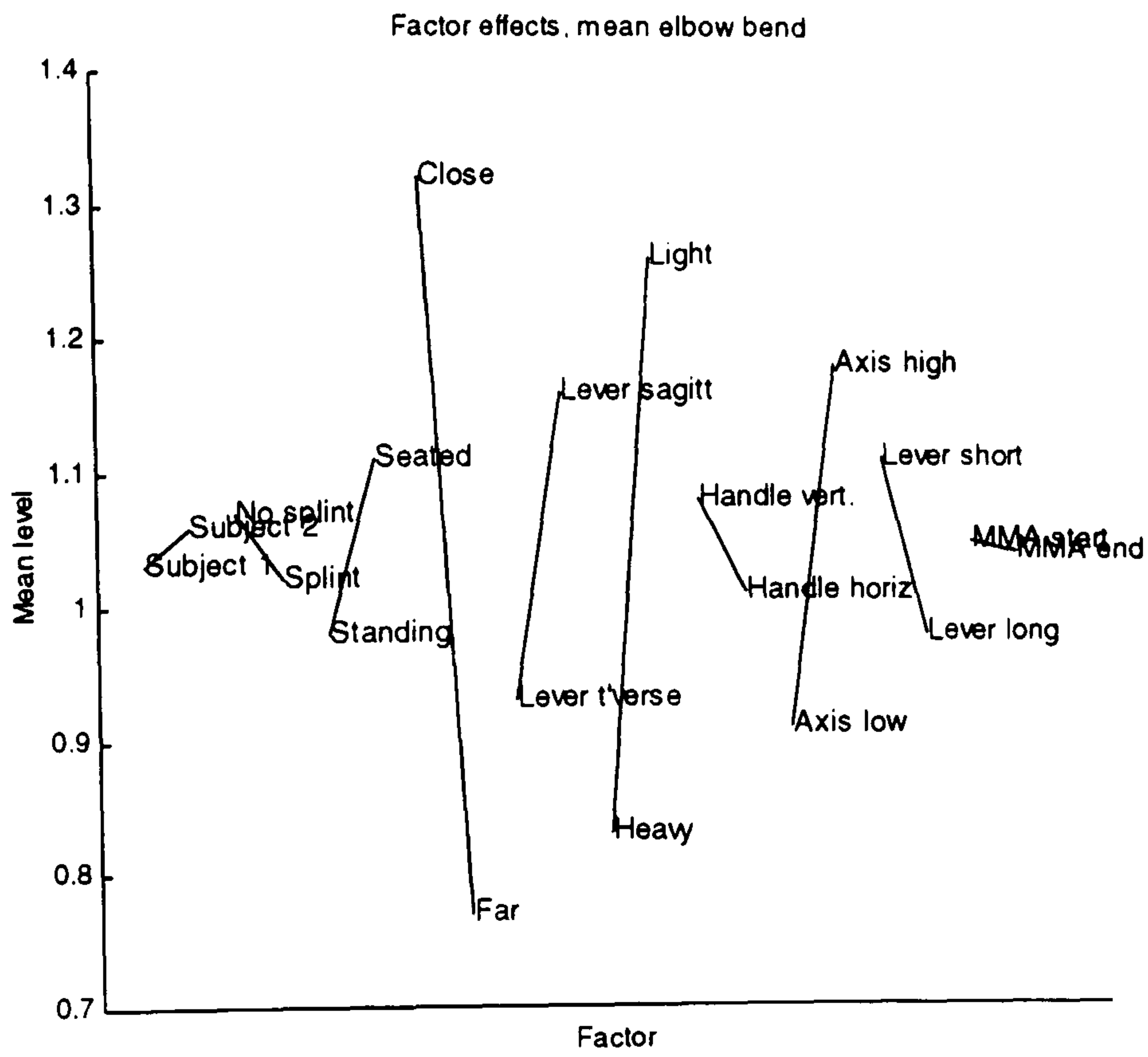
7.5.2.4 Shoulder elevation factor effects plot: range



7.5.2.5 Shoulder elevation ANOVA: range

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	.762	10	.076	11.469	.000
SUBJECT	.004	1	.004	.552	.461
SPLINT	.009	1	.009	1.301	.260
POSTURE	.129	1	.129	19.483	.000
DISTANCE	.009	1	.009	1.399	.243
LOAD	.159	1	.159	23.899	.000
AXIS_DIR	.068	1	.068	10.231	.002
HANDLE_D	.006	1	.006	.899	.348
AXIS_HEI	.011	1	.011	1.648	.205
LEVER_LE	.366	1	.366	55.189	.000
MECH_ADV	.001	1	.001	.087	.769
Explained	.762	10	.076	11.469	.000
Residual	.325	49	.007		
Total	1.087	59	.018		

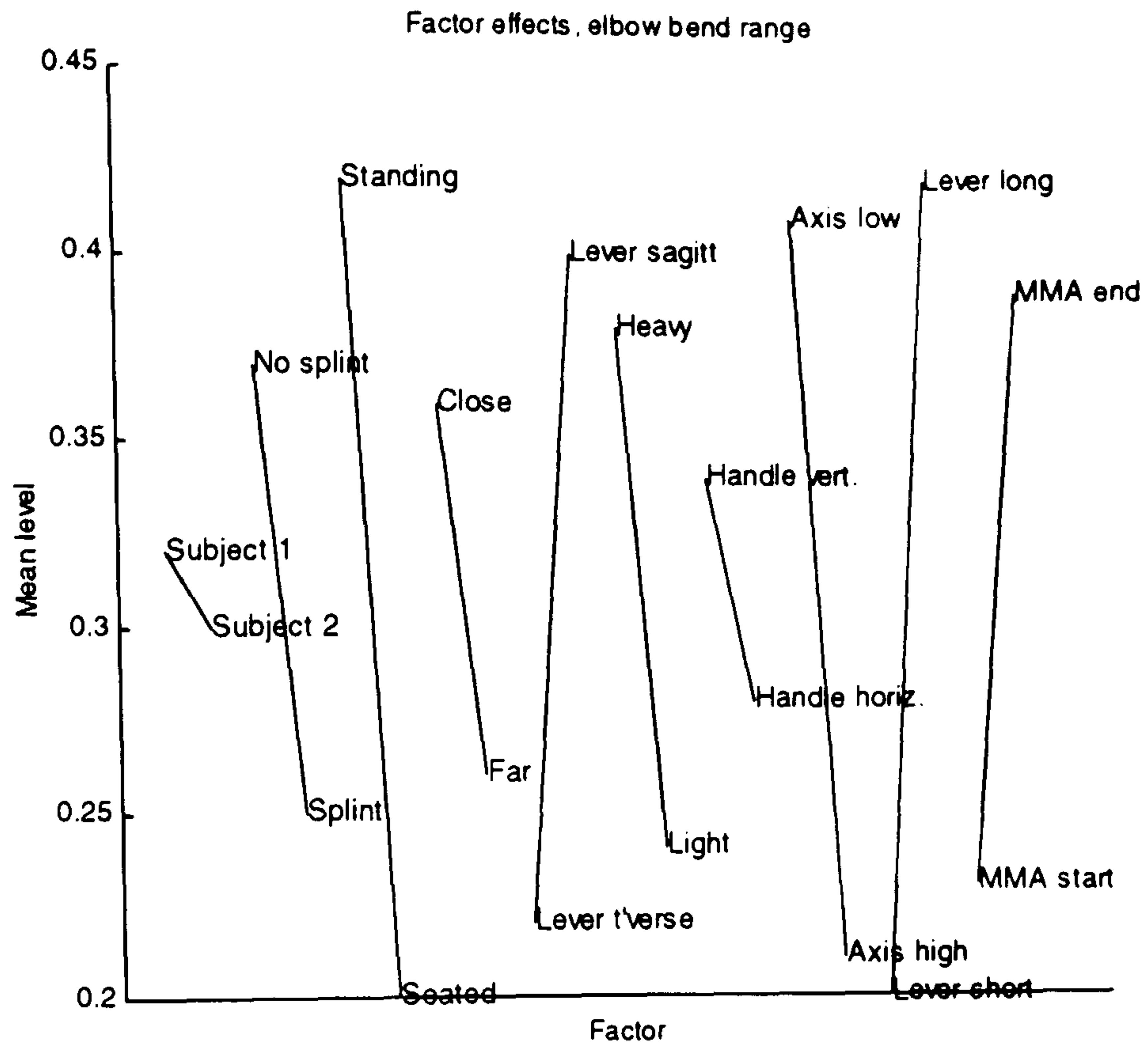
7.5.2.6 Shoulder elevation factor effects plot: mean values



7.5.2.7 Shoulder elevation ANOVA: mean values

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	9.864	10	.986	41.438	.000
SUBJECT	.019	1	.019	.815	.371
SPLINT	.038	1	.038	1.598	.212
POSTURE	.229	1	.229	9.603	.003
DISTANCE	4.436	1	4.436	186.329	.000
AXIS_DIR	.807	1	.807	33.899	.000
LOAD	2.847	1	2.847	119.594	.000
HANDLE_D	.072	1	.072	3.009	.089
AXIS_HEI	1.136	1	1.136	47.718	.000
LEVER_LE	.278	1	.278	11.671	.001
MECH_ADV	.004	1	.004	.147	.703
Explained	9.864	10	.986	41.438	.000
Residual	1.166	49	.024		
Total	11.031	59	.187		

7.5.2.8 Shoulder elevation factor effects plot: range



7.5.2.9 Shoulder elevation ANOVA: range

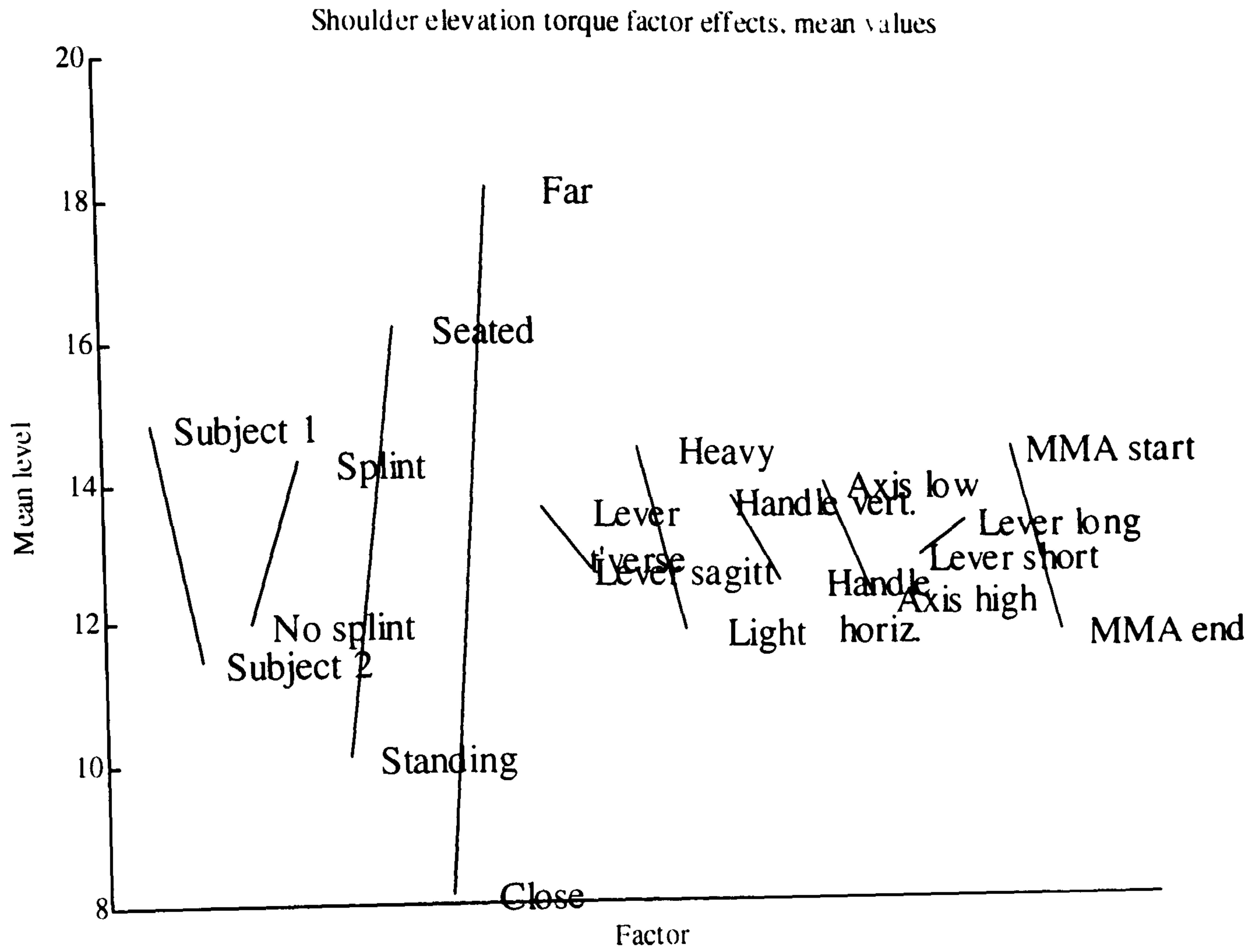
Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	3.700	10	.370	65.274	.000
SUBJECT	.009	1	.009	1.533	.222
SPLINT	.245	1	.245	43.274	.000
POSTURE	.701	1	.701	123.594	.000
DISTANCE	.169	1	.169	29.827	.000
LOAD	.306	1	.306	54.031	.000
AXIS_DIR	.517	1	.517	91.146	.000
HANDLE_D	.060	1	.060	10.551	.002
AXIS_HEI	.543	1	.543	95.753	.000
LEVER_LE	.737	1	.737	130.066	.000
MECH_ADV	.414	1	.414	72.970	.000
Explained	3.700	10	.370	65.274	.000
Residual	.278	49	.006		
Total	3.978	59	.067		

7.5.3 Torque measures

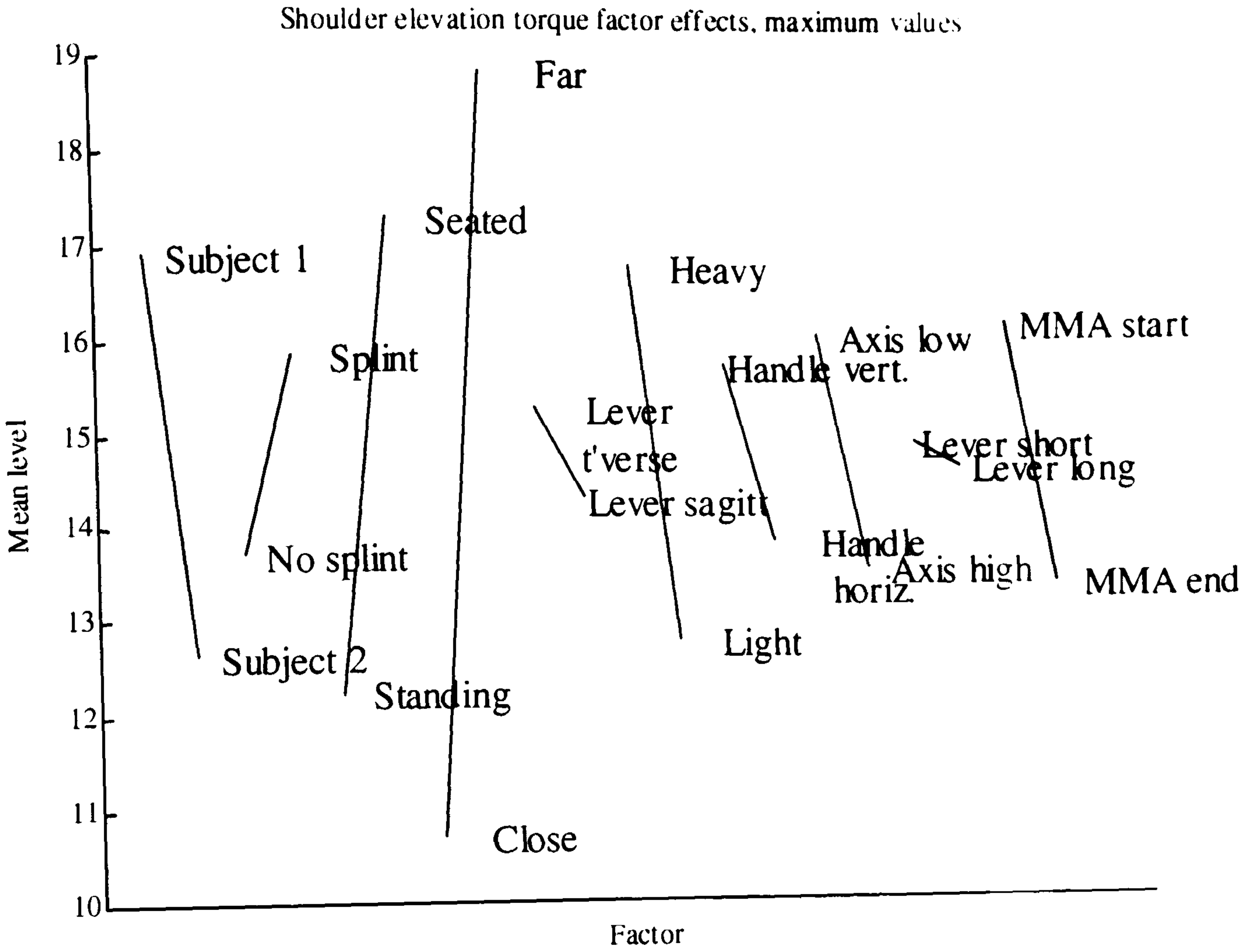
7.5.3.1 Data

Subject	Splint	Posture	Distance	Lever axis	Load	Handle dir	Axis height	Lever length	Mech adv po	Noise	Shoulder elevation		Shoulder rotation		Elbow bend	
											Mean	Max	Mean	Max	Mean	Max
1	1	1	1	1	1	1	1	1	1	1	8.58	14.93	0.91	1.23	12.55	14.86
1	1	1	1	1	2	2	2	2	2	2	3.51	4.57	8.53	9	12.57	12.93
1	1	2	2	2	1	1	1	2	2	2	24.28	25.17	0.8	1.16	14.3	14.64
1	2	1	2	2	1	2	2	1	1	2	19.83	20.95	5.71	6.23	15.28	15.83
1	2	2	1	2	2	1	2	1	2	1	9.08	11.84	11.49	11.8	7.13	7.41
1	2	2	2	1	2	2	1	2	1	1	23.68	24.1	2.41	4.27	14.63	15.2
2	1	2	2	1	1	2	2	1	2	1	15.78	16.63	1.45	1.81	10.28	10.71
2	1	2	1	2	2	2	1	1	1	2	9.27	9.95	4.82	4.95	6.99	8.08
2	1	1	2	2	2	1	2	2	1	1	10.51	11.02	1.37	1.89	9.66	10.63
2	2	2	1	1	1	1	2	2	1	2	15.06	16.14	6.13	7.18	8.3	10.29
2	2	1	2	1	2	1	1	1	2	2	14.88	15.22	1.9	2.25	10.93	11.22
2	2	1	1	2	1	2	1	2	2	1	3.25	6.83	1.25	2.88	7.51	9.53

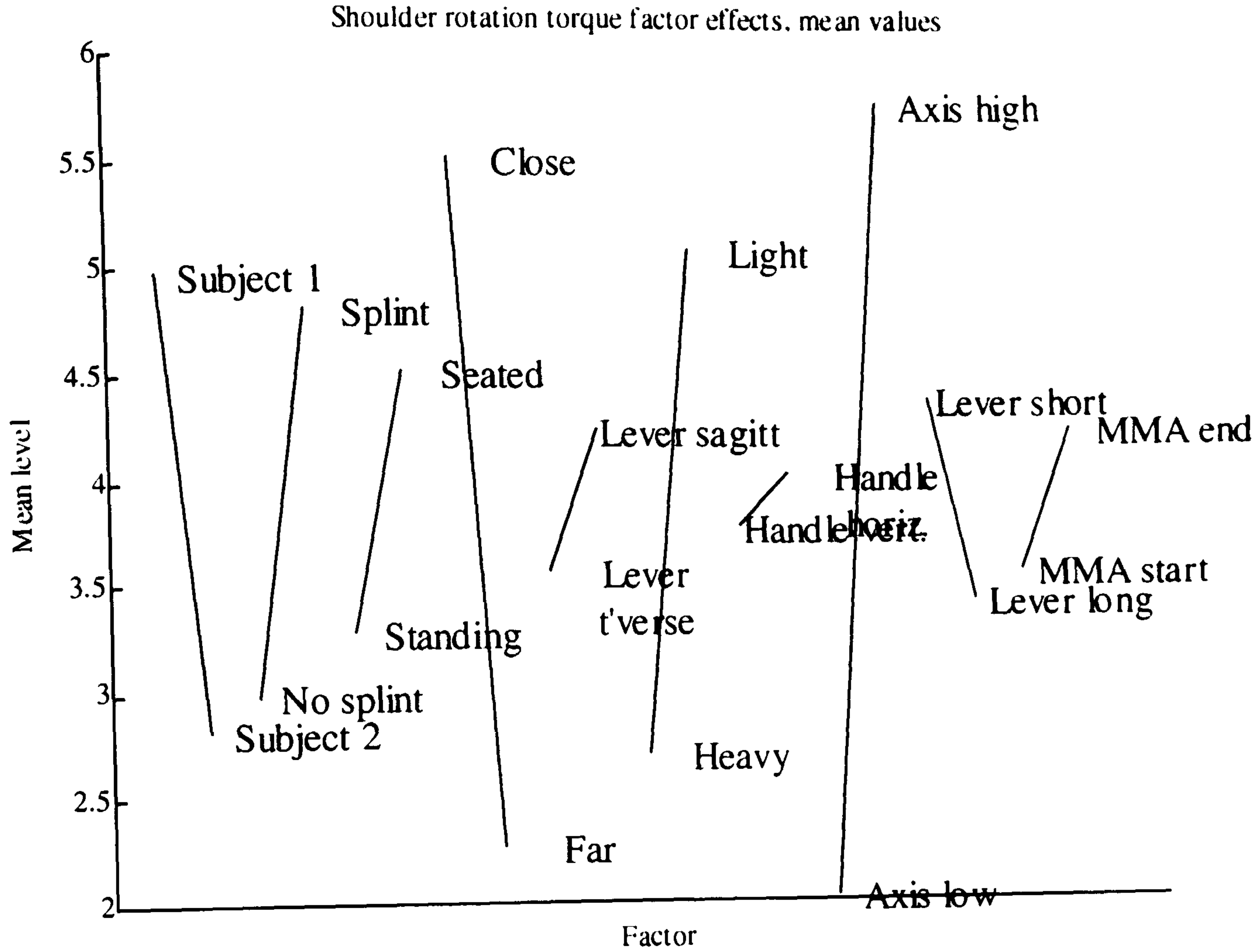
7.5.3.2 Shoulder elevation factor effects plot: mean values



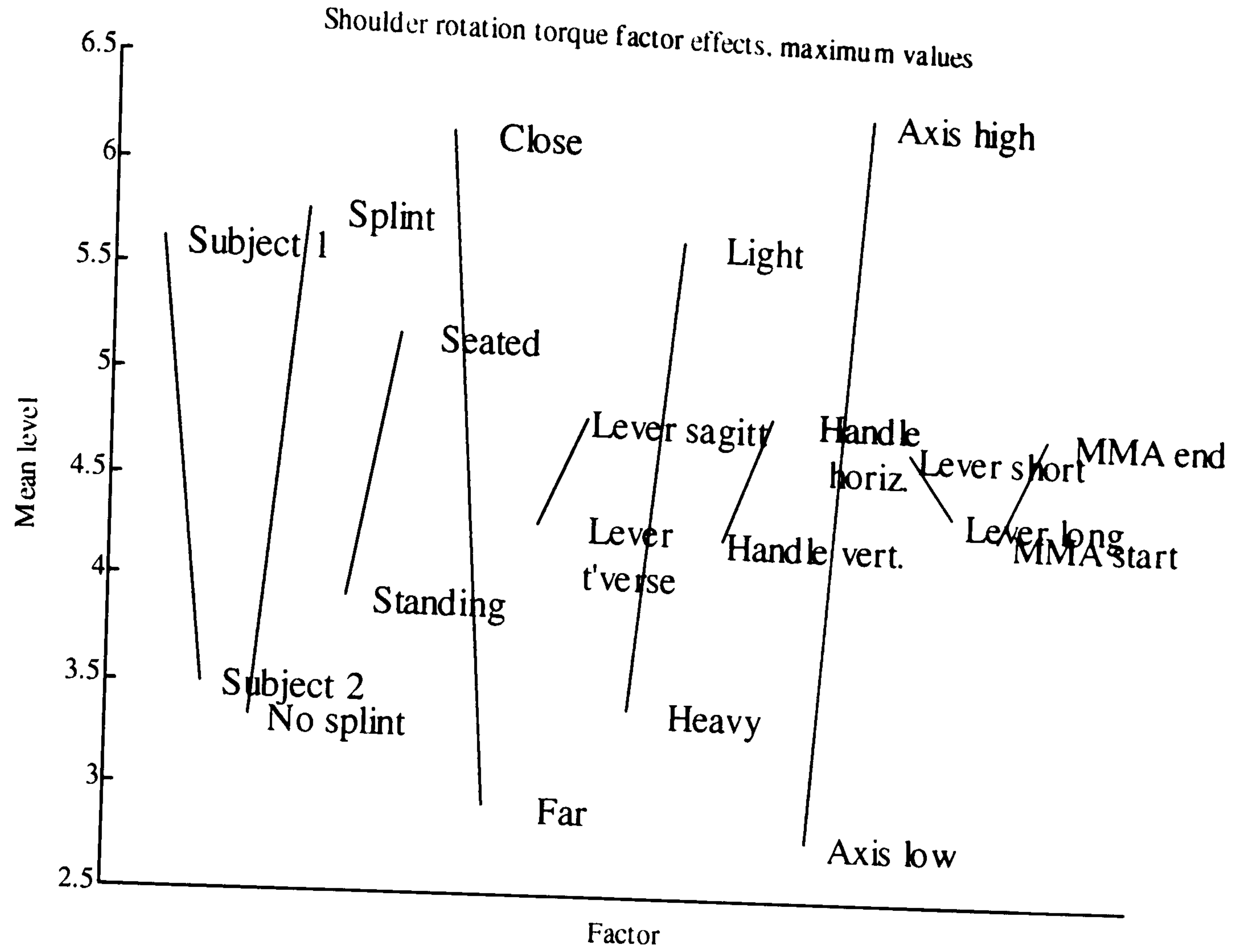
7.5.3.3 Shoulder elevation factor effects plot: maximum values



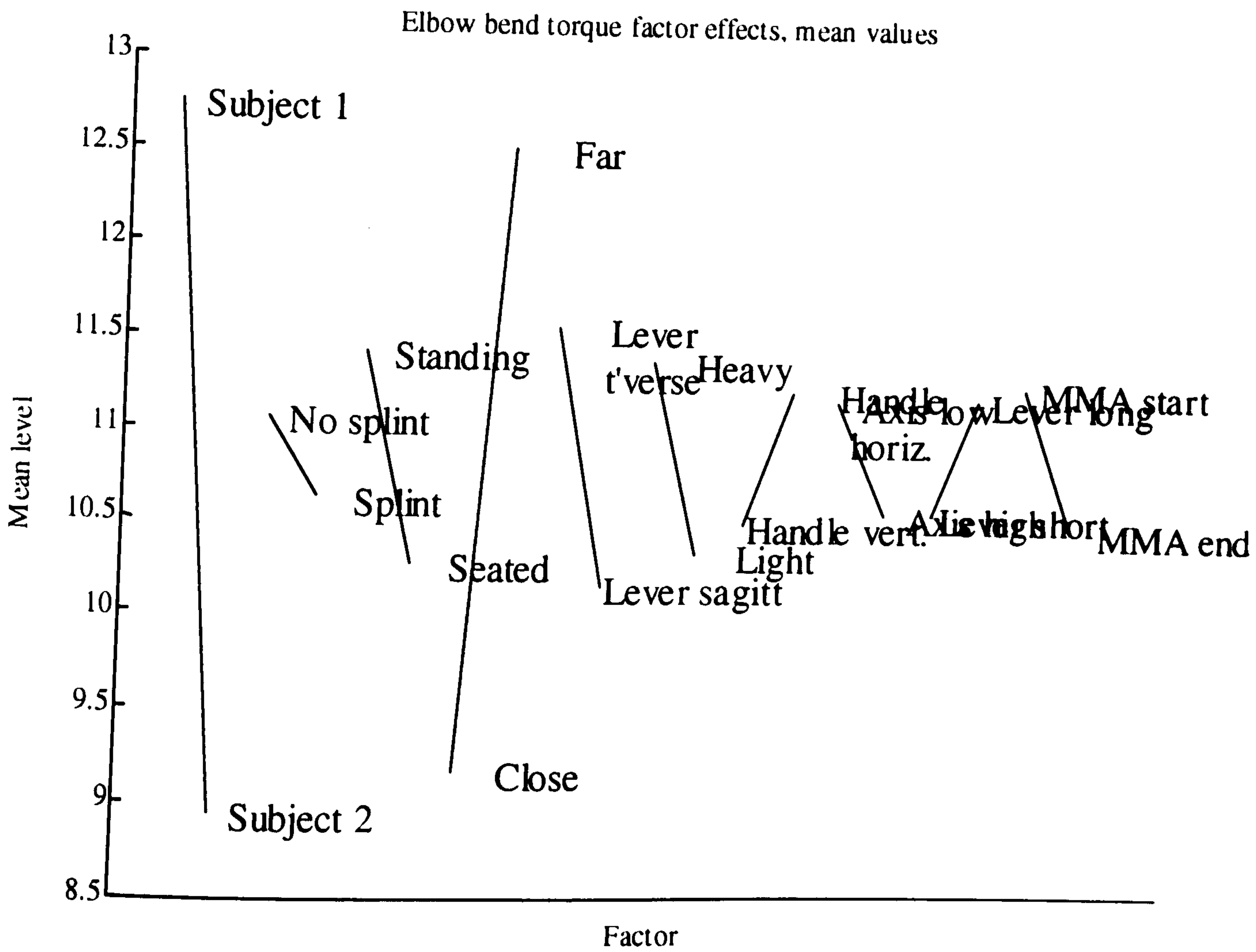
7.5.3.4 Shoulder rotation factor effects plot: mean values



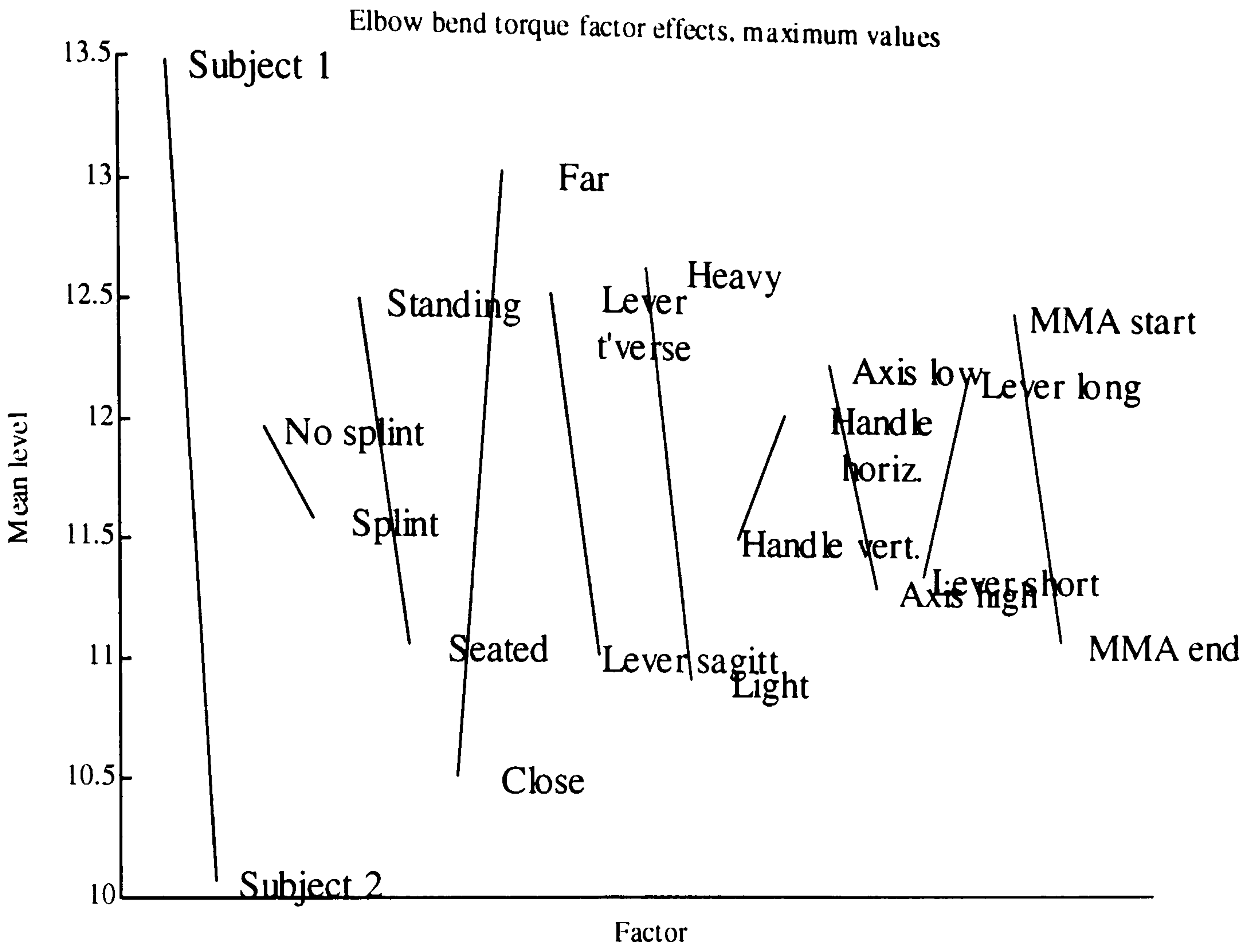
7.5.3.5 Shoulder rotation factor effects plot: maximum values



7.5.3.6 Elbow bend factor effects plot: mean values



7.5.3.7 Elbow bend factor effects plot: maximum values



7.6 Product design, signal experiment: results

7.6.1 Angular measures

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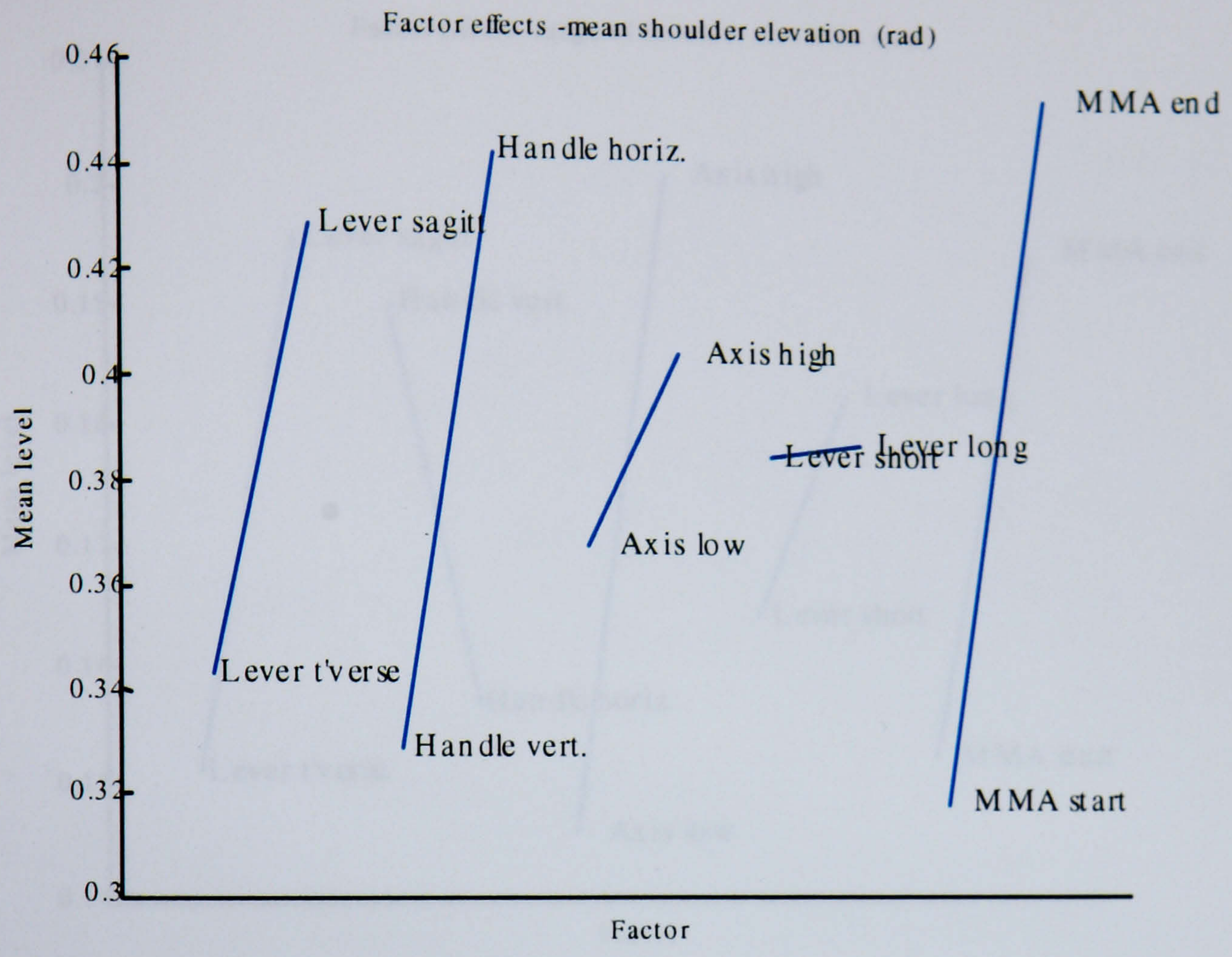
7.6.1.1 Averages

		Shoulder elevation					Elbow bend				
Factor	**Level**	**Mean**	**STD**	**Min**	**Max**	**Range**	**Mean**	**STD**	**Min**	**Max**	**Range**
Lever Axis	Transverse	0.3430	0.0524	0.2646	0.4157	0.1510	1.2065	0.1247	1.0081	1.3831	0.3749
	Sagittal	0.4291	0.0691	0.3231	0.5189	0.1958	1.3180	0.1471	1.1163	1.5357	0.4195
Handle Direction	Vertical	0.3288	0.0666	0.2235	0.4138	0.1903	1.2813	0.1532	1.0638	1.5059	0.4421
	Horizontal	0.4433	0.0549	0.3642	0.5207	0.1566	1.2433	0.1185	1.0606	1.4129	0.3523
Noise 1	1	0.3689	0.0474	0.2964	0.4313	0.1349	1.3463	0.1357	1.1257	1.5275	0.4018
	2	0.4032	0.0740	0.2913	0.5032	0.2119	1.1782	0.1360	0.9987	1.3913	0.3927
Axis Height	Low	0.3675	0.0518	0.2922	0.4380	0.1457	1.2325	0.1289	1.0410	1.4224	0.3814
	High	0.4046	0.0696	0.2955	0.4965	0.2011	1.2921	0.1429	1.0834	1.4964	0.4130
Lever length	Short	0.3848	0.0578	0.2953	0.4595	0.1642	1.2088	0.1245	1.0371	1.3897	0.3525
	Long	0.3872	0.0636	0.2923	0.4750	0.1827	1.3158	0.1473	1.0873	1.5291	0.4419
Mma pos	Start	0.3179	0.0535	0.2452	0.3970	0.1518	1.0694	0.1820	0.8467	1.3587	0.5121
	End	0.4542	0.0680	0.3425	0.5375	0.1950	1.4552	0.0897	1.2777	1.5601	0.2823
Noise 2	1	0.3841	0.0643	0.2852	0.4697	0.1846	1.2445	0.1161	1.0883	1.4225	0.3342
	2	0.3880	0.0571	0.3025	0.4648	0.1623	1.2800	0.1556	1.0360	1.4963	0.4602

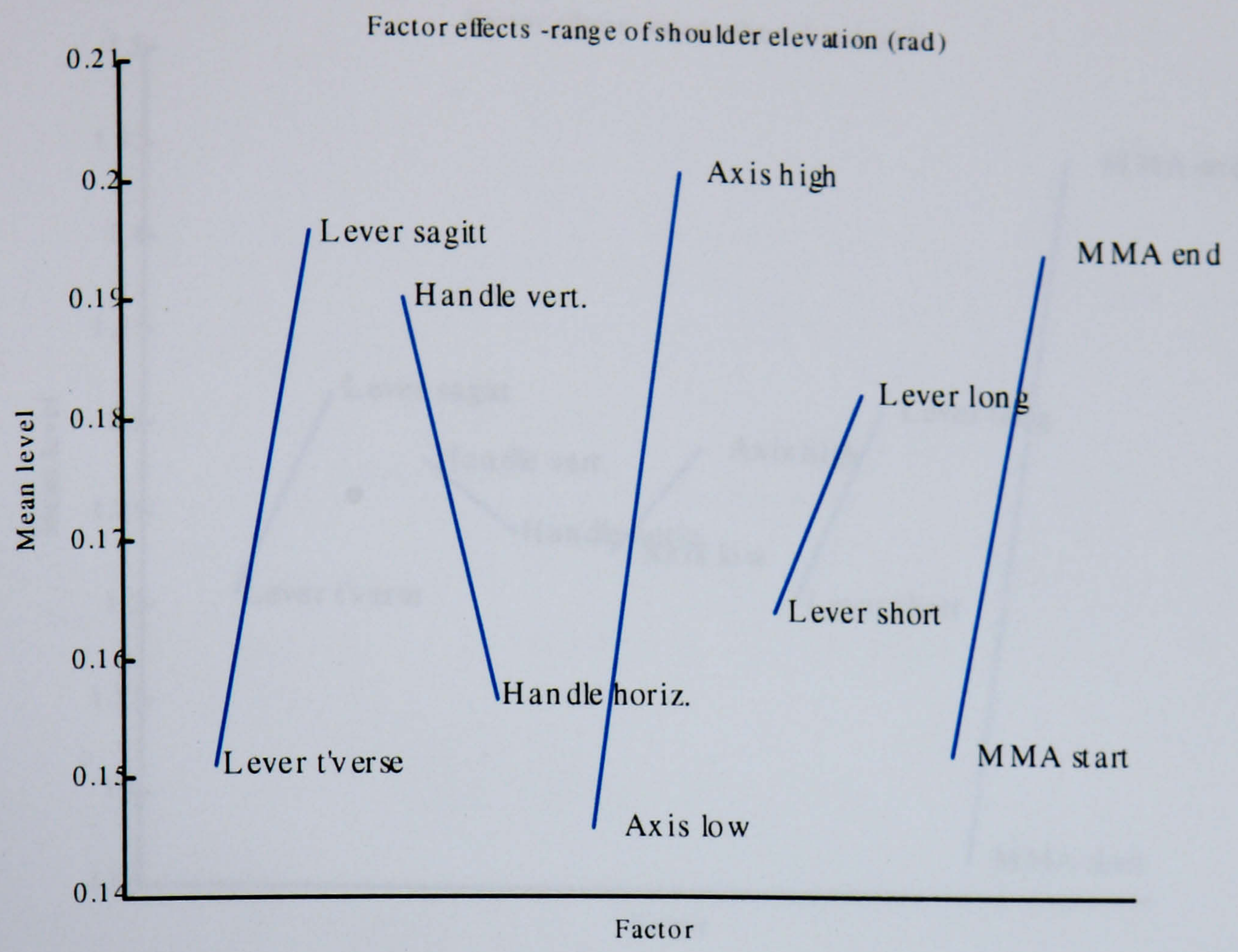
7.6.1.2 Shoulder elevation factor effects, Mean values



7.6.1.3 Shoulder elevation ANOVA, Mean values

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	10.222	14	.730	48.504	.000
SUBJECT	6.176	9	.686	45.588	.000
LEVER_AX	.741	1	.741	49.196	.000
HANDLE_D	1.312	1	1.312	87.134	.000
AXIS_HEI	.138	1	.138	9.146	.003
LEVER_LE	.001	1	.001	.038	.845
MMA_POSI	1.855	1	1.855	123.242	.000
Explained	10.222	14	.730	48.504	.000
Residual	5.796	385	.015		
Total	16.018	399	.040		

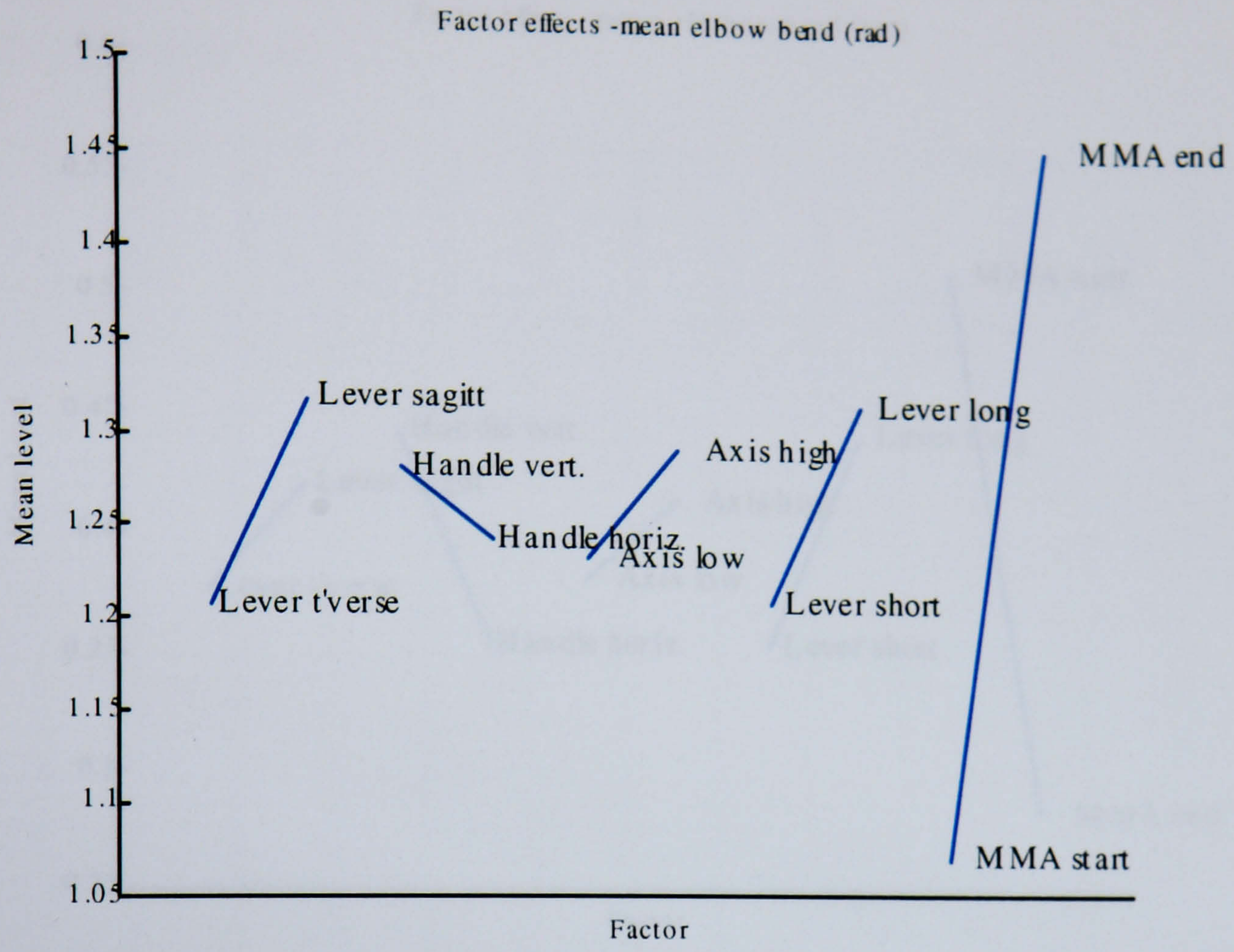
7.6.1.4 *Shoulder elevation factor effects Range*



7.6.1.5 *Shoulder elevation ANOVA, Range*

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	1.776	14	.127	14.008	.00
SUBJECT	.935	9	.104	11.473	.00
LEVER_AX	.200	1	.200	22.114	.000
HANDLE_D	.114	1	.114	12.542	.000
AXIS_HEI	.306	1	.306	33.834	.000
LEVER_LE	.034	1	.034	3.780	.053
MMA_POSI	.186	1	.186	20.575	.000
Explained	1.776	14	.127	14.008	.00
Residual	3.487	385	.009		
Total	5.263	399	.013		

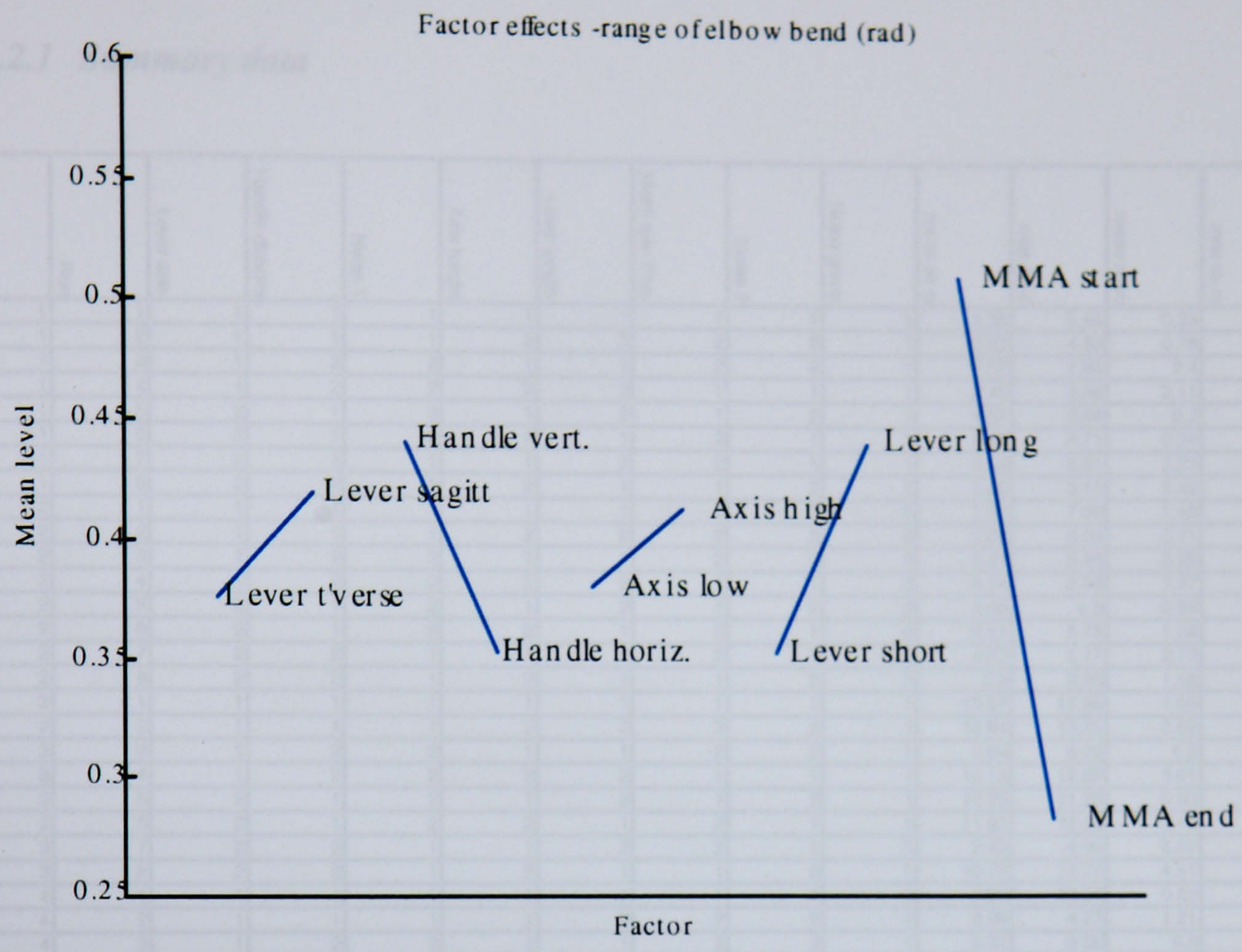
7.6.1.6 Elbow bend factor effects, Mean values



7.6.1.7 Elbow bend ANOVA, Mean values

Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	24.599	14	1.757	63.569	.000
SUBJECT	6.824	9	.758	27.430	.00
LEVER_AX	1.244	1	1.244	44.998	.000
HANDLE_D	.145	1	.145	5.233	.023
AXIS_HEI	.356	1	.356	12.880	.000
LEVER_LE	1.145	1	1.145	41.437	.000
MMA_POSI	14.886	1	14.886	538.544	.000
Explained	24.599	14	1.757	63.569	.000
Residual	10.642	385	.028		
Total	35.241	399	.088		

7.6.1.8 Elbow bend factor effects Range



7.6.1.9 Elbow bend ANOVA, Range

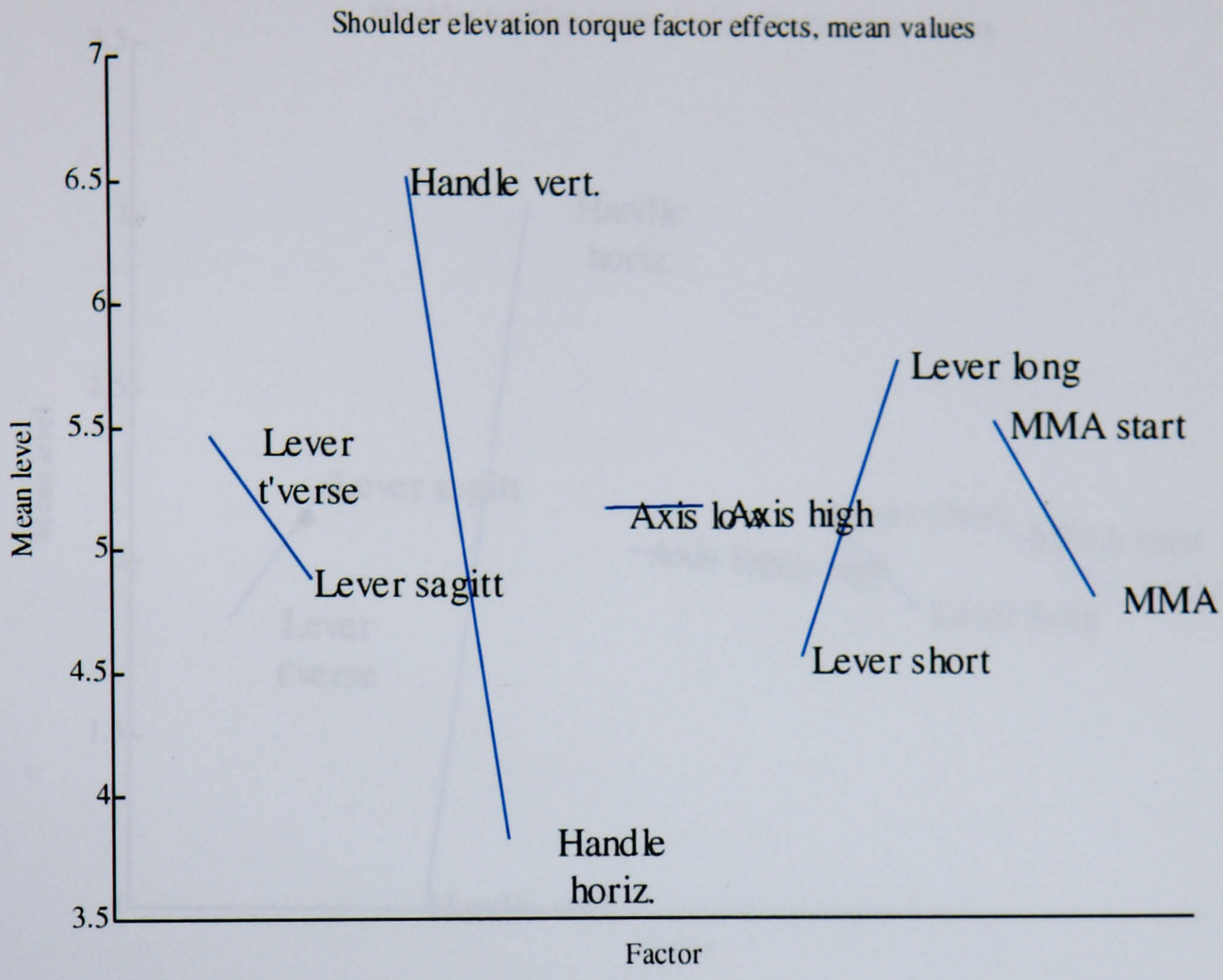
Source of Variation	Sum of Squares	DF	Mean Square	F	Sig of F
Main Effects	7.825	14	.559	31.435	.000
SUBJECT	.646	9	.072	4.035	.000
LEVER_AX	.198	1	.198	11.144	.001
HANDLE_D	.806	1	.806	45.334	.000
AXIS_HEI	.100	1	.100	5.649	.018
LEVER_LE	.798	1	.798	44.876	.000
MMA_POSI	5.277	1	5.277	296.777	.000
Explained	7.825	14	.559	31.435	.000
Residual	6.845	385	.018		
Total	14.670	399	.037		

7.6.2 Torque measures

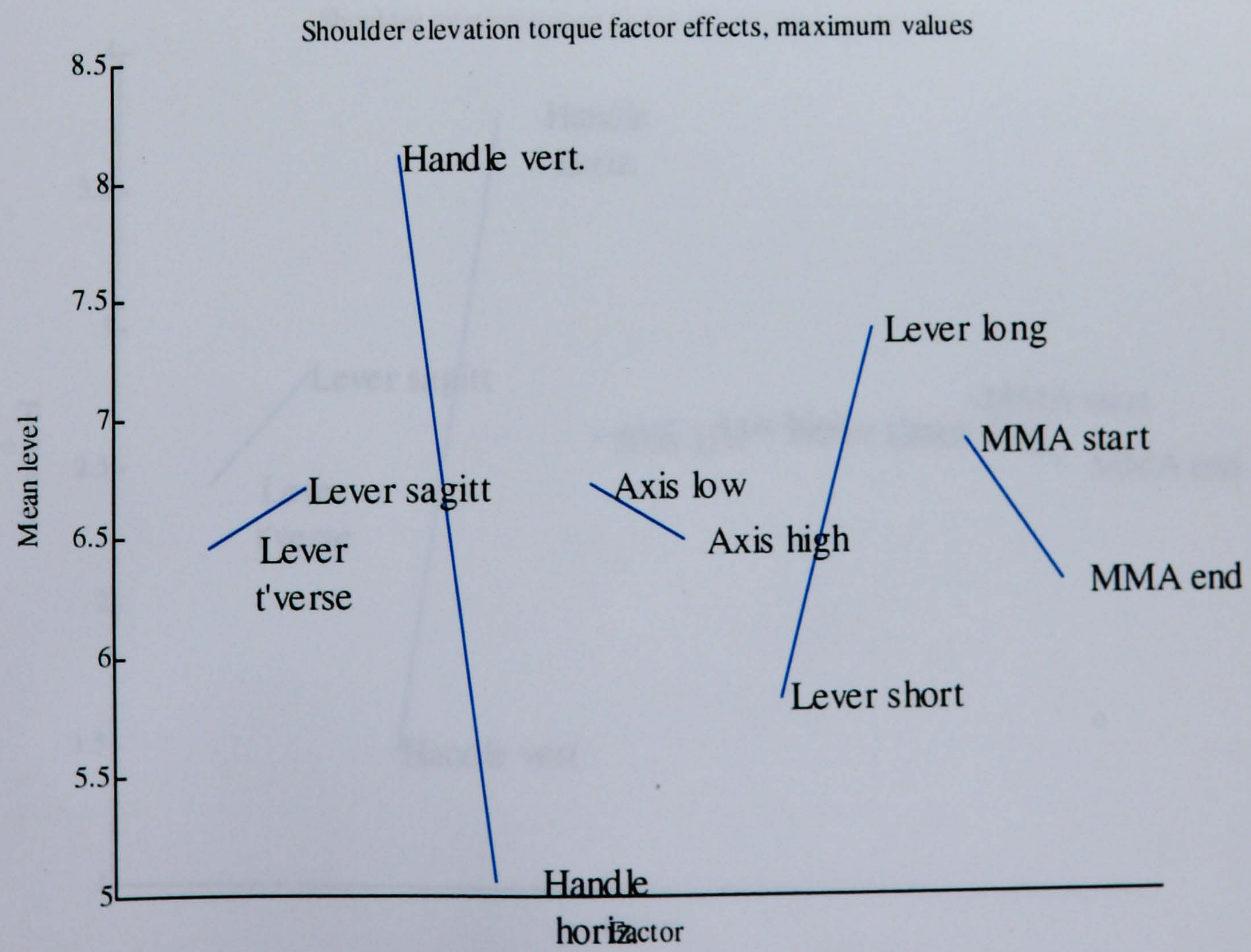
7.6.2.1 Summary data

Subject	Run	Lever axis	Handle directio	Noise 1	Axis height	Lever length	Mech adv. Pos.	Noise 2	Noise group	mean sh el	max sh el	mean sh ro	max sh ro	mean el be	max el be
1	1	1	1	1	1	1	1	1	1	4.35	5.88	0.23	0.37	7.56	9.52
1	2	1	1	1	2	2	2	2	1	2.83	4.83	0.76	1.04	11.52	11.68
1	3	1	2	2	1	1	2	2	1	7.57	7.85	2.4	2.6	12.97	13.15
1	4	1	2	2	2	2	1	1	1	2.46	3.59	2.11	2.84	11.12	12.55
1	5	2	1	2	1	2	1	2	1	4.57	6.68	0.7	0.94	6.79	9.96
1	6	2	1	2	2	1	2	1	1	5.49	8.71	0.24	0.83	11.5	11.58
1	7	2	2	1	1	2	2	1	1	3.52	6.91	3.23	3.66	12.52	12.72
1	8	2	2	1	2	1	1	2	1	1.86	3.11	2.42	3.33	12.22	13.58
2	1	1	1	1	1	1	1	1	0	7.34	7.65	1.48	2.1	5.15	5.52
2	2	1	1	1	2	2	2	2	0	5.63	6.69	0.71	1.3	3.64	4.93
2	3	1	2	2	1	1	2	2	0	5.21	5.96	2.25	2.57	5.7	6.13
2	4	1	2	2	2	2	1	1	0	6.34	6.56	1.37	2.2	4.98	5.12
2	5	2	1	2	1	2	1	2	0	4.02	4.8	0.68	0.82	4.36	4.92
2	6	2	1	2	2	1	2	1	0	6.61	6.78	1.58	1.84	4.39	4.84
2	7	2	2	1	1	2	2	1	0	4.02	5.17	2.73	2.85	4.38	5.07
2	8	2	2	1	2	1	1	2	0	5.9	6.65	1.58	2.32	5.8	6.06
3	1	1	1	1	1	1	1	1	1	13.97	15.26	1.09	1.7	14.07	15.59
3	2	1	1	1	2	2	2	2	1	12.64	15.75	0.62	1.25	14.1	15.2
3	3	1	2	2	1	1	2	2	1	5.69	6.22	5.3	6.18	12.3	13.46
3	4	1	2	2	2	2	1	1	1	10.13	12.83	3.61	5.99	12.38	13.21
3	5	2	1	2	1	2	1	2	1	10.29	11.23	0.83	1.16	12.32	14.14
3	6	2	1	2	2	1	2	1	1	11.83	15.65	3.49	5	15.28	15.59
3	7	2	2	1	1	2	2	1	1	2.43	4.05	6.97	7.73	12.9	13.09
3	8	2	2	1	2	1	1	2	1	10.75	13.77	4.51	5.98	13.67	14.95
4	1	1	1	1	1	1	1	1	1	9.95	10.39	0.82	0.97	13.25	15.1
4	2	1	1	1	2	2	2	2	1	2.98	4.27	1.21	1.72	14.41	15.3
4	3	1	2	2	1	1	2	2	1	0.31	0.65	5.6	5.75	12.62	12.89
4	4	1	2	2	2	2	1	1	1	2.03	2.53	4.45	6.16	11.35	12.98
4	5	2	1	2	1	2	1	2	1	7.8	9.12	0.98	1.78	12.22	13.92
4	6	2	1	2	2	1	2	1	1	6.45	11.83	1.05	1.41	16.05	16.43
4	7	2	2	1	1	2	2	1	1	3.85	5.96	5.3	6.22	13.57	13.79
4	8	2	2	1	2	1	1	2	1	2.47	4.14	5.2	6.47	12.69	14.18
5	1	1	1	1	1	1	1	1	1	9.93	10.26	0.16	0.44	11.07	12.25
5	2	1	1	1	2	2	2	2	1	4.59	9.33	0.26	0.53	11.21	11.85
5	3	1	2	2	1	1	2	2	1	1.5	2.24	3.32	3.65	10.81	11.28
5	4	1	2	2	2	2	1	1	1	6	6.97	2.34	3.72	8.96	10.19
5	5	2	1	2	1	2	1	2	1	2.39	5.13	2.31	2.42	9.96	11.4
5	6	2	1	2	2	1	2	1	1	14.59	16.05	0.57	1.36	12.82	13.15
5	7	2	2	1	1	2	2	1	1	4.48	7.92	5.33	5.84	10.05	10.27
5	8	2	2	1	2	1	1	2	1	3.49	5.63	3.13	3.91	11.12	12.43
6	1	1	1	1	1	1	1	1	0	2.61	3.71	1.1	1.35	7.4	7.97
6	2	1	1	1	2	2	2	2	0	7.34	8.48	0.97	1.11	5.68	6.94
6	3	1	2	2	1	1	2	2	0	1.81	2.35	4.25	5.04	6.24	6.54
6	4	1	2	2	2	2	1	1	0	3.75	4.02	3.57	4.31	4.98	5.47
6	5	2	1	2	1	2	1	2	0	2.01	3.06	0.82	1.59	5.1	6.39
6	6	2	1	2	2	1	2	1	0	3.29	4.83	4.43	5.12	5.69	7.06
6	7	2	2	1	1	2	2	1	0	0.76	1.36	3.91	4.18	5.07	5.37
6	8	2	2	1	2	1	1	2	0	0.59	0.84	3.82	4.67	6.19	6.38
7	1	1	1	1	1	1	1	1	0	6.61	7.44	0.69	1.49	7.37	8.05
7	2	1	1	1	2	2	2	2	0	3.31	4.11	0.29	0.4	6.59	7.4
7	3	1	2	2	1	1	2	2	0	2.09	2.69	1.93	3.01	7.92	8.11
7	4	1	2	2	2	2	1	1	0	3.68	4	2.07	2.41	6.02	6.94
7	5	2	1	2	1	2	1	2	0	3.45	4.16	0.24	0.47	5.08	6.53
7	6	2	1	2	2	1	2	1	0	3.86	6.32	0.82	1.04	7.62	8.4
7	7	2	2	1	1	2	2	1	0	2.38	3.05	2.32	2.37	6.85	6.98
7	8	2	2	1	2	1	1	2	0	3.27	3.52	2.49	2.88	7.51	8.18
8	1	1	1	1	1	1	1	1	0	1.94	3.5	0.46	1.16	6.56	7.41
8	2	1	1	1	2	2	2	2	0	6.78	7.65	0.25	0.39	5.98	7.01
8	3	1	2	2	1	1	2	2	0	5.59	5.92	2.21	2.51	7.54	7.95
8	4	1	2	2	2	2	1	1	0	7.46	7.67	1.27	1.97	6.3	6.97
8	5	2	1	2	1	2	1	2	0	2.6	4.37	0.34	0.5	4.79	6.63
8	6	2	1	2	2	1	2	1	0	7.92	8.85	0.41	0.93	7.36	7.67
8	7	2	2	1	1	2	2	1	0	3.07	4.37	3.45	3.82	6.13	6.71
8	8	2	2	1	2	1	1	2	0	4.38	6.28	2.21	3.48	7.39	7.81
9	1	1	1	1	1	1	1	1	0	8.32	9.07	1.32	2.09	8.1	8.64
9	2	1	1	1	2	2	2	2	0	6.2	7.44	0.25	0.68	6.66	8.07

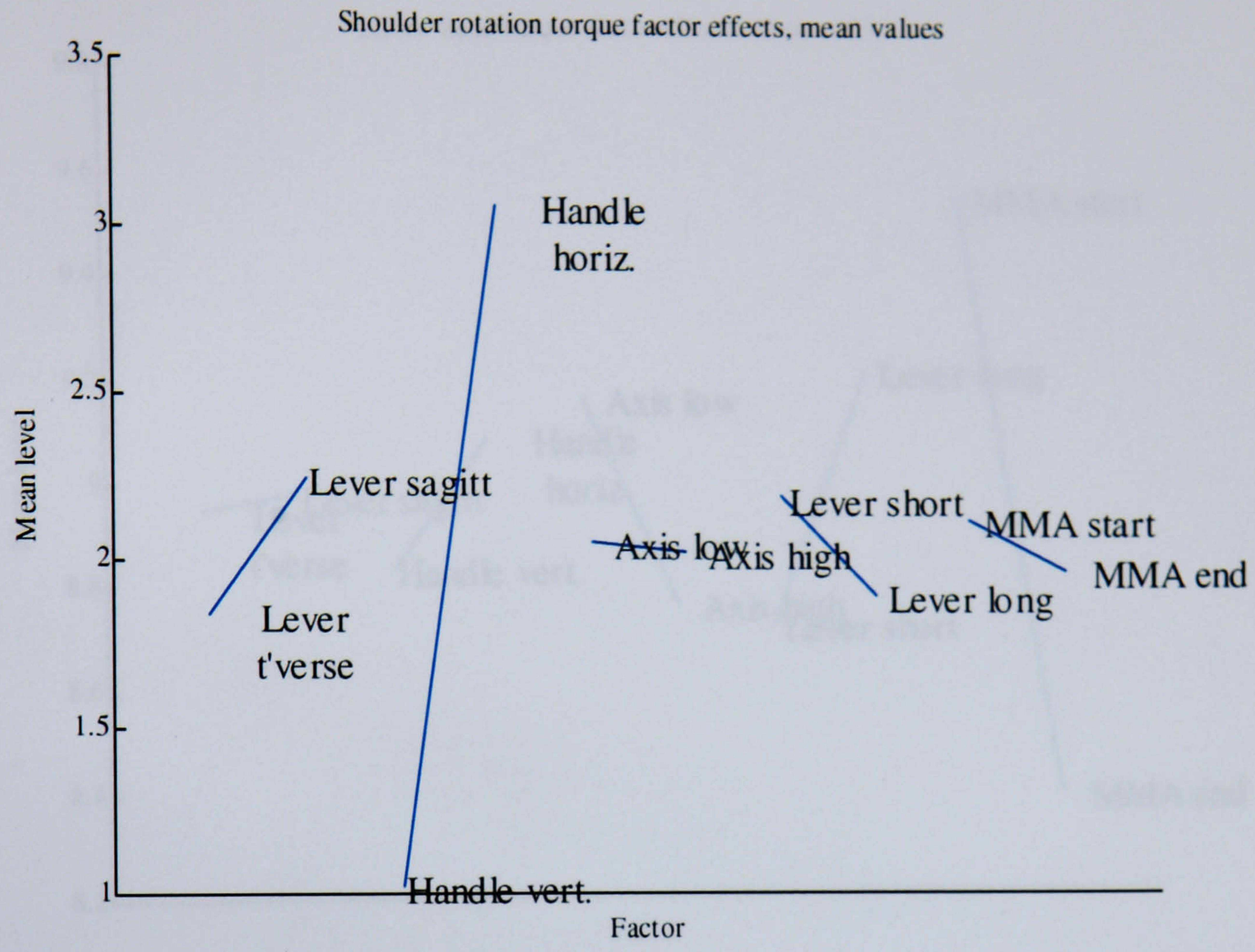
7.6.2.2 Shoulder elevation factor effects, Mean values



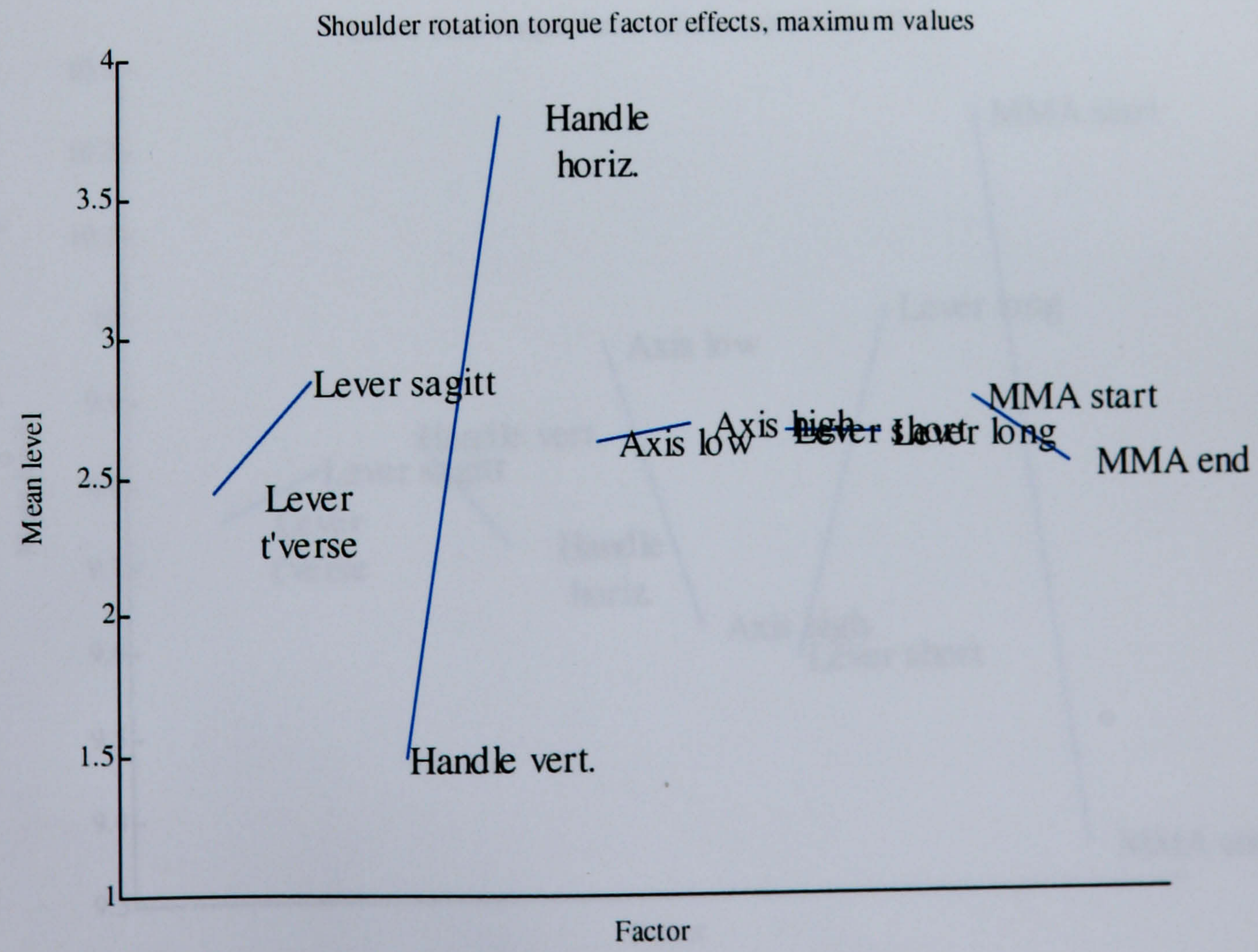
7.6.2.3 Shoulder elevation factor effects, Maximum values



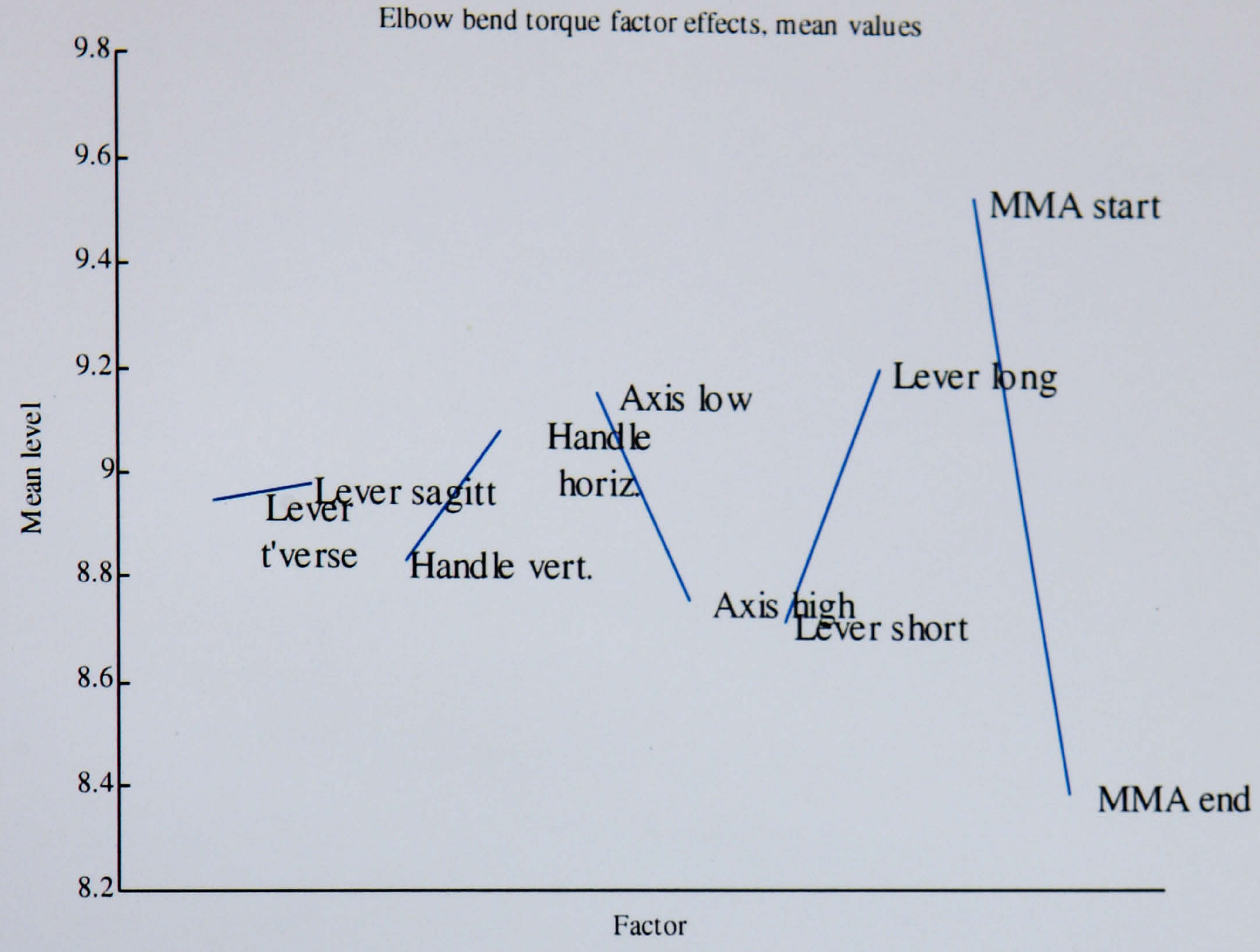
7.6.2.4 *Shoulder rotation factor effects, Mean values*



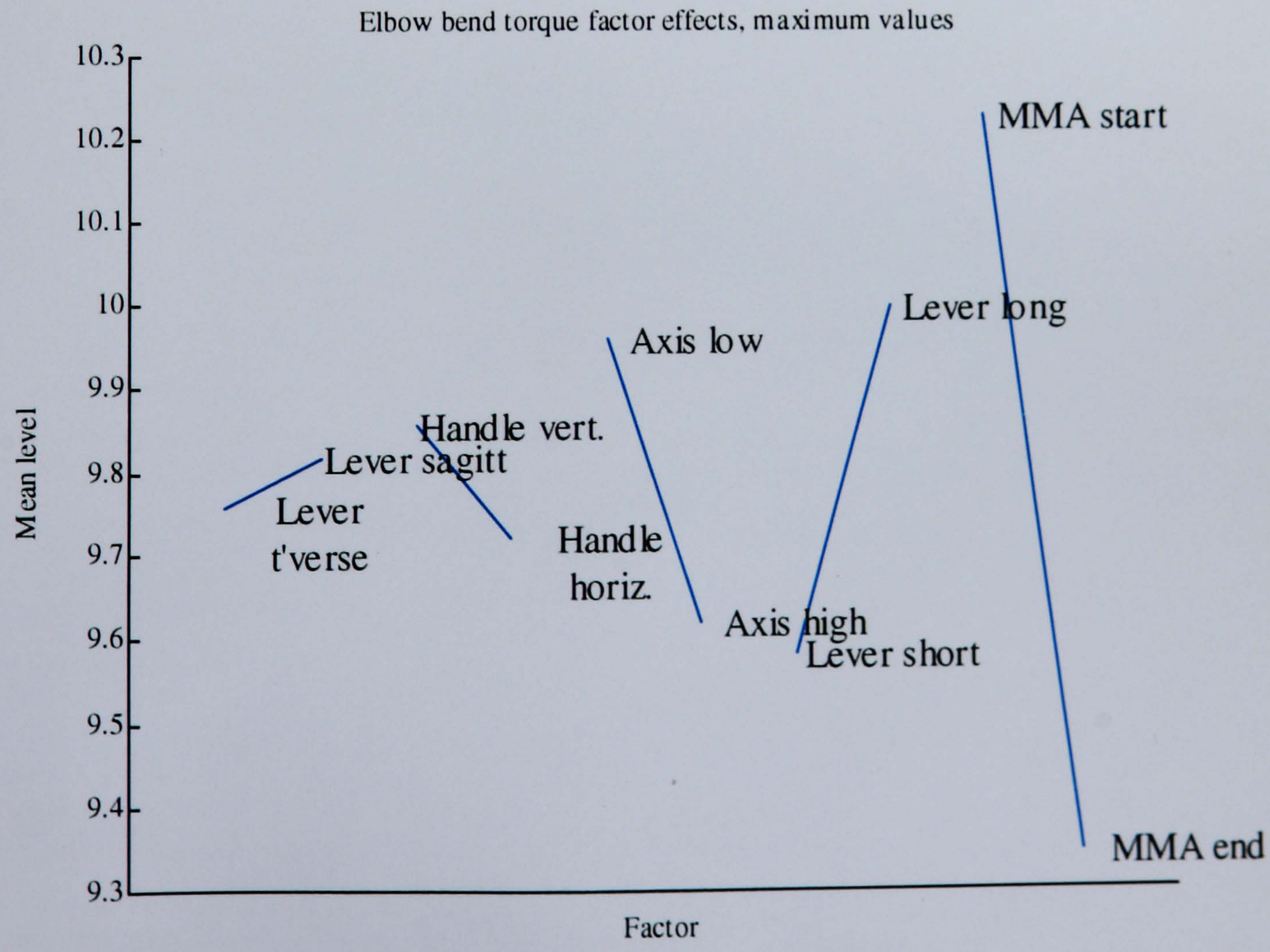
7.6.2.5 *Shoulder rotation factor effects, Maximum values*



7.6.2.6 Elbow bend factor effects, Mean values



7.6.2.7 Elbow bend factor effects, Maximum values



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7.7 The ETALOT program

The ETALOT program described in Section 2.2.3 was used as an interface to the Polhemus tracking system in all the experimental phases of this work. The program was written in Borland C++ for DOS. A full listing is given below.

```
/*************************************************************************
Program ETALOT

Birthday 19/9/95(three_t)

Last Modified 14/1/97

               Cosmetic changes to background text and initial view
               parameters

               10/01/97

               Addition of command line arguments, the first argument
               will now contain the data file directory, and is optional

               Changes to boresight commands to remove some sort
               of Windows 95 conflict, alterations to file output so
               first file name is OUTPUT0

               06/01/97

               Changes to initgraph routine to allow
               compatibility with windows 95, no longer requires
               VGA driver. This might cause problems on other systems???

               01/10/96

               Output files moved from temp directory to
               current one

               25/09/96

               Changes to file output system,
               boresighting commands added.

By Jonathan Ward

Comments       This program is derived from THREE_T it is a Graphical
               interface for the Insidetrak board, combined with
                some man-modelling functions

       all routines are mine except those which communicate
       directly with the board. These have been adapted from
       Polhemus Inc. source code.

*************************************************************************/
/*************************************************************************
                          Include Files
*************************************************************************/
#include <graphics.h>
#include <stdlib.h>
#include <iostream.h>
#include <conio.h>
#include <math.h>
#include <dos.h>
#include <stdio.h>
#include <string.h>
#include <ctype.h>
#include <fstream.h>
#include <dir.h>
/*************************************************************************
                          Value and macro definition
*************************************************************************/
#define BUS_ADDR 0x340
#define WORDS_IN_RECORD 17
```

```
#define SPATIAL_CALIBRATION_VALUE 0.09155553
#define RADIAN_CALIBRATION_VALUE 9.5876E-5
#define COSINE_CALIBRATION_VALUE 3.0519E-05
        //calibration values must be float or int calculation takes place.
#define RMS_ACCURACY 26
#define RAD_TO_DEG 57.295
#define PI 3.141592654
#define ASTEP 0.0981875
#define PSTEP 20
#define ZSTEP 0.1
#define GSTEP 50
#define STATUS_WINDOW 500,140,620,370,1
#define STATUS_WINDOW_BORDER 499,139,621,371
#define CURSOR_WINDOW 500,20,620,120,1
#define CURSOR_WINDOW_BORDER 499,19,621,121
#define GRAPHICS_WINDOW 20,20,480,460,1
#define GRAPHICS_WINDOW_BORDER 19,19,481,461
#define MEMORY_WINDOW 500,390,620,460,1
#define MEMORY_WINDOW_BORDER 499,389,621,461
#define LS 11
#define SENSOR_0_COLOUR LIGHTBLUE
#define SENSOR_1_COLOUR LIGHTMAGENTA
#define FLOOR_COLOUR YELLOW
#define ON_COLOUR RED
#define OFF_COLOUR DARKGRAY
#define ERROR_COLOUR RED
#define ARM_COLOUR LIGHTGREEN
#define DEFAULT_COLOUR WHITE
/**********************************************************************
 Function Prototypes, and Structure Instatiations. [Now I know what they are]
**********************************************************************/
typedef double MATRIX[3][3];

struct p3type {double X,Y,Z;};

struct sensortype      {p3type pos,eul;
                        MATRIX mat;};

struct segment_type
        {
        float length;
        float distance_to_sensor;
        float sensor_height;
        p3type base;
        p3type sens_pos_centre;
        p3type sens_pos_surface;
        p3type end;
        int error;
        };

struct armtype
        {
        segment_type torso;
        segment_type humerus;
        segment_type radius;
        segment_type hand;
        segment_type load;
        float   shoulder_elev,
                shoulder_plane,
                shoulder_rot,
                elbow_bend,
                wrist_plane,
                wrist_elev,
                wrist_rot;
        int onscreen;
        };

armtype arm,old_arm;

p3type  viewpoint,
        origin,
        sensor_0_motion_data[500],
        sensor_1_motion_data[500];

sensortype      sensor[2],
                old_sensor[2];

MATRIX viewmatrix;

int     main(int argc,char *argv[]),
        set_graph_mode(void),
        init_display(void),
        capture_board_off_bus(void),
        is_equal(p3type j,p3type k);
```

```
long double    get_distance(p3type start,p3type finish);

void initialise_board(void),
        getXYZ(void),
        getDXYZ(void),
        rotate_sensor(int sensor_no,p3type axis,double angle),
        toggle_sensor_0(void),
        toggle_sensor_1(void),
        set_display_vars(float vx,float vy,float vz,int xo,int yo,float s),
        setviewmatrix(void),
        drawline(p3type start,p3type finish),
        draw_text(p3type point,char text[]),
        draw_world(void),
        draw_floor(void),
        draw_spot(p3type position,float size),
        cursor(int n),
        draw_cursor(sensortype position),
        display_status(void),
        record_status(void),
        file_out(void),
        control(char key),
        display_motion_record(void),
        record_motion(void),
        draw_cube(sensortype s),
        output_to_board(char *cbuf, int nbr_chro),
        display_arm(armtype limb_to_draw),
        draw_segment(segment_type seg),
        calc_arm(void),
        evaluate_arm_geom(void),
        initialise_arm(void),
        calc_angles(void);

p3type translate(p3type s,p3type f),
        euler_rotate(p3type point,p3type angles),
        setviewmatrix(p3type angles),
        matrix_by_point(double[3][3],p3type),
        get_unit_vector(p3type start, p3type finish),
        get_unit_vector(p3type v),
        point_from_vector(p3type start,p3type vector, double distance),
        rotate(p3type point,p3type angle),
        rotateX(p3type point,double angle),
        rotateY(p3type point,double angle),
        rotateZ(p3type point,double angle),
        point_along_line(p3type s,p3type f,float d);

float   get_h_distance(p3type start,p3type finish),
        angle_between_vectors(p3type first,p3type second),
        angle_between_vectors(p3type first,p3type second,p3type third);

/***********************************************************************
                External Functions and Variables
***********************************************************************/
float   scale = 1;

int     xorig = 200,
        yorig = 150,
        floor_size = 500,       //the overall size of the axes
        grid = 50,      //the grid spacing

        cursor_toggle = 1,
        show_big_cursor_text =0,
        show_path_toggle = 1,
        limb_toggle = 0,
        sensor_0_toggle = 1,
        sensor_1_toggle = 1,
        cursor_to_display =0,
        memory_toggle =0,
        sensitivity = 10,
        sensor_0_current_point = 0,
        sensor_1_current_point= 0,      //for line record
        file_flag=0,
        act_flags = 1,
        dr_rate=10,
        dr_count=0,
        file_number=1,
        data_recording=0;

int     fast_trak_bus_data[24];

char    data_out[256],
        file_name[128];

ofstream file;
```

```
/*********************************************************************
main.
If the program was well-structured, main should call all the initialisation
routines and then become a loop whose purpose is to get data off the board
as rapidly as possible and display it/ send it to file. Everything else
should be an event-driven thingy.
*********************************************************************/
int main(int argc,char *argv[])
{
int     tmp;
int     exitprogram=0;
char    key;

if (argc>0) chdir(argv[1]);

initialise_arm();
init_display();
initialise_board();
draw_world();
do
        {
        getXYZ();
        if (file_flag) file_out();
        if (memory_toggle) record_motion();
        if (cursor_toggle)
                {
                if (sensor_0_toggle)
                        {
                        setcolor(SENSOR_0_COLOUR);
                        cursor(0);
                        }
                if (sensor_1_toggle)
                        {
                        setcolor(SENSOR_1_COLOUR);
                        cursor(1);
                        }
                }
        if (limb_toggle)        {
                                calc_arm();
                                }

        if (kbhit())
                {
                key=getch();
                switch(key)
                        {
                        case 'K': exitprogram = 1; break;
                        default : control(key);
                        }
                }

        setviewport(GRAPHICS_WINDOW); //why is this here?
        }
while(exitprogram==0);
return(1); //why is this function not void?
}
/*********************************************************************
init_display sets up intitial values for the global display values and draws all the
background stuff that doesn't change thoughout the program.

Things to do:- it would be good to reduce all the viewpoint variables to a single
transformation matrix, initialised elsewhere.
*********************************************************************/
int init_display(void)
{
if (set_graph_mode() != 1) {
                cout << "VGA not detected, nightmare!";
                return(0);
                }
viewpoint.X =4.15;
viewpoint.Y =0.70;
viewpoint.Z =0.42;
scale=0.4;
setviewmatrix();
origin.X=origin.Y=origin.Z=0;
old_sensor[0].pos=old_sensor[1].pos=origin;
setfillstyle(SLASH_FILL,DARKGRAY);
bar(0,0,getmaxx(),getmaxy());
setcolor(LIGHTGREEN);
//settextstyle(SANS_SERIF_FONT,0,1);
settextstyle(SMALL_FONT,0,5);
outtextxy(5,462,"ETA-LOT Barely Functional Version. DERC. Cardiff. 1997");
```

```
setcolor(DEFAULT_COLOUR);
rectangle(STATUS_WINDOW_BORDER);
rectangle(CURSOR_WINDOW_BORDER);
rectangle(GRAPHICS_WINDOW_BORDER);
rectangle(MEMORY_WINDOW_BORDER);
rectangle(0,0,getmaxx(),getmaxy());
setviewport(CURSOR_WINDOW);
clearviewport();
setviewport(STATUS_WINDOW);
clearviewport();
setviewport(MEMORY_WINDOW);
clearviewport();
setviewport(GRAPHICS_WINDOW);
clearviewport();

//file_name is initialised here for convienience.
strcpy(file_name,"output1");

return(1);
}
/*********************************************************************.....
set_display_vars is used to toggle between the preset display modes.

to do: if this was a function that set up a transformation matrix then it could have default
values which would allow it to do the initialising process as well.
***********************************************************************/
void set_display_vars(float vx,float vy,float vz,int xo,int yo,float s)
{
viewpoint.X=vx;
viewpoint.Y=vy;
viewpoint.Z=vz;
xorig=xo;
yorig=yo;
scale=s;
setviewmatrix();
return;
}
/************************************************************************.....
draw_world updates the graphics window. it contains some funny bits to ensure that
the limb and cursor drawing routines don't draw a "cover-up" item onto the now blank
screen, these aren't too elegant.

to-do: create a "fresh-screen" variable that tells everything else when to over-draw
themselves
***********************************************************************/
void draw_world(void)
{
setviewport(GRAPHICS_WINDOW);
clearviewport();
old_sensor[0].pos=old_sensor[1].pos=origin;
arm.onscreen=0;
draw_floor();
if (show_path_toggle) display_motion_record();
display_status();
record_status();
return;
}

/**********************************************************************
draw_floor draws the basic grid that everything else sits upon.
***********************************************************************/
void draw_floor(void)
{
extern int      floor_size, //the overall size of the axes
                grid;   //the grid spacing
p3type start,finish;
setcolor(FLOOR_COLOUR);
for(start.Y=0; start.Y<=floor_size; start.Y+=grid)
{
        start.Z = finish.Z = 0;
        start.X =0;
        finish.X=floor_size;
        finish.Y = start.Y;
        drawline(start,finish);
}
for(start.X=0; start.X<=floor_size; start.X+=grid)
{
        start.Z = finish.Z = 0;
        start.Y = 0;
        finish.Y =floor_size;
        finish.X =start.X;
        drawline(start,finish);
}
start.X=start.Y=start.Z=0;
```

```
finish=start;
finish.Z-=grid;
drawline(start,finish);
start.X=grid;
setcolor(GREEN);
draw_text(start,"+X");
start.X=0;
start.Y=grid;
draw_text(start,"+Y");
start.Y=0;
start.Z=-grid;
draw_text(start,"-Z");
return;
}



/*************************************************************************
cursor displays the sensor as a cube on a stick, it's primary purpose should be for debugging
and clibration etc. but up till now it has been the crux of the program. I think it should
probably be left alone now and the limb segment modelling aspects concentrated upon.
*************************************************************************/
void cursor(int n)
{
int ls,j=0;
char t[20];

if      ((sensor[n].pos.X!=old_sensor[n].pos.X)
        ||(sensor[n].pos.Y!=old_sensor[n].pos.Y)
        ||(sensor[n].pos.Z!=old_sensor[n].pos.Z))
                {
                setwritemode(XOR_PUT);
                draw_cursor(sensor[n]);
                if
((old_sensor[n].pos.X!=0)||(old_sensor[n].pos.Y!=0)||(old_sensor[n].pos.Z!=0))
                        draw_cursor(old_sensor[n]);
                old_sensor[n]=sensor[n];
                if (n==cursor_to_display)
                        {
                        setwritemode(COPY_PUT);
                        if (show_big_cursor_text)
                                {
                                settextstyle(SANS_SERIF_FONT,0,7);
                                ls =75;
                                }
                        else    {
                                setviewport(CURSOR_WINDOW);
                                ls = LS;
                                }
                        clearviewport();
                        sprintf(t,"X: %6.2fmm",sensor[n].pos.X);outtextxy(5,ls*j++,t);
                        sprintf(t,"Y: %6.2fmm",sensor[n].pos.Y);outtextxy(5,ls*j++,t);
                        sprintf(t,"Z: %6.2fmm",sensor[n].pos.Z);outtextxy(5,ls*j++,t);
                        sprintf(t,"AZ:
%6.2fdeg",sensor[n].eul.Z*RAD_TO_DEG);outtextxy(5,ls*j++,t);
                        sprintf(t,"AT:
%6.2fdeg",sensor[n].eul.Y*RAD_TO_DEG);outtextxy(5,ls*j++,t);
                        sprintf(t,"RO:
%6.2fdeg",sensor[n].eul.X*RAD_TO_DEG);outtextxy(5,ls*j++,t);
                        j++;
                        setcolor(ON_COLOUR);
                        if              (file_flag)                     {sprintf(t,"File:
%6.2fKb",file_flag*0.23);outtextxy(5,LS*j++,t);}
                        setviewport(GRAPHICS_WINDOW);
                        settextstyle(SMALL_FONT,0,5);
                        setwritemode(XOR_PUT);
                        }
                }
setwritemode(COPY_PUT);
return;
}
/*************************************************************************
draw_cursor should be combined with draw_cube and then left as discussed before.
*************************************************************************/
void draw_cursor(sensortype position)
{
p3type  base;

base=position.pos;
base.Z=0;
drawline(base,position.pos);
draw_cube(position);
}
```

```
/************************************************************************
record_motion checks to see if a cursor has moved above a sensitivity threshold.and if it
has it records the new point in an array, this will probably be useful as the static analysis
section develops. It could do with tidying up, by turning SENSOR_0_COLOUR into a
member of sensor_type things could be reduced by half.
************************************************************************
void record_motion(void)
{
if (sensor_0_toggle)
{
setcolor(SENSOR_0_COLOUR);
if (get_distance(sensor_0_motion_data[sensor_0_current_point],sensor[0].pos)>sensitivity)
                {
                sensor_0_motion_data[++sensor_0_current_point]=sensor[0].pos;
                if (show_path_toggle)
                if (is_equal(sensor_0_motion_data[sensor_0_current_point-1],origin)==0)
                        drawline(sensor_0_motion_data[sensor_0_current_point],
                                sensor_0_motion_data[sensor_0_current_point-1]);
                record_status();
                }
        if (sensor_0_current_point>=1000) sensor_0_current_point=0;
}
if (sensor_1_toggle)
{
setcolor(SENSOR_1_COLOUR);
if (get_distance(sensor_1_motion_data[sensor_1_current_point],sensor[1].pos)>sensitivity)
                {
                sensor_1_motion_data[++sensor_1_current_point]=sensor[1].pos;
                if (show_path_toggle)
                if (is_equal(sensor_1_motion_data[sensor_1_current_point-1],origin)==0)
                        drawline(sensor_1_motion_data[sensor_1_current_point],
                                sensor_1_motion_data[sensor_1_current_point-1]);
                record_status();
                }
        if (sensor_1_current_point>=1000) sensor_1_current_point=0;
}
return;
}
/************************************************************************
display_motion_record is used to redraw the path when the whole display is refreshed by
draw_world. another part that could be tidied and reduced.

************************************************************************/
void display_motion_record(void)
{
int j;
setcolor(SENSOR_0_COLOUR);
for (j=0;j<=sensor_0_current_point;j++)
        {
        if ((is_equal(sensor_0_motion_data[j-1],origin)==0)
                && (is_equal(sensor_0_motion_data[j],origin)==0))
                drawline(sensor_0_motion_data[j],sensor_0_motion_data[j-1]);
        }
setcolor(SENSOR_1_COLOUR);
for (j=0;j<=sensor_1_current_point;j++)
        {
        if ((is_equal(sensor_1_motion_data[j-1],origin)==0)
                && (is_equal(sensor_1_motion_data[j],origin)==0))
                drawline(sensor_1_motion_data[j],sensor_1_motion_data[j-1]);
        }
return;
}
/************************************************************************
is_equal is a useful little routine that could be re-written as an overloaded operator.
************************************************************************/
int is_equal(p3type j,p3type k)
{
int n=1;
if (j.X!=k.X) n=0;
if (j.Y!=k.Y) n=0;
if (j.Z!=k.Z) n=0;
return(n);
}
/************************************************************************
toggle_sensor routines (two of them) talk to the board and to the rest of the program, having
the sensors as an array would tidy this bit up as well, and it would allow more
boards/sensors
to be added at a later date.

************************************************************************/
void toggle_sensor_0(void)
{
char command_buf[12];
if (sensor_0_toggle)
```

```
		{
		if (sensor_1_toggle)
			{
			strcpy(command_buf,"l1,0\r");
			output_to_board(command_buf,strlen(command_buf));
			cursor_to_display=1;
			}
		else sensor_0_toggle=!sensor_0_toggle;
		}
	else
		{
		strcpy(command_buf,"l1,1\r");
		output_to_board(command_buf,strlen(command_buf));
		}
	sensor_0_toggle=!sensor_0_toggle;
	return;
	}
	void toggle_sensor_1(void)
	{
	char command_buf[12];
	if (sensor_1_toggle)
		{
		if (sensor_0_toggle)
			{
			strcpy(command_buf,"l2,0\r");
			output_to_board(command_buf,strlen(command_buf));
			cursor_to_display=0;
			}
		else sensor_1_toggle=!sensor_1_toggle;
		}
	else
		{
		strcpy(command_buf,"l2,1\r");
		output_to_board(command_buf,strlen(command_buf));
		}
	sensor_1_toggle=!sensor_1_toggle;
	return;
	}
	/************************************************************************
	control is a huge switch statement to handle keyboard events. it also causes a screen
	refresh.

	************************************************************************/
	void control(char key)
	{

	char command_buf[8], temp[3];

	switch (key)
		{
		case 'x' : viewpoint.X+=ASTEP;setviewmatrix(); break;
		case 'X' : viewpoint.X-=ASTEP;setviewmatrix(); break;
		case 'y' : viewpoint.Y+=ASTEP;setviewmatrix(); break;
		case 'Y' : viewpoint.Y-=ASTEP;setviewmatrix(); break;
		case 'z' : viewpoint.Z+=ASTEP;setviewmatrix(); break;
		case 'Z' : viewpoint.Z-=ASTEP;setviewmatrix(); break;
		case 'u' : ;
		case 'U' : yorig+=PSTEP; break;
		case 'd' : ;
		case 'D' : yorig-=PSTEP; break;
		case 'l' : ;
		case 'L' : xorig+=PSTEP; break;
		case 'r' : ;
		case 'R' : xorig-=PSTEP; break;
		case 'T' : scale-=ZSTEP; break;
		case 't' : scale+=ZSTEP; break;
		case 'f' : floor_size+=grid; break;
		case 'F' : floor_size-=grid; break;
		case 'g' : grid+=GSTEP; break;
		case 'G' : grid-=GSTEP; break;
		case 'n' : cursor_to_display=!cursor_to_display;
				if ((cursor_to_display)&&(sensor_1_toggle==0))
				cursor_to_display = 0;break;
		case 'p' : show_path_toggle=!show_path_toggle; break;
		case 'm' : sensor_0_motion_data[sensor_0_current_point++]=
				sensor_1_motion_data[sensor_1_current_point]=origin;
				memory_toggle=!memory_toggle; break;
		case 's': sensitivity--; break;
		case 'S': sensitivity++; break;
		case 'E': sensor_0_current_point=sensor_1_current_point=0; break;
		case '1': toggle_sensor_1(); break;
		case '0': toggle_sensor_0();break;
		case 'h': show_big_cursor_text=!show_big_cursor_text;
				setviewport(CURSOR_WINDOW);
```

```
                        clearviewport();
                        setviewport(GRAPHICS_WINDOW);
                        break;
        case 'a': limb_toggle=!limb_toggle;
                  cursor_toggle=!cursor_toggle;
                  setviewport(CURSOR_WINDOW);
                  clearviewport();
                  setviewport(GRAPHICS_WINDOW); break;
        case '2': set_display_vars(PI,PI,PI,20,420,scale); break;
        case '3': set_display_vars(3*PI/2,0,0,20,420,scale);break;
        case '4': set_display_vars(3*PI/2,-PI/2,0,20,420,scale); break;
        case '5': set_display_vars(4.15,0.70,0.42,200,50,0.6); break;
        case '.': getch(); break;
        case ' ': if (file_flag)        {
                                          file.close();
                                          file_flag=0;
                                          file_number+=1;
                                          sprintf(temp,"%i",file_number);
                                          strcpy(file_name,"output");
                                          strcat(file_name,temp);
                                          }
                  else                  {
                                        file.open(file_name);
                                        file_flag=1;
                                        }; break;
        case 'q' : ;
        case 'Q' :      strcpy(command_buf,"B1\n");
                        output_to_board(command_buf,strlen(command_buf)); break;
        case 'w' : ;
        case 'W' : strcpy(command_buf,"B2\n");
                        output_to_board(command_buf,strlen(command_buf)); break;
        case 'œ' : data_recording=0; strcpy(file_name,"wrist"); break;
        case '$' : data_recording=0; strcpy(file_name,"elbow"); break;
        case '%' : data_recording=0; strcpy(file_name,"shoulder"); break;
        case '^' : data_recording=1;
        }
// a bit of error checking
if (scale<ZSTEP) scale=ZSTEP;
if (grid<GSTEP) grid=GSTEP;
if (sensitivity<1) sensitivity=1;
if (floor_size<grid) floor_size=grid;
draw_world();
return;
}
/**********************************************************************
display_status operates the side text window. I think this window will have to be made multi-
mode. for extra functionality
**********************************************************************/
void display_status(void)
{
char    t[40];
int     j=0;
setviewport(STATUS_WINDOW);
setwritemode(COPY_PUT);
clearviewport();
if (sensor_0_toggle) setcolor(SENSOR_0_COLOUR);
else setcolor(OFF_COLOUR);
sprintf(t,"Sensor 0");outtextxy(5,LS*j++,t);
if (sensor_1_toggle) setcolor(SENSOR_1_COLOUR);
else setcolor(OFF_COLOUR);
sprintf(t,"Sensor 1");outtextxy(5,LS*j++,t);
setcolor(DEFAULT_COLOUR);
j++;
sprintf(t,"Viewpoint :");outtextxy(5,LS*j++,t);
sprintf(t,"X: %6.2fdeg",viewpoint.X*RAD_TO_DEG);outtextxy(5,LS*j++,t);
sprintf(t,"Y: %6.2fdeg",viewpoint.Y*RAD_TO_DEG);outtextxy(5,LS*j++,t);
sprintf(t,"Z: %6.2fdeg",viewpoint.Z*RAD_TO_DEG);outtextxy(5,LS*j++,t);
j++;
sprintf(t,"Scale: %6.2f",scale);outtextxy(5,LS*j++,t);
sprintf(t,"Grid: %dmm",grid);outtextxy(5,LS*j++,t);
j++;
sprintf(t,"Xo: %d",xorig);outtextxy(5,LS*j++,t);
sprintf(t,"Yo: %d",yorig);outtextxy(5,LS*j++,t);
j++;
if (file_flag==1)
        setcolor(ON_COLOUR);
else
        setcolor(OFF_COLOUR);
outtextxy(5,LS*j++,file_name);
setcolor(DEFAULT_COLOUR);
//sprintf(t,"");outtextxy(5,LS*j++,t);
setviewport(GRAPHICS_WINDOW);
return;
}
```

```
/*********************************************************************
record_status operates the memory window.

*********************************************************************/
void record_status(void)
{
char t[30];
int     j=0,
        lh=LS;
setviewport(MEMORY_WINDOW);
setwritemode(COPY_PUT);
clearviewport();
if (memory_toggle) setcolor(ON_COLOUR); else setcolor(OFF_COLOUR);
sprintf(t,"Recorder");outtextxy(5,lh*j++,t);
setcolor(DEFAULT_COLOUR);
sprintf(t,"Mem
%d%%",(sensor_0_current_point+sensor_1_current_point)/10);outtextxy(5,lh*j++,t);
sprintf(t,"Sensitivity %d",sensitivity);outtextxy(5,lh*j++,t);
if ((show_path_toggle)&(memory_toggle)) setcolor(ON_COLOUR); else setcolor (OFF_COLOUR);
sprintf(t,"Path Display");outtextxy(5,lh*j++,t);
setviewport(GRAPHICS_WINDOW);
return;
}
/*********************************************************************
initialise arm sets up the arm structure
*********************************************************************/
void initialise_arm(void)
{
arm.humerus.length=265;
arm.radius.length=192;
arm.hand.length=40;
arm.humerus.distance_to_sensor=135;
arm.humerus.sensor_height=50;
arm.hand.distance_to_sensor=20;
arm.hand.sensor_height=10;

arm.torso.length=300;
arm.onscreen=0;
}
/*********************************************************************
calc_arm this is the latest development to replace calc_limb, it assumes one
sensor on the upper arm and another on the hand, and copes with noisy data by
making the forearm an adjustable length segment

some error detection should be built in.
*********************************************************************/
void calc_arm(void)
{
float check;

evaluate_arm_geom();

arm.radius.error=0;
check=get_distance(arm.radius.base,arm.radius.end);
if ((check>arm.radius.length+RMS_ACCURACY)||(check<arm.radius.length-RMS_ACCURACY))
        arm.radius.error=1;

if ((is_equal(arm.humerus.base,old_arm.humerus.base)==0)
        ||(is_equal(arm.radius.base,old_arm.radius.base)==0)
        ||(is_equal(arm.hand.base,old_arm.hand.base)==0))
        {
        display_arm(arm);
        if (arm.onscreen) display_arm(old_arm);
        old_arm = arm;
        arm.onscreen=1;
        }
}

void evaluate_arm_geom(void)
{
arm.humerus.sens_pos_surface=sensor[0].pos;
arm.hand.sens_pos_surface=sensor[1].pos;

arm.humerus.sens_pos_centre=origin;
arm.humerus.sens_pos_centre.Z=arm.humerus.sensor_height;
arm.humerus.sens_pos_centre=matrix_by_point(sensor[0].mat,arm.humerus.sens_pos_centre);
arm.humerus.sens_pos_centre=translate(arm.humerus.sens_pos_centre,arm.humerus.sens_pos_surfac
e);
arm.humerus.base=arm.humerus.end=origin;
arm.humerus.base.X=-arm.humerus.distance_to_sensor;
arm.humerus.base=matrix_by_point(sensor[0].mat,arm.humerus.base);
arm.humerus.base=translate(arm.humerus.base,arm.humerus.sens_pos_centre);
arm.humerus.end.X=+(arm.humerus.length-arm.humerus.distance_to_sensor);
arm.humerus.end=matrix_by_point(sensor[0].mat,arm.humerus.end);
```

```
arm.humerus.end=translate(arm.humerus.end,arm.humerus.sens_pos_centre);

arm.hand.sens_pos_centre=origin;
arm.hand.sens_pos_centre.Z=arm.hand.sensor_height;
arm.hand.sens_pos_centre=matrix_by_point(sensor[1].mat,arm.hand.sens_pos_centre);
arm.hand.sens_pos_centre=translate(arm.hand.sens_pos_centre,arm.hand.sens_pos_surface);
arm.hand.base=arm.hand.end=origin;
arm.hand.base.X=-arm.hand.distance_to_sensor;
arm.hand.base=matrix_by_point(sensor[1].mat,arm.hand.base);
arm.hand.base=translate(arm.hand.base,arm.hand.sens_pos_centre);
arm.hand.end.X=+(arm.hand.length-arm.hand.distance_to_sensor);
arm.hand.end=matrix_by_point(sensor[1].mat,arm.hand.end);
arm.hand.end=translate(arm.hand.end,arm.hand.sens_pos_centre);

arm.torso.end=arm.torso.base=arm.humerus.base;
arm.torso.base.Z+=arm.torso.length;

arm.radius.base=arm.humerus.end;
arm.radius.end=arm.hand.base;

calc_angles();
}
/************************************************************************
display_arm does the obvious
************************************************************************/
void display_arm(armtype arm_to_draw)
{
char t[20];
int ls;
int j=0;
setcolor(ARM_COLOUR);
setwritemode(XOR_PUT);
draw_segment(arm_to_draw.torso);
draw_segment(arm_to_draw.humerus);
draw_segment(arm_to_draw.radius);
draw_segment(arm_to_draw.hand);
drawline(arm_to_draw.humerus.sens_pos_surface,arm_to_draw.humerus.sens_pos_centre);
drawline(arm_to_draw.hand.sens_pos_surface,arm_to_draw.hand.sens_pos_centre);
if (dr_count++>dr_rate)
        {
        dr_count=0;
        setwritemode(COPY_PUT);
        if (show_big_cursor_text)
                {
                settextstyle(SANS_SERIF_FONT,0,7);
                ls =75;
                }
        else
                {
                setviewport(CURSOR_WINDOW);
                ls = LS;
                }
        clearviewport();
        sprintf(t,"SE: %6.2f",arm.shoulder_elev*RAD_TO_DEG);outtextxy(5,ls*j++,t);
        sprintf(t,"SP: %6.2f",arm.shoulder_plane*RAD_TO_DEG);outtextxy(5,ls*j++,t);
        sprintf(t,"SR: %6.2f",arm.shoulder_rot*RAD_TO_DEG);outtextxy(5,ls*j++,t);
        sprintf(t,"E : %6.2f",arm.elbow_bend*RAD_TO_DEG);outtextxy(5,ls*j++,t);
        sprintf(t,"WE: %6.2f",arm.wrist_elev*RAD_TO_DEG);outtextxy(5,ls*j++,t);
        sprintf(t,"WP: %6.2f",arm.wrist_plane*RAD_TO_DEG);outtextxy(5,ls*j++,t);
        sprintf(t,"WR: %6.2f",arm.wrist_rot*RAD_TO_DEG);outtextxy(5,ls*j++,t);
        if (arm.radius.error)
                {
                setcolor(ERROR_COLOUR);
                sprintf(t,"FAIL");outtextxy(5,ls*j++,t);
                }
        setviewport(GRAPHICS_WINDOW);
        settextstyle(SMALL_FONT,0,5);
        setwritemode(XOR_PUT);
        }
}

void draw_segment(segment_type seg)
{
draw_spot(seg.base,grid/8);
drawline(seg.base,seg.end);
}
/************************************************************************
initialise_board sends a series of characters to the board to set up the configuration
required by the interogation routines. At the moment board config is hard coded, making it
software adaptable might be a good thing to do later on.

to do: get it all working as a single string.
************************************************************************/
void initialise_board(void)
```

```
{
char command_buf[80];

/*strcpy(command_buf,"c\n\rl1,1\n\rl2,1\n\ru\n\rO1,2,4,5,6,7,1\n\rO2,2,4,5,6,7,1C\n\r");
output_to_board(command_buf,strlen(command_buf));
delay(500);*/
strcpy(command_buf,"c\r");
output_to_board(command_buf,strlen(command_buf));
delay(500);
strcpy(command_buf,"l1,1\r");
output_to_board(command_buf,strlen(command_buf));
delay(500);
strcpy(command_buf,"l2,1\r");
output_to_board(command_buf,strlen(command_buf));
delay(500);
strcpy(command_buf,"u\r");
output_to_board(command_buf,strlen(command_buf));
delay(500);
strcpy(command_buf,"O1,2,4,5,6,7,1\r");
output_to_board(command_buf,strlen(command_buf));
delay(500);
strcpy(command_buf,"O2,2,4,5,6,7,1\r");
output_to_board(command_buf,strlen(command_buf));
delay(500);
strcpy(command_buf,"C\r");
output_to_board(command_buf,strlen(command_buf));
delay(500);
}
/*************************************************************************
function        capture_board_off_bus

purpose         call principal functions

inputs          ISA bus address
                Insidetrak outputs

description     used for board status number of captured words

outputs         record of incoming data
                indicator of which FTK is coming

*************************************************************************/

int     capture_board_off_bus()
{
int i;
char bsts;

bsts = inp(BUS_ADDR|1)&1;
for(i=0; (bsts &1)&& i < 512;
                        bsts = inp(BUS_ADDR|1)&1,i++) /* data available == bit 0 */
        {
        fast_trak_bus_data[i] = inpw(BUS_ADDR);
        }
return i;
}
/*************************************************************************
function        output_to_board

purpose

inputs          command_data
                index for current output board
                number of output characters

description     Oput an array of data to the bus

outputs

*************************************************************************/
void    output_to_board( char *cbuf, int nbr_chro)
{
int i, ib;

for(i=0;i<nbr_chro;i++)
        {
        ib=inp(BUS_ADDR|1);
        if( (ib&2) == 0)        /* test for full == bit 1 */
                {
                setviewport(CURSOR_WINDOW);
                setfillstyle(BKSLASH_FILL,ERROR_COLOUR);
                bar(0,0,300,300);
                delay(200);
                }
```

```
        outportb(BUS_ADDR, cbuf[i]);
        }
}

/*********************************************************************
getXYZ reads the board until it gets a record of the correct length, than it fills the sensor
arrays with thre requisite data
*********************************************************************/
void getXYZ(void)
{
int sensor_0_read,sensor_1_read;
int     k,sensor_no;
char    command_buf[6];

sensor_0_read=sensor_1_read=0;
if (sensor_0_toggle==0) sensor_0_read=1;
if (sensor_1_toggle==0) sensor_1_read=1;
do
        {
        do
                {
                k=capture_board_off_bus();
                //if (k==0) cout<<"."; //diagnostic
                //else cout<< k;
                }
        while (k!=WORDS_IN_RECORD);
        sensor_no=((fast_trak_bus_data[0]>>8)&3)-1;
        if (sensor_no==0) sensor_0_read=1;
        else sensor_1_read=1;
        sensor[sensor_no].pos.X=fast_trak_bus_data[1]*SPATIAL_CALIBRATION_VALUE;
        sensor[sensor_no].pos.Y=fast_trak_bus_data[2]*SPATIAL_CALIBRATION_VALUE;
        sensor[sensor_no].pos.Z=fast_trak_bus_data[3]*SPATIAL_CALIBRATION_VALUE;
        sensor[sensor_no].eul.Z=fast_trak_bus_data[4]*RADIAN_CALIBRATION_VALUE;
        sensor[sensor_no].eul.Y=fast_trak_bus_data[5]*RADIAN_CALIBRATION_VALUE;
        sensor[sensor_no].eul.X=fast_trak_bus_data[6]*RADIAN_CALIBRATION_VALUE;
        sensor[sensor_no].mat[0][0]=fast_trak_bus_data[7]*COSINE_CALIBRATION_VALUE;
        sensor[sensor_no].mat[0][1]=fast_trak_bus_data[8]*COSINE_CALIBRATION_VALUE;
        sensor[sensor_no].mat[0][2]=fast_trak_bus_data[9]*COSINE_CALIBRATION_VALUE;
        sensor[sensor_no].mat[1][0]=fast_trak_bus_data[10]*COSINE_CALIBRATION_VALUE;
        sensor[sensor_no].mat[1][1]=fast_trak_bus_data[11]*COSINE_CALIBRATION_VALUE;
        sensor[sensor_no].mat[1][2]=fast_trak_bus_data[12]*COSINE_CALIBRATION_VALUE;
        sensor[sensor_no].mat[2][0]=fast_trak_bus_data[13]*COSINE_CALIBRATION_VALUE;
        sensor[sensor_no].mat[2][1]=fast_trak_bus_data[14]*COSINE_CALIBRATION_VALUE;
        sensor[sensor_no].mat[2][2]=fast_trak_bus_data[15]*COSINE_CALIBRATION_VALUE;
        }
while ((sensor_0_read==0)||(sensor_1_read==0));
return;
}

/*********************************************************************
drawline displays the 3d lines produced elswhere on the screen as 2d
*********************************************************************/
void drawline(p3type start,p3type finish)
{
extern float scale;
extern int xorig,yorig;
extern p3type viewpoint;
int SX,SY,FX,FY;

start = matrix_by_point(viewmatrix,start);
finish = matrix_by_point(viewmatrix,finish);
SX = start.X*scale;
FX = finish.X*scale;
SY = start.Y*scale;
FY = finish.Y*scale;
line(SX+xorig,yorig-SY,FX+xorig,yorig-FY);
return;
}
/*********************************************************************
set_graph_mode switches on the graphics adapter, it was pinched from the on-line help
turbo C
*********************************************************************/
int set_graph_mode(void)
{
        int graphdriver = DETECT, graphmode, error_code;

        initgraph(&graphdriver, &graphmode, "C:\\tc\\bgi");
        error_code = graphresult();
        if (error_code != grOk)
                return(0); // No graphics hardware found

        return(1); // Graphics OK, so return "true"
}
```

```
/*********************************************************************
rotateX,rotateY,rotateZ these set up a matrix and do a 3d transformation. at the moment
they use a polhemus routine,
to-do : add my own simple point by matrix routine. using pointers might be be clever
*********************************************************************/
p3type rotateX(p3type point,double angle)
{
MATRIX matrix;
p3type newpoint;

matrix[0][0]=1;
matrix[0][1]=0;
matrix[0][2]=0;
matrix[1][0]=0;
matrix[1][1]=cos(angle);
matrix[1][2]=sin(angle);
matrix[2][0]=0;
matrix[2][1]=-sin(angle);
matrix[2][2]=cos(angle);

newpoint=matrix_by_point(matrix,point);
return(newpoint);
}
//*********************************************************************

p3type rotateY(p3type point,double angle)
{
MATRIX matrix;
p3type newpoint;

matrix[0][0]=cos(angle);
matrix[0][1]=0;
matrix[0][2]=-sin(angle);
matrix[1][0]=0;
matrix[1][1]=1;
matrix[1][2]=0;
matrix[2][0]=sin(angle);
matrix[2][1]=0;
matrix[2][2]=cos(angle);

newpoint=matrix_by_point(matrix,point);
return(newpoint);
}
//*********************************************************************

p3type rotateZ(p3type point,double angle)
{
MATRIX matrix;
p3type newpoint;

matrix[0][0]=cos(angle);
matrix[0][1]=sin(angle);
matrix[0][2]=0;
matrix[1][0]=-sin(angle);
matrix[1][1]=cos(angle);
matrix[1][2]=0;
matrix[2][0]=0;
matrix[2][1]=0;
matrix[2][2]=1;

newpoint=matrix_by_point(matrix,point);
return(newpoint);
}
/*********************************************************************
rotate sequential calls the routines above, I think it is now outdated by euler-rotate which
uses a concatenated matrix, as noted before this is all pretty inefficient as the matrix is
constructed each time. it really needs a permenant viewpoint matrix.
*********************************************************************/
p3type rotate(p3type point,p3type angle)
{
p3type newpoint;
newpoint = rotateZ(point,angle.Z);
newpoint = rotateX(newpoint,angle.X);
newpoint = rotateY(newpoint,angle.Y);
return newpoint;
}
/*********************************************************************
draw_spot draws a little cross
*********************************************************************
void draw_spot(p3type position,float size)
{
p3type start,finish;
start=finish=position;
start.X-=size;
```

```
finish.X+=size;
drawline(start,finish);
start=finish=position;
start.Y-=size;
finish.Y+=size;
drawline(start,finish);
start=finish=position;
start.Z-=size;
finish.Z+=size;
drawline(start,finish);
return;
}
/***********************************************************************
get_distance returns the distance between two 3D points
***********************************************************************/
long double get_distance(p3type start,p3type finish)
{
long double K;
p3type dists;
dists.X = start.X-finish.X;
dists.Y = start.Y-finish.Y;
dists.Z = start.Z-finish.Z;
K =(dists.X*dists.X)+(dists.Y*dists.Y)+(dists.Z*dists.Z);
return sqrtl(K);
}
/***********************************************************************
get_h_distance returns the horizontal distance between two points, useful
for calculating the static torques: it assumes the X-Y plane is horizontal
as this is the normal Trak configuration.
***********************************************************************/
float get_h_distance(p3type start,p3type finish)
{
long double K;
p3type dists;
dists.X=start.X-finish.X;
dists.Y=start.Y=finish.Y;
K=(dists.X*dists.X)+(dists.Y*dists.Y);
return sqrtl(K);
}
/***********************************************************************
angle_between_vectors returns the nagle between 2 unit vectors, useful for
providing the elbow angle of a limb.
***********************************************************************/
float angle_between_vectors(p3type first,p3type second)
{
float cosangle;
first=get_unit_vector(first);
second=get_unit_vector(second);
cosangle=first.X*second.X+first.Y*second.Y+first.Z*second.Z;
return acos(cosangle);
}
float angle_between_vectors(p3type first,p3type second,p3type third)
{
p3type f,s;
float cosangle;
f=get_unit_vector(second,first);
s=get_unit_vector(second,third);
cosangle=f.X*s.X+f.Y*s.Y+f.Z*s.Z;
return acos(cosangle);
}
/***********************************************************************
draw_text puts text in graphics space at a 3d position. it always faces the screen.
***********************************************************************/
void draw_text(p3type point,char text[])
{
point=euler_rotate(point,viewpoint);
point.X*=scale;
point.Y*=scale;
outtextxy(point.X+xorig,yorig-point.Y,text);
return;
}
/***********************************************************************
get_unit_vector returns the i,j,k(XYZ) components of a unit vector pointingfrom Start to
Finish
***********************************************************************/
p3type get_unit_vector(p3type start,p3type finish)
{
p3type vector;

long double distance = get_distance(start,finish);
vector.X=(finish.X-start.X)/distance;
vector.Y=(finish.Y-start.Y)/distance;
vector.Z=(finish.Z-start.Z)/distance;
return(vector);
```

```
}
p3type get_unit_vector(p3type v)
{
p3type r;
long double length;
length=sqrtl((v.X*v.X)+(v.Y*v.Y)+(v.Z*v.Z));
r.X=v.X/length;
r.Y=v.Y/length;
r.Z=v.Z/length;
return r;
}
/*******************************************************************
 point from vector returns the end point of a vector of lenght distancefrom start along
unit vector "vector"
*********************************************************************/
p3type point_from_vector(p3type start,p3type vector, double distance)
{
p3type point;

point.X=start.X+(vector.X*distance);
point.Y=start.Y+(vector.Y*distance);
point.Z=start.Z+(vector.Z*distance);
return(point);
}
/*******************************************************************
function Euler_rotate

purpose Does a Euler Transformation

inputs point, angle


description

outputs new point

*********************************************************************/
p3type euler_rotate(p3type point,p3type angles)
{
MATRIX matrix;
p3type newpoint;
double t1,t2,t3;

t1=angles.X;
t2=angles.Y;
t3=angles.Z;

matrix[0][0]=cos(t2)*cos(t3);
matrix[0][1]=cos(t1)*sin(t3)+sin(t1)*sin(t2)*cos(t3);
matrix[0][2]=sin(t1)*sin(t3)-cos(t1)*sin(t2)*cos(t3);
matrix[1][0]=-cos(t2)*sin(t3);
matrix[1][1]=cos(t1)*cos(t3)-sin(t1)*sin(t2)*sin(t3);
matrix[1][2]=sin(t1)*cos(t3)+cos(t1)*sin(t2)*sin(t3);
matrix[2][0]=sin(t2);
matrix[2][1]=-sin(t1)*cos(t2);
matrix[2][2]=cos(t1)*cos(t2);

newpoint=matrix_by_point(matrix,point);
return(newpoint);
}
/**********************************************************************
setviewmatrix is only called when the viewpoint changes
**********************************************************************/
void setviewmatrix(void)
{
viewmatrix[0][0]=cos(viewpoint.Y)*cos(viewpoint.Z);
viewmatrix[0][1]=cos(viewpoint.X)*sin(viewpoint.Z)+sin(viewpoint.X)*sin(viewpoint.Y)*cos(view
point.Z);
viewmatrix[0][2]=sin(viewpoint.X)*sin(viewpoint.Z)-
cos(viewpoint.X)*sin(viewpoint.Y)*cos(viewpoint.Z);
viewmatrix[1][0]=-cos(viewpoint.Y)*sin(viewpoint.Z);
viewmatrix[1][1]=cos(viewpoint.X)*cos(viewpoint.Z)-
sin(viewpoint.X)*sin(viewpoint.Y)*sin(viewpoint.Z);
viewmatrix[1][2]=sin(viewpoint.X)*cos(viewpoint.Z)+cos(viewpoint.X)*sin(viewpoint.Y)*sin(view
point.Z);
viewmatrix[2][0]=sin(viewpoint.Y);
viewmatrix[2][1]=-sin(viewpoint.X)*cos(viewpoint.Y);
viewmatrix[2][2]=cos(viewpoint.X)*cos(viewpoint.Y);
}
/*******************************************************************
function cross_product

purpose does the vector product of three vectors
```

```
inputs


description

outputs

***************************************************************************/
p3type cross_product(p3type v,p3type w)
{
p3type result;

result.X=(v.Y*w.Z)-(w.Y*v.Z);
result.Y=-((v.X*w.Z)-(w.X*v.Z));
result.Z=(v.X*w.Y)-(w.X*v.Y);

return(result);
}
/**************************************************************************
function draw_cube

purpose test my rotation ability.

inputs


description

outputs

***************************************************************************/
void draw_cube(sensortype s)
{
p3type vertex[20] =     {
                        {-1,-1,-1},{-1,-1,1},{1,-1,1},
                        {1,-1,-1},{-1,1,-1},{-1,1,1},
                        {1,1,1},{1,1,-1},
                        {1,0.5,-0.5},{1,0.5,0.5},{1,-0.5,-0.5},{1,-0.5,0.5},
                        {-0.5,1,-0.5},{0,1,0},{0.5,1,-0.5},{0,1,0.5},
                        {-0.5,0.5,1},{0.5,0.5,1},{-0.5,-0.5,1},{0.5,-0.5,1}
                        };
int edge[20][2] =       {
                        {0,1},{1,2},{2,3},{3,0},{4,5},{5,6},{6,7},{7,4},
                        {0,4},{1,5},{2,6},{3,7},{8,11},{9,10},{12,13},
                        {13,14},{13,15},{16,17},{17,18},{18,19}
                        };
int size=20/scale;
int j;
p3type newpoint;

for (j=0;j<20;j++)
        {
        vertex[j]=matrix_by_point(s.mat,vertex[j]);
        vertex[j].X*=size;
        vertex[j].X+=s.pos.X;
        vertex[j].Y*=size;
        vertex[j].Y+=s.pos.Y;
        vertex[j].Z*=size;
        vertex[j].Z+=s.pos.Z;
        }
for (j=0;j<20;j++) drawline(vertex[edge[j][0]],vertex[edge[j][1]]);
}
/***************************************************************************
 matrix_by_point is the main matrix routine;
***************************************************************************/
p3type matrix_by_point(double m[3][3] ,p3type p)
{
p3type z;
z.X=m[0][0]*p.X+m[0][1]*p.Y+m[0][2]*p.Z;
z.Y=m[1][0]*p.X+m[1][1]*p.Y+m[1][2]*p.Z;
z.Z=m[2][0]*p.X+m[2][1]*p.Y+m[2][2]*p.Z;
return z;
}
/***************************************************************************
translate does the obvious
***************************************************************************/
p3type translate(p3type s,p3type f)
{
p3type r;
r.X=s.X+f.X;
r.Y=s.Y+f.Y;
r.Z=s.Z+f.Z;
return r;
}
```

```
/***************************************************************************
point_along_line is used to calculate the positions of segment cg's
***************************************************************************/
p3type point_along_line(p3type s,p3type f,float d)
{
p3type r;

r.X=s.X+((f.X-s.X)*d);
r.Y=s.Y+((f.Y-s.Y)*d);
r.Z=s.Z+((f.Z-s.Z)*d);

return r;
}
/***************************************************************************
file_out sends currently interesting stuff to a file for post-processing etc.
***************************************************************************/
void file_out(void)
{
//this bit sends out the sensor positions and angles as direction cosines


int j;

for (j=0;j<2;j++)
	{
	file<<sensor[j].pos.X<<'\t'<<sensor[j].pos.Y<<'\t'<<sensor[j].pos.Z<<"\n";
	file<<sensor[j].mat[0][0]<<'\t'<<sensor[j].mat[0][1]<<'\t'<<sensor[j].mat[0][2]<<"\n";
	file<<sensor[j].mat[1][0]<<'\t'<<sensor[j].mat[1][1]<<'\t'<<sensor[j].mat[1][2]<<"\n";
	file<<sensor[j].mat[2][0]<<'\t'<<sensor[j].mat[2][1]<<'\t'<<sensor[j].mat[2][2]<<"\n\n
";
	}
file_flag++;


}

/*************************************************************************/

void calc_angles(void)

//this routine uses five limb-segment points to calculate the
//biomechanical limb angles, its principle assumptions are:
//the elbow is a simple hinge,


{
p3type data[4];
p3type t1,t2,t3;
int j;

//first put the 4 relevent data points into an array for ease of rotations

data[0]=arm.radius.base;
data[1]=arm.hand.base;
data[2]=arm.hand.sens_pos_centre;
data[3]=arm.hand.sens_pos_surface;

//next subtract the humeral base point to put the limb base at the origin

for (j=0;j<=3;j++)
	{
	data[j].X-=arm.humerus.base.X;
	data[j].Y-=arm.humerus.base.Y;
	data[j].Z-=arm.humerus.base.Z;
	}

//get the plane of shoulder elevation by projecting onto a horizontal
//plane and getting the angle to the Y axis

t1=origin;
t1.Y=100;
t2=data[0];
t2.Z=0;
arm.shoulder_plane=angle_between_vectors(t2,origin,t1);
if (data[0].X<0) arm.shoulder_plane=-arm.shoulder_plane;

//rotate arm to align humerus with Y axis

for (j=0;j<=3;j++) data[j]=rotateZ(data[j],-arm.shoulder_plane);

//get the shoulder elevation- angle of humerus to Z axis

t1=origin;
t1.Z=100;
arm.shoulder_elev=angle_between_vectors(data[0],origin,t1);
```

```
//rotate arm to align humerus with Z axis

for (j=0;j<=3;j++) data[j]=rotateX(data[j],-arm.shoulder_elev);

//get humeral rotation

t1=data[1];
t1.Z=0;
t2=origin;
t2.X=-100;
arm.shoulder_rot=angle_between_vectors(t1,t2);
if (data[1].Y<0) arm.shoulder_rot=-arm.shoulder_rot;

//un-rotate arm by humeral rotation

for (j=0;j<=3;j++) data[j]=rotateZ(data[j],-arm.shoulder_rot);

//translate elbow to origin

for (j=0;j<=3;j++)
        {
        data[j].X-=data[0].X;
        data[j].Y-=data[0].Y;
        data[j].Z-=data[0].Z;
        }

// get elbow bend

t1=origin;
t1.Z=-100;
arm.elbow_bend=angle_between_vectors(t1,origin,data[1]);

// un bend elbow by rotation about Y axis

for (j=0;j<=3;j++) data[j]=rotateY(data[j],arm.elbow_bend);

//translate wrist to origin

for (j=0;j<=3;j++)
        {
        data[j].X-=data[1].X;
        data[j].Y-=data[1].Y;
        data[j].Z-=data[1].Z;
        }


// get wrist plane in same manner as humeral plane

t1=data[2];
t1.Z=0;
t2=origin;
t2.Y=100;

arm.wrist_plane=angle_between_vectors(t1,origin,t2);

// un rotate arm by wrist plane

for (j=0;j<=3;j++) data[j]=rotateZ(data[j],-arm.wrist_plane);

//get wrist elevation

t1=origin;
t1.Z=100;
arm.wrist_elev=angle_between_vectors(t1,origin,data[2]);


//un rotatate wrist

for (j=0;j<=3;j++) data[j]=rotateX(data[j],-arm.wrist_elev);

//get wrist rotation

t1=origin;
t1.X=100;
t2=data[3];
t2.Z=0;
arm.wrist_rot=angle_between_vectors(t1,origin,t2);
if (t2.Y<0) arm.wrist_rot=-arm.wrist_rot;
}
```