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Creation of a design methodology for devices that improve human mobility

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Creation of a design methodology for devices that improve human mobility

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Abstract

Occupational therapists and physiotherapists encourage older people and people with physical disabilities to use normal movement patterns where possible as it is anecdotally considered as being the most functionally efficient. It is thus important that assistive devices should be designed to enhance functional performance and provide the opportunity for people to carry out movement tasks in a normal manner if desired.

Recognised design methodologies do not provide detailed methods or strategies to aid designers in creating devices that enable the aforementioned groups to continue using normal movement patterns. A review of existing computer human models has also found that designers do not use manikin representatives to aid the creation of assistive devices in the very early conceptual design phase.

The aim of this research project was to create a design methodology to enhance the current functional performance, while at the same time enabling people to continue using normal movement strategies. This methodology has been based on comparisons of natural movement strategies reported in literature, experimental investigations and simulations of these movements using a computer manikin. Its aim was to employ a computer manikin during the early stages of the conceptual design phase to reduce the time and cost of a new design.

A case study employing the proposed design methodology to design a device to aid three people with osteoarthritis in rising from a sitting posture showed that the proposed design methodology had enabled a device to be designed that improved their mobility. The device enhanced their functional performance, eliminated the pain previously experienced on rising and enabling them to continue using movement strategies similarly used by able-bodied people. This outcome showed that the proposed methodology had assisted in designing a device that enabled people with osteoarthritis to continue rising from a sitting posture in a normal manner and carry out this daily activity independently.

Dedication

I wish to dedicate this thesis to:

Rev. Robert Goodson
9 April 1947 – 22 April 2004

The day you left, you filled the sky with an unforgettable red sunset.
Followed by a low lying sickle moon and a single bright planetary orb.
The next morning was a blaze of sunshine...
A typical day for family barbecues and drinking cold beer.

Thanks for all your love, support and understanding Rob.
And 'yes, I did get round to finishing the bibliography'.

and

Dr Robert Goodson

You have been my rock

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Contents

Chapter 1 Introduction 1

1.0 Introduction 1

1.2 Project aims and objectives 5

Chapter 2 Design Processes 8

2.0 Introduction 8

2.1 Existing design processes 8

2.1.1 Description of existing design process 8

2.2 Contribution of design processes towards the project aims 26

2.3 Conclusions 33

Chapter 3 Proposed design procedures for human mobility aids 34

3.0 Introduction 34

3.1 Brief description of proposed design procedures 34

3.2 Detailed description of proposed design procedures 37

3.3 Phase 1 Define problem and user needs 37

3.3.1 *Phase 1a* User attributes 37

3.3.2 *Phase 1b* Definition of the task 38

3.3.3 *Phase 1c* Observational study of able-bodied people and the user 38

3.3.4 *Phase 1d* Analysis of existing designs 40

3.3.5 *Phase 1e* Anthropomorphic measurements 40

3.3.6 *Phase 1e* Segmental lengths 41

3.3.7 *Phase 1e* External body measurements 41

3.3.8 *Phase 1e* Measurement of joint angular rotation 41

3.3.9 *Phase 1f* Other user needs 42

3.4 Phase 2 Design Specification 42

3.4.1 *Phase 2a* User requirements 42

3.4.2 *Phase 2b* Task requirements 43
3.4.3 *Phase 2c* Engineering constraints 43
3.4.4 *Phase 2d* Manufacturing requirements 43
3.4.5 *Phase 2e* Company requirements 44
3.4.6 *Phase 2f* Other requirements/constraints 44
3.5 Phase 3 Experimental study of able-bodied people and potential users 44
3.5.1 The subject group 45
3.5.2 External artefacts 45
3.5.3 Explanation of the task 45
3.5.4 Video camera recording 46
3.5.5 Analysis of the data 46
3.6 Phase 4 Compare movement strategies of able-bodied people and potential users 46
3.7 Phase 5 Model able-bodied and potential users' movement strategies 47
3.8 Phase 6 Conceptual design 48
3.9 Phase 7 Validate and test 49
3.9.1 *Phase 7a* Make prototype 49
3.9.2 *Phase 7b* Experimental validation 49
3.9.3 *Phase 7c* Subjective questioning 49
3.9.4 *Phase 7d* Comparisons with initial experiments 50
3.10 Conclusions 50

Chapter 4 Human stability 52
4.0 Introduction 52
4.1 The sensorimotor mechanism for maintaining stability 52
4.1.1 Summary 53
4.2 Mechanical determinants of stability 53
4.3 Experimental location of the centre of gravity 55
4.3.1 Summary 58
4.4 Theoretical location of the centre of mass 59
4.4.1 Summary 61

4.5 Movement strategies when maintaining stability 61
4.5.1 Summary 63
4.5.2 Strategies for maintaining stability in the bipedal erect stance 63
4.5.3 Summary 64
4.6 Stable postures maintainable during dynamic movement 64
4.6.1 Summary 64
4.7 Conclusions 65

Chapter 5

Definition and measurement of the sit-to-stand movement 66
5.0 Introduction 66
5.1 Distinct movement strategies employed by young adult able-bodied people 66
5.1.1 Summary 73
5.2 Comparisons of movement strategies of young adult able-bodied people, older adults and people with physical disabilities 75
5.2.1 Summary 77
5.3 Differences of movement strategies with variability of chair design 78
5.3.1 Summary 80
5.4 Techniques employed to define the sit-to-stand movement 81
5.4.1 Summary 83

Chapter 6 Computer Based Human Models 84
6.0 Introduction 84
6.1 Ergonomic computer models 84
6.2 Biomechanical computer models 87
6.3 Control models 89
6.4 Discussion 89
6.5 A computer manikin developed within SWORDS 90
6.5.1 The software program SWORDS 90

6.5.2 Model spaces 93
6.5.3 The manikin 94
6.6 The skeletal structure 95
6.6.1 The wireframe structure 98
6.6.2 Joint range of movement 99
6.6.3 Manipulation of the computer manikin 102
6.6.5 Stability calculation 105
6.7 Conclusions 107

Chapter 7

Experimental study to define movement strategies employed by able-bodied people 109

7.0 Introduction 109
7.1 The experimental study 109
7.1.1 The task 109
7.2 Procedures 110
7.3 Analysis 112
7.4 Results 116
7.4.1 Movement phases employed when rising from a chair 117
7.4.2 Movement strategies employed when reclining onto a chair 118
7.5 Consistency of movement strategies 122
7.5.1 Discussion of results 125
7.6 Comparisons of sequential movements 127
7.7 Conclusions 131

Chapter 8

Simulation of the sit-to-stand strategy using SWORDS 132

8.0 Introduction 132
8.1 The movement strategy 132

8.2 Modeling the sit-to-stand movement strategies 133
8.2.1 Geometric representation of artifacts 133
8.2.2 Subject measurements 135
8.3 Modelling of the intermediate postures 139
8.3.1 The sitting posture 139
8.3.2 Maximum hip flexion 143
8.3.3 Maximum ankle dorsiflexion 150
8.3.4 The erect stance 152
8.4 Presentation and discussion of results 154
8.4.1 The sitting posture 154
8.4.2 Maximum hip flexion 156
8.4.3 Maximum ankle dorsiflexion 158
8.4.4 The erect stance 159
8.5 Conclusions 160

Chapter 9 Case Study 161

9.0 Introduction 161
9.2 Phase 1 Define problem and user needs 161
9.2.1 *Phase 1a* User attributes 163
9.2.2 *Phase 1b* Definition of task 163
9.2.3 *Phase 1c* Observational study of able-bodied and user 163
9.2.3.1 Results 164
9.2.4 *Phase 1d* Analysis of Existing designs 165
9.2.4.1 Results 167
9.2.5 *Phase 1e* Anthropomorphic measurements 168
9.2.6 *Phase 1f* Other user needs 168
9.3 Phase 2 Design Specification 168
9.3.1 *Phase 2a* User requirements 169
9.3.2 *Phase 2b* Task requirements 170
9.3.3 *Phase 2c* Engineering constraints 171
9.3.4 *Phase 2d* Manufacturing requirements 172

9.3.5 *Phase 2e* Company requirements 172
9.3.6 *Phase 2f* Other requirements/constraints 172
9.4 Phase 3 Experimental study of able-bodied people and potential users 172
9.5 Phase 4 Compare able-bodied and potential user movement strategies 173
9.6 Phase 5 Model able-bodied and potential user movement strategies 179
9.6.1 The sitting posture 179
9.6.2 Maximum hip flexion 181
9.6.3 The erect stance 183
9.6.4 Conclusions 185
9.7 Phase 6 Conceptual design 186
9.7.1 Design Iteration 1 187
9.7.2 Design Iteration 2 188
9.7.3 Design Iteration 3 189
9.7.4 Design Iteration 4 190
9.7.5 Design Iteration 5 190
9.7.6 Design Iteration 6 191
9.7.7 Design Iteration 7 192
9.7.8 Design Iteration 8 193
9.7.9 Remarks 195
9.8 Phase 7 Validation and test 195
9.8.1 *Phase 7a* Make prototype 196
9.8.2 *Phase 7b* Experimental validation 199
9.8.3 *Phase 7c* Subjective Questioning 200
9.8.4 *Phase 7d* Comparisons with initial experiments 201
9.8.4.1 The sitting posture 206
9.8.4.2 Maximum hip flexion 209
9.8.4.3 The erect stance 212
9.9 Discussion 213
9.10 Conclusions 216

Chapter 10 Conclusions and Recommendations 217

10.0 Introduction 217

10.1 Stability required for mobility (Chapter 4) 217

10.2 The sit-to-stand movement (Chapter 5) 220

10.2.1 Experimental study to define the sit-to-stand movement (Chapter 7) 221

10.3 Computer based human models (Chapter 6) 222

10.4 Existing, proposed design methodology and case study (Chapters 2, 3 and 9) 224

Publications 229

References 230

Appendix A 238

List of Figures

Figure 2.1 Design process model developed by Pahl and Beitz (1996) 15

Figure 2.2 Design process described in BS7000 Part 2 (1997) 16

Figure 2.3 Design process model described in German standard VDI 2221 17

Figure 2.4 Design process model developed by Hubka et al (1988) 18

Figure 2.5 Design process model developed by French (1985) 19

Figure 2.6 Design process model developed by Pugh (1990) 20

Figure 2.7 Design process model developed by Hales (1993) 21

Figure 2.8 The combination of the three elements of marketing, product and production throughout the design process as described by Andreasen and Hein (1987) 22

Figure 2.9 A design process model created by Andreasen and Hein (1987) 22

Figure 2.10 Design process model developed by Medland and Mullineux (1989) 23

Figure 2.11 Design process model developed by Orpwood (1990) 24

Figure 2.12 Design model provided by Keates and Clarkson (2001) 25

Figure 3.1 The proposed design methodology 36

Figure 4.1 The balance method, from Özkaya and Nordin (1991) 56

Figure 4.2. The reaction board method, from Özkaya and Nordin (1991) 57

Figure 4.3 The reaction board method, from Hay (1993) 58

Figure 4.4 The segmentation method, from Hay (1993) 61

Figure 4.5 Diagram of a two dimensional convex hull 62

Figure 4.6 The ankle, hip and stepping strategies, from Kuaffman et al (1997) 63

Figure 5.1 Pictorial diagram of the movement strategies used when able-bodied people rise from a chair, as described by Butler et al (1991) 67

Figure 5.2 The initiation and termination of the two phases of movement that occur during the sit-to-stand movement, as described by Alexander et al (1991) 68

Figure 5.3 Diagram of the three phases of movement during rising from a chair as described by Bahrami et al (2000) 69

Figure 5.4 Diagram illustrating the initiation and termination of three phases of movement described by Schenkman et al (1990) and Ikeda et al (1991) when able-bodied subjects rise from a sitting posture 70

Figure 5.5 A diagram of the three events described by Jeug et al (1991) to define the sit-to-stand movement strategy 71
Figure 5.6 Two telescopic pendulums simulating the dynamic movement of initially the upper body and then the body as a whole when rising from a sitting posture, as described by Papa and Cappozzo (1999) 72
Figure 5.7 Summary of sit-to-stand phases defined by various authors 74
Figure 6.1 Assembly of three lines provided by Medland et al (1995) 91
Figure 6.2 (a) Motion trajectory of the mechanism provided by Medland et al (1995) 91
Figure 6.2(b) The selection of a mechanism provide Medland et al (1995) 92
Figure 6.3 Conceptual design of bicycle provided by Medland and Mullineux (2000) 92
Figure 6.4 Variable conceptual design of a bicycle provided by Medland and Mullineux (2000) 92
Figure 6.5 Design solution for child rider provided by Medland and Mullineux (2000) 93
Figure 6.6 A typical model space hierarchy provided Leigh et al (1989) 94
Figure 6.7 Graphics interface of manikin representative created in SWORDS 95
Figure 6.8 Diagram of rigid links representing the human skeletal structure provided the Technical University of Delft, ADAPS (2003) 96
Figure 6.9 The model apace hierarchy containing the geometric attributes of the human form in SWORDS 97
Figure 6.10 A schematic representative of the 50th percentile Dutch man provided by the University of Delft, ADAPS (2003) 98
Figure 6.11 Wire frame structure of the 50th percentile Dutch man incorporated into the Swords program 99
Figure 6.12 Cartesian co-ordinate system used to manipulated the manikin 100
Figure 6.13 Range of joint movement of a 50^{th} percentile Dutch man provided by the Technical University of Delft, ADAPS (2003) 101
Figure 6.14 Excel spread sheet showing rules and model space variables used to manipulate manikin 103
Figure 6.15 Graphical representation of manikin placed in neutral position 104
Figure 6.16 Manikin pointing and looking at ball while standing 104
Figure 6.17 Manikin looking and pointing at ball using with modified ball placement 105

Figure 6.18 Manikin shown to be statically balanced 106
Figure 6.19 Graphical display of convex hull of the base of support form by feet 107
Figure 7.1 A video frame of the sitting posture, that each subject was requested to undertake before and after rising to an erect stance, as shown by subject A 111
Figure 7.2 Diagram to illustrate the definition of the hip segmental angle 113
Figure 7.3 Diagram to illustrate the definition of the knee segmental angle 114
Figure 7.4 Diagram to illustrate the definition of the head segmental angle 115
Figure 7.5 Diagram to illustrate the definition of the ankle segmental angle 116
Figure 7.6 Diagram to illustrate the definition of the trunk segmental angle 116
Figure 7.7 A typical graphical representation of the sit-to-stand-to-sit movements of subject A 119
Figure 7.8 A typical graphical representation of the sit-to-stand-to-sit movements of subject B 120
Figure 7.9 A typical graphical representation of the sit-to-stand-to-sit movements of subject C 121
Figure 7.10 Graph of hip flexion and extension produced during five repetitive trials of the sit-to-stand task carried out by subject A 122
Figure 7.11 Graph of hip flexion during five repetitive trials of the stand-to-sit task carried out by subject A 123
Figure 7.12 Graph of knee extension during five repetitive trials of the sit-to-stand task carried out by subject A 123
Figure 7.13 Graph of knee flexion during five repetitive trials of the stand-to-sit task carried out by subject A 124
Figure 7.14 Graph of head extension during five repetitive trials of the sit-to-stand task carried out by subject A 125
Figure 7.15 Graph of head extension during five repetitive trials of the stand-to-sit task carried out by subject A 125
Figure 8.1 Coding written in the SWORDS program to manipulate the geometric entities representing a chair seat 134
Figure 8.2 Diagram of chair graphically represented using the constraint based modeller SWORDS 135

Figure 8.3 Example of external measurements encoded in SWORDS, taken from female subject 137
Figure 8.4 External body points incorporated into computer manikin in SWORDS 138
Figure 8.5 Rules that constrained the manikin to a sitting posture on the chair modelled in SWORDS 140
Figure 8.6 Video frame of sitting posture carried out by subject A in Chapter 7 and manikin representation of subject A constrained to the sitting posture using constraint rules and variables defined in Table 8.1 143
Figure 8.7 Video frame of 'subject A' during maximum hip flexion that occurred during sit-to-stand trail, carried out in Chapter 7, and manikin representation of 'subject A' using constraint rules and variables defined in Table 8.4 148
Figure 8.8 Modification of the rules applied to attain maximum hip flexion 149
Figure 8.9 Video frame of 'subject A' attaining maximum ankle dorsiflexion during sit-to-stand trail carried out in Chapter 7, and manikin representation of 'subject A' using constraint rules and variables defined in Table 8.4 152
Figure 8.10 Video frame of 'subject A' attaining erect stance during sit-to-stand trial carried out in Chapter 5, and manikin representation of 'subject A' using constraint rules and variables defined in Table 8.5 154
Figure 9.1 The proposed design methodology 162
Figure 9.2 Common movement strategy employed by able-bodied and subjects with osteoarthritis 164
Figure 9.3 Movement strategy employed by subject F with osteoarthritis 164
Figure 9.4 The 'Arran' spring operated lifted seat used for observational analysis 166
Figure 9.5 The 'Grimstead Easy Stand' device used for observational analysis 166
Figure 9.6 Movement strategy employed when using 'Grimstead easy stand' 167
Figure 9.7 Graphical illustration of segmental angles produced by able-bodied subject 'A' during stand-to-sit movement 175
Figure 9.8 Graphical illustration of segmental angles produced by able-bodied subject 'D' during stand-to-sit movement 176
Figure 9.9 Graphical illustration of segmental angles produced by able-bodied subject 'E' during stand-to-sit movement 177

Figure 9.10 Graphical illustration of segmental angles produced by able-bodied subject 'F' during stand-to-sit movement 178
Figure 9.11 Video frame of 'subject D' during sitting posture that occurred during stand-to-sit trail and manikin representation of 'subject D' using constraint rules and variables defined in section 7.3.1 180
Figure 9.12 Video frame of 'subject D' during maximum hip flexion that occurred during stand-to-sit trail and manikin representation of 'subject D' using constraint rules and variables defined in section 7.3.2 182
Figure 9.13 Video frame of 'subject D' attaining erect stance during stand-to-sit trial, and manikin representation of 'subject D' using constraint rules and variables defined in section 6.3 184
Figure 9.14 140% of popliteal height (49.1cm), feet placement 4.5cm in front of seat 187
Figure 9.15 160% of popliteal height (562mm), feet placement 45mm in front of seat 188
Figure 9.16 160% of popliteal height (562mm), feet placement 4.5cm in front of seat, rotation of front seat 40° 189
Figure 9.17 175% of popliteal height (61.4cm), feet placement 4.5cm in front of seat, rotation of front seat 40° 190
Figure 9.18 175% of popliteal height (61.4cm), feet placement directly under front of seat, rotation of front seat 40° 191
Figure 9.19 75% of popliteal height (61.4cm), feet placement directly under front of seat, rotation of front seat 30° from the horizontal 192
Figure 9.20 Recliner, with additional lower leg rest to enable relaxation 193
Figure 9.21 Final chair design 193
Figure 9.22 General assembly drawing of prototype 197
Figure 9.23 Prototype made for experimental validation of conceptual design 198
Figure 9.24 Video picture frame of subject E able to employ able-bodied strategy while using prototype 200
Figure 9.25 Graphical representation of able-bodied subject 'A' during stand-to-sit movement using prototype 202
Figure 9.26 Graphical representation of able-bodied subject 'D' during stand-to-sit movement using prototype 203

Figure 9.27 Graphical representation of able-bodied subject 'E' during stand-to-sit movement using prototype 204
Figure 9.28 Graphical representation of able-bodied subject 'F' during stand-to-sit movement using prototype 205
Figure 9.29 Video picture frame of subject D and corresponding manikin representative during the initial sitting posture using the prototype 208
Figure 9.30 Video picture frame of subject A and corresponding manikin representative during the initial sitting posture using the prototype 208
Figure 9.31 Video picture frame of subject D and corresponding manikin representative during the intermediate posture of maximum hip flexion using prototype 211
Figure 9.32 Video picture frame of subject A and corresponding manikin representative during the intermediate posture of maximum hip flexion using the prototype 211
Figure 9.33 Video picture frame of subject D and corresponding manikin representative during erect stance using prototype developed 213
Figure 9.34 Video picture frame of subject A and corresponding manikin representative during erect stance using the prototype developed 213

List of Tables

Table 2.1 Summary of strengths and limitations of the design processes reviewed 30

Table 7.1 The mean and ranges of the maximum segmental angles of the experimental analysis of five trials carried out by subjects rising from a chair, compared to similar studies reported in literature 129

Table 7.2 The mean and ranges of the maximum segmental angles of the experimental analysis of five trials carried out by subjects reclining onto a chair 129

Table 7.3 The order and mean percentage of time taken for each subject to attain maximal flexion and extension of body segments that define the movement phases when rising from, standing and reclining onto a chair 130

Table 8.1 Excel spreadsheet containing the rules and variables invoked to constrain the manikin to a sitting posture 142

Table 8.2 Segmental angles (mean values shown in bold) of the five trials carried out by subject A when rising from a chair 144

Table 8.3 Description of rules used to transform the manikin into maximum hip flexion after the sitting posture was obtained 146

Table 8.4 Excel spreadsheet containing rules and variables used to invoke the manikin into maximum hip flexion 148

Table 8.5 Excel spreadsheet of constraint rules and variables used to simulate maximum ankle dorsiflexion 151

Table 8.6 Excel spreadsheet of constraint rules and variables used for erect stance 153

Table 8.7 Results of segmental angles determined in SWORDS (shown in bold) and experimental study during the sitting posture (mean and ranges given) 155

Table 8.8 Results of segmental angles determined in SWORDS (using subject specific rules) and experimental study during maximum hip flexion (mean and ranges given) 156

Table 8.9 Results of segmental angles determined in SWORDS (using generic rules) and experimental study during maximum hip flexion (mean and ranges given) 157

Table 8.10 Results of segmental angles determined by SWORDS (using initial rules) and experimental study during maximum ankle dorsiflexion (mean and ranges given) 158

Table 8.11 Results of segmental angles determined by SWORDS (using modified rules) and experimental study during maximum ankle dorsiflexion (mean and ranges given) 159

Table 8.12 Results of segmental angles determined by SWORDS and experimental study during the erect stance (mean and ranges given) 160
Table 9.1 User attributes 163
Table 9.2 User joint range of motion measured before discomfort was experienced 169
Table 9.3 Joint range of motion of subjects measured during the STS movement shown in bold 174
Table 9.4 Results of segmental angles determined in SWORDS and experimental study during the sitting posture (mean and ranges given) 181
Table 9.5 Results of segmental angles determined in SWORDS (using generic rules) and experimental study during maximum hip flexion (mean and ranges given) 183
Table 9.6 Results of segmental angles determined by SWORDS and experimental study during the erect stance (mean and ranges given) 185
Table 9.7 Segmental angles measured in SWORDS during iterative development of conceptual design,whilst mimicking subject D undertaking the maximum hip posture 194
Table 9.8 Preferred seat height of prototype and corresponding % of popliteal height 199
Table 9.9 Results of segmental angles determined in SWORDS and experimental study during the sitting posture (mean and ranges given) 206
Table 9.10 Results of the hip and knee flexion found using the manikin model, shown as a * percentage outside the range of the actual hip and knee flexion measured 207
Table 9.11 Comparisons of the average reduction in hip and knee flexion found using the manikin and the actual flexion measured 207
Table 9.12 Results of segmental angles determined in SWORDS and experimental study during maximum hip flexion (mean and ranges given) 209
Table 9.13 Results of the hip and knee flexion found using the manikin model, shown as a * percentage outside the range of the actual hip and knee flexion measured 210
Table 9.14 Comparisons of the average reduction in hip and knee flexion found using the manikin and the actual flexion measured 210
Table 9.15 Results of segmental angles determined in SWORDS and experimental study during erect stance (mean and ranges given) 212

Chapter 1 Introduction

1.1 Introduction

Design methodologies are created to form a strategy to enable the design of technical systems. They describe plans of action to be linked into working steps and design phases formulated to achieve goals and to solve design problems. A typical example of these phases would begin with understanding and defining the customer needs. This would be formulated into a design specification of user requirements, along with any design constraints such as the cost of the end product or a manufacturing process that has to be used. The design specification would be used to create a concept design. If the concept design is acceptable then detail drawings and instructions for manufacture are completed before the product is made.

Design methodologies show various emphases, which tend, according to Pahl and Beitz (1996), to be influenced by the area in which the author has specialised. Andreason (1987), for example, has made significant contribution to design for assembly. Conversely, Pugh (1990) has developed a 'total design' process where emphasis was placed upon the product design specification and multi-disciplinary teamwork. These are some of the internationally recognised methodologies that are renowned for their contribution to engineering, but have considered to various degrees the human usability of the end product.

French (1985) and Medland and Mullineux (1989), for example, did not mention the need to design for the user requirements. In contrast Pugh (1990) recognised that ergonomics should be incorporated into the design specification phase and that it impinges on the whole of the design process. Pahl and Beitz (1996) have described in more detail the need to design for the various physiological and psychological abilities of the user, but as with many other design methodologies, they do not provide a method or strategy to enable these ergonomic considerations to be met.

Socio political legislation has placed more emphasis and responsibility upon the designer to design products suitable for people with a disability. The Disability Discrimination Act 1995 and the 'rights of access' that came into force in October 1999 and 2004, have placed the responsibility upon designers to creatively overcome the shortfalls of the environment with appropriate solutions for people with disabilities. Investigators such as Orpwood (1990) have created design methodologies that focus upon understanding the individual needs of the disabled user early in the design process. Keates and Clarkson (2001) have incorporated many existing design and ergonomic techniques to analyse the sensory, cognitive and motor capabilities of the user and validate these capabilities with respect to the design being created. The focus of Keates and Clarkson (2001) was to also design for as large a population of people with various capabilities. However, they did recognise that there are severely impaired users where a 'special purpose design' would be more suitable and therefore their approach would not always be appropriate.

Globally there is an ever expanding population of ageing people with an increasing life expectancy (WHO (2004) and Norris and Wilson (1999)), and also a substantial group of people with physical disabilities who desire to remain independent within their own home. Some of these people are able to employ movement patterns that are similar to those commonly used by able-bodied people (Turner, 2002). Occupational therapists (OT) and physiotherapists encourage these people to continue using these normal movement patterns as it is anecdotally considered as being the most functionally efficient. Where this is not possible compensatory techniques or the use of an assistive device are sought. When an assistive device is used normal movement patterns are still encouraged as it is again considered the most functionally efficient. The people who require a device to maintain reasonable mobility would like, according to Green and Jordan (1999), to carry out their daily tasks in a normal manner and often discard products that attract unwanted attention. This observation is supported by Trombly (2001) and The Disability Discrimination Act 1995 that advocate that assistive devices should remain transparent in they do 'not call attention to the person as being disabled or reveal the extent of the disability'. It could be said that if assistive devices are designed to include other family members and able-bodied people who generally use normal movement patterns, a user would be more likely to accept a device because the majority accepts it. It is therefore important that devices are designed to enhance functional performance and provide the opportunity for people to carry out movement tasks in a normal manner if desired.

Design methodologies such as those as Orpwood (1990) and Keates and Clarkson (2001) are very useful in understanding and designing for the needs of people with varying capabilities. However, they do not focus upon and provide methods to enable people to continue using common patterns of movement that they have routinely employed throughout their lives. Also, as with many of the methodologies reviewed in Chapter 2, Orpwood (1990) and Keates and Clarkson (2001) employ experimental techniques to evaluate and understand the needs of the user. This could prove to be time consuming and costly due to the high level of subject involvement, as well as being tiring for the user, especially if there were many design iterations, in the form of prototypes, that would need to be evaluated.

There are a variety of ergonomic software packages commercially available that decrease the need for subject involvement. They allow designers to evaluate their designs for the users ability to fit into, see, reach, and physically manipulate various objects (Porter et al, 1994). Although these packages provide a useful tool when evaluating a conceptual design, they often require a geometrical representation of the design to be well defined before an evaluation can realistically take place. This approach, therefore, does not necessary take the mobility problems of the user into consideration before and during the initial development of the conceptual design.

In summary, a review of well known design methodologies in Chapter 2 has found that they do not provide detailed methods or strategies to aid designers in creating devices that enable people with physical disabilities, to continue using similar movement patterns commonly employed by able-bodied people. Also, a review of existing computer human models has found that designers are not able use a manikin representative to aid the creation of a device in the very early conceptual design phase. This is because the evaluation of a conceptual design using a human manikin initially requires detailed drawings to make a prototype of the design, to enable the movements of a human user to be measured and then mimicked using the manikin. This is before an evaluation of the conceptual design can be carried out. Thus the geometry of a conceptual design has to be well defined, which is more likely at the latter stage of the concept design phase, before it can be evaluated using a human manikin. This could prove to be both costly and time consuming if a conceptual design proves to be unsuitable and the process has to be iterated until a solution is found.

This research project has focused on the creation of a design methodology to enable the design of devices that improves the mobility of people with physical disabilities. The aim was to enhance the current functional performance, while at the same time enabling people to continue using normal movement strategies that they have used all their lives. This methodology has been based upon an investigation of natural human movement determined experimentally, and the mimicking of this movement using a computer manikin. Its aim was to reduce the time and cost of a new design through the development of a computer manikin during the early stages of the conceptual design phase.

1.2 Project aims and objectives

The aim of this research project was to create a design methodology to aid in the design of products to improve the mobility of older people and people with physical disabilities. This methodology was aimed at enhancing the current functional performance of people that were able to carry out movement patterns similar to those normally employed by able-bodied people.

The design methodology was created to focus specifically on the pre-conceptual and conceptual design phases. It was created to improve the mobility of people with physical disabilities who wish to continue using similar movement patterns as those commonly used by able-bodied people. This meant that emphasis was given to the functional design rather than the aesthetic design, even though it is recognised that the appearance of a device is an important consideration in user acceptance. The proposed design methodology was also focused on designing for a small number of individuals rather than a large population size. The objectives required to achieve the aims described above are as follows:

- To review existing design methodologies and processes published in the literature for their strengths, and limitations in the context of the aims of this project (Chapter 2).
- To present a design methodology aimed at improving the mobility of older people and with physical disabilities. To enable movement patterns similar to those commonly used by able-bodied people (Chapter 3).
- To review how stability is defined in the literature (Chapter 4).
- To review how stability is mechanically, mathematically and experimentally determined. This is to establish a method to be used to calculate stability of the human manikin model (Chapter 4).
- To review the distinct movement strategies commonly employed by able-bodied people when rising from a sitting posture (Chapter 5).

- To review the comparisons made between the movement strategies employed by able bodied people, older people and people with physical disabilities, when rising from a sitting posture (Chapter 5).
- To understand the effect of the variance of chair design upon the movement strategies that older people and people with disabilities may employ (Chapter 5).
- To review experimental techniques employed to define the sit-to-stand movement (Chapter 5).
- To review the computer manikin models employed to simulate human movement (Chapter 6).
- To determine and describe the model that will be used for this research project (Chapter 6).
- To carry out an experimental study to determine the movement patterns employed by able-bodied people when rising from and declining into a sitting posture (Chapter 7).
- To determine the consistency of the movement patterns employed during the experimental study previously carried out (Chapter 7).
- To compare these findings with experimental results published in the literature (Chapter 7).
- To replicate the movement patterns determined from the experimental study carried out in the chapter 7, employing the computer human model chosen in chapter 6 (Chapter 8).
- To compare these results with both the findings in the literature, described in section 5.1, and the experimental results detailed in chapter 7 (Chapter 8).
- To carry out a case study to validate the proposed design methodology used in designing a chair. This aim of this case study was to improve the mobility of a group of subjects with osteoarthritis and to enable them to use similar movement patterns to those employed by able-bodied people (Chapter 9).
- To discuss the objectives carried out to enable the aims of this research project (Chapter 10).
- To discuss the strengths and limitations of this research project (Chapter 10).

- To describe the further work that could be undertaken from the findings of this research (Chapter 10).

Chapter 2
Design Processes

2.0 Introduction

This review of the literature has initially provided a brief description of established design processes that are later reviewed for their approach towards improving the mobility of users. This was undertaken with the view of enabling the ageing population and people with physical disabilities to gain optimum function while continuing to use normal movement patterns. Finally, conclusions are presented at the end of this chapter.

2.1 Existing design processes

There were numerous descriptive theories and models that have been developed to understand, describe and prescribe how the design process should be carried out. Many of which are procedural. The core of sequential phases that were mainly aimed at defining and understanding the customer needs and creating an abstract concept to suit these needs. This was in turn refined into detailed drawings and instructions for manufacture.

2.1.1 Description of existing design processes

Pahl and Beitz (1996) presented a design process model, shown in Figure 2.1, which consisted of four phases, where emphasis was on developing the concept design. These phases are the planning and clarifying the task, conceptual design, embodiment design and detail design which were carried out sequentially. In general, the 'planning' stage involved the generation of product ideas based upon the market, the company and the economy, and the 'clarifying the task' was the collation of information about the product's requirements and existing constraints. This phase involved the development of a specification document listing the product requirements. The 'conceptual design' phase of developing an abstract solution was then carried out and evaluated against the requirements specified. The following 'embodiment design' phase involved a firming up of the conceptual ideas into a layout design, where the function, durability, production and economic viability can be analysed. Finally, the 'detailed design' phase laid down all the criteria required for production, such as individual part dimensioned drawings and production costs.

British standard BS 7000 Part: 2 (1997) published a guide to managing the design of manufactured products that was based up on the design process developed by Pahl and Beitz (1996), referred to above. This standard defined a model of the design process, as shown in Figure 2.2, which outlined the sequential phases that, as the authors of this guide suggested, were 'usually iterative' and 'where possible should be performed in parallel', to reduce costs and time scales. The model was initiated by, what was termed, a concept phase and even went onto consider the disposal of the product at a final 'termination' phase. Each sequential phase within this model, depicted the actions that should be undertaken and their expected outputs. The initial 'concept phase' involved the realisation, evaluation and preliminary research of design alternatives generated from the market, the customer or new technologies. The 'feasibility phase' considered the requirements and constraints upon the design such as performance, cost and time scales. These considerations form a design brief, which was used as a guideline during the following phases. The following 'design development' phase was when the design team undertakes the development of the concept design and the 'implementation' phase was when the detailing of individual components, the design for manufacture and literature, and the construction and testing of prototypes takes place. The following 'manufacturing phase' required the purchasing of tools and premises, for the production of the design, which also included the product launch and sales. It was during this phase that feedback for future design modifications and new product ideas were suggested. The final phase involved the decommissioning of the activities where the product was withdrawn and the spare parts and maintenance considerations would be carried out.

The German standard VDI2221 (1973), entitled 'Systematic approach to the Design of Technical Systems and Products' was also based on the design process developed by Pahl and Beitz (1996). It suggested a procedural approach that was separated into seven separate stages where each has an output (see Figure 2.3). Stage 1 of this process involved defining the task requested by the customer or the product-planning department. The outcome of this stage was a 'specification' of requirements list that was reviewed throughout the design process. This approach differed from Pahl and Beitz (1996) in that the model guides the designer to separate the design solution in sub-functions to be solved and if possible, modularised to save costs. The second stage diagrammatically determined both the overall and sub- 'functions' that the design has to fulfil. The third stage required a search for solutions to these functions. Stage 4 determined the basic geometric shapes of the design, which can be modularised to establish familiar parts. Stage 5 involved the 'layout' of the geometric models main dimensions, assemblies and material choice, and the following stage 6 resulted in the 'definitive' layout of more detailed dimensions. Stage 7 produced final detailed drawings for production and operating instructions.

Hubka et al (1988) also developed a procedural design model, shown in Figure 2.4 that consists of six stages, similar to the German standard VDI2221 previously mentioned. The initial stage developed the 'problem statement' into a list of requirements that formed the design specification. Stage 2 involved the diagrammatic, hierarchical structure of functional abstract solutions. Stage 3 produced a sketch of the intended conceptual design that was developed into a layout sketch in stage 4, with rough drawings. Stage 5 involved both optimisation and evaluation of the design and the dimensional layout. Stage 6 finalised the detailed dimensions for production.

French (1985) produced a model of the design process that emphasised the importance of the conceptual design phase and the initial analysis of the design problem. The conceptual phase, according to French (1985), placed the greatest demands on the designer, where the greatest design improvements and the most important decisions were made. The model, shown in Figure 2.5, shows a flow diagram where the circles represent 'the stages reached' and the rectangles represent 'the work in progress'. The 'work in progress' phases of this model followed a similar pattern described by other authors previously mentioned in this section. The 'Analysis of the problem' was a statement of the design problem, the limitation and requirements of the design, and cost limitations which provided guidelines for the inclusion or exclusion of design features that were fed back during the conceptual design phase. During the 'embodiment phase', after the 'conceptual design' phase, the final choice of conceptual design was made, where the outcome of this phase was to produce a general engineering drawing. Finally, the 'detail design' phase involved more detailed refinement of the component design.

Pugh (1990) developed a 'core design' activity model, shown in Figure 2.6, that was initiated and led by the 'market' research of customer needs, and also incorporated an additional marketing 'sell' activity phase at the end of the process. The final 'sell' marketing activity involved distribution and providing an after service to the customer, as well as feeding back vital product information to the initial market research phase for the next generation of products. The initial 'market' research phase of customer needs formed a 'product design specification'. The 'product design specification' (PDS) was used to form the design boundaries of the subsequent 'concept design', 'detail design' and design for 'manufacture' phases and continually evolved to encompass the changes to the product which occurred at each phase that it interacted. Even though these design phases were sequential, Pugh (1990) stated that any of these phases could be reiterated at any stage of the design process.

Hales' (1993) cyclic design process model, depicted in Figure 2.7, showed greater emphasis on understanding how environmental issues and customer marketing needs relate to the company, management, the project, the design and production. This model showed, for example, how the environment, depicted as 'cultural, social and scientific' may influence the product or how, if the product was not suitable for customer needs, the economy of the company would be affected. The core 'design activity' however was similar to the four phase sequential model developed by Pahl and Beitz (1996). This consists of the 'Task clarification' phase that forms the design specification, the 'conceptual design' phase which involved the development of conceptual designs, the 'embodiment design' phase that produced the final layout of the design and the 'detail design' phase where every component was 'dimensionally fixed'. The output from this final stage in the design activity stage produced information for the production of the design.

Andreasen and Hein (1987) advocated the 'integrated product development' (IPD) model that was based up on the initial recognition of a need and was focused on combining three elements, i.e. market, product and production throughout the design process, as shown in Figure 2.8. These elements were described by Andreasen (1987) as recognition and creation of a market and sales, the creation of a product to satisfy the market, and a production system to produce the product. These elements were developed in parallel through 0-5 phases shown in Figure 2.9. The output from the first phase was marketing, defining the need, the product and process type. The output from the second phase was the clarification of the product use, the principle of the design and the production required for realisation. The third stage was a feasibility of the working product, the size of the market and the production process, as well as the product cost. The fourth phase was a demonstration that the product was of good quality and that the production and sales systems have been set up. The final phase was where the product was produced and sold.

Medland and Mullineux (1989) alternatively presented a model of the design process, based upon problem solving using constraint based techniques, as shown in Figure 2.10. This approached the design process in a more iterative and interactive manner. The six primary activities were described as concept, scheming, analysis, manufacture, evaluation and control, where the concept formed a closely linked loop with the scheming and analysis functions. The analysis of a product, for example, may need to be carried out through calculations before geometric scheming can take place or alternatively a concept design may need to be schemed before an analysis is carried out. The control function enabled the evaluation and the manufacturing requirements to be both regulated and modified. This scheme advocated developing a design from any stage within the design process depending on the company and the type of product being developed.

Medland and Mullineux (1989) also classified the type of product as being either technically over constrained or under constrained. An over constrained product is one that was highly technical, such as an aeroplane, where emphasis was placed upon the analysis of variable design proposals to find a solution. An under constrained product could be one of three types. One type evolved around the development of conceptual ideas to satisfy the market, similar to many of the design processes previously described, where far more effort was based upon developing schemes e.g. prototypes, that dictate the manufacturing process employed. Another under constrained type evolved around utilising the manufacturing skills of a company, where the main concern was centred on supplying a product to others, irrespective of the type and purpose of the product. The final under constrained type was when the design process was focused on scheming or the refinement of a product to reduce costs, for a competitive market, for example. This process in terms of recognising the effect of the market or the manufacturing process on the product is similar to Hales (1993).

Orpwood (1990) recognised the problems that occur from using the general systematic approach when designing aids for people with a disability. The emphasis was thus focused on the development of a product for the human user. Orpwood (1990) stated that even though the users functional needs may be well documented in the design specification, the designer may still develop a design that is not suitable for the user with a disability. This was because the 'human interface requirements were unfamiliar unless the designer happens to suffer from the same disability that was being studied'. Orpwood (1990) thus proposed a design methodology, shown in Figure 2.11 that involved building a prototype of the design features that interfaced with the human user, with a disability, and iteratively developed these features through observational and subjective studies that ran in parallel to the development of the conceptual design. Once a satisfactory solution was found the standard systematic design approach could be followed to develop the supporting features of the design, such as replacing a manual drive mechanism with a motor.

The 'design for all' is a general approach to design in which designers endeavour to enable their products and services to address the needs of the largest population of users irrespective of their age or ability. There are some well-defined principles and definitions of this ethos, rather than design processes, known as 'universal design' in America, as described by Keates and Clarkson (2001). Whereas in Europe, methods such as the 'user pyramid approach', again described by these authors, have been developed to understand the full range of users abilities and the effects their age and disabilities have on carrying out daily tasks. There are however very few structured descriptions of how this 'design for all' approach can be implemented into a design process, as stated by Keates and Clarkson (2001)

Keates and Clarkson (2001) provided a systematic structured approach that analysed the interaction with the interface of the design, as well as the usability of the design. This seven level approach was continually verified throughout each level, as shown in Figure 2.12. These levels were separated into three phases that initially defined the problem, which defined the user requirements and specifies the user needs. A solution was then developed. This initially involved analysing the sensory understanding of information given by the interface of the design, by the user. This was followed by the analysis of the cognitive ability of the user to decide on a course of action. Finally, an analysis of the implementation of a response was carried out, in the form of the investigation of the motor capabilities of the user. The last stages of this design process were to evaluate the solution in respect to the design being created. This was done by incorporating existing design and ergonomic techniques to evaluate the whole of the design, through user trials, and usability and accessibility assessments. The final evaluation was to assess the solution against the user needs through interviews, surveys and questionnaires. Even though the aim of Keates and Clarkson (2001) was to design for as large a population of people with varying capabilities as possible. They do however, recognise that there are severely impaired users where a 'special purpose design' would be more suitable and therefore their approach would not be appropriate.

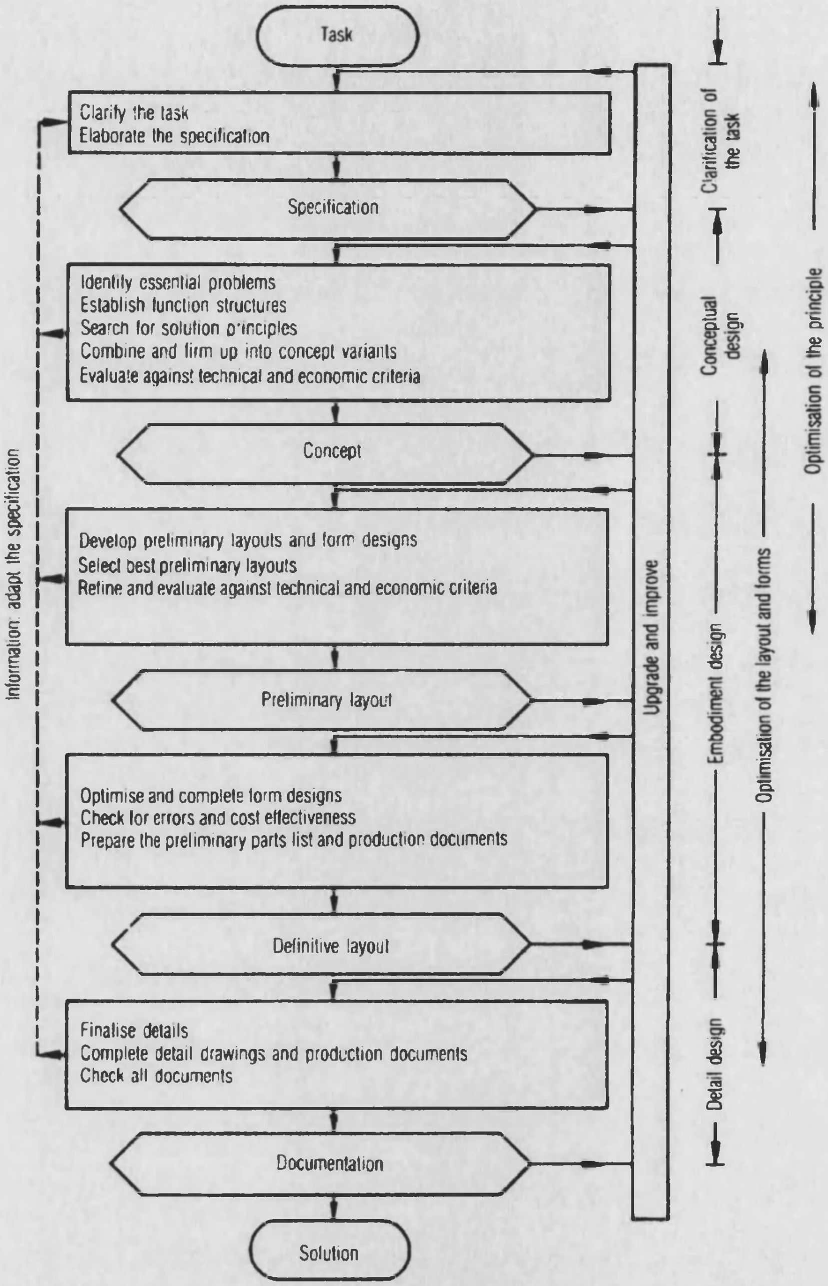


Figure 2.1 Design process model developed by Pahl and Beitz (1996)

Phase of project	Process	Output
		Internal to the organization
Concept phase	Inception of a new or improved product Analysis of opportunities	Perceived opportunities Alternative business and product concepts
	Formation of individual or core team	
	Analysis of business concepts and product identification	Identification and selection of preferred business concept and product characteristics
	Formulation of the project, objectives and strategies	Preliminary definition and project proposal
	Preliminary evaluation and approval of the project by the corporate body	Permission to proceed
Feasibility phase	Planning, research and feasibility studies leading to the formulation of a project proposal	Criteria of acceptability to organization
	Refinement of characteristics. Development of a functional specification	Product design brief
	Development of project configuration and work programme	Project plan. Resource plan
	Evaluation and sanctioning of project by corporate body and commitment of resources	Project approval
Design/development stage	Bringing together of a multi-disciplinary team of specialists to realize the project	Roles and responsibility matrix
	Design concept development. 'Rehearsing' the customer-product experience	Preferred option
	Outline design (embodiment design or general arrangement)	Product resolution
Implementation (or realization) phase	Detailed design	Specification for product
	Construction and testing of pre-production design	Confirmation of performance including reliability and maintainability
	Finalization of the completed design ready for manufacture.	Product package
Manufacturing stage	Design support for manufacture. Provisions for manufacture and delivery	
Liability starts		*External to the organization*
	Product launch, introduction, promotion, and on-going customer support	Product availability
	Selling and use	Fulfilment of business objectives and customer requirements
	Monitoring 'in-use' performance for feedback and refining the design as necessary. On-going product testing	Potential improvement Product enhancements, modification and retrofits
	Evaluation of the whole project and identification of areas of improvement in the design management process for the benefit of future projects	Identified design process improvements
Termination phase	Termination of the project	
	Design support for decommissioning activities. Formal termination of the project	Handover of responsibilities and redeployment of staff
	Disposal of the product	Continuing liability

Figure 2. Model of the design process for manufactured products

Figure 2.2 Design process described in BS7000 Part 2 (1997)

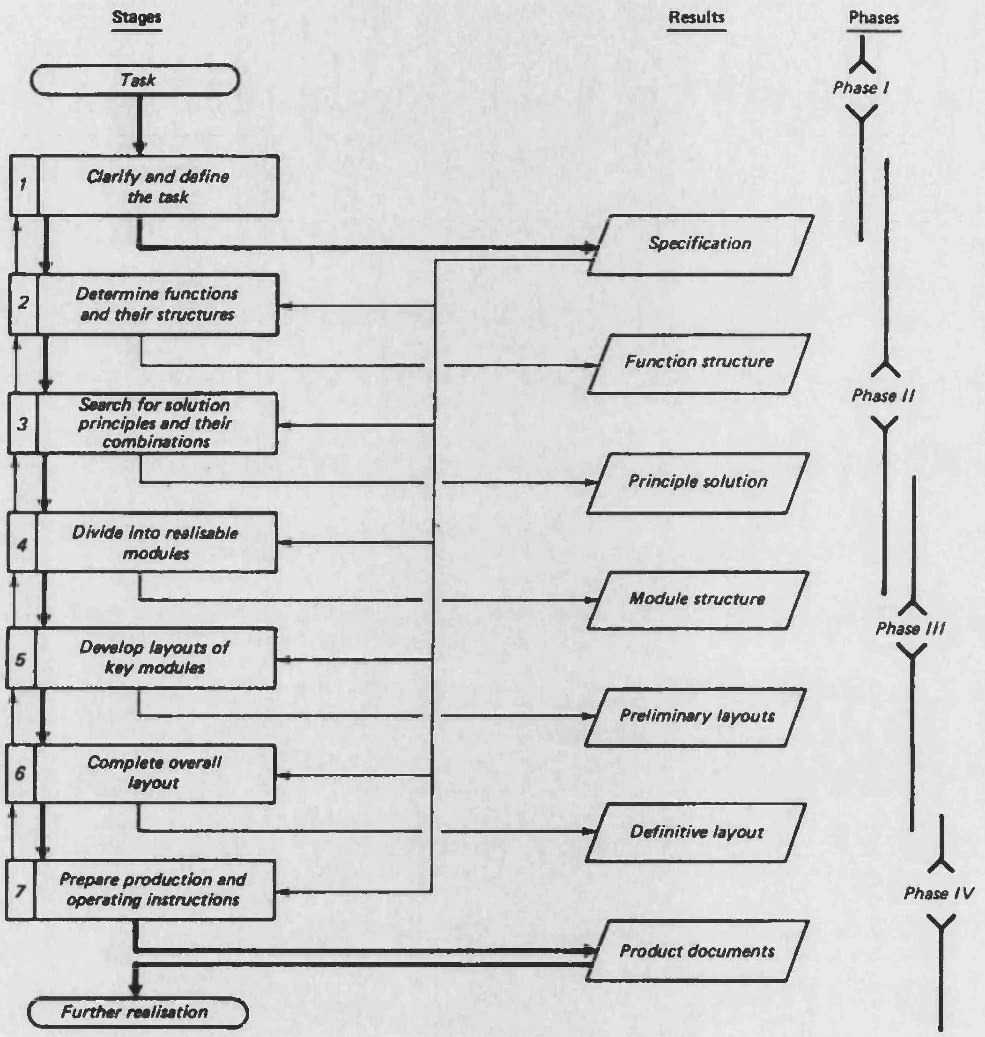


Figure 2.3 Design process model described in German standard VDI 2221

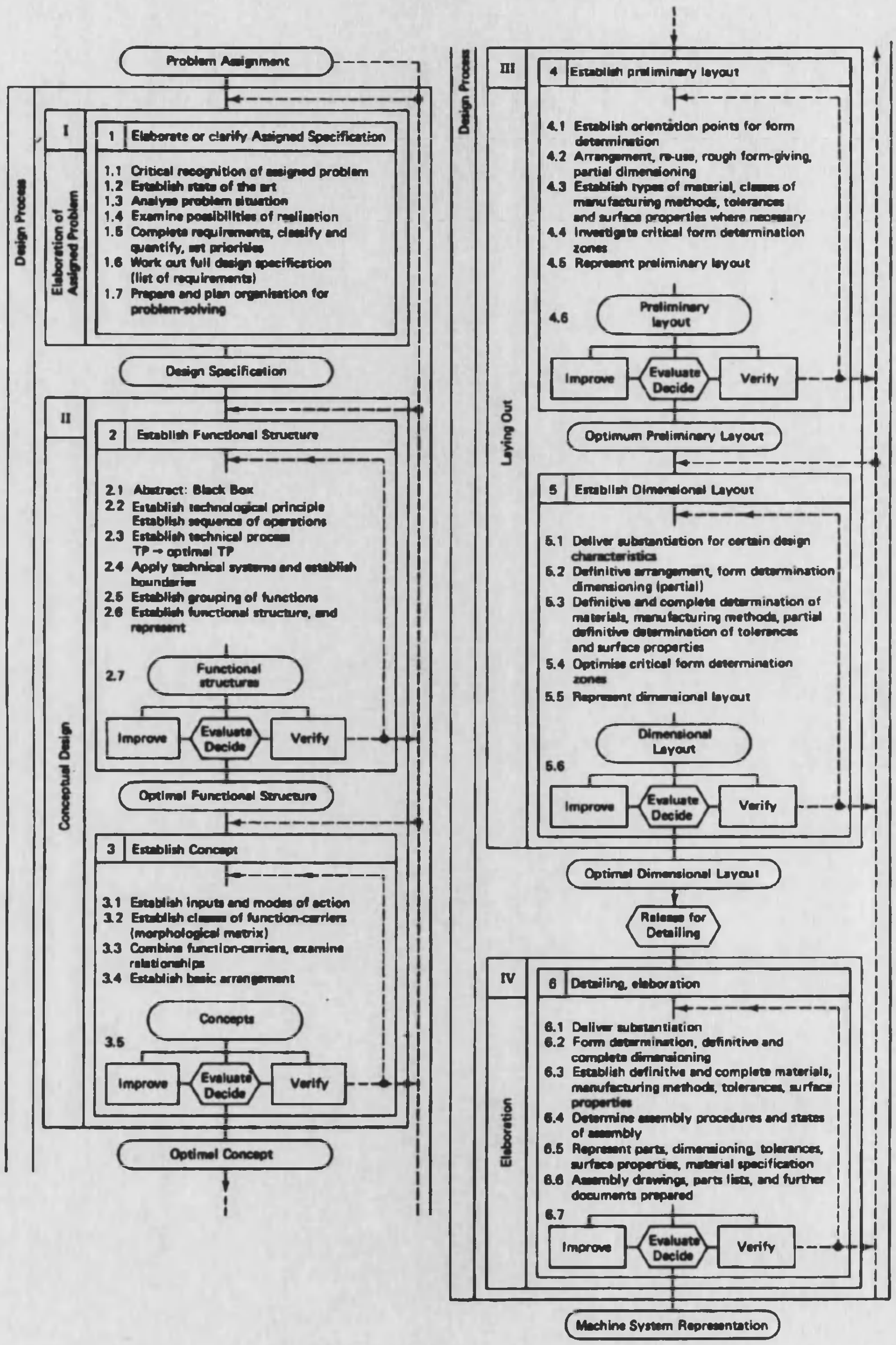


Figure 2.4 Design process model developed by Hubka et al (1988)

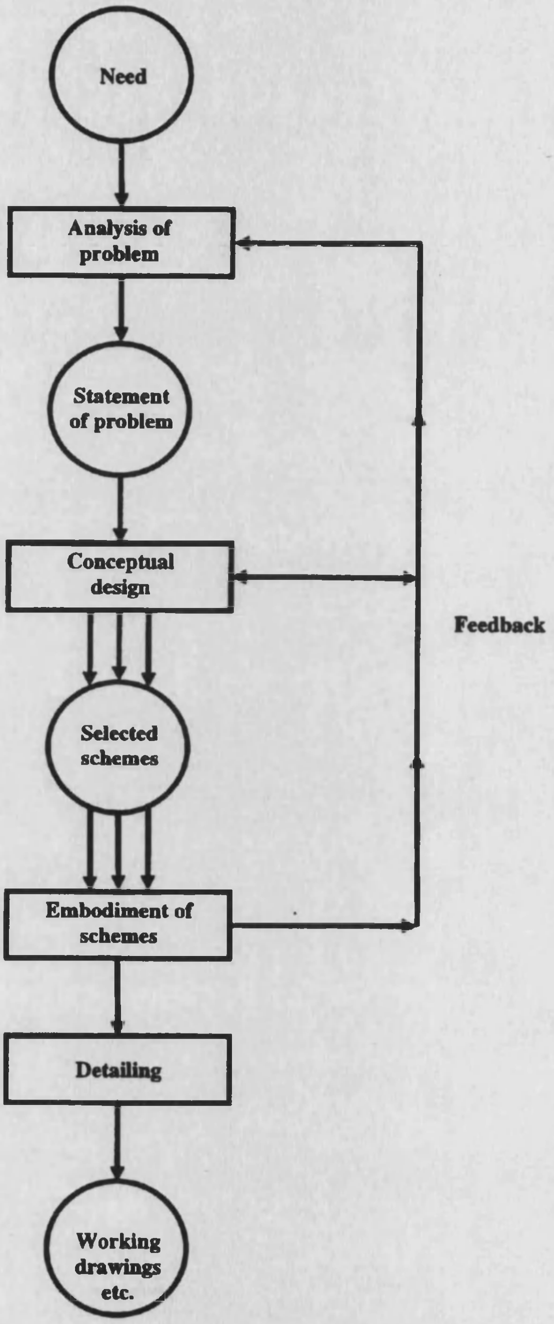


Figure 2.5 Design process model developed by French (1985)

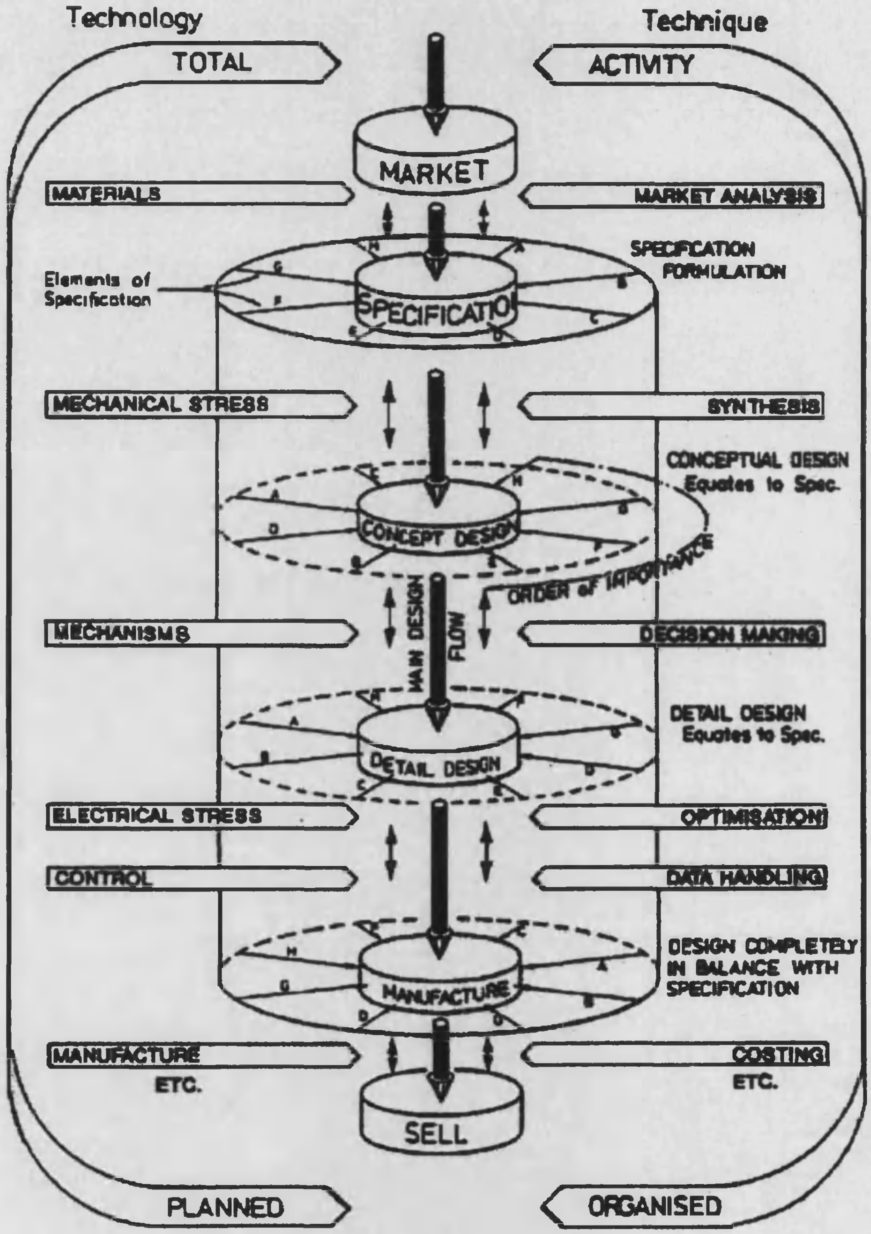


Figure 2.6 Design process model developed by Pugh (1990)

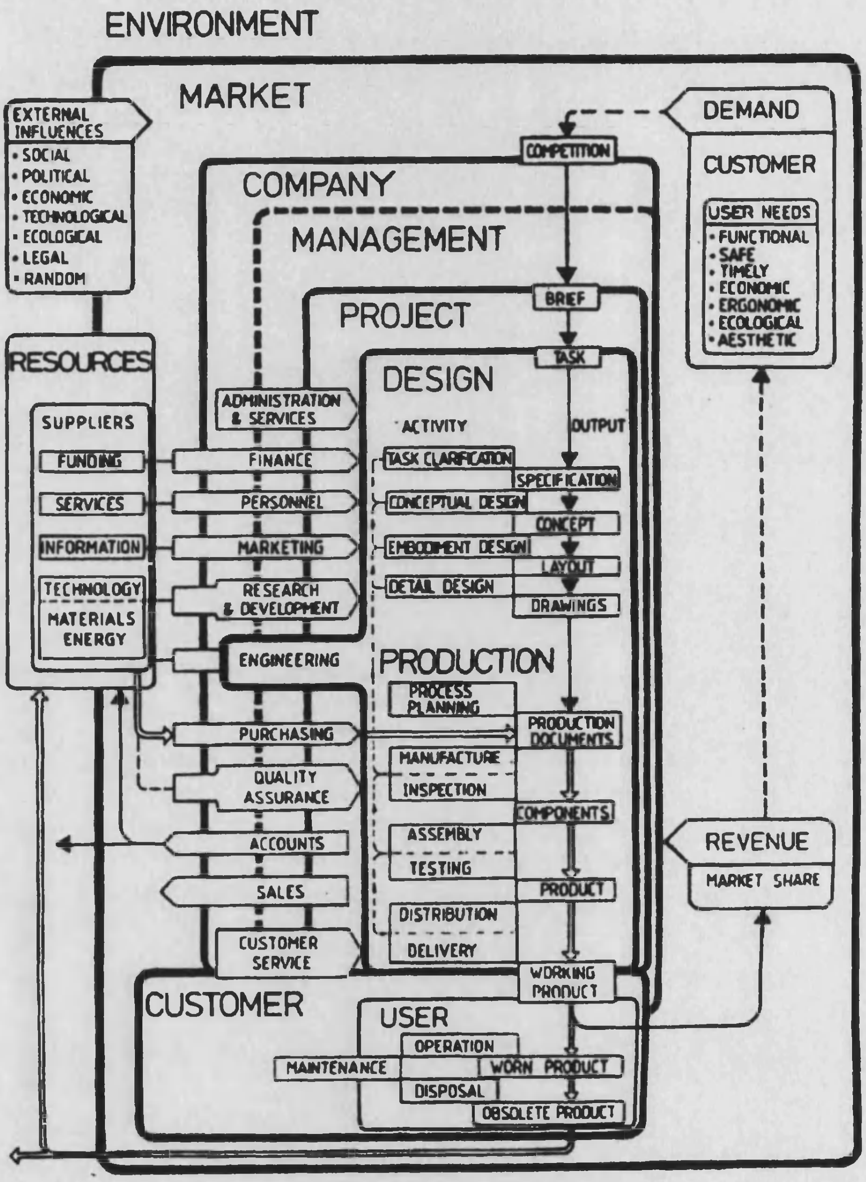


Figure 2.7 Design process model developed by Hales (1993)

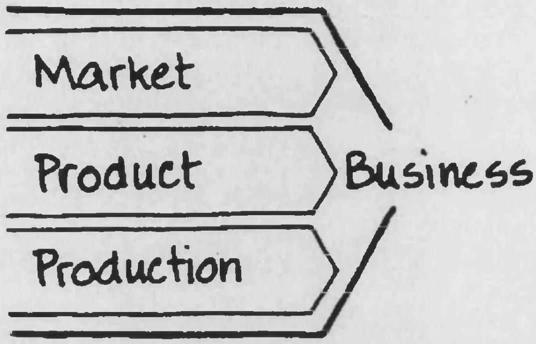


Figure 2.8 The combination of the three elements of marketing, product and production throughout the design process as described by Andreasen and Hein (1987)

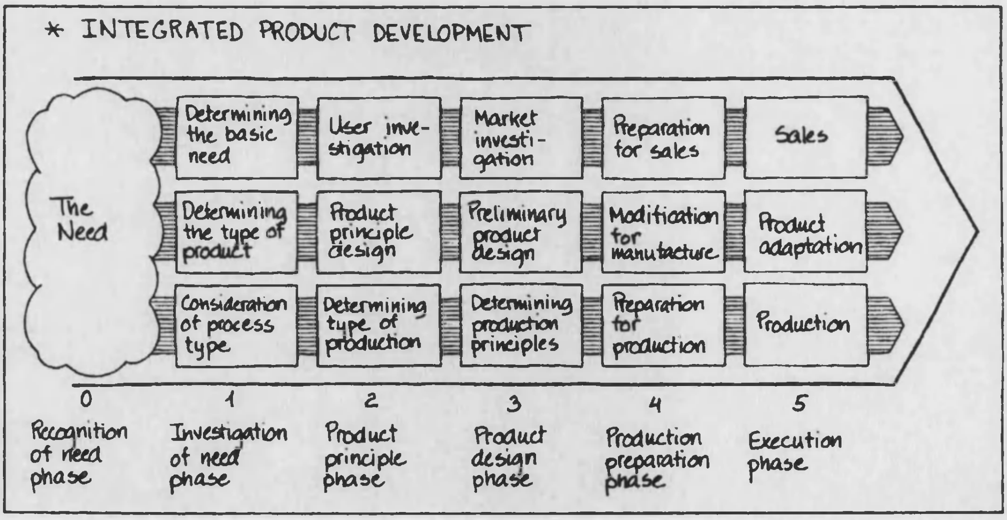


Figure 2.9 A design process model created by Andreasen and Hein (1987)

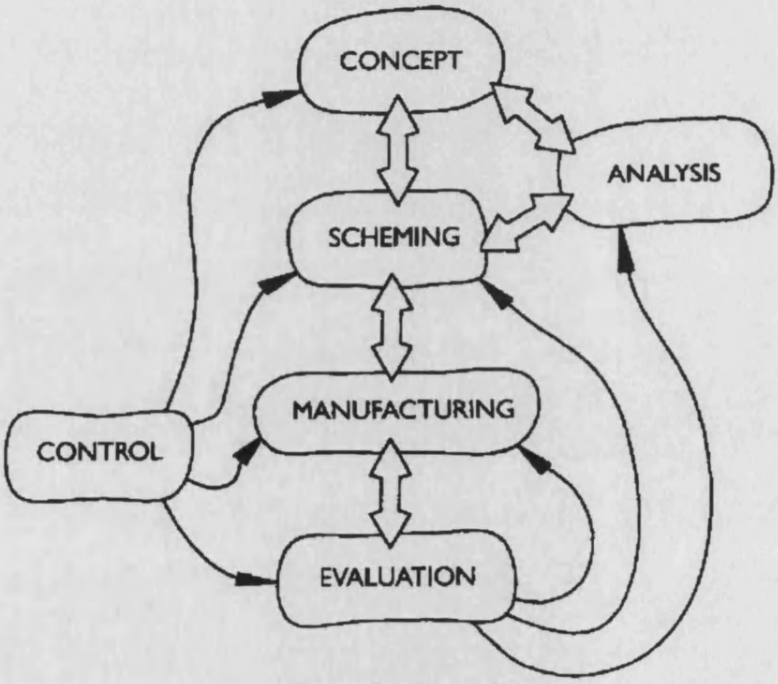


Figure 2.10 Design process model developed by Medland and Mullineux (1989)

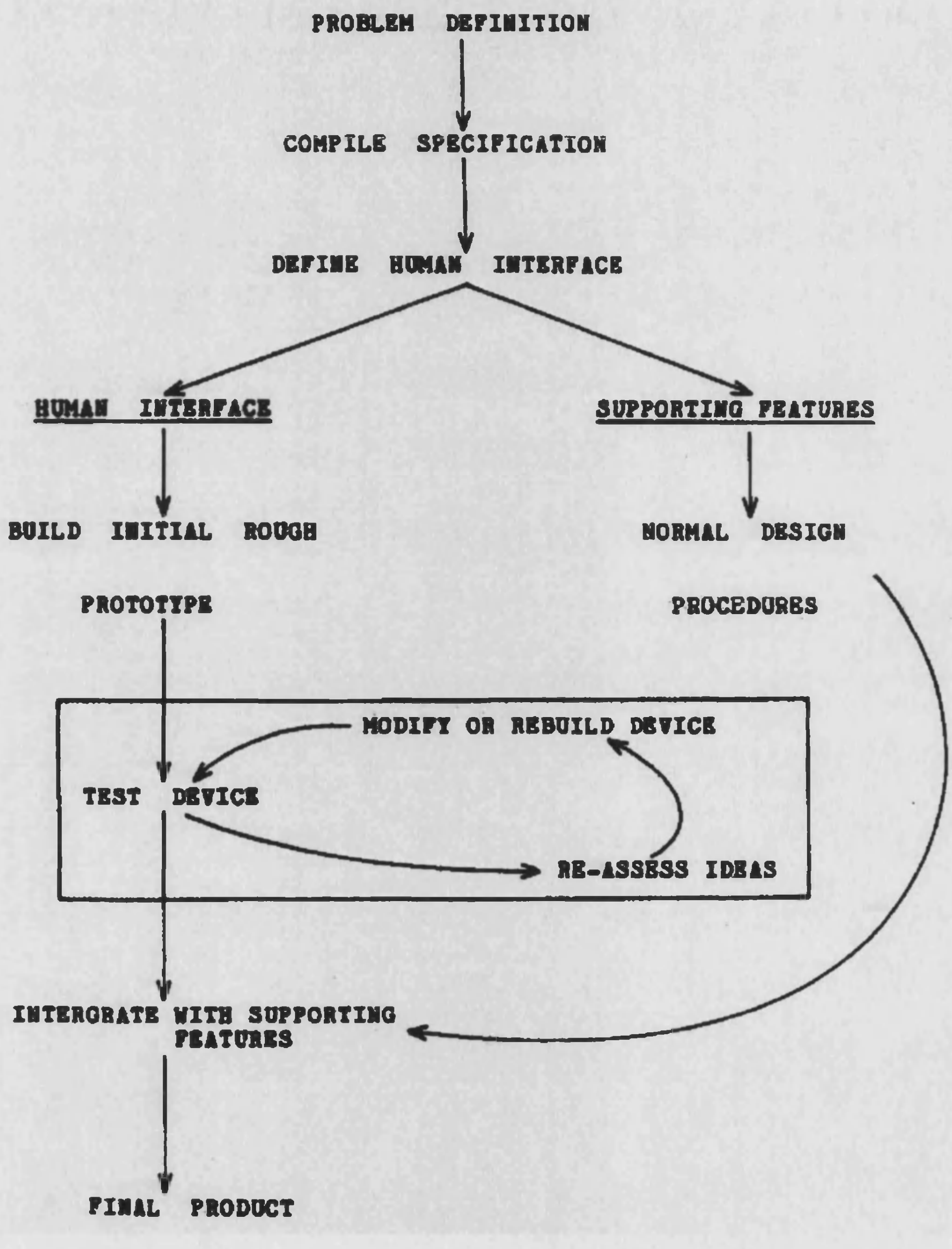


Figure 2.11 Design process model developed by Orpwood (1990)

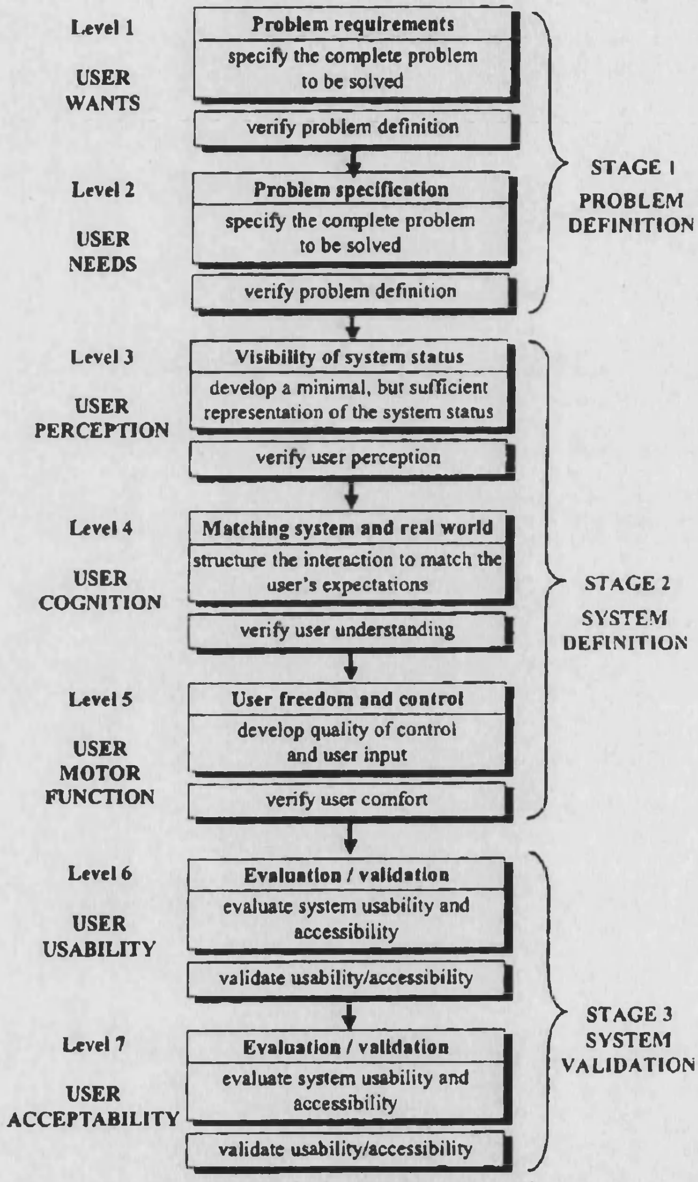


Figure 2. The 7-level design approach.

Figure 2.12 Design model provided by Keates and Clarkson (2001)

2.2 Contribution of design processes towards the project aims

The following section discusses the contribution of the design processes previously described towards the aims of this research project:

Pahl and Beitz (1996) recognised the need to 'carefully' plan for the functional involvement of humans as early on in the design process as the initial stage of 'clarifying the task'. They also mentioned that the requirements of a product, collated from the initial stage, should determine its function during the conceptual stage of its development. However, the emphasis in terms of evaluation of the human interaction with the product, was placed at the later embodiment phase, after the conceptual design phase. This could prove to be both time consuming and costly if the functional needs of a user with a possible impairment are not met at this later stage of the design process. Pahl and Beitz (1996) did discuss the need to consider the 'body postures and movements resulting from the operation and use of technical products'. This was undertaken from the perspective of loads, stresses and fatigue that the muscles of a user may experience. They did not, however, prescribe how to design a technical product to enable older people or people with a physical disability, to continue using normal movement strategies similarly employed by able-bodied people.

The British Standard BS7000 Part 2 (1997) provided a list of factors to consider when formulating a design brief. One of these factors included 'ergonomics' when considering the 'performance requirements' of the product. There are no prescription provided as to how the 'performance requirements' were to be made through out the design process provided and no other reference made towards human movement considerations, throughout this document in particular.

The German standard VDI2221 (1973) document did recognise the 'increasing important role of ergonomics' in the design of products incorporating semi-conductor technology, in particular. It also recognised that the importance or repetitive evaluation and testing of products when designing for the mass market. However, no further reference to human movement considerations was made.

Hubka et al (1988) acknowledged the need to satisfy human needs throughout the design process and that 'specialists' should evaluate the ergonomic aspect of the design during the later stage 5 of the design process. However, the use of specialists to evaluate the design may prevent the designer being involved with any user trials. This would, as stated by Orpwood (1990), exclude them from experiencing the problems of people with a physical disability, in particular, first hand and thus preventing 'crucial design modifications being made through second hand information' being provided.

French (1985) did not make any specific reference to analysing, designing or evaluating the human interaction with the product, throughout the design process proposed.

Pugh (1990) advocated that the product specification document (PDS) incorporated the needs of the customer gained from market research and, although evolving, forms the boundaries of the subsequent design phases. This document consisted of many 'elements' of information applicable to the product, that are case dependant. One of these elements, defined as 'ergonomics' is, according to Pugh (1990), where the 'interaction of the product with the man' was considered. Pugh (1990) suggested that, the ergonomics 'element' should consider human posture and operating torques, and stated that 'devices must be a delight to use', and that 'potential users must be consulted'. However, Pugh (1990) did not prescribe how these considerations were to be carried out.

Hales (1993) design approach would be useful in recognising the external issues that may have an impact upon the design of a product, such as the 'social political' impact on a design. This recognition may possibly encourage designers to design appropriate devices for people with disabilities. This approach would also aid the designer in being aware of the political influences such as the Disability Discrimination Act 1995, which requires that all businesses and organisations that provide goods and services to be accessible to all persons irrespective of their disability.

The core 'design activity' phases, described by Hales (1993) however, were similar to the four phase sequential model developed by Pahl and Beitz (1996), that prescribed the use of checklists and worksheets throughout each phase. The checklist was a list of questions to be asked by the design manager about the product, and the worksheet is an evaluation of negative or positive influences on the project. Hales (1993) described examples of these stages, which do consider human interaction. The initial design specification checklist defined the requirements of the product and considers the 'comfort and operational needs' of the user. The 'conceptual design checklist' was a further review of the quality of the conceptual design, where the 'types of user' and different users of the product, including the 'conditions of use, misuse and difficulties incurred by the user' need to be considered. An example of a checklist during the 'embodiment design phase' was also provided where 'the ease of use' of the conceptual design is questioned. Finally, the 'functional performance' and 'suggested improvements' are considered during the last detailed design phase. These 'points to consider' could lead to a better quality product, in terms of the ergonomic and user functional needs, however, Hales (1993) did not prescribe a method in which the functional needs and problems of the user can be understood or provide a design method to overcome them. The need to improve the optimal functional of the disabled user, to carry out tasks in a normal manner, where possible, was not mentioned.

Andreasen and Hein (1987) design process model was based upon the initial recognition of a need created by a market, which proceeds in parallel with the design and production elements, to clarify the product use. Even when the recognition of the need were for the user to carry out a daily task in a normal manner, this approach did not provide any guidelines to enable the designer to analyse, understand and create a solution to improve the mobility of the user.

Medland and Mullineux (1989) interactive and iterative approach would allow the constraints imposed by the movements of the user to dictate the conceptual design, scheming, and hence the analysis required of such a product until a satisfactory design was sought. Medland and Mullineux (1989) did not however mention how to design, analyse or scheme for the functional requirements of the user.

Orpwood (1990) provided a methododology that, when compared to the previous design processes described, was possibly more suitable when creating appropriate design solutions, rather than being aimed at providing commercial success. It was based upon the experiences of designing for people with physical disabilities. It was, however, focused upon modifying the design interface to suit the individual, rather than designing the device to improve mobility by enabling the individual to move in a manner utilised by able-bodied people.

Keates and Clarkson's (2001) 'design for all' approach endeavours to ensure that the potential user's psychological and physiological needs were understood, considered and evaluated throughout the whole of the design process. It would be possible, when using this method, to realise the user needs which could be to carry out a specific task using a similar normal movement strategy, used by able-bodied people. Also to develop a prototype through the experimental observations and evaluations proposed to improve mobility. However, repetitive validations during the conceptual design phase, through the use of prototypes, may prove to be both time consuming and costly, considering the many different anthropomorphic and psychological variables of the subjects that would need to be involved. Also this approach did not specifically guide the designer towards how they may design for the possible shortcomings of the physical capabilities of the user to enable them to use movement strategies similar to those commonly used able-bodied people.
The following table 2.1 summarises the strengths and limitations of the design processes previously reviewed.

Author	Strengths	Limitations
Pahl and Beitz (1996)	Procedural approach, with emphasis on concept design stage. Plan for functional involvement of humans before concept design stage.	Evaluation of human interaction with product was after concept design phase, which could prove costly and time consuming if re-design was required at this later stage.
British Standard BS7000 Part 2 (1997)	Procedural approach based on Pahl and Beitz (1996). Stated that ergonomics was a performance requirement of product.	No prescription of how ergonomics could be integrated into the design process.
German Standard VDI2221 (1973)	Procedural model, recognised importance of role of ergonomics in design of products, as well as testing and evaluation for mass market.	No prescription of how role of ergonomics can be integrated into design process
Hubka et al (1988)	Procedural model similar to VDI2221 (1973). Advocated that specialists should evaluate ergonomics of product after conceptual design stage.	Evaluation of human interaction with product was after concept design phase, could prove costly and time consuming if re-design was required at this later stage.
French (1985)	Procedural approach focused on conceptual design.	No mention of analysing, designing or evaluating product for human user.

Table 2.1 Summary of strengths and limitations of the design processes reviewed

Author	Strengths	Limitations
Pugh (1990)	Sequential model that could be reiterated at any stage of design process. Use of product design specification (PDS) continually evolved to form specification of product through out design process. Ergonomics was one of the PDS considerations.	Did not suggest how the user needs and ergonomics considerations could be made and incorporated into the design process.
Hales (1993)	Cyclic design model. Emphasis on social political and cultural impact on company and design. Considers comfort and operational needs of users.	Did not prescribe how the functional needs and problems of users could be understood and overcome.
Andreasen and Hein (1987)	Integrated product development (IPD) model, where market, product and production are developed in parallel throughout the design process.	Did not mention how to analyse, understand or create a solution to take user needs and problems into consideration.
Medland and Mullineux (1989)	A non-procedural iterative approach. Could be useful when the user imposes usability constraints.	Did not mention human user considerations or how to analyse, design or manufacture for them.

Table 2.1 (continued) Summary of strengths and limitations of the design processes reviewed

Author	Strengths	Limitations
Orpwood (1990)	Focused on the individual needs of the user with a physical disability	Focus was on design interface rather than improving mobility of user by gaining optimum function while carrying out normal movements
Keates and Clarkson (2001)	Design for all approach considers physiological and psychological needs and evaluates users interaction throughout design process.	Extensive user interaction may be time consuming and costly. Also did not mention how to design for optimum function of user to enable normal movement.

Table 2.1 (continued) Summary of strengths and limitations of the design processes reviewed

2.3 Conclusions

Many of the authors of the published literature described in this chapter have recognised the need to satisfy the functional and physiological requirements of the user, throughout various phases of the design process to varying degrees. They do not, however, prescribe a well-structured procedure to enable them to understand and create a device to enable potential users to employ or improve their mobility by continuing to use normal movement strategies, similarly used by able-bodied people. The effect of this could result in the designer creating a device that would force the user into using a movement strategy that they would not commonly use.

It is thus proposed that the analysis of the common movement strategies employed by able-bodied people and by the user group, with a physical disability, be incorporated into a design methodology, before the conceptual design stage. This will enable the designer to understand the similarities and the shortcomings of the physical capabilities of the potential user compared to able-bodied people.

Reiterative subject involvement to validate conceptual prototypes may prove to be both time consuming and costly. It is thus also proposed that the movement strategies of both groups be mimicked by a computer human model, through the understanding gained through the analysis of the movement strategies used. This could enable the designer to simultaneously develop a conceptual design to enable optimal function at the very beginning of the conceptual design and thus possibly prevent costly and time-consuming redesigns.

Chapter 3
Proposed design procedures for human mobility aids

3.0 Introduction

The review carried out in the previous chapter has shown that the majority of design processes acknowledged the need to focus upon the functional needs of the user. Many of them, however, did not provide detailed strategies to enable the designer to understand and create products that consider the needs and difficulties experienced by the older people and people with physical difficulties. Some design processes, however, such as those of Keates and Clarkson (2001) and Orpwood (1990), did show the need to consider the needs of people with functional movement difficulties, through observations and evaluation of the intended design. However they did not provide detailed strategies to enable designers to create products that enable people to carry out daily activities in a normal manner.

It was proposed, in section 1.1, that the use of a computer human manikin be employed during the conceptual design phases to reduce the time and cost of making prototypes and re-testing of designs through subject involvement. This chapter thus describes a design methodology to aid the creation of mobility aids that enable people to move in a manner similarly employed by able-bodied people.

3.1 Brief description of proposed design procedures

The proposed design procedures were intended specifically for designers to create appropriate devices to aid the mobility of people that may have a physical disability. It was also intended for those who wish to employ the movement strategies similarly used by able-bodied people when undertaking a functional task.

The design procedures proposed were similar to those reviewed in Chapter 2, in that the user requirements, a design specification, conceptual design, embodiment and manufacturing phases were sequentially and reiteratively carried out. The emphasis of this approach, however, was placed upon the conceptual design phase where the creation of a design solution was focused on analysing, understanding and creating a prototype design using a manikin representative.

This design methodology initially defined the problems and the user needs when carrying out a given task, through observational and subjective studies of both young able-bodied people and the potential user group using existing designs. This information should be used to develop a product specification document of user requirements. If the movement strategies of both groups are found to be similar, during these initial observations a kinematic experimental study should be carried out to analyse and compare their similarities and differences in further detail.

It was proposed that the movement strategies of the potential user group are studied and then mimicked using a computer manikin representative. This is to reduce the time consuming task of evaluating prototypes of possible conceptual design solutions with subject involvement. The manikin can then be employed to develop a conceptual design. This phase involves iteratively evaluating the concept design as it is being created, using the manikin mimicking the natural movement strategy employed by the users. This should aid the designer in creating a device that will support normal movements instead of unintentionally forcing the user into employing compensatory movement strategies. When a design solution is found that enables the computer manikin representatives to carry out a given task using normal movement patterns. A prototype of the concept design can then be made to enable experimental validations to be carried out. If the validation of the concept design proves to be beneficial to the user, when compared to the original experimental studies, the detailed embodiment design phase can be carried out. If the design proves to be ineffectual, the procedure should be re-iterated until a satisfactory solution is found, before proceeding to the embodiment and manufacturing phases. The main contribution therefore of this research project are the design phases contained within the grey shaded box presented in Figure 3.1, which are explained in further detail in the following sections.

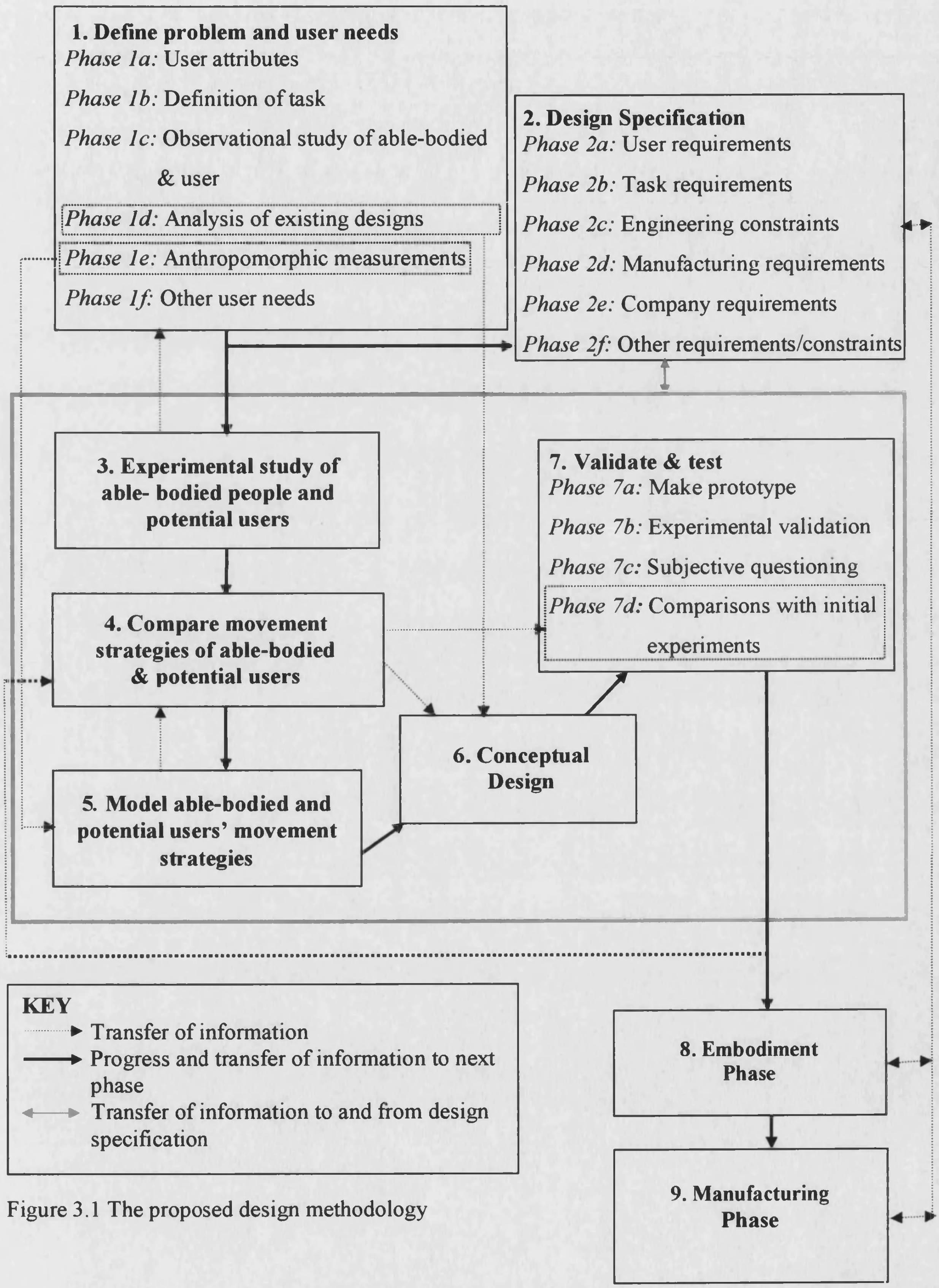


Figure 3.1 The proposed design methodology

3.2 Detailed description of proposed design procedures

The following sections provide a detailed description of the proposed design methodology previously shown in Figure 3.1. It was the intention of this methodology to enable designers to create mobility aids for the elderly and people with physical disabilities that wish to move in a similar manner to those normally used by able-bodied people when undertaking a specific task. Therefore emphasis was given to the functional requirements, abilities and limitations of the user. It was recognised, however, that these procedures are not inexhaustible and should therefore be employed as a foundation to be built upon, through the use of other methods or tools, where appropriate. The term 'potential user' solely refers to persons who experiences a physical difficulty in carrying out a given task and would benefit from the use of a mobility device, such as older people and people with a physical disability.

3.3 Phase 1 **Define problem and user needs**

The initial design phase, of the proposed methodology, is similar to the preliminary phase of many other design processes reviewed in Chapter 2. It was aimed at defining the needs of the user and their problems experienced when a specific movement task is undertaken whilst using existing designs. Unlike other design processes this initial stage is also used to ascertain whether potential users are able and wish to move using a similar pattern commonly employed by the able-bodied. This information is used to define the user requirements of the design, as part of the design specification document in the following phase 2. It is also used to understand and prepare for the experimental study in phase 3. The following sections describe these initial procedures, contained within phase 1, in more detail:

3.3.1 *Phase 1a* **User attributes**

The collation of the users attributes are concerned with the information required to understand the physical needs of the user of the design. This initially relates to general information such as total body weight, age and the physical problems and limitations associated with their functional abilities. More specific anthropomorhic measurements are taken, in *phase 1c*, after an observational study of the subjects' movements have taken place. This is carried out in this particular order to prevent the unnecessary measurements being taken to find that potential user is not able or does not wish to carry out movements in a similar natural manner employed by able-bodied people. This information is used to define the user requirements in *phase 2a.*

It was considered more useful to study the actual users for which the design is intended. This will enable a more accurate analysis of the movement strategies and a better understanding of an individual's limitations due to a possible physical disability. If this is not possible, then representatives of the potential user group's anthropomorphic sizes, age range and physical disabilities can be employed.

3.3.2 *Phase 1b* Definition of the task

A definition of the task initially requires a general description of body movements, such as using the right hand to reach and retrieve an object placed at a particular height on a shelf. This description will become more defined when the initial observations of the user takes place in the following *phase 1c*, and then become more specific when a more subscribed experimental study has taken place in *phase 3*. These descriptions should be continuously updated and used to define the requirements of the task within the design specification document, shown in *phase 2b*.

3.3.3 *Phase 1c* Observational study of able-bodied people and the user

This initial observational study should include young healthy able-bodied people carrying out exactly the same task using the same devices as the potential users. Comparisons of potential users with able-bodied people carrying out the same task will enable the designer to initially understand both the movement strategies commonly employed by able-bodied people, as well as the functional problems experienced by the potential user.

It is important to note that if the potential user group with a physical disability are, for example, obese, pregnant, or older, the able bodied group should incorporate people who are similarly matched. This is to enable the designer to ascertain where a difficulty carrying out a task is due to a physical disability or is related to possible restricted movements due to, for example, pregnancy, obesity or age.

Video recordings of the study group performing the task should be carried out using the artefacts commonly employed by both the user and able-bodied people. If the artefact commonly used by the potential user group is non-standard, observations of both the user and able-bodied subjects should include these artefacts and, where possible, the artefacts commonly used by able-bodied people. This will aid the designer in understanding whether mobility problems experienced by the user are caused by the design of an artefact or their physical disability.

The user and the able-bodied group should perform the movement task in a manner that they would commonly use. The subjects should understand the task required for them to perform, but not be forced into using movement strategies that they would not naturally use. The video recorder should be placed perpendicular to the plane of motion of the subject, ensuring that that all the subject's body movements are with in the range of view of the camera. During this study it is important to subjectively question and simultaneously audio record the comfort and the degree of mobility experienced by the user and the able bodied group. This will enable later observations to be made.

If the movement strategies employed by both groups are not in essence the same, the knowledge gained by the designer should be highly beneficial in directing them towards a more radical conceptual design approach, that would be entirely specific and tuned to the user group and their particular movement strategy. The basis of this research project, and the proposed design methodology, is to design devices specifically for older people with mobility problems and people with a physical disability to employ the similar movement strategies as those commonly used by able-bodied people. Therefore, if the movement strategies of both groups are found to be generally comparable then this observational study can then continue to the following *phase 1d* that analyses existing designs.

3.3.4 *Phase 1d* Analysis of existing designs

This extension of the latter observational analysis was aimed at providing an understanding of the advantages and limitations of existing designs and should enable the designer to either improve or modify the positive aspects of a device. This should also help them avoid badly designed attributes in their own design solution created during the conceptual *phase 6*. This is undertaken in accordance to the previous described procedures in *phase 1c*, where both potential user and able-bodied people are observed using video analysis, and subjectively questioned upon their comfort and degree of mobility while using the devices. This is to be used to formulate part of the design specification regarding the user and task requirements, in *phases 2a and 2b*, respectively

3.3.5 *Phase 1e* Anthropomorphic measurements

If the movement strategies employed by the potential users are found to be similar to the able-bodied people, anthropometric measurements should be carried out. Measurements of the segmental lengths, external body size and joint range of motion are essential in enabling manikin representatives of the user group to be created in *phase 5*. These measurements are also used to evaluate whether a person can fit, reach and be capable of attaining specific postures and movements during the conceptual design *phase 6*.

The decision whether the design is intended for a mass market or a specific group of people will reflect on the anthropomorphic data used. If the device is intended for a mass market then the outer body sizes, segmental lengths and range of joint motion should reflect the percentile ranges of the age, genders and nationalities of people that will potentially use the device. Otherwise individual measurements can be taken if the device is being developed for a small known user group. This research project is limited to the design of devices for specific individuals therefore the latter will apply. The following sections will discuss individual measurements of the potential user group.

3.3.6 *Phase 1e* Segmental lengths

Measurements of all the segmental body lengths of the potential users should be taken using manual goniometers. Descriptions of how they are determined can be found in section 8.2.2. All segmental measurements are to be assigned to their corresponding link lengths for each individual subject represented by the manikin model, as described in Chapter 6.6.

3.3.7 *Phase 1e* External body measurements

Measurements of the appropriate external body parts should be taken using anthropometers. The measurements required depend upon the mobility aid being developed. In the case of a chair, for example, it is imperative that the width of the buttocks be measured when the person is measured in a sitting posture as well as standing erect. However, if the mobility aid were only to be used when ambulating, this measurement would not be necessary. (For a more comprehensive example of how these measurements are made and incorporated into the representation of the computer manikin see section 8.2.2).

3.3.8 *Phase 1e* Measurement of joint angular rotation

The joint range of motion should be measured in accordance to a method well known to clinicians, such as the Cave and Roberts Neutral Zero method as described by Heck et al (1965). Only the rotational movements of each body segment about the primary plane of interest are required. Once taken the joint angular rotation measurements can then be later input into the individual corresponding file related to the computer manikin. This will be used to limit the rotation of the geometric entities representing each body segment and thus emulate the joint range of motion of each individual subject. (Again, for a more comprehensive example of how these measurements are made and incorporated into the representation of the computer manikin see sections 8.2.2).

3.3.9 *Phase 1f* Other user needs

This phase enables the designer to find out if there are any other user problems, needs or requirements that the previous phases may not have established. This may include the function, cost or appearance that they wish the device created, to have.

3.4 Phase 2 Design Specification

The design specification phase involves the development of a control document aimed at specifying the design solution to be achieved through the understanding of all the requirements of the design. It is commonly used in the majority of design processes, as previously described in Chapter 2. The design specification document is meant to continually evolve through information gained from each phase of the design procedures proposed. The double headed, grey shaded arrow shown on the design model in Figure 3.1 represents this exchange of information. The design specification document should also constrain the design solution to ensure that the user, engineering and manufacturing, for example, requirements are met. The information described in the following sections is again not exhaustible and therefore should be extended where applicable. This information is also only applicable where it describes a specific requirement of the design.

3.4.1 *Phase 2a* User requirements

- Attributes of the subject applicable to the design only e.g. maximum weight of user
- Description of physical limitations of the potential user
- Environment where the device is used
- Attributes of device normally found in context of environment used:

This should describe features of a device that would normally be used in a given environment. Seating devices normally used within a kitchen environment, for example, such as a barstool or a table chair, would have certain design features. The features of the barstool would normally be a seat that is higher than average (e.g. more than 44 cm) incorporating a footrest, with the optional addition of a backrest and armrests. Whereas, the normal features of a table chair could be described as having an average seat height and would include a backrest with optional armrests.

- Comfort requirements
- Attributes of artefacts that to be incorporated or discarded in the design solution, from analysis of existing devices
- Safety requirements
- Cost constraints
- Other requirements

3.4.2 *Phase 2b* Task requirements

- Definition of the task
- Definition of movement strategy employed when carrying out task
- Problems experienced while carrying out task

3.4.3 *Phase 2c* Engineering constraints

This is any restriction on the design solution by the influences such as, standard components that are available, the current state of technology or design standards.

3.4.4 *Phase 2d* Manufacturing requirements

This involves any requirements of the design to use a specific manufacturing process or conversely the constraints on the design by the manufacturing process available. This information is has a two-way flow of information between the manufacturing *phase 9*.

3.4.5 *Phase 2e* Company requirements

This research was focused on the development of a device to suit specific functional needs of the user and has therefore not considered the many external elements that can effect a design. The 'company requirements' however encompasses any requirements of the design by marketing, the social and cultural needs of the external environment and of the company.

3.4.6 *Phase 2f* Other requirements/constraints

These are any other requirements or constraints put on the design such as material choice, aesthetics, standards or other functional needs of the device, for example, the need for the design to be collapsible.

The safety, cost constraints, material, aesthetics and other functional requirements should be ascertained through subjective questioning of the user, the experience of the designer and comparisons made with similar products, which involves both the marketing and manufacturing disciplines. These considerations are not exhaustible. The design specification should also incorporate many other aspects, mentioned in the PDS described by Pugh (1994), pertaining to the design such as patents, life cycle expectancy and disposal.

3.5 Phase 3 Experimental study of able-bodied people and potential users

The aim of the experimental study is to observe, measure, analyse and define the movement strategies employed by both young healthy able-bodied people and the potential user group. It requires a more rigorous study of the subjects, which involves slightly constraining their movements. This enables the identification of the common intermediate postures and subtle differences between strategies employed by both groups. This experimental and observational phase should also provide a more thorough understanding of the users mobility requirements, when comparisons of movements are made between the two groups during *phase 4*.

3.5.1 The subject group

This study should be carried out using the same able-bodied people, and the potential user group observed in the initial stage of this design procedure, for which the device is to be made. As stated earlier, this will enable a more accurate analysis of the movement strategies and a better understanding of an individual's physical limitations. If this is not possible, appropriate representatives of the potential user group's nationalities, sizes, age range and physical disabilities should be used. Again, as explained in *phase 1c*, it is important to note that if the potential user group with a physical disability are, for example, obese, pregnant, or elderly, the able bodied group should incorporate people who have the same disposition.

3.5.2 External artefacts

If the task being analysed involves the use of an external artefact, it is recommended that the artefact is one that is considered standard and commonly used by the majority of the user and able-bodied groups. This will ensure both familiarity and minimise the effect on the movement strategies of the user.

3.5.3 Explanation of the task

The movement task that each subject is expected to carry out, during the experimental analysis, must be explicitly explained so that each individual fully understands the task required to be undertaken. This approach can impinge on the natural movements that a person would use. However, if the subjects are not provided with instructions then it is sometimes difficult to make comparisons between subjects. It is thus suggested that every subject be requested to perform the movement task starting and ending with a prescribed posture and practice the movements without causing fatigue.

3.5.4 Video camera recording

To enable more detailed observations and measurements to be made of the users carrying out the specified task, a video camera recording and analyses using suitable motion analysis software, such as 'Peak Motus' (www.PeakMotus.com), should be made. Movements that predominantly occur about one plane can be recorded using one camera recording the movement about the plane of interest only, as they are considered to be two-dimensional (2D). Other tasks that involve movements about more than one plane must be considered to be three-dimensional. For the purpose of this study all references will be made in a two-dimensional manner. Further descriptions of video camera recording, marker placement and analysis of the video recording, of an experimental analysis is described in sections 7.2 and 7.3, respectively.

3.5.5 Analysis of the data

The intermediate body postures that occur during the movement task carried out by each subject can be determined through the identification of the maximum and minimum values of the joint angles produced between each body segment. This can be done using a motion analysis software. The corresponding video frames can also be simultaneously analysed to support the identification and understanding of the movement strategies employed by both groups. An example of this can be found in later in this research project in section 7.4.2

3.6 Phase 4 Compare movement strategies of able-bodied people and potential users

Once the intermediate postures of all subjects have been determined, both graphically and pictorially, as undertaken in section 7.4, the designer should then be able to compare the intermediate movement strategies employed by both the potential users and able-bodied people. This should enable a greater understanding of the common movement strategies employed by both groups. Comparisons of the variability of the magnitude of the segmental angles, measured between each intermediate posture, will also enable the designer to understand the differences between the movement strategies used, as carried out by Ikeda et al (1991) to describe the task of rising up from a sitting posture.

These comparisons should also enable the designer to appreciate and quantify the subtle differences between the movement strategies employed by both groups and hence enable a greater understanding of the problems that the potential user experiences when carrying out the same task. This information should be fed back to the design specification document for a more comprehensive description of the user problems and requirements. This first hand analysis of the users physical problems and needs, by the designer, should also be used to create the conceptual design solution in *phase 6.*

3.7 Phase 5 Model able-bodied and potential users' movement strategies

Through the understanding of the intermediate postures, employed by both potential users and able-bodied people, it was anticipated that the designer can model the movement strategies for both groups. This phase involves translating the intermediate postures commonly employed by the able-bodied group, to manipulate the movements of the computer manikin. The anthropomorphic measurements taken in *phase 1c*, of the body segmental lengths, the external body measurements and joint range of rotation of the body segments of each potential user, are then also incorporated into the computer manikin, as described in section 8.2.2. This will enable the manikin to mimic the size and restricted movements of an individual and in turn be used aid the creation of a conceptual device during the conceptual design *phase 6.*

The device used by the subjects, during the experimental task, should also be modelled in the form of a geometric wireframe, as described in section 8.2.1. This will enable the computer manikin software to simulate the interaction of the user and the device. The structure of the computer manikin representation, along with an example of how it is employed to model the transitional body movements, are explained more comprehensively in Chapters 6 and 8, respectively. All intermediate postures, described in these chapters, should be invoked sequentially as they occur when performed by the user.

The computer manikin used to model the intermediate postures should then be validated through comparisons with the experimental study carried out for each individual subject in the previous design *phase 4*. This is carried out by initiating the segmental lengths and joint range of motion of each potential user represented and sequentially manipulating the movements of the manikin, as described in section 8.3. The joint angles produced between each body segment during each transitional posture can then be compared to the actual angles measured. If comparisons are found to be similar and in good agreement, the designer is then able to use these rules for the creation of a device during the following phase.

3.8 Phase 6 Conceptual design

The designer should now be able to create a conceptual design through the manipulation of wire frame geometric entities that represent the design. Geometric entities representing an existing design can be modified or new geometric entities can be created to represent the conceptual design through the use of the interactive software, similarly to that described in section 8.2.1. The designer should continuously evaluate the affect of the iterative developments of the conceptual design by invoking the intermediate movement strategies of the manikin representatives of the subject or subjects with possibly the most extreme sizes or limited joint movement. This is done, for example, by comparing the segmental angles of interest, for example, an elbow joint when the height of a shelf has been increased, throughout each intermediate posture. When the designer is satisfied that the design fulfils the requirements of the design specification, they should test the representations of each individual by manipulating each representative through the intermediate postures used to carry out a task, to evaluate the design. This is to ensure that a device is created to suit the different body sizes and physical limitations of each individual. If the design meets the criteria stipulated by the design specification and the manikin representatives are able to follow similar movement patterns commonly used by the able-bodied group, the design can then be validated through experimental analysis, in the following *phase 7*.

3.9 Phase 7 Validate and test

The validation of the conceptual design again involves a detailed experimental analysis similarly to that carried out in *phase 3*, using a prototype of the conceptual design. These results should then be compared to those initially carried out in *phase 3*. This is described in more detail in the following sections.

3.9.1 *Phase 7a* Make prototype

Once the designer is satisfied that the concept design has fulfilled the design intent, according to the requirements of the design specification document, a prototype of the conceptual design should then be made according to the dimensions of the geometric model created. The prototype should be made as simple as possible to reduce the time taken to make it. It should be sufficient enough to replicate the dimensional sizes and design intent created during the conceptual design phase.

3.9.2 *Phase 7b* Experimental validation

An experimental study of the users employing the prototype design, using the same method described in *phase 3*, should be conducted employing the same two groups previously used in experimental *phase 3*.

3.9.3 *Phase 7c* Subjective questioning

Subjective questioning of the both groups, for example, upon the comfort, ease of carrying out the task, feelings of stability, should be carried out during and after the experimental validation

3.9.4 *Phase 7d* Comparisons with initial experiments

Comparisons of the movements patterns and the intermediate postures found during both the initial experiment, carried out in *phase 3* and that using the prototype, should aid the designer in understanding and validating the benefits or problems resulting from the conceptual design created. The prototype should also be simultaneously validated through comparisons of the potential user's requirements defined in the specification. If it is found that these requirements are not met, then the procedure of subjective questioning, comparing and modelling the movement strategies, employed by both the able-bodied people and the potential user, initiated in *phase 4*, should be re-addressed. The designer can either readdress the experimental analysis carried out in *phase 4* through observations of the video analysis or re-iteration of the initial experimental study with a better understanding of the analysis required. This will depend on whether the video analysis and comparisons carried out in *phases 3* and *4* provide sufficient information. This should enable the designer to understand the design shortfalls and thus modify the conceptual design accordingly by reiterating the conceptual *phase 6* described. These phases, contained within the grey shaded box of Figure 3.1, can be continually reiterated, until the design is found to fulfil all the requirements defined through comparisons with the design specification and experimental validation. When the requirements have thus been fulfilled, the design can proceed to the embodiment and manufacture phases in a manner to that described by Pahl and Beitz (1996), (see section 2.2.1).

3.10 Conclusions

The design methodology, as proposed in this chapter, focuses upon improving the mobility of older people and people with physical disabilities by employing a device that will enable them to move using a similar movement strategy used by able-bodied people. A case study employing this methodology will later be carried out in Chapter 9, to design a device to aid rising from a sitting posture.

The Department of Trade and Industry (DTI, 1999) reported that the main cause for physical injury for people over 65 years in the UK, was due to a fall within the home environment. Dowswell et al (1999) suggest that conditions such as impaired mobility and instability were associated to the occurrence of these falls. Stability, when designing for the improvement of mobility, should thus be considered. The following chapter will review how human stability is determined theoretically, mechanically and experimentally. This will be used to establish a method to calculate stability when using a computer manikin, during the creation of a device to improve mobility, as proposed.

Chapter 4
Human stability

4.0 Introduction

This chapter reviews the complex human sensorimotor mechanism for maintaining stability and discusses how balance is determined mechanically. This includes a review of experimental and mathematical methods of determining the centre of mass (CoM) and the base of support used to evaluate stability. Strategies to maintain the erect stance, along with a brief description of a static posture, have also been described. These descriptions are punctuated with concluding remarks.

4.1 The sensorimotor mechanism for maintaining stability

Balance is described as a highly integrative process by Kuaffman et al (1997) and depends on the processing of information received by the brain. This information is received from the physical body's internal sensory system and its interaction with the external environment. Once accumulated, the brain uses this information to ascertain the body's position and postural stability to formulate the next plan of body movement. This information is transmitted through the central nervous system (CNS) to the outer extremities through the peripheral nervous system, in the form of electrical impulses. These impulses stimulate the motor nerves to produce a chemical reaction, causing the skeletal muscles to contract and produce the new body movement. Information resulting from the new body movement is detected by the sensory system and the process described is repeated (Kuaffman et al, 1997).

Stability is also maintained by automatic reflexes of the muscles, that also respond to stimuli from the sensory system (Kreighbaum and Barthels, 1990). Instead of transmitting electrical impulses from the sensory system directly to the brain, the signals will 'synapse' (i.e. transmit from one cell to another) with a motor nerve, at the base of the CNS and produce instantaneous body movement. The event of whether body movement is caused through an automatic reflex depends on the 'variation and importance of stimuli on the tissues' (Kreighbaum and Barthels, 1990), which determines the strength and the frequency of the electrical impulses transmitted to the CNS.

Johansson and Magnusson (1991) and Kuaffman et al (1997) categorised the information required to maintain balance as the somatosensory, the visual and the vestibular inputs. The somatosensory input originates from the position of the physical human body and its interaction with the external environment. The body's posture can be detected from the somatosensory input by various means, including joint position, muscle length and tension. Its interaction with the external environment can be sought from cutanious touch and pressure. Whereas the visual input depends upon information received via the ocular system from the external environment. The body's position, in relation to the external environment, can thus be sought using objects as an aid of reference. Body movements can also be assessed for accuracy and corrected using this sensory input. Finally, the vestibular input is the labyrinthine receptor found in the inner ear. This input, as previously described, originates from the orientation of the head to gravity and should detect angular or linear acceleration when the head moves.

4.1.1 Summary

If any impairment occurs with the proprioceptive (i.e.sensory), musculoskeletal, or visual impairments, as stated by Kuaffman et al (1997), an individuals capability to maintain balance can be affected. It is thus important to determine the nature of the impairment that may cause instability. Due to the complex nature of the maintenance of human stability this project has concentrated on people with musculoskeletal or physical impairments and not on people have that any sensory or visual impairments. The determination of the stability of subjects has been explained in further detail in the following sections.

4.2 Mechanical determinants of stability

Human balance is the ability to control equilibrium of the physical body. This occurs statically when a subject is required to sustain a posture over a period of time and dynamically when maintaining continual movement, without experiencing a fall, Kreighbaum and Barthels (1990).

Stability is the body's resistance to losing its static or dynamic equilibrium, or its resistance to changing its state of motion, (Kreighbaum and Barthels, 1990). This resistance can be found when moving in a straight line (i.e. linear stability) or when preventing a fall (i.e. rotary stability). Linear stability in a stationary body is the body's resistance to being moved in a given direction by an external force. Linear stability in a moving body is the body's resistance to being stopped or having its direction changed. Rotary stability of a body, is the body's resistance to losing its equilibrium, when being rotated about a fixed point by a net external torque.

The centre of gravity (CoG) is the concentrated resultant force or weight of an object that is acted upon by gravity. The centre of mass is a point at which the entire mass of an object is concentrated. The CoG and the CoM will be considered as the same, in this study, due to the human subjects being not being significantly large enough or far enough away from the earth to make any negligible difference to gravitational forces acting upon them and the position of the CoG.

Once the 'line of gravity', which is vertically projected downwards from CoG, falls to one side or other of the body's axis of rotation, it becomes torque producing. This can observed when a person is in an erect stance, with feet together. When the body sways in a specific direction about the feet (i.e. the base of support), the body will become torque producing by virtue of the centre of gravity rotating about the axis. When the body sways in the opposing direction, for example during standing, it is maintaining stability by preventing the centre of gravity being taken outside of the base of support. Simultaneously it is maintaining a static posture by returning to its original position.

To prevent the body from falling, the body's segments can be moved to maintain stability. This can be achieved either by changing the a body segment to effect the position of the CoG relative to the base supports, or by changing the base support to maintain the new position of the centre of gravity within its boundaries. The centre of gravity can be located using various methods, described in the following section.

4.3 Experimental location of the centre of gravity

The centre of mass (CoM) of the individual body segments and the human body as a whole can be determined both experimentally and theoretically. The following briefly describes some of the methods that have been experimentally employed to find the CoM of both individual body segments and the CoM of the whole body.

Braune and Fischer (1889) placed metal rods at right angles to the three cardinal planes (i.e. the sagittal, transverse and frontal planes), driven into frozen cadaver body segments to find the CoM of an individual segment. Each body segment was then suspended from the rods and the planes of intersection of the rod with the segments marked. The intersection of the three planes was determined as the CoM.

The 'suspension method', described by Hall (1995) similarly involves a plumb line being attached to the object and suspending it in three different planes. The CoM is located at the intersection of the plumb line in the three different positions found when the object is stationary.

Dempster (1955) used a balance plate to locate the CoG of individual body segments. This method consists of positioning a plate such that it pivots 'around the turned down ends of one of the diagonals', to locate the plane of the CoG 'along the longitudinal axis relative to the ends of the segments'. The balance plate method can also be used to find the CoM of the whole of the body of living people. This method requires a person to remain statically balanced on a board while placed upon a fulcrum in three different positions, i.e. the supine and the erect stance (initially in one plane and then rotating 90 degrees about the vertical axis), as shown in Figure 4.1. The CoG can be found by locating the intersection of the imaginary planes passing through a person and the fulcrum.

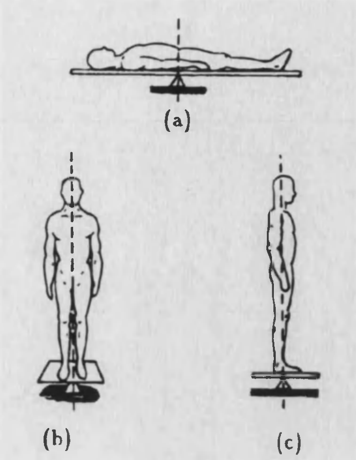


Figure 4.1 The balance method, from (Özkaya and Nordin, 1991).

The moment table or reaction board method is also an experimental technique that is used to find the CoG of the whole body. The reaction board method described by Hall (1995), Hay (1993) and Özkaya and Nordin (1991), shown in Figure 4.2, similarly requires a person to remain statically balanced upon a board in the same three postures as previously shown in Figure 4.1. It involves measuring the reaction force caused by a subject when they are placed upon a flat board. The flat board, known as the 'reaction board', is balanced on a thin edge running along both sides of the board as shown in Figures 4.2a and 4.2b. One edge of the board, A, is placed upon a block which acts as a fulcrum and the other, B, upon platform scales. The difference between the reaction force Rb, produced before and after the subject is placed upon the board, is taken from the platform scales. This reaction force, along with the known length of the board from the fulcrum to the scales, produces an anticlockwise moment, which is in equilibrium, due to both the board and the person being statically balanced. An equal and opposite clockwise moment to the reaction force is caused by the downward weight force of the subject Wp, which is also in equilibrium, thus equating these two moments about the fulcrum. The position of the plane, upon which the CoG lies, can then be calculated by solving the moment equation, given that the sum of the moments equals to zero. The same method is repeated with the subject in the other two postures previously mentioned so as to locate their actual CoG position by finding the intersection of all three planes measured.

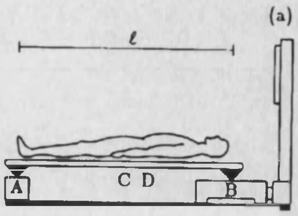


Figure 4.2a

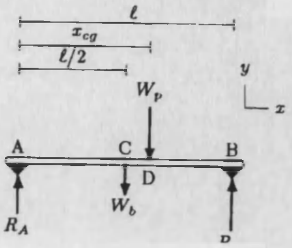


Figure 4.2b

Figure 4.2. The reaction board method, from Özkaya and Nordin (1991)

A similar method to the reaction board method as shown in Figure 4.3 and described by Hay (1993), is used when the position of the CoG of a person is required from a video recording. The exact static body position of interest is repeated using the same subject on a reaction board. This reaction board method measures the reaction forces caused by the weight of the subject using two scales, shown at points A and B, and one at the fulcrum at C (see Figure 4.3). The reaction board is placed such that the 'knife edges', upon which it rests, forms an equilateral triangle with the scales and the fulcrum point. The difference between the reaction forces taken from the scales, before (Ra1 and Rb1), and after the subject is statically placed upon reaction board (Ra2 and Rb2), can be used to calculate the moments about the axes about which they act, once the height, h, of the equilateral triangle is known. The CoG of the person is found by the intersection of two lines These lines are found by calculating the perpendicular distances x and y, which are determined from Equations 4.1a and 4.1b respectively, where W is the weight force of the subject.

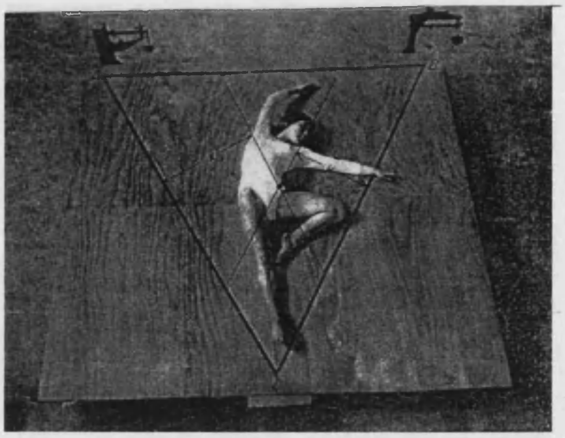


Figure 4.3 The reaction board method, from Hay (1993)

$$x = \frac{(Rb2 - Rb1)}{W}h$$

Equation 4.1a

$$y = \frac{(Ra2 - Ra1)}{W}h$$

Equation 4.1b

4.3.1 Summary

The data published on the CoM position by Dempster (1955) and Braune and Fischer (1889), along with authors such as Clauser et al (1996) and Chandler (1975) (as stated by Martin et al (1989) and De Leva (1996)) was limited due to the small number of cadavers used for these studies and little data based upon women.

The balance plate and reaction board experimental methods were also limited in that the CoM can only be derived from a given static posture, which has to be maintained by the subject of interest. Also the subject has to be present throughout the whole measurement process and the time taken to find the CoM is time consuming. These methods were therefore not considered to be practical for the purpose of this research.

4.4 Theoretical location of the centre of mass

There are various well-known theoretical mathematical models developed to determine the CoM of both individual body segments and of the human body as a whole. The following briefly describes some of these methods:

The Hanavan model developed in 1964, as described by Nigg (1994), consists of 15 simple geometric solids that can be modified according to 25 anthropomorphic measurements taken from an individual subject. The CoM and mass of each body segment is derived from these solids and regression equations. This model was based on the assumption that the human body is made up of rigid solids and consists of a uniform density. Also, According to Nigg (1994), that the weights of the body segments are determined using regression equations that may or may not be representative of a given individual.

The photogrammetric method developed by Jensen (1978) was developed to overcome the fluctuations in shape of the human form, such as the endomorph, ectomorph and mesomorph body types of children. This method involves photographing a subject in a prone position from the front and side views. Horizontal and vertical grids placed on the board positioned behind the subject in both views are then digitised, which according to Jensen (1978) takes two hours for each subject. The whole of the body is then split into 2cm wide elliptical sections, predominately in the transverse plane, that are employed to calculate the volume of 16 individual body segments. The density of each segment is obtained through published literature to find the segmental masses and consequently the centroid of the ellipses, the body segments and the whole body CoM is determined mathematically. This method was considered time consuming especially when there are a large number of subjects to measure.

The Hatze model, as described by Hatze (1980) has certain advantages over the previous models mentioned. It allows for the anthropomorphic differences in gender, pregnancy, obesity and age. It also accounts for the fluctuations in body shape, as it does not assume that the body segments are symmetrical and allows for the non-uniform densities of the body. This method separates the body into 17 segments and requires 242 separate anthropomorphic measurements to be taken for each subject which can be time consuming and is, according to Nigg (1994), highly complex both mathematically and computationally.

The Yeadon model, as described by Nigg (1994), developed an 11 segmental model where 95 anthropomorphic measurements were required to determine the shape of the solids that represented an individual. The segments were considered rigid and simplified to assume that no movement occurred in the neck, wrists or ankles. The density values, taken from literature, were also considered to be linear for all segments. This method could be time consuming when the subjects to be measured are increased.

Zatziorsky and Seluyanov, described by Nigg (1994), combined a gamma ray scanner technique with anthropomorphic measurements of 100 young adults to find the CoM position of individual body segments using regression equations. The CoM positions are defined as a percentage distance along a specific body segment from one bony landmark to another. However, according to De Leva (1996) this data was not used extensively due to the bony landmarks defining the body segments. De Leva (1996) thus adjusted these reference points to specific joint centres of rotation through the use of regression equations. The data published by De Leva (1996) also provided data for both male and female subjects.

The segmentation method is the most practical due to its versatility of being able to find the CoG of a whole body of a subject in most postures. This method locates the CoG of a person by calculating its x, y, z co-ordinates, provided that the CoG and mass of each individual body segment is known. It can be used as a two dimensional photographic assessment of the CoG position of a person as shown in Figure 4.4. It involves finding the sum of the moments about a given origin O, produced by the CoG position of each body segment along a given axis, for example OY, as shown in Figure 4.4. This result, when divided by the total mass of the body segments, provides the co-ordinate of the CoG along a specific axis. The co-ordinate along the other axis can be found using the same method.

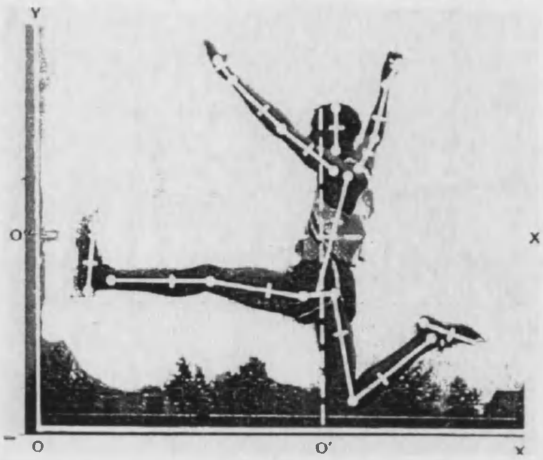


Figure 4.4 The segmentation method, from Hay (1993)

The time taken to calculate the CoG of a human subject using the segmentation method, can be greatly reduced when calculated computationally. However, This method depends on the CoM positions of each individual body segment being known.

4.4.1 Summary

The calculation of the CoM of the individual body segments using the manikin representative, were based upon the data published by De Leva (1996). This was due to the method not requiring extensive anthropomorphic measurement, which can be time consuming when numbers of subjects are large. Also the data produced by De Leva (1996) was based upon a larger number of subjects than other authors previously mentioned and takes both genders into consideration. The CoM of the whole body of the manikin representative was also computationally calculated using the segmentation method for reasons previously discussed in section 4.4.

4.5 Movement strategies when maintaining stability

A body is in a static state of equilibrium when at rest, for example when a person is in the supine position, as described by Kreighbaum and Barthels (1990). The body weight force is acting downward and is opposed by the ground force. No other external forces or torques are acting on the body's equilibrium, so that no change in motion occurs except for slight movements of the heart and lungs. There are many other daily activities while sitting or standing, in which the human body is required to maintain a static posture but due to the slight movements produced internally, the body has to continuously alter its position slightly to maintain rotary stability (Hellebrant et al, 1943). A static posture can thus be described as a static position that is maintained through slight dynamic movements of a subject's own body segments.

The maintenance of a static stable posture, as previously described, is associated with the position of the CoG in relation to the body's base of support and the moment that its weight force exerts about the axis of rotation. According to Todd (1985), Kreighbaum and Barthels (1990) and Hall (1995), static stability is when the CoG is held above and within the boundaries, known as the convex hull, created by the base of support.

The base of support is the area bounded by the body parts that contact a resistive surface that exerts a reaction force, for example a wall or the ground surface, known as a convex hull. A convex hull is formed by the intersection of the most outer points of a shape and, according to Vince (1984), 'is a shape that surrounds another without including any concavities', as shown in Figure 4.5 below. An Informal description would be that of an elastic band encompassing a set of pegs placed on a board.

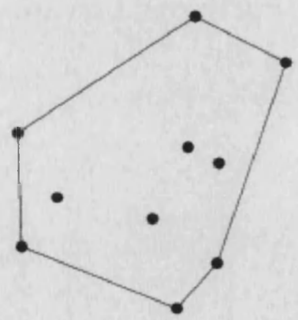


Figure 4.5 Diagram of a two dimensional convex hull

4.5.1 Summary

This research was concerned with the base of support formed on the ground surface alone and was thus defined by a two dimensional convex hull, which will lie on the ground surface, as previously described.

4.5.2 Strategies for maintaining stability in the bipedal erect stance

The motor components of balance, according to Kuaffman et al (1997), are controlled partially by automatic reflexes in response to external disturbances. These automatic responses can be categorised into various movement strategies. Kuaffman et al (1997), for example, defines the movement strategies while maintaining the erect stance as being the ankle, hip, suspensory, and the stepping strategy as shown in Figure 4.6. To remain stable the body has to maintain the centre of gravity above its base of support. If there are no external disturbances to the body during the bipedal erect stance, a person is likely to sway the body slightly about the ankle joint to maintain the CoG above its base of support. If this strategy does not maintain stability due to an external disturbance such as a moving standing board then the body's automatic response will be to change it's strategy for stability, by either swaying about the hips or to lower its CoG position. If stability is not achieved using these strategies when the CoG approaches its limit of stability (LOS) i.e. where the CoG, when vertically projected, is close to the convex hull where a person begins to feel unstable. The person must either step, stumble, or grasp an external object to regain balance or alternatively risk a fall.

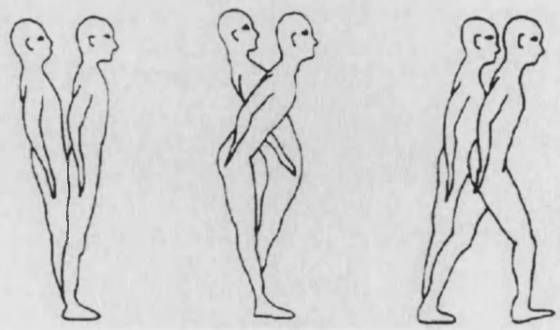


Figure 4.6 The ankle, hip and stepping strategies, from Kuaffman et al (1997)

McCollum and Leen (1989) stated that the limit of stability during the erect stance is when the vertical gravity line is on the edge of the base of support formed by the feet. However, a study of the range of excursion of the CoG within the base of support, while maintaining the erect stance, as found by Brouwer et al (1998), showed that each individual's limit of stability varies. This could be due to parameters such as the size of the base of support (i.e. the distance of the inner feet with respect to each other), the height, weight, ability, or the confidence level of each subject.

4.5.3 Summary

A person's ability to maintain balance is highly variable due to their many different physical and mental attributes, as previously discussed. It was thus concluded that even though a person may be theoretically considered to be stable, user involvement and subjective questioning of individuals, representative of the user group being studied, must be carried out to ascertain human stability.

4.6 Stable postures maintainable during dynamic movement

There are two forms of movement described by Todd et al (1985). The simplest form is when a body passes through one stable state to another, i.e. from one static posture to another. This usually happens when a human is moving relatively slowly, for example when a person walks slowly. The person will move through a series of stable states. It should be possible for the individual to maintain stability if each stable state is held for a period of time. The other form is when a person moves through a stable cycle of motion, which does not involve passing through stable states. This normally occurs at high speeds, for example while running, when the body will periodically leave the ground.

4.6.1 Summary

This research project was focused on improving the mobility of people who wish to carry out common daily tasks, instead of more complex high speed tasks, such as running. Thus the analysis of human movement, as part of this research project, was considered to be the stable static postures that are employed when moving slowly from one intermediate posture to another.

4.7 Conclusions

The sensorimotor mechanism for maintaining stability explained at the beginning of this chapter, found that humans use automatic movement strategies to maintain balance. It was also suggested that if an impairment of the musculoskeletal system occurs balance could be effected. Similar findings have been reported when maintaining mobility. The following chapter describes the distinct movement strategies used while rising from a sitting posture and how these strategies are effected when a person ages or experiences a physical disability.

The integration of the methods, described in this chapter, to calculate stability using a computer manikin is described in further detail in chapter 6.

Chapter 5

Definition and measurement of the sit-to-stand movement

5.0 Introduction

This chapter provides a review of published clinical studies carried out to define distinct patterns of movement employed when young able-bodied people rise from a chair. It also provides a review of clinical studies where comparisons have been made of the movement strategies employed by able-bodied people to analyse the variations of movement strategies used by both older people and people with physical disabilities. The variability of movement strategies caused by different chair designs was also reviewed. Again concluding remarks for each review are provided at the end of each section.

5.1 Distinct movement strategies employed by young adult able-bodied people

Distinct patterns of movement exist and can be observed when repetitive tasks are carried out. Trombly (2001) described a good example of this. When a person initially starts to drive a car it is very difficult for an individual to master the co-ordination and protocol required to move the gear stick, the steering wheel and, at the same time, concentrate on the road ahead. Eventually after much practice the task becomes easier and is stored as a general motor program or preferred movement strategy within the brain. This motor program or preferred movement strategy consists of an abstract representation of the order of movement, timing and force required to carry out a task. This can be automatically activated when required. Postural adjustments to carry out a task can be made either by the brain or through automatic reflexes, as discussed in section 4.1, to allow for variations of the task that may occur. The movement patterns used to drive a car can therefore be repeated at will and distinct movement patterns can be observed.

We use distinct repetitive patterns of movement to carry out common tasks from an early age. Able-bodied people of all ages use similar distinct patterns of movement from as early as 9 months old as observed by McMillian and Scholz (2000), when learning to stand from a sitting posture, which is essentially a similar strategy to older people in their seventies Ikeda et al (1991). Even though the variance of the patterns of movement differ slightly from each individual they can be recognised simply through observation. These movement patterns do however tend to differ far more when an individual's muscle strength is decreased, or when a person's movement is limited.

Studies of young adult able-bodied people have shown that a distinct pattern of movement is employed when rising from a sitting posture. This distinct pattern has been separated into phases of movement for comparative purposes by many authors and is described as follows:

An observational study carried out by Butler et al (1991) described the movement strategy of able-bodied adults to have two distinct phases when rising from a chair. The first phase is characterised by the 'forward trunk lean' that brings the body weight above the base of support formed by the feet. The second phase is an upward movement of the body, with an extension of the hips and knees and 'relative' plantar flexion (i.e. bending the toes downward and so arching the foot) of the ankle. This series of movements are shown in Figure 5.1.

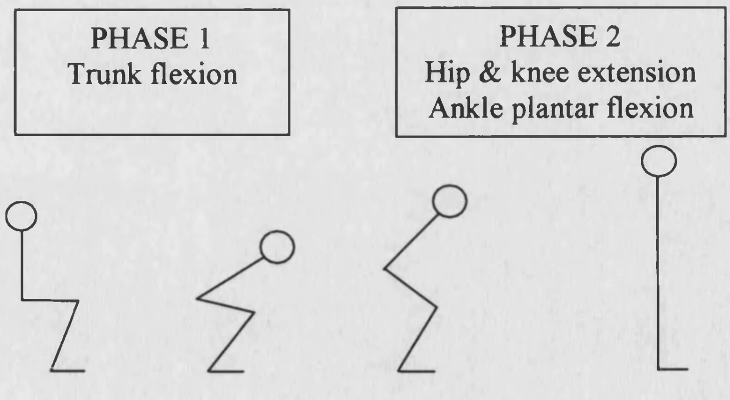


Figure 5.1 Pictorial diagram of the movement strategies used when able-bodied people rise from a chair, as described by Butler et al (1991)

A clinical study carried out by Alexander et al (1991) also concluded that there were two distinct phases of body movements found during a study of a group of 17 young adult able-bodied people of mean age 23 years. The authors defined the initiation and end of these phases through the measurement of the translations and angular rotations of each individual's body segments. The first movement phase is described as beginning with a predefined upright sitting posture and ends when the head has reached its' maximum anterior position which, according to Alexander et al (1991), is approximately when the buttocks have lifted off the seat of the chair. The second phase of movement starts when the head has reached its' maximum anterior position and ends when the subject is standing fully erect, as shown in Figure 5.2.

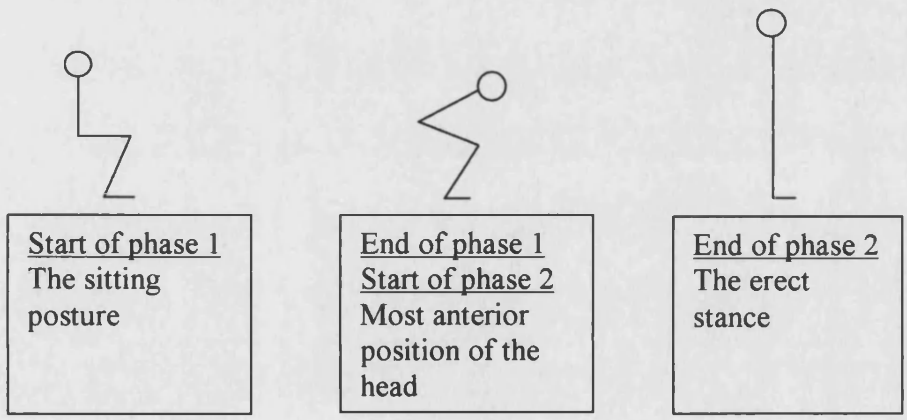


Figure 5.2 The initiation and termination of the two phases of movement that occur during the sit-to-stand movement, as described by Alexander et al (1991)

A more recent study of the sit-to-stand movement carried out by Bahrami et al (2000) also divided the sit-to-stand movement task into two movement phases, as shown in Figure 5.3. Their analysis involved the measurement of torques, momentum and the total body centre of mass (CoM) displacement of 10 able-bodied subjects of mixed gender, aged 26-33 years. Their description of the movement strategies employed by able-bodied people were similar to those described by the observational study of Butler et al (1991) and the kinematic study of Alexander et al (1991), previously mentioned. Bahrami et al (2000) described the first movement phase as beginning from the sitting posture and ending just before the buttocks leave the chair. The second phase is described as beginning at, what the authors described as the 'seat-off', when the buttocks leave the chair until the erect standing posture is obtained. Bahrami et al (2000) also found that the total body CoM of able-bodied subjects, without arm support, moves initially horizontal until the buttocks left the seat, and then vertically upwards towards a standing posture. The total body CoM, according to this study, was placed well within the base of support formed by the feet before the buttocks left the seat. Schenkman et al (1990) and Jeug et al (1991) similarly describe the movement of the total body CoM as follows.

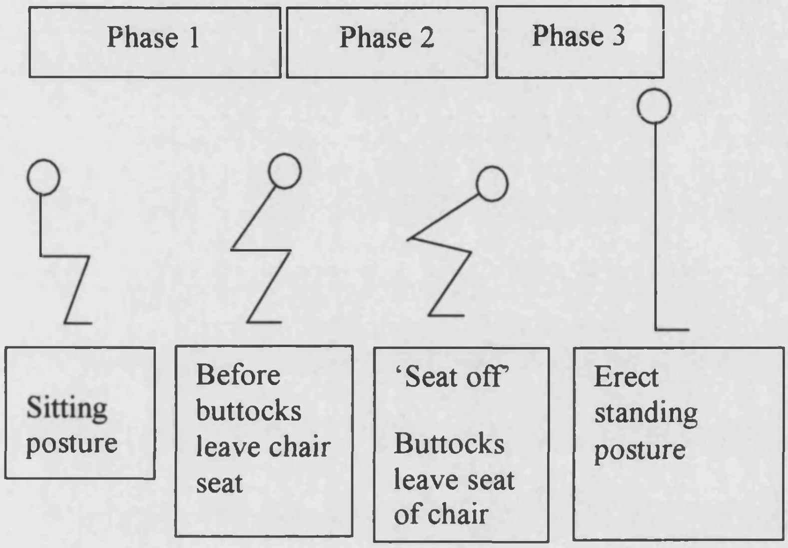


Figure 5.3 Diagram of the three phases of movement during rising from a chair as described by Bahrami et al (2000)

Schenkman et al (1990) divided the sit-to-stand movement further into 3 phases of body movement. These movements are described in detail by Schenkman et al (1990) through an experimental study of 9 young healthy able-bodied adult females (aged 25-36 yrs) performing the sit-to-stand task. These definitions of rising from a sitting posture are also employed in a similar study undertaken by Ikeda et al (1991), as shown in Figure 5.4, who analysed the velocities and positions generated by the body segments of each subject to distinguish the following movement phases. The first phase, described by Schenkman et al (1990), is termed the 'flexion-momentum' phase where the primary rotations forward were found to occur in the pelvis and the trunk flexion. The second 'momentum transfer' phase was stated, without providing supporting evidence, by Schenkman et al (1991) to be the most challenging part of the movement. This is when the CoM of the total body is transferred from being above the base of support formed by the buttocks, to the back of the base of support formed by the feet alone. This phase is initiated when the buttocks are lifted off the seat and completed sequentially when maximum hip flexion, trunk flexion, head extension, and finally ankle dorsiflexion are reached respectively. The third 'extension' phase begins when the maximum dorsiflexion of the ankle is attained and the hip extension velocity has reached 0°/sec. A fourth 'stabilisation' phase was initially studied that begins when the velocity of the hip extension reaches 0°/sec. In hindsight the authors decided not to analyse this latter phase due to the difficulties in specifying 'stabilisation' when lateral, anterior-posterior sway continues to occur during the erect stance.

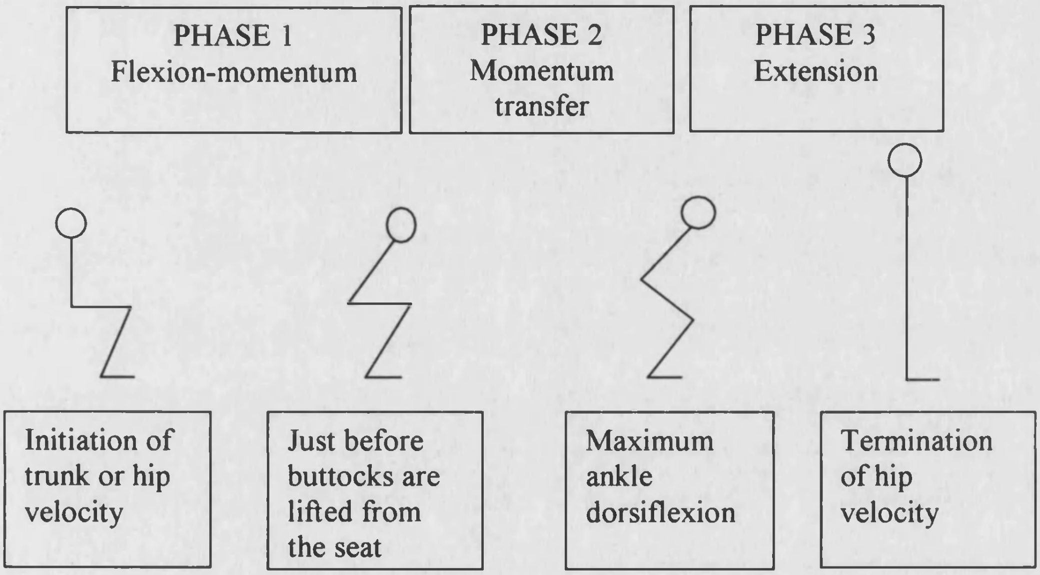


Figure 5.4 Diagram illustrating the initiation and termination of three phases of movement described by Schenkman et al (1990) and Ikeda et al (1991) when able-bodied subjects rise from a sitting posture

Jeug et al (1990) described three events, which they considered to be key events which are concluded from the strategies defined by Schenkman et al (1990). These were established through the measurement of angular rotations only of the body segments of 15 healthy young adults (mean age 29 years) during the task of rising from a chair. The key phases characterised by the authors are described as events. The first event is the when the maximal trunk flexion is attained, which the authors described as the movement that produces the momentum required to rise from a sitting posture. The second event is a 'lift-off' of the buttocks from the chair seat, when the CoM begins to move from a forward and downward direction to an upward one, and the third event is the achievement of maximum truck extension i.e. an upright standing posture, as shown in Figure 5.5.

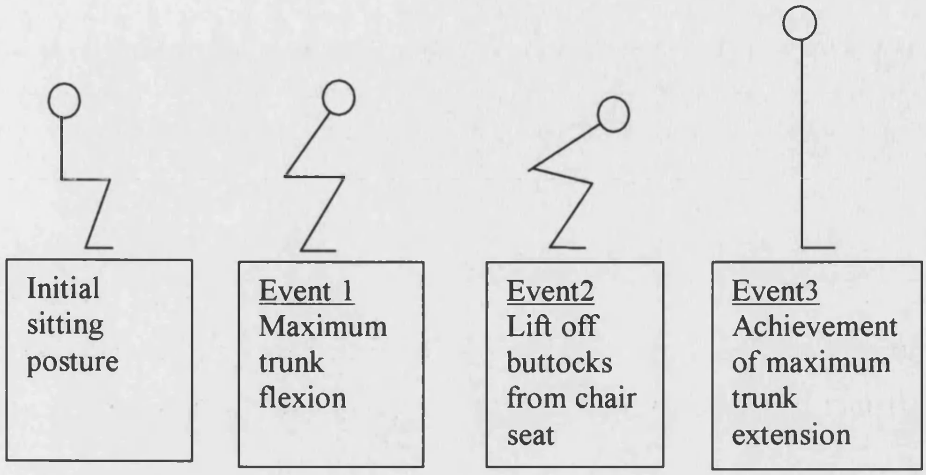
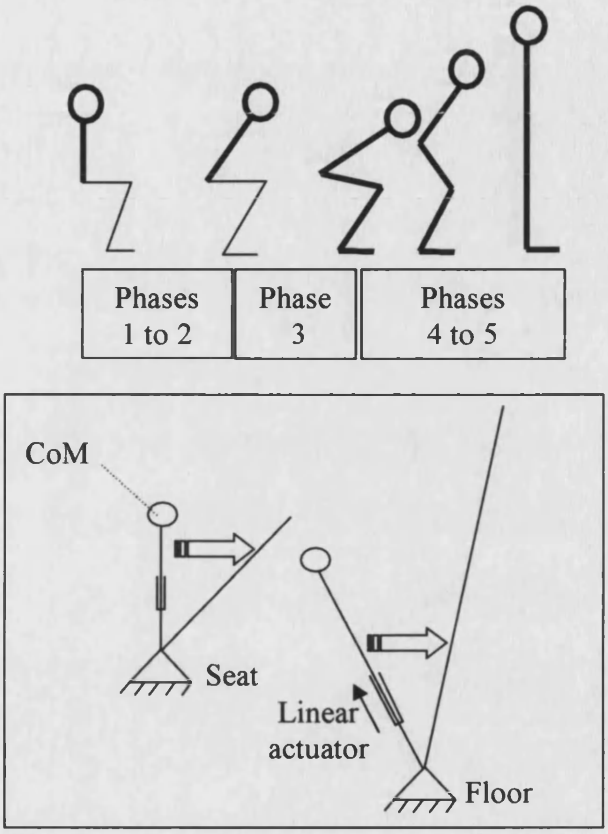


Figure 5.5 A diagram of the three events described by Jeug et al (1991) to define the sit-to-stand movement strategy

A more recent study carried out by Papa and Cappozzo (1999) described five phases during an analysis of the movement produced by twelve able-bodied people (age range 22-34 years) when rising from a sitting posture, as shown in Figure 5.6. Each phase is distinguished in terms of acceleration and deceleration of the CoM of initially the upper body, then the body as a whole and modelled as two inverted telescopic pendulums. The first pendulum, which describes the upper body alone, pivots about a position at which the buttocks are in contact with the seat. The second pendulum pivots about a position, which is defined as being where the feet are in contact with the ground. The first and second phases of the movement strategy are modelled by the first pendulum, which is described as occurring when the momentum of the upper body initially pivots forwards in acceleration, and then deceleration, about the buttocks. The third 'transfer' phase occurs when the momentum of the upper body, i.e. the first pendulum, is transferred to the body as a whole, i.e. the second pendulum, as the buttocks leave the seat and the feet become the only base of support. The fourth and fifth phases are then described as an upward linear acceleration and finally a deceleration of the second telescopic pendulum alone, which models the vertical upwards movement of the body as a whole towards the erect standing posture.



- Phase 1 to 2

Rotational acceleration and deceleration of upper body (i.e. head, arms and torso)

- Phase 3

Momentum transfer as buttocks leave seat and feet become base of support

- Phase 4 to 5

Upward linear acceleration and deceleration of whole body

Figure 5.6 Two telescopic pendulums simulating the dynamic movement of initially the upper body and then the body as a whole when rising from a sitting posture, as described by Papa and Cappozzo (1999)

5.1.1 Summary

This review of experimental studies has shown, even though the population size of the subjects analysed were relatively small, that all studies were in agreement in that young able-bodied adults employ relatively the same movement strategies when rising from a sitting posture to a standing one, as shown in Figure 5.7. These phases are generally described by these authors to begin with the initial sitting posture, where upper body sways forwards, until the buttocks are brought off the seat of the chair. Maximum hip and trunk flexion is then obtained, before the knees and hips begin to extend and maximum ankle dorsiflexion occurs, before the trunk and hip are extended to produce the erect stance.

Authors	I	II	III	IV	V	VI	VII
Butler et al (1991)				Trunk			
Alexander et al (1991							
Bahrami et al (2000)							
Schenkman et al (1990)				Hip			
Ikeda et al (1991)				Hip			
Jeug et al (1991)				Trunk			
Papa and Cappozzo (1999)							

KEY

I	Sitting posture
II	Just before buttocks leave seat
III	'Seat off' just after buttocks leave seat (Head in most anterior position (Alexander et al (1991) only))
IV	Maximum hip/trunk flexion
V	Begin hip & knee extension, plantar flexion
VI	Maximum ankle dorsiflexion
VII	Standing posture

Figure 5.7 Summary of sit-to-stand phases defined by various authors

5.2 Comparisons of movement strategies of young adult able-bodied people, older adults and people with physical disabilities

A disability can occur from birth, through trauma or age, (Trombly (2001)). When an able bodied person experiences a physical disability through trauma or age, an OT will initially assess a person's ability carry out various common tasks by comparing them to distinct patterns of movement that are normally used. If it is thought that an individual can continue to carry out a task similarly to the one normally used, they will encourage that person to continue doing so. Otherwise they would have to teach them to use an alternative compensatory strategy through rehabilitation.

This section provides a review of the comparisons of movement strategies employed by able-bodied adults, older adults and people with physical disabilities published in literature. The variations of movement, the reasons why they occur and the problems reported by the older and people with physical disabilities when rising from a chair are also discussed.

Many clinical studies published in literature, including some of those mentioned in the previous section 5.1, have employed young adult able-bodied subjects to distinguish a repeatable and distinct movement strategy when undertaking the task of rising from a sitting posture. These measurements and observations have then been used as a benchmark to make comparisons with the movement strategies employed by both older people and people with physical disabilities.

The comparisons reported further on in this section show that the strategies used by young and older adult able-bodied people vary only slightly. Many of the authors mention that the slight variation, i.e. the increased trunk flexion prior to rising from the chair, is to enable older people to gain greater postural stability. This is when the buttocks are lifted off from the seat, transferring the total body's CoM from being above the base of support formed by the buttocks, thighs, and feet, to the base of support formed by the feet alone. Some clinical studies have reported that people with physical disabilities found difficulty undertaking this task. However, once these people were provided with a support aid, such as armrests that aided postural stability throughout the task of rising from a chair, they were able to rise to a standing posture using a similar strategy to that employed by able-bodied people.

Alexander et al (1991), previously mentioned in section 5.1, made comparisons of the movement strategies used by young adult able-bodied people (mean age 23 years), with older able-bodied people (mean age 72 years), and older people with difficulties in rising (mean age 84.4 years). The latter subjects, who experienced difficulty in rising from a sitting posture, invariably had muscle weakness and primarily osteoarthritis in the lower extremities, also identified that they had previously suffered with 'vertebral fractures, vision impairment, dizziness and difficulty with balance and falls'. This group, referred to by the authors as the 'unable' group, was instructed to use hand grips throughout the experiments to enable them to complete the task. Comparisons showed that the older able-bodied group flexed their trunks and knees to a greater degree and extended their thighs more than the younger group, when their arms were folded across their chests. When comparisons were made between all subjects using hand grips it was found that the older 'unable' group, previously described, flexed their trunks far more than both the able-bodied younger and older adult groups. Alexander et al (1991) concluded that the reason for the differences in chair rise strategy between the able-bodied young, the older group, and the 'unable' older group, was the requirement of both older groups to achieve postural stability. This was achieved through increased trunk flexion and placement of the total body CoM within the base of support formed by the feet alone, during lift-off of the buttocks from the seat of the chair.

Papa and Cappozzo (1999) also compared the differences of movement strategies between 16 young able-bodied people and a significantly larger sample size of 35 older adult people when rising from a chair with their arms folded. Of the older group studied, 70% used an orthosis (i.e. an external device used to aid a physical disability) and 52% complained of 'chronic articular pain'. Results of their investigation showed, similarly to that of Alexander et al (1991), that the older group brought the CoM closer to the base of support formed by the feet before lift-off. This was carried out by rotating the hips further in forward flexion, until the CoM had been placed above the base of support formed by the feet, before they began elevation. Thus showing that the older subjects tried to gain postural stability before moving the total body CoM forwards and then upwards into a standing posture.

Wheeler et al (1984) carried out a study of young and older adult able-bodied people, age range 22-28 years and 67-81 years respectively, when rising from a chair with the option of using armrests. Similarly, to the studies previously mentioned by Alexander et al (1991) and Papa and Cappozzo (1999), comparisons showed that the older group flexed their trunks more when rising from a chair and placed their feet slightly further back, thus aiming to gain postural stability when preparing to stand up.

The study previously mentioned by Bahrami et al (2000) in section 5.1, also compared 10 able-bodied subjects of mixed gender with 2 people (aged 26-33), who had lower body paralysis, when rising from a chair with the aid of hand grips. The subjects who had lower body paralysis tended to place the CoM horizontally forwards between the support of the hand grips and above the base of support formed by the feet. This enabled them to gain postural stability before they vertically elevated themselves from this position, similar to the studies of older adults undertaken by Alexander et al (1991), Papa and Cappozzo (1999) and Wheeler et al (1984). Thus, allowing them to employ a movement trajectory similar to the able-bodied people reported by these latter studies, in which no hand support was employed during the sit-to-stand movement.

5.2.1 Summary

Experimental studies carried out by the authors mentioned in this section have shown that comparisons of movement strategies employed by able-bodied people are required to distinguish the variation of movement employed by people with physical disabilities. The recognition of the variance of movement strategy, such as increased trunk flexion when rising from a chair to gain postural stability before standing erect, can provide an understanding of the problems experienced by older people and people with a physical disability when undertaking a movement task. Once identified, these problems may be overcome through the use of support aids, such as hand grips, thus enabling the individual to perform a given task using a similar strategy to that of able-bodied people.

5.3 Differences of movement strategies with variability of chair design

This section provides a review of the differences in movement strategies employed by both young and older adult able-bodied people, some with mobility problems, which can be significantly altered through the variation of chair design. A discussion of how chair designs can either aid or hinder the ability to rise from a sitting posture is also included in this section.

A review of the studies of young able-bodied and older people has found that variable seat height, and seat and backrest recline, can either increase or decrease the ease of rising out of a chair. This is invariably the reason that the majority of the clinical studies, discussed in section 5.1, that focused on analysing the movement strategies used when rising from a chair, adjust the height of the chair to suit the individual size of the subject. Schenkman et al (1990) stated that these adaptations enabled comparisons to be made between the adult able-bodied subjects being analysed. The heights of the chairs employed in the studies mentioned in section 5.1 were predominantly adjusted between 80% (by Schenkman et al, 1990), 99.4% (which was an average preference of subjects studied by Bahrami et al, 1999), and 100% (Riley et al,1999) of individual knee to floor height. Whereas authors such as Alexander et al (1991) adjusted the seat height to constrain the position of the feet such that, when placed flat on the floor, they produced a 110° knee flexion and 20° ankle dorsiflexion. This ensured that each individual's base of support formed by the feet was placed in the same position according to their individual body sizes.

A long-term study carried out by McMillan and Scholz (2000) of infants from the age of 9 months old rising from a chair involved the seat height being initially adjusted to 90% of the knee to floor length. The majority of trials showed that the children continually used a similar pattern of movement to those of able-bodied adults described in section 5.1, i.e. flexing the trunk forwards before rising. However, when the authors lowered the seat height to 60%, the children primarily used an alternative pattern of shuffling their buttocks forward to the front of the seat, to gain postural stability before rising, by moving the total body CoM closer to the base of support formed by the feet. This pattern occurred during this long-term study of a year until, as the authors postulated, the muscles of the children were strong enough to stand up using the predominant pattern that they initially used when rising from a 90% height chair.

Alexander et al (1996) carried out a more in-depth study to find the differences in movement strategies used to rise when various chair designs were investigated. This study involved 21 young adult able-bodied people (age range 20 - 28 years) and 29 older adult able-bodied people (age range 73 - 93 years). The experiment employed chairs with variable seat heights of 60%, 80%, 100%, 120%, 140% of floor to knee height (not individually reported), with backrest reclines of 95° to the horizontal. These variable heights were intended to simulate a footstool, a low standard chair, a standard chair, a high standard chair and a barstool, respectively. The to floor to knee height of the subjects ranged from 39-55 cm (mean 44cm) which represented a standard 100% seat height for each individual. To simulate a lounge chair and a recliner, often used by the older people, the authors also included two other chairs with a posterior seat tilt of 10° and a backrest recline of 105°, and a 20° posterior seat tilt with 115° backrest, respectively. Alexander et al (1996) reported that a lowered seat height, a backrest recline (found to increase the user comfort) and a greater posterior seat tilt increased both the body motion (i.e. hip flexion) and the difficulty in rising reported by both age groups. Whereas, the increase of seat height decreased the joint range of motion and hence increased the ease of rising but, however, not the comfort of all users. The authors postulated that the lack of comfort reported when using the higher chairs (i.e. 120% and 140%) was due to a compromised 'peripheral circulation', presumably caused by the front of the seat, particularly when feet were not in contact with the floor.

A later almost identical study was carried out by Alexander et al (2000) to study the rise performance of 116 older adults aged over 65 years (mean age of 82 years) who required assistance from a person, or the use of a device when bathing, transferring or walking. The seat heights studied were adjusted to 80%, 100%, 120% and 140% of knee to floor height of each individual subject. The authors found that the use of hand rests became more necessary with the increased difficulty imposed by the reduction of seat height. Alexander et al (2000) also reported that the seat height of 140% of knee to floor height, that produced an initial posture between sitting and standing, was deemed to be the least challenging of tasks. When the seat height was adjusted to 140% only the ischial tuberosities (the sitting bones located at the bottom of the pelvis) were in contact with the seat. In some cases, a shallow seat depth of only 20cm was required to enable the feet of some subjects to make contact with the floor.

A subjective study was carried out by Kirvesoja et al (1999) of 55 Finnish older adult men and women, between the age range of 70-80 years when rising from a chairs of variable height. From the total of 55 subjects, 41 were reported to be able-bodied, whereas 14 required a walking-stick to move around. The seat heights chosen for the study were standard chairs of heights 350mm, 450mm and 550mm and the knee height of the subjects ranged from 460mm to 603mm. The subject's prescribed task was to sit down on each chair, change their shoes then rise out of each chair. The results showed that the 450mm seat height was considered by the subjects to be most suitable. For comparative purposes this seat height was approximately 102% of the mean floor to knee height of the study carried out by Alexander et al (1991). The seat height of 350mm was considered too low and the seat height of 550mm was 'slightly too high', even though, as previously reported, some subjects considered the 550mm height easier to rise from than the lower chairs. The reason for the discomfort caused by the higher chair was not reported by the authors. It could be speculated however, based on the studies carried out by Alexander et al (1996 and 2000), that it was due to a compromised 'peripheral circulation', presumably caused by the front of the seat, particularly when feet were not in contact with the floor.

5.3.1 Summary

The majority of the authors reviewed in this section have found that the higher the seat placement the easier the task of rising from a chair. These results have been based on the proportional seat height to each individual's body size. These authors have also employed various artefacts commonly employed to provide comparisons. These findings have been used to carry out experimental comparisons of movement strategies and create a conceptual design for people with a physical disability.

Many people have used distinct patterns of movements all their lives to carry out common daily tasks. Due to the onset of a physical disability during adult life, such as muscular dystrophy or arthritis, people experience difficulty carrying out daily tasks and are ever more dependent on aids to help them remain independent. To enable these people to continue using familiar movement strategies, the support aids that they use need to be designed to enable them to move in natural manner.

5.4 Techniques employed to define the sit-to-stand movement

This section briefly reviews some of the techniques used to identify the movement strategies employed by able-bodied people and people with disabilities. Conclusions are provided.

The authors, previously mentioned in this chapter, have all employed video recordings of subjects rising from a chair to describe, measure and quantify the movement strategies that they have observed. Video analysis enables the researcher to slowly play back the sequences of movements repetitively without further subject involvement. Some authors, such as Butler et al (1991), have simply observed video recordings, which in their case was made by two video cameras, each placed perpendicular to the sagittal and coronal planes (i.e. the side and views above the body). They were able to define and describe major movements of the body such as the flexion of the trunk, the extension of the knees and hips and the dorsiflexion of the ankles. Butler et al (1991) were also able to provide an objective description of the position of the total body CoM relative to the feet from these observations.

Other empirical studies such as those carried out by Jeug et al (1990) and Alexander et al (1996) placed markers on the palpable bony extremities close to the joint centres of rotation of their subjects. The body movement of the subjects was then recorded using only one video camera, placed perpendicular to the sagittal plane of movement, as the movements of the able-bodied subjects were considered symmetrical. The maximum trunk extension and flexion was measured by Jeug et al (1991) using manual goniometers lined up with the joint markers (placed on the subjects) which were recorded on video. The lift-off of the buttocks from the seat was however defined through observation. Alexander et al (1996) who identified the onset of the head movement to initiate rising from a chair, alternatively employed a light which switch off when the buttocks lifted off the seat.

Schenkman et al (1990) used light emitting diodes (LEDs) fixed to plastic discs called 'arrays' attached by bands to the subject's body segments (i.e.the left and right feet, shank, thighs, arms, and the pelvis trunk and head). These movements were then video recorded while the subjects undertook the task of rising to a standing posture. The angles, torques and velocities of the body segments and total body CoM were calculated using commercial software. The onset of the movement was identified through the use of a force platform placed underneath the feet. The authors used the segmental angles measured during the whole of the performance, to determine the events of the sit-to-stand movement reported in section 5.1. These angles were the maximum flexion of the hip, trunk, head extension, ankle dorsiflexion, knee and hip extension, which occurred sequentially.

The movement patterns defined by McMillan and Scholz (2000) were found by comparing the contributions of the individual momentum of the shank and trunk to the momentum of the total body CoM and the relative timing of the peak momentum of the shank, thigh and trunk. Body movements were measured using joint markers placed on the joint centres of rotation and recorded using 2 video cameras placed at the side and the back of the subject. The co-ordinates of these joint markers were then used to calculate the CoM and angles produced between body segment using Peak Technologies software. This enabled the authors to analyse the onset of flexion or extension of individual body segments.

Papa and Cappozzo (1999) identified five phases of movement when rising from a sitting posture. Their analyses were performed through the use of data being transmitted from force plates, (which were located on the seat of the chair and on the floor in front of the chair) to a computer model of two telescopic inverted pendulums. The head, arms and torso were represented as a one inverted pendulum, and the whole body as the other when the subject buttocks were lifted off the seat. Although these authors' computer model was a useful tool in terms of measuring the momentum of the upper, and then the body as a whole, when rising using the strategy mentioned throughout this chapter, it did not however, account for any possible permutations of this movement, such as the use of the head to aid stability.

5.4.1 Summary

The studies undertaken by Schenkman et al (1990), Jeug et al (1991) Alexander et al (1991, 1996, 2000) and Bahrami et al (2000), have all used markers placed either upon or close to the joint centre of rotation of individual body segments to measure the segmental body rotations. This technique, along with the analysis of video recordings through the use of computer software, has enabled these authors to identify distinct movement strategies, which have been found to be in agreement. It was therefore considered that these methods of measuring body movements to be appropriate when identifying movement strategies two-dimensionally.

Designers have measured the body movement of people and mimicked them using computer human representatives, to enable them to study the interaction with both existing machines and conceptual design prototypes, (Porter et al, 1994). The following chapter reviews the computer manikins that simulate human movement, to determine a human model that could suitably be used for this research.

Chapter 6
Computer Based Human Models

6.0 Introduction

This chapter provides a brief review of some of the ergonomic, biomechanical and control based computer human models that have been developed for both 'in house' and commercial use. A description of the constraint based modeler SWORDS and the manikin representative developed within this package has also been provided, and finally conclusions have been made.

6.1 Ergonomic computer models

Computer technology has enabled the ergonomist to evaluate human interaction with machines and products, the workplace or workspace and communicate their ideas to persons involved in the design process. Increasing legislation for a 'good design' has led to industries involving the ergonomist during the concept stage, instead of at the prototype stage (Porter et al, 1994) of the design process. This early involvement prevents later modifications which can prove to be both difficult and costly (Dooley, 1982).

During the late 1960's ergonomists realised the potential of developing computer human models, in a similar fashion to that of engineering CAD (computer aided design) software. These systems are design tools to provide the means of evaluating postural comfort and assess the clearances, reach and vision of a chosen human population, with conceptual designs.

The majority of computer human models used for ergonomic purposes have been developed as a rigid link system, where each link is representative of an individual body segment. Nowadays, a three dimensional shape is attributed to the link in order to represent the external form of a body part. The links are joined together, to represent the bony joints and normally given three constrained degrees of rotation, which reflect the limitations of human joint movement.

The anthropomorphic dimensions of various populations of people are usually held within a database to be accessed by the user and are usually displayed graphically on a VDU in the form of a wireframe or solid model. In order to evaluate a product or work environment the user is generally able to draw, either within the ergonomics package or import two or three-dimensional geometry from another CAD modelling package, the basic form of the design or environment to be analysed. The man model can then be placed into position within the environment in a given posture, thus enabling the user to assess the human model's ability to reach, see, and fit into specific objects within the workplace. The capabilities of some computer human models have extended towards a biomechanical assessment of the model and the external environment, which are also discussed.

There are commercial software packages available such as PEOPLESIZE (2000) that contain solely anthropomorphic data on the sizes and abilities of population samples of humans. PEOPLESIZE contains a large database of anthropomorphic information and a graphics display of the human body that enables the user to chose a body part and obtain information on 280 dimensions on various nationalities, age groups and percentile ranges. However, this type of package does not enable the user to alter the posture of the manikin or create geometric graphical images of a design to evaluate the interaction with the manikin.

There were various rigid link based computer human models reviewed by Porter et al (1994) and Dooley (1988), that have been developed for specific ergonomic assessment purposes. The aerospace industry has funded and developed several man models, for both 'in house' and commercial purposes, to varying degrees of complexity. BOEMAN for example, was developed by the Boeing Corporation in 1969 to check the cockpit layout but did not provide the interaction of a graphics terminal. Likewise CAR, developed for the same purpose, is a pure mathematical system. Whereas BURFORD, provided a simple graphical model of an astronaut but depends upon the user to manipulate each body segment into a desired posture. CREW CHIEF and COMBIMAN developed by the Armstrong Aerospace Industry, are slightly more advanced. They both evaluated the ability of the human model to reach and visually see the work environment, which can be created within these packages, as well as performing a static strength analysis based on empirical data.

RAMSIS (2003) was a commercial ergonomics tool also created for the development of vehicles and cockpits, which analyses reach, sight and fit capabilities and well as postural comfort.

Other similar software packages developed outside the aerospace industry included WERNER, ANYBODY, APOLIN, CYBERMAN and ERGOSPACE and MINITAC (which, according to Porter et al (1994), was only suitable for evaluations in heavy working conditions). All these packages have anthropomorphic databases based on various nationalities.

There are packages, including CREW CHIEF and COMBIMAN that extended their capabilities further towards a static biomechanical analysis of the forces and stresses experienced by the human model. ERGOMAN and ERGOSHAPE provided an evaluation of postural stress resulting from vertical loads, whereas MANNEQUIN, a commercial package developed by HUMANCAD, enables various joint torques to be calculated. TADAPS, based upon ADAPS, predicted compression and shear forces for the intervertebral disc (L5-S1) for various postures and external loads. ADAPS (2003) was created, and was currently used for academic purposes, at the Faculty of Industrial Design Engineering at the Technical University of Delft (TUD). This software enabled the user to choose a percentile range of population sizes, to manipulate the manikin into various postures, assess reach and sight capabilities of the hands and feet, as well as look at the field of view of the manikin.

SAMMIE, SAFEWORK and JACK were software packages that have been commercially developed for general-purpose use. They all provided the option to simulate human motion through animation. SAMMIE (2003), originally developed at both Loughborough and Nottingham Universities and owned by SAMMIE CAD Ltd, had a large database of anthropomorphic information on size, shape, postures, weight of segments, joint ranges and CoG of segments (Porter et al, 1994). It also had the capacity to evaluate both the kinematics of the human model and it's working environment with regard to fit, reach, vision and collision detection (Porter et al, 1999). SAMMIE has been used for many industrial ergonomic assessments, for example, computer, tram, car and cockpit workstation layouts, (Porter et al, 1994 and

1999), where its advanced options such as reach envelopes and field of view of reflective surfaces has proved to be invaluable.

SAFEWORK (2003) had similar features to that of SAMMIE, including clothing and virtual reality modules. The clothing module contained a library of various garments that could be customised, for example helmets and backpacks, where the weight and functional limitations on the human model created by the garment, such as a decreased joint movement of the appendages can be calculated. The virtual reality module allowed the user to visualise and move through the geometric design. Using a head display and gloves the user could experience the environment or product created while being a chosen percentile size. The movement of the user steers the movement of the manikin, when using the helmet and the gloves.

JACK had similar attributes to both SAMMIE and SAFEWORK, including virtual reality capabilities. JACK (2003), however, also provided the user with the option of constraining or deactivating specific activities, known as 'behaviours'. This option enabled certain body segments to be constrained to a geometric entity representing an artefact, so that no matter how the dimensions or location of the artefact is modified the segment will still remain attached. It also enabled the user to chose which body segments that are likely to move when these constraints are activated, for example, the location of the CoG in relation to the feet or the behaviour of the torso when reaching for an object with an arm. This option relies solely on the user's knowledge of human movement, which could cause errors during interpretation.

6.2 Biomechanical computer models

There were computer human models that focused more on the biomechanical analysis of a human. SIMM, for example, was a commercial graphics based software that was designed solely to enable users to create and analyse musculoskeletal models. It was used to analyse surgical procedures and causes of movement abnormalities. According to Delp and Loan (1995), the external three dimensional form of a bone can be imported into SIMM using methods such as computer tomography (CT), magnetic resonance imaging (MRI), or using skeletal files where the data is already predefined. The user must then specify the kinematics of the joints and the points at which the tendon-muscles are attached to the skeletal structure. The analysis of each muscle could be made through the computation of its length, moment arms, force and joint movements. Motion files could be imported into SIMM which were created through motion analysis systems, to visualise and animate a skeletal model. If the motion file includes electromyographic (EMG) data, then the animation displays the level of activation of the muscle through changes in thickness and colour. Comparisons of moment arms coul be made between either a moving joint centre or a fixed joint centre.

The development of the model, created within SIMM, depended upon the reliability of the data providing the skeletal structure. It was also restricted by the definition of the muscles that are often more complex than singular attachments, and the pre-definition of joint movement. SIMM did not incorporate the facility to access the human model's interaction with the external environment and was therefore not suitable for the development of conceptual designs, when simulating a movement task and postural stability.

LIFEMOD (2003) was also a biomechanics modelling software based on the mechanical simulation package ADAMS (2003) and was developed by the Biomechanics Research Group Inc. LIFEMOD has been used to develop orthopaedic designs, joint replacement prostheses, sport equipment and simulate both human movement and injury. It contained a database of all the bones of the human skeleton, which are scaleable, with attachable ligaments and muscles that can be overlaid with a skin layer. It could be used to analyse the forces, velocities and displacement experienced by the human model when coming into contact with the external environment, when for example simulating a vehicle crash. Conversely the human model can also be manipulated using motion capture data, derived from a subject, to simulate the effects on the external environment, such as a prosthesis. This software used 'motion agents' that are located on a specific body segment on the model that corresponds to markers placed on a subject. The markers placed on the subject provide information regarding the trajectory of, for example, a body segment that moves the corresponding model segment. This simulation enabled joint movement and muscle elongation to be measured. Although the data obtained from this human model was very useful when designing, for example, an external prosthesis, the movement of the human model depends on information that has to be predefined by subject involvement, which can be time consuming when reiterations of a concept design are necessary.

6.3 Control models

Control models have been solely created with the aim of understanding postural stability of a human maintaining stability while, for example, standing erect and being perturbed mainly by an external force. Even though complex control models, such as Kuo (1995) and Kooij et al (1999), have been developed to integrate multi-sensory feedback from, for example, the accelerations of the head and pressure forces of the feet, with neural time delays. The limited number of rigid links that exclude for example the arms and the movement about one plane only was restrictive. These models have not been developed to evaluate the interaction with the external environment and therefore could not be used to assess stability during conceptual design. They have also been confined to evaluations of stability while maintaining a fixed posture, such as the erect stance. This eliminates the possibility of assessing stability during variable postures or tasks, such as sitting, reaching or standing from a sitting position. It should also be noted that these models have been developed for the research and assessment of postural stability only and are therefore not available for commercial general-purpose use.

6.4 Discussion

Commercial computer models such as SAFEWORK and SAMMIE and have been developed to successfully evaluate the reach, vision, fit and posture capabilities of a human model within a variable environment. Although these packages provided a useful tool when evaluating conceptual designs, their approach restricts the designer into using the animated movements of the manikin predefined into the program. If a modification was made to the design a new animation of the human movement may be required to re-evaluate the design, which can be time consuming due to subject involvement. JACK had the advantage of being able to constraint certain body segments to either be attached to the external environment or to constrain the movement of the CoG relative to the feet, which would be useful when simulating human movement during the creation of a conceptual design. This option however, was limited in the amount of segments and variables that the user is able to activate or constrain.

6.5 A computer manikin developed within SWORDS

The SWORDS constraint based modelling program was originally developed as RASOR at Brunel University in 1986. It is a software tool that can be used to develop, evaluate and optimise both conceptual and existing designs comprising of moving components. Although, it is mainly used for the optimal design of machines in the manufacturing industry, as described by Leigh et al (1989) and Medland et al (1995).

A collaboration between the creators of SWORDS, currently based at the University of Bath, and the developers of ADAPS, based at the Technical University of Delft (TUD) has enabled the anthropomorphic and joint movement limitation data collected from ADAPS system to be transferred into SWORDS. This has enabled the creation of a research tool where a manikin and an environment can be created to aid both the assessment and development of products for humans, as described by Molenbroek and Medland (2000). Both the software program SWORDS and the manikin representative developed within SWORDS will be described in more detail in the following sections:

6.5.1 The software program SWORDS

The SWORDS software can be used to resolve algebraic expressions in the form of both design parameters and constraints known as rules. The resolution of the rules is to find the optimum solution through the use of variables, which can be changed in order to find the truth value of zero. If a value of zero is found all the rules are considered to be true and thus a solution that fulfils all the constraints is found, as described by Mulleneux (2001).

The rules, expressed as algebraic expressions, are initially grouped and the sum of the rule values is formed. A direct search optimisation strategy is then used, as described by Mulleneux (2001). The search is completed when a minimum value is found, that is close to zero as possible, or when a specified number of iterations have been reached. Variables have to be specified as 'freed' to be used within the search. If it is a model space variable (described in section 6.5.2), it will only be able to rotate or translate according to the axes chosen.

An example provided by Medland et al (1995) describes how constraint rules can be invoked to assemble components represented geometrically. The objective was to fit the three lines shown in Figure 6.1(a) between the points to form a triangle. The constraint rules were initially written such that the end point of each line must lie on the respective points, which resulted in the resolution shown in Figure 6.1(b). Another rule was then invoked to place the points on a specified circle as shown in Figure 6.1 (c). Since the location of the lines were also specified, the resolution caused both the points to lie on the circle and the lines to remain in respect to their relationship, specified by the initial constraint rules described.

(a) (b) (c)

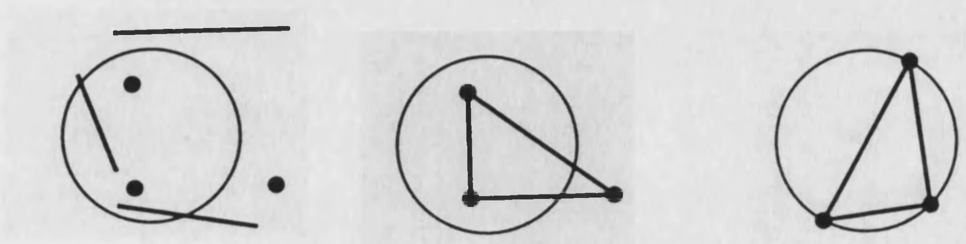


Figure 6.1 Assembly of three lines provided by Medland et al (1995)

A similar approach can be used to design a linkage mechanism. The definition of constraint rules enabled both the motion trajectory, shown in Figure 6.2(a), and the number of pivot points, about which a variable number of linkages may rotate, to be specified. The program can then search for standard components that form viable design resolutions and graphically display their motion, as shown in Figure 6.2(b).

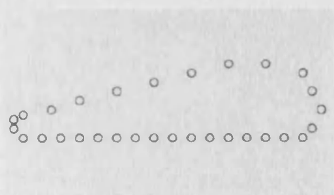


Figure 6.2 (a) Motion trajectory of the mechanism provided by Medland et al (1995)

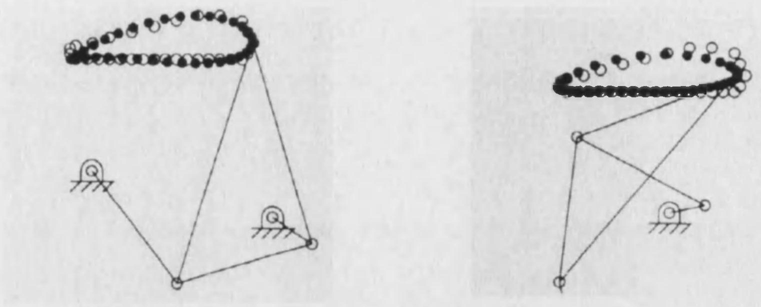


Figure 6.2(b) The selection of a mechanism provide Medland et al (1995)

Likewise, by specifying user design constraints, motion trajectories and standard components, this process can be used for conceptual design, such as a bicycle shown in Figure 6.3. Considering that the decision to invoke various design constraints is variable according to the design, a variety of conceptual design resolutions can be sought, as shown in Figure 6.4, for the variety of human sizes, such as a child shown in Figure 6.5.

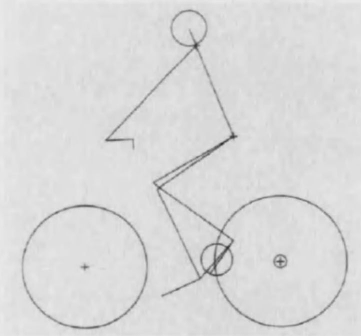


Figure 6.3 Conceptual design of a bicycle provided by Medland and Mullineux (2000)

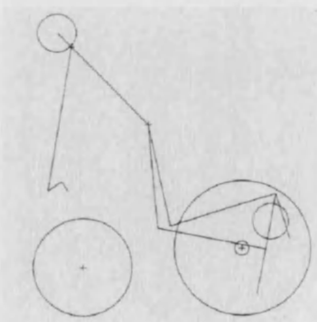


Figure 6.4 Variable conceptual design of a bicycle provided by Medland and Mullineux (2000)

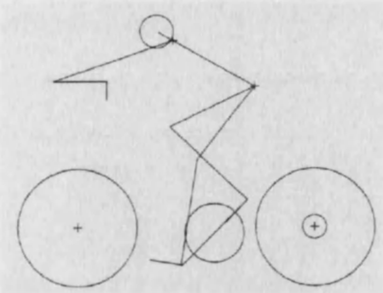


Figure 6.5 Design solution for a child rider provided by Medland and Mullineux (2000)

A similar approach has been explored at Loughborough University to aid 'inclusive design' as described by Goonetilleke et al (2003). Where the constraint based modeller SWORDS is being used to find the optimum design parameters to maximise the user population. HADRAIN, a prototype software package that contains a database of 100 people of a wide range of ages and abilities, is integrated with SWORDS via mathematical analysis software for this purpose.

6.5.2 Model spaces

The interactive software environment within the SWORDS program uses a similar language to that of C and BASIS that allows the creation of geometric entities. This is done by assigning entities, in the form of lines, circles or arcs, to simulate the geometric form of a component in wire frame or a solid block. The geometry of each component can be assigned to either a global space environment, or to a local space, known as a 'model space'. Each model space can be related or 'embedded' into another in the form of a hierarchical tree, such that each model space, or node, along the tree is transformed in relation to the former, in which it is embedded. An example of this is provided in Figure 6.6, which shows a graphical representation of a typical model space hierarchy. The root of the tree is the only link, which transforms its model space in relation to the world space, such that any transform made to the root model space will normally be reflected along the hierarchy.

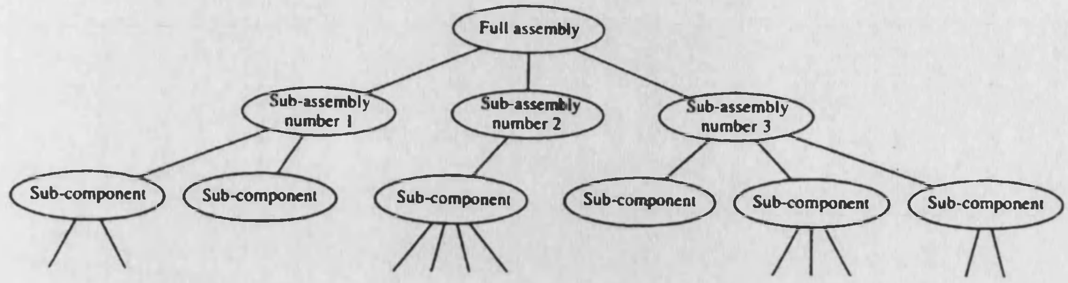


Figure 6.6 A typical model space hierarchy provided Leigh et al (1989)

A model space has nine degrees of freedom, which are translational, rotational and scaling. The user is able to specify, through the interactive language, both the degrees of freedom of each model space and consequently the movement of the geometric entities held within a specific model space. These degrees of freedom are variables that can be manipulated by constraint 'rules'. These rules can, for example, be used to constrain the movement of an entity or model space such that it pivots, rotates or moves linearly about, along or between given positions.

6.5.3 The manikin

The computer manikin representative is made up of a series of functions written and contained within separate files within the SWORDS program, that are activated by reading a specific file into the SWORDS graphics interface. These functions contain data pertaining to an individual's segmental lengths, external body dimensions, their range of joint motion and the geometric entities that represent external artefacts with which the manikin representative interacts. Certain functions are activated through a windows menu that calculate static stability and manipulate the manikin into either a static posture or a series of postures, which may be invoked through the use of constraint rules.

When the main file is read into the SWORDS program, a wireframe representative of the human manikin is graphically displayed along with the windows menu, shown in Figure 6.7.

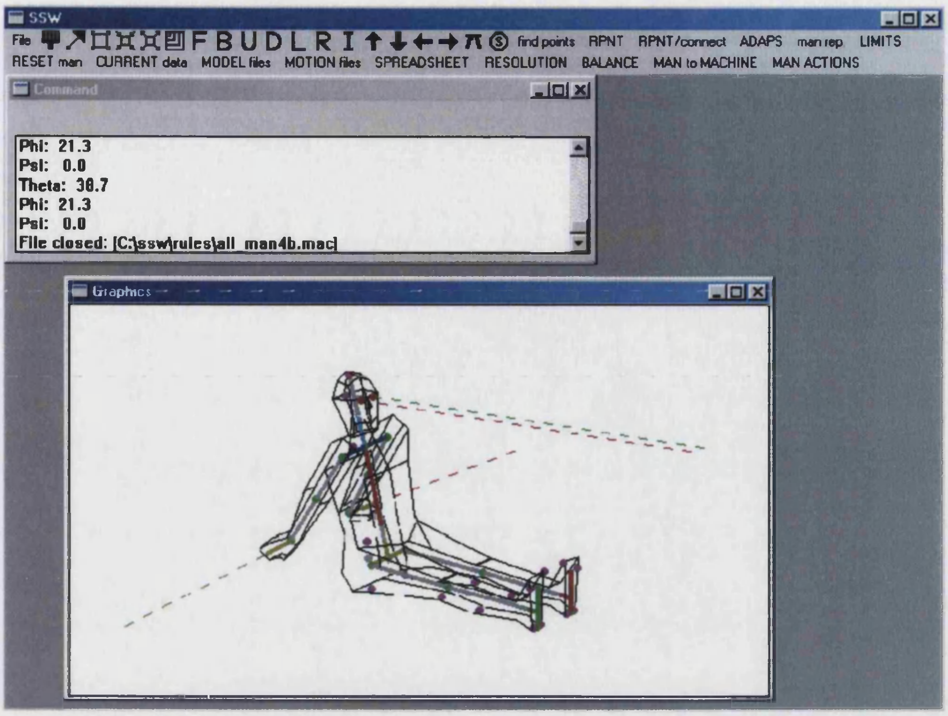


Figure 6.7 Graphics interface of manikin representative created in SWORDS

6.6 The skeletal structure

The structure of the computer manikin developed in the SWORDS program was based on the computer manikin developed at the Technical University of Delft as described by Molenbroek and Medland (2000). The original model was developed as a stick model, by Prof. Tony Medland at Bath University, where each body segment is represented by rigid links, shown in Figure 6.8. This model consists of 25 rigid links and 23 pivot points. The length of each link can be variable according to either the anthropomorphic data provided by Delft University or to the individual dimensions of a chosen subject. Each link is connected by a pivot joint that represents a bony articulation. This assumes that all body segments are rigid and that the rotation of each articulation acts about fixed axes.

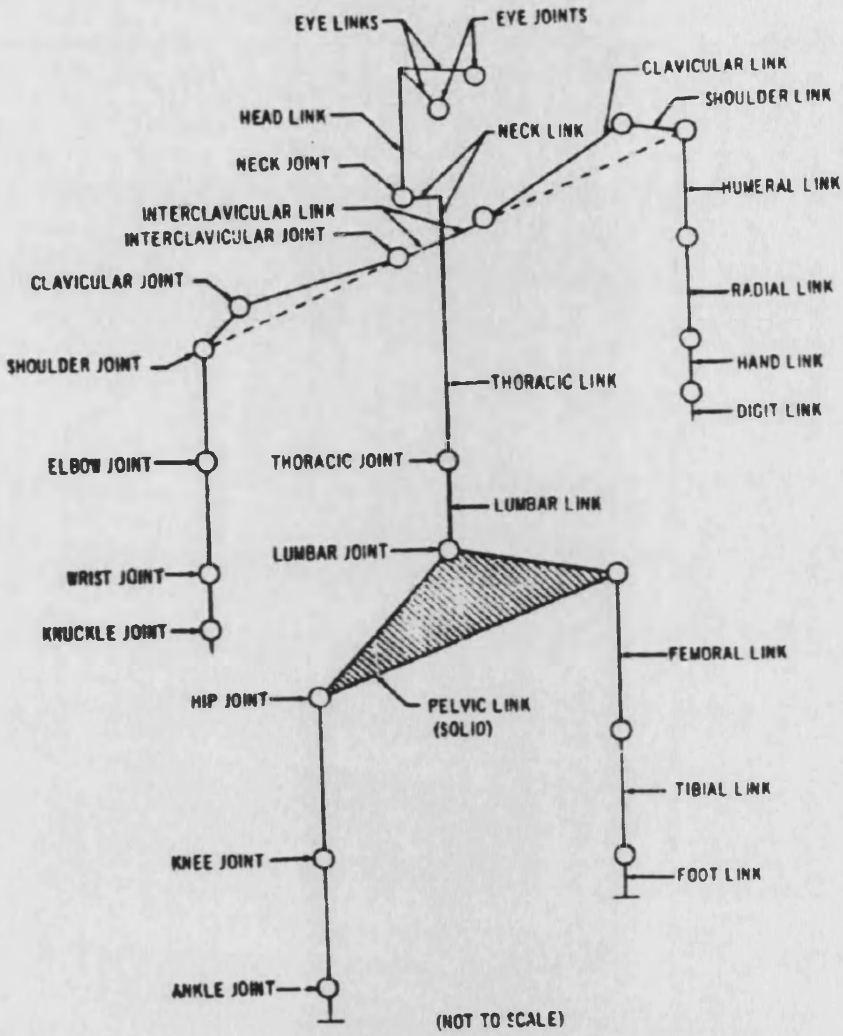


Figure 6.8 Diagram of rigid links representing the human skeletal structure provided the Technical University of Delft, ADAPS (2003)

The geometrical attributes of each body segment were allocated their own local model space. Each local model space was embedded into the local model space of the connecting segment. This allows the embedded segment to be transformed in relation to the neighbouring segment. For example, model space 'right_hs', containing the geometric attributes of the right hand, is embedded into the model space 'right_as', containing the attributes of lower arm, as shown in Figure 6.9. When the right lower arm moves, the right hand is moved with respect to the lower arm according to its rotations and transformations. The model spaces that contain the entities of each body segment are arranged such that the upper and lower body segments are held within two hierarchical trees, where the outer most nodes of the upper body and lower body are found at the hands and at the feet, respectively. The model space 'zpelvis_ *s*', denotes the root of both hierarchical trees, which are linked or transformed to the global space. The only difference between the skeletal structure integrated from the ADAPS model, shown in Figure 6.8, is that the clavicular link has been excluded in the model shown in Figure 6.9.

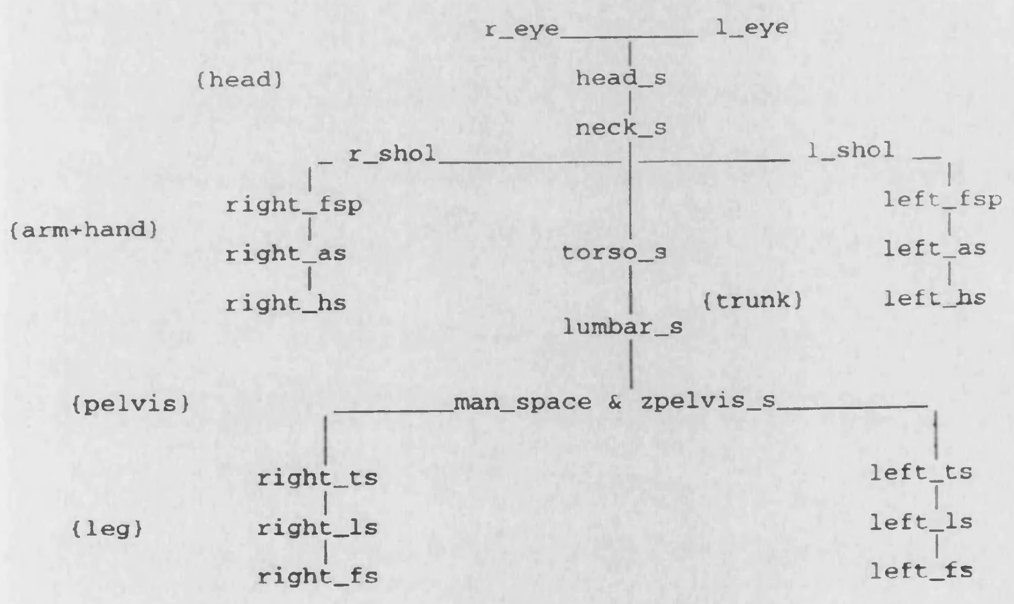


Figure 6.9 The model apace hierarchy containing the geometric attributes of the human form in SWORDS

6.6.1 The wireframe structure

The wireframe structure of the manikin was based upon a 50^{th} percentile Dutch man provided by the University of Delft in the form of reference points. Each reference point, denoted by Cartesian co-ordinates, was embedded into the respective segmental model spaces. The wireframe was constructed using constraint rules that produced lines joining each point respectively, as shown in Figure 6.11. Body measurements taken from individual subjects, are graphically displayed as points on the manikin, as shown in Figure 6.10, which are referenced from the joint articulations. These measurements are more comprehensively defined in Chapter 8.

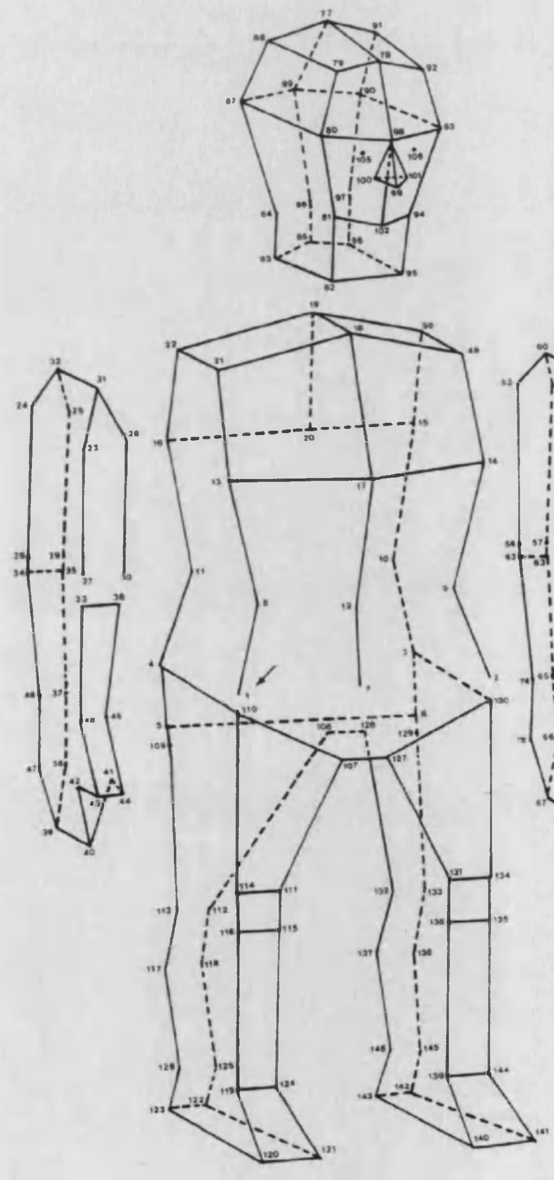


Figure 6.10 A schematic representative of the 50th percentile Dutch man provided by the University of Delft, ADAPS (2003)

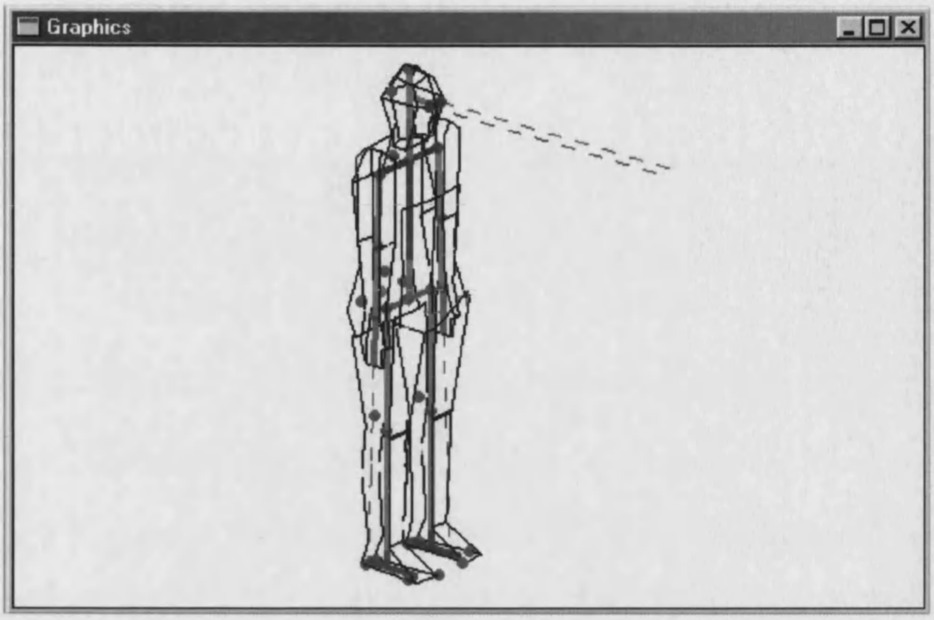
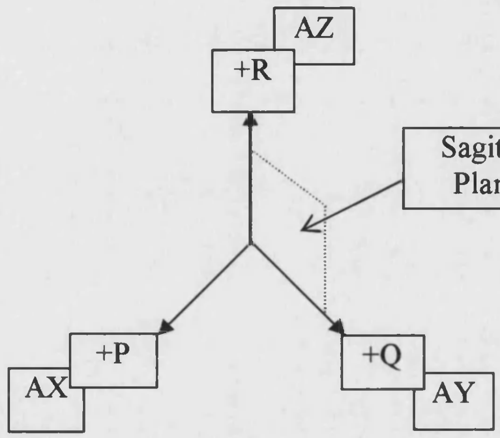


Figure 6.11 Wire frame structure of the 50th percentile Dutch man incorporated into the Swords program

6.6.2 Joint range of movement

The human skeletal system is joined together by tendons, ligaments and muscle. The point at which each bone is joined together is known as an articulation. There are three types of articulation, known as the synarthrodial, the amphiarthrodial and the diarthrodial or synovial joint, as described by Hall (1995). The synarthrodial articulation does not display any movement and is therefore considered as immovable, such as that found in the skull. The amphiarthrodial has slightly more movement, such as the pubic symphysis when the female pelvic girdle opens slightly to aid childbirth. The diarthrodial or synovial articulation is freely moveable and is categorised according to the one, two or three axes of rotation, referred to as uniaxial, biaxial and triaxial, respectively.

The range of movement of an articulation is measured rotationally about three imaginary axes, which are perpendicular to three imaginary planes used describe body movement. These axes are known as the transverse (or frontal axis), which is perpendicular to the sagittal plane, the sagittal axis, which is perpendicular to the frontal plane and the longitudinal axis, which is perpendicular to the transverse plane. To simplify the manipulation of the computer manikin by the designer, that may not be familiar with biomechanical terminology, the axes of rotation and translation are referenced as cartesian co-ordinates as shown in diagram 6.12. Even though certain joints, according to Lundberg (1997), do not have a fixed centre of rotation, it is assumed that all joint centres are fixed for the purpose of this research.



- Translations along respective axes = R, P, Q
- Rotations about respective axes = AX, AY, AZ
- '+' = positive direction

Figure 6.12 Cartesian co-ordinate system used to manipulated the manikin

When designing or evaluating assistive aids the range of movement of the individual must be taken into account, considering that the range of joint movement can be highly variable according to age or the degree and type of disability.

To simulate the actual range of movement of each joint each model space, containing the attributes of each body segment, was given an upper and lower boundary limit of rotation about specific axes. The boundary limits restrict the rotation of each body segment, contained within a model space, about all the possible axes, which a joint may actually pivot. The limitations of the range of joint movement of a 50th percentile Dutchman, shown in Figure 6.13, was provided by Delft University in the form of an excel spread sheet, which was used to form the upper and lower boundary limits. These boundary limits can be altered so that the range of motion of an individual can be simulated.

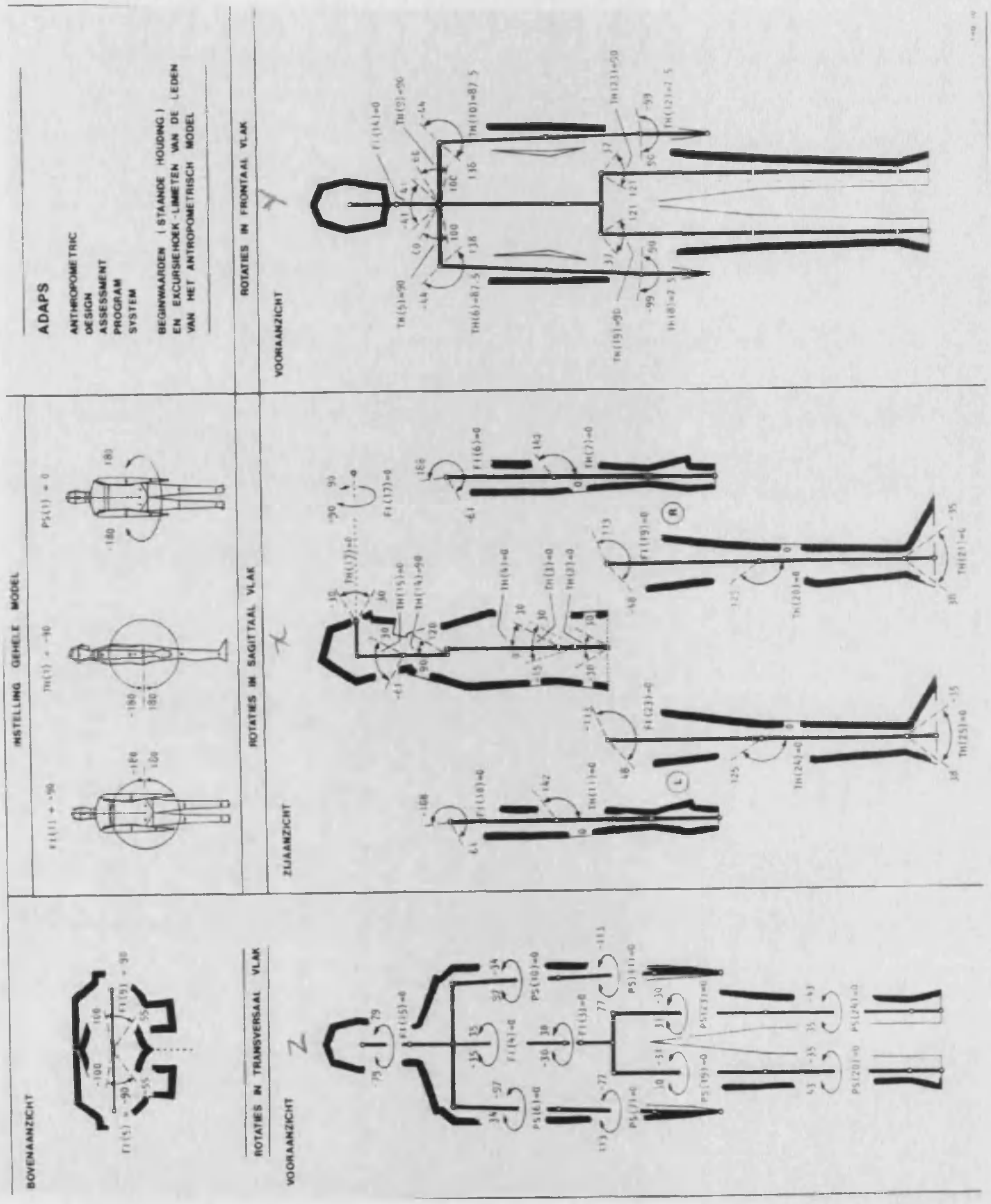


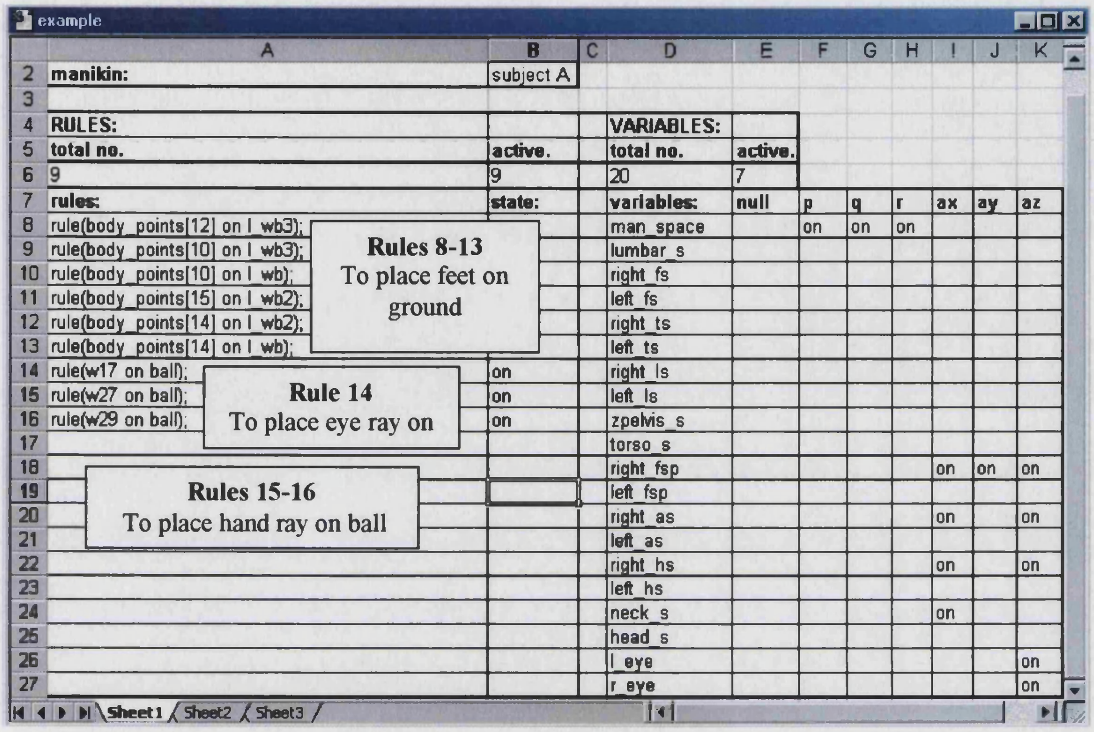
Figure 6.13 Range of joint movement of a 50th percentile Dutch man provided by the Technical University of Delft, ADAPS (2003)

6.6.3 Manipulation of the computer manikin

The posture of the SWORDS manikin can be manipulated through the use of constraint rules and model space variables, which can be accessed via a Excel spreadsheet read into the SWORDS program, as shown in Figure 6.14. The left column 'A' of the spreadsheet shows a list of the constraint rules and the right column 'D' the list of variables, which are the model spaces that contain the geometric entities of the body segments. Each model space can be invoked to move either linearly along p, q or r, or rotationally about the x, y z axes (as shown previously in diagram 6.12) by typing in the command 'ON' in the respective column and row in the excel spreadsheet. The user is able to choose the rules that constrain the movement of the manikin or add their own rules. To invoke the rules the command 'ON' has to be typed in column B at the side of the rules listed in the respective row.

Before the manikin can be manipulated into a posture it is initially placed in a neutral position, shown in Figure 6.15. This is where all model spaces are equal to zero, with the exception of the left and right arm model spaces, which are rotated 2.5 degrees about the 'q' axis, before the rules are invoked.

To manipulate the movement of the manikin, for example, to point and look at a chosen geometric entity, such as a ball, while standing. Rules can be written to place points, embedded in the model space representing the feet, to be placed on lines placed on the ground, as shown in Figure 6.14. Similarly the eye and hand rays can be manipulated to be placed on the ball, shown in Figure 6.16. The model space variables that contain the geometric entities representing the body segments, in this case, the right arm, neck, pointing and sight rays can be selected to rotate or translate about selected axes.



	A	B	C	D	E	F	G	H	I	J	K
2	manikin:	subject A									
3											
4	RULES:			VARIABLES:							
5	total no.	active.		total no.	active.						
6	9	9		20	7						
7	rules:	state:		variables:	null	p	q	r	ax	ay	az
8	rule(body_points[12] on l_wb3);			man_space		on	on	on			
9	rule(body_points[10] on l_wb3);			lumbar_s							
10	rule(body_points[10] on l_wb);			right_fs							
11	rule(body_points[15] on l_wb2);			left_fs							
12	rule(body_points[14] on l_wb2);			right_ts							
13	rule(body_points[14] on l_wb);			left_ts							
14	rule(w17 on ball);	on		right_ls							
15	rule(w27 on ball);	on		left_ls							
16	rule(w29 on ball);	on		zpelvis_s							
17				torso_s							
18				right_fsp					on	on	on
19				left_fsp							
20				right_as					on		on
21				left_as							
22				right_hs					on		on
23				left_hs							
24				neck_s					on		
25				head_s							
26				l_eye							on
27				r_eye							on

Figure 6.14 Excel spreadsheet showing rules and model space variables used to manipulate manikin

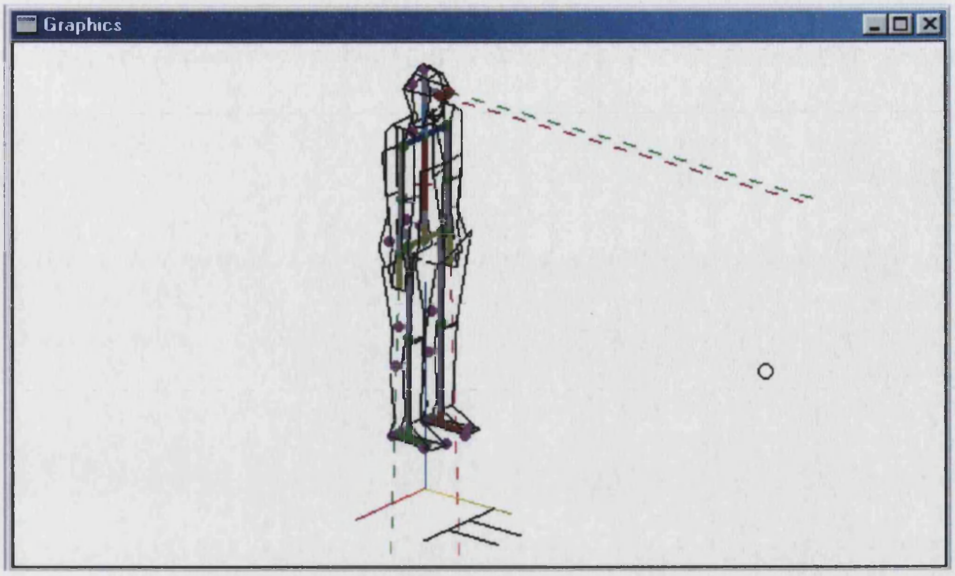


Figure 6.15 Graphical representation of manikin placed in neutral position

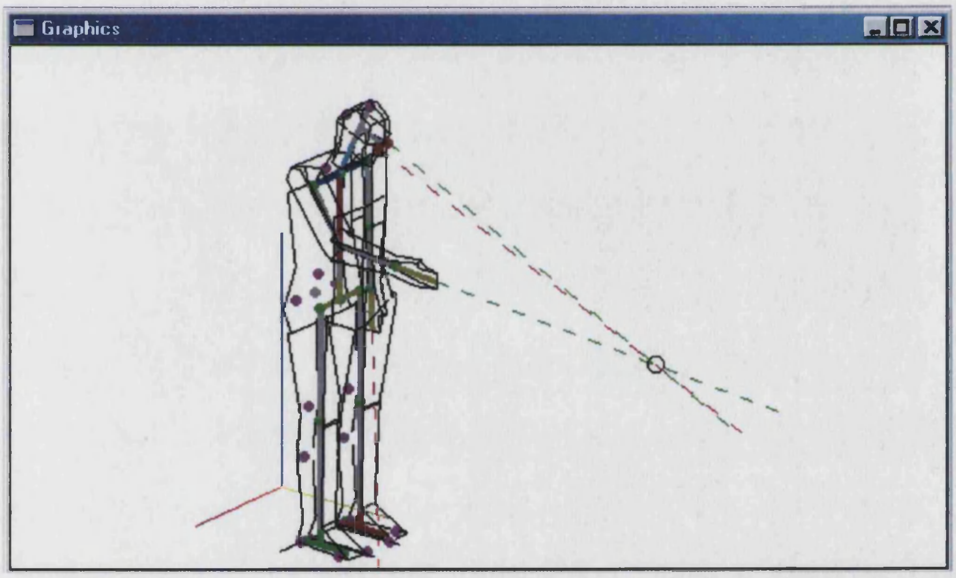


Figure 6.16 Manikin pointing and looking at ball while standing

The advantage of employing the manikin created in SWORDS, is that the designer is able to modify the geometric representative of the conceptual design, in this case the height of the ball, as shown in Figure 6.17, by invoking the same constraint rules and variables. This enables the evaluation of interaction between potential user and the external environment without having to reproduce the posture through individual body segmental manipulation, which can, in some cases, be time consuming, as discussed by Williams and Medland (2001).

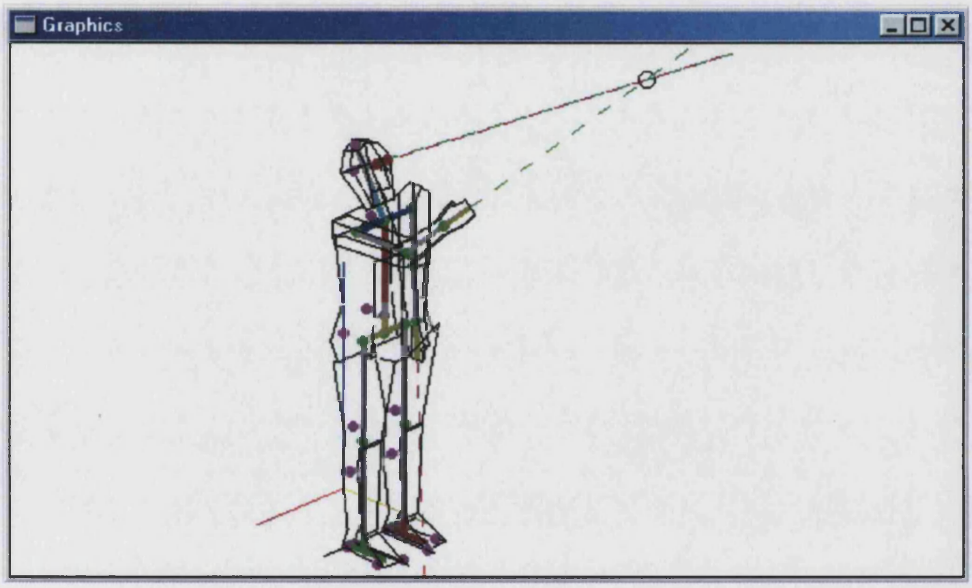


Figure 6.17 Manikin looking and pointing at ball using with modified ball placement

6.6.5 Stability calculation

The calculation of the total body CoM position of the computer manikin is made through the use of the segmentation method, as described in chapter 4. Each rigid link, denoting a body segment, is attributed with it's own individual CoM position, according to De Leva (1996).

The base of support is calculated by four orthogonal lines that pass through the maximum and minimum co-ordinates along on the 'p' and 'q' axes, of any body point defined on the manikin that lies on the 'zero' ground plane. If the vertical line projected from the total body CoM lies within these orthogonal lines a second calculation, written by the author, is carried out. This calculation graphically connects the most outer points placed on the ground plane, which forms the convex hull, described in section 3.5. If the CoM lies within the convex hull the graphics displays a 'BALANCED' statement, as shown in Figures 6.18 and 6.19, conversely a 'UNBALANCED' statement is shown if it lies outside.

Currently the base of support is restricted to the ground plane only for this particular study. However, this calculation can be easily modified, so that any body part of the computer manikin that comes into contact with any support surface, for example a chair, can be included into the base of support calculation.

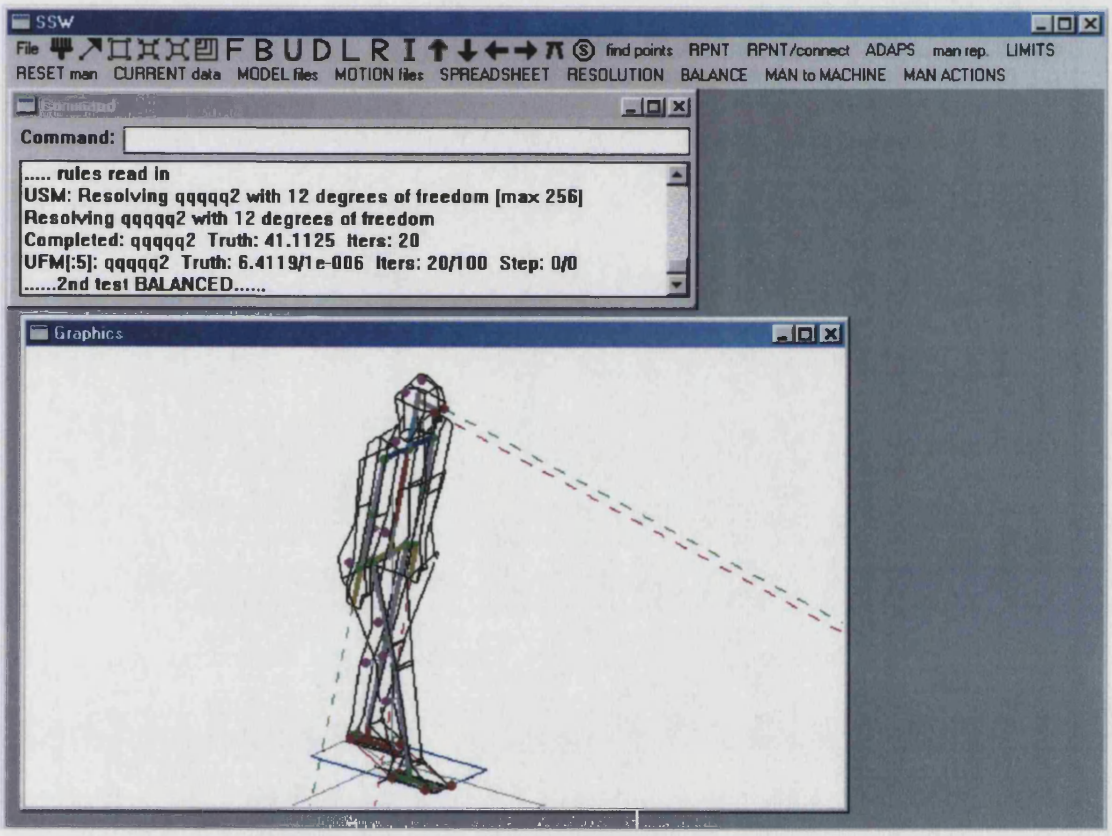


Figure 6.18 Manikin shown to be statically balanced

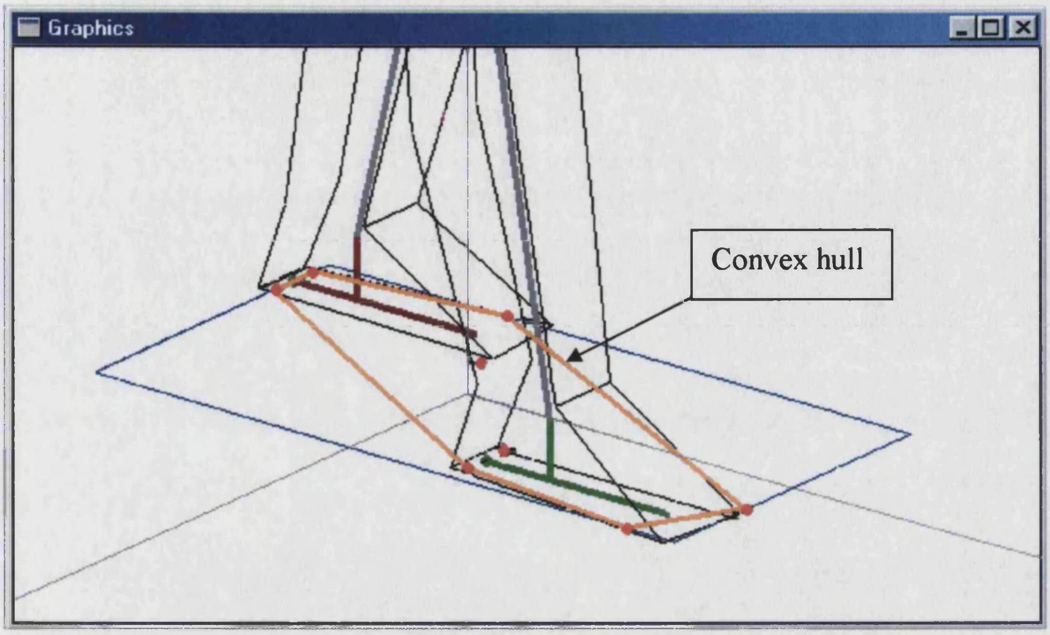


Figure 6.19 Graphical display of convex hull of the base of support form by feet

The stability calculation can also be included as part of the resolution of the constraint rules, which can be used to manipulate the manikin into stable postures.

6.7 Conclusions

The constraint program SWORDS was thus chosen to model stable intermediate movement strategies that will be employed to evaluate and develop a conceptual design of a device to aid stability for the following reasons:

- The option to modify the geometric representative of a conceptual design without having to manipulate the individual body segments into what could be both a complicated posture, which could be time consuming.

- The ability to apply constraints to any part of the human modeller to enable the interaction with the external environment to be analysed without having to reiterate subject involvement could reduce the conceptual design development time.

- The choice of being able to incorporate the stability calculation into the rules being resolved enables stable postures to be sought.

These options, however, rely on the user's knowledge of human movement.

The following chapter describes an experimental study that was carried out to understand and determine the distinctive movement patterns employed by able-bodied people, when rising from a sitting posture. The consistency of these movements has been analysed, along with the experimental findings that have been compared to those found in published in literature.

Chapter 7
Experimental study to define movement strategies employed by able-bodied people

7.0 Introduction

The aim of this experimental study was to identify the distinct movement strategy employed by adult able-bodied people, while rising up from a sitting posture. The results of this study were used to determine whether the strategy defined was repeatable, through comparisons of various subjects and with similar studies published the in literature. The comparisons made with the literature were also used to validate the techniques employed in this experimental study.

7.1 The experimental study

This study was carried out using only three, randomly chosen, able-bodied people, due to their availability. The only female (termed 'subject B' for confidentiality purposes) was aged 37 years, height 1.50 metres and weight 60kg. The two males were of age 24 years, height 1.75 metres, weight 67kg and 41 years, height 1.87 metres and weight 75kg, are referred to as subjects A and C respectively. Each subject reported that they had no physical disabilities and were not taking any prescribed medication prior and during this investigation.

7.1.1 The task

The movement task to be analysed was to rise from a sitting posture to an erect stance and then to recline back to the same sitting posture again. This task was undertaken in a laboratory setting using a chair of adjustable seat height with a depth of approximately 440mm and width of 410mm. The backrest had no curvature, a height of 1020mm (to constrain the initial sitting posture and support of the whole upper body, including the head), a width of 410mm and was reclined at 5 degrees to aid the comfort of the subject during the initial sitting posture. It was decided that no armrests should be included for this study so as to enable comparisons with similar studies published in the literature.

7.2 Procedures

To ensure that the challenge imposed by the task was consistent, in that no subjects were advantaged or disadvantaged by, for example, the chair height, feet placement or head movement, all subjects were requested to follow certain movement constraints. These constraints also enabled comparisons to be made between each subject, are described and carried out in the following order:

The sitting posture, which initiated and terminated the movement task, involved constraining the buttocks and upper thighs on the seat of the chair and the whole of the upper body, i.e. pelvis, lumbar, torso and head, to the support of the backrest of the chair, as shown in Figure 7.1.

The feet were placed parallel to each other, i.e. 15cm distance apart from the inner heels, and the heels were positioned directly underneath the front of the seat of the chair. Each subject was requested to maintain the same feet placement throughout the whole of the movement and for each subsequent trial.

The height of the chair was adjusted to suit the variable leg lengths of each individual to enable them to attain approximately 10 degrees ankle flexion.

The vision of all three subjects was constrained in that they were required to look at a marker, placed 150cms from the edge of the seat at a height of 100cm on the end of pole, throughout the whole of the sit-to-stand-to-sit movement.

The arm placement was such that each subject was requested to relax both arms at their sides throughout the whole of the movement task and to avoid using them to support their body weight.

Figure 7.1 A video frame of the sitting posture, that each subject was requested to undertake before and after rising to an erect stance, as shown by subject A

The video recording of the movement task, chosen due to availability, was carried out using a Panasonic S-VHS, PAL VHS 625 AG-DP200B (50 fields per second, 50Hz), set at a shutter speed of 1000. Studies of the sit-to-stand movement, by Schenkman et al (1990) and Wheeler et al (1984), as mentioned in section 5.4, reported that the differences of movements made between the left and the right side of the body were insignificant. Video observations of all three subjects, prior to this study, showed that the movements of both the left and right body segments to be approximately the same throughout and thus the sit-to-stand movement task was considered to be symmetrical and that all movements predominantly move about the sagittal plane. This study was therefore carried out as two-dimensional and the video camera was thus placed perpendicular to the sagittal plane of movement. A rectangular calibration frame of 200cm in height and 100cm width was used to calibrate the co-ordinates derived using the Peak Performance Technologies, Motion Measurement System, software as described by PeakMotus (2003).

Reflective markers were placed on the right side of the body to define the endpoints of the body segments analysed. These were the observed joint centres of rotation, listed as follows:

- knee
- hip
- shoulder
- elbow
- wrist

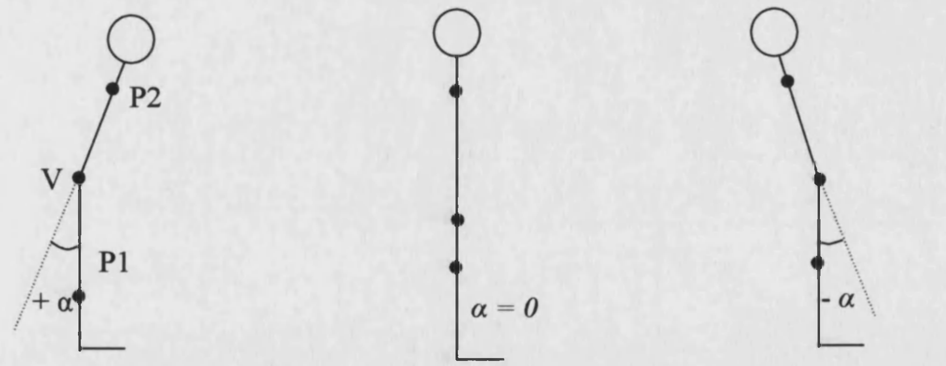
Markers were also placed on the right hand at the end of the third metatarsal and upon the head, vertically above the marker defining the shoulder. Markers originally placed on the heel and the fifth metatarsal to define the right foot, were obscured by the base of the chair, were subsequently placed on the top of the third metatarsal and at the lateral side of the heel. The ankle marker was placed on the lateral malleolus.

The subjects were requested to start at the initial sitting posture, previously described and shown in Figure 7.1, rise to a standing position, remain standing until instructed, and return to the initial sitting position. Each person was instructed to pause for an undefined period of time to ensure that that the erect stance was gained before reclining back towards a sitting posture. The subjects were given the opportunity to practice the task twice, to ensure the instructions were understood, before the task was repeated five times sequentially while video recording the whole of the movement task.

7.3 Analysis

The video recording of each trial, i.e. the period of time prior to the subject rising from the chair and after returning to the sitting posture, was transferred and analysed in the Peak Performances Technologies, Motion analysis software. On the occasions when lighting during the recording of the subject trials was of inadequate quality, a manual digitisation of the joint markers was carried out, otherwise automatic digitisation was employed. Segmental body angles were calculated about the hip, knee, ankle, head and trunk using the motion analysis software. The segmental movements relating to the arm were not analysed as the subjects were requested not to use their arms during this study. The segmental angles were defined in relation to the anatomical body movements defined by Heck et al (1965) and are described in Figures 7.2 to 7.6, as follows.

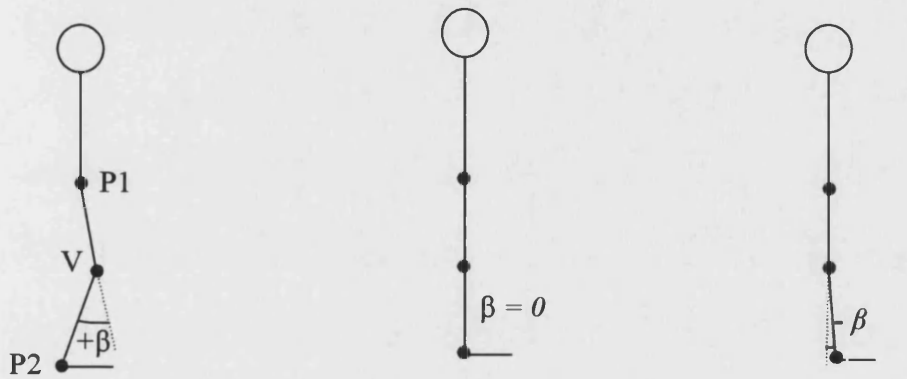
The hip segmental angle (α), shown in Figure 7.2(a), was formed between a line extended from the trunk segment (whose end points are defined by joint centres of rotation of the shoulder (P2) and the hip (V)), the upper leg segment (whose end points are defined as the joint centres of rotation of the hip (V) and the knee (P1)). The neutral position was found when the shoulder, hip and knee joint centres of rotation are in alignment, as shown in Figure 7.2(b). This angle (α) was positive when the trunk is rotated in a clockwise direction from the neutral position, shown in Figure 7.3(a) and negative when rotated in an anti-clockwise direction from the neutral position, as shown in Figure 7.2 (c). The hip segmental angle, shown in Figures 7.2(a) and (c) were equivalent to hip flexion and extension, respectively, as defined in the neutral zero method by Heck et al (1965)



(a) Hip flexion (b) Neutral position (c) Hip extension

Figure 7.2 Diagram to illustrate the definition of the hip segmental angle

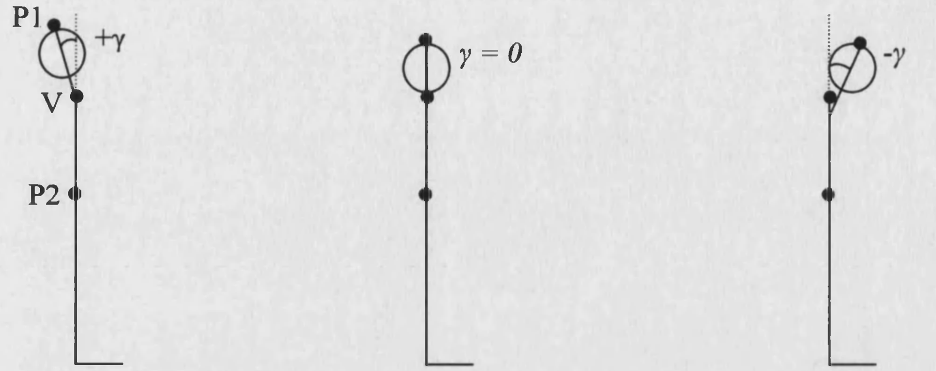
The knee segmental angle (β), as shown in Figure 7.3(a), was defined between the line extended from the upper leg segment (whose end points are defined by joint centres of rotation of the hip (P1) and the knee (V)) and the lower leg segment (whose end points are defined as the joint centres of rotation of the knee (V) and the ankle (P2)). This angle (β), shown to be positive in Figure 7.3(a), was equivalent to zero when the hip, knee and ankle joint centres of rotation are in alignment, as shown in Figure 7.3(b). The knee segmental angle, shown in Figures 7.2(a) and (c) were equivalent to knee flexion and hyperextension, respectively, also defined in the neutral zero method by Heck et al (1965).



(a) Knee flexion (b) Neutral position (c) Knee hyperextension

Figure 7.3 Diagram to illustrate the definition of the knee segmental angle

The head segmental angle (γ), as shown in Figure 7.4(a), was defined between a line extended from the trunk segment (whose end points were defined by joint centres of rotation of the hip (P2) and the shoulder (V)) and the head segment (whose end points were defined as the joint centres of rotation of the shoulder (V) and the top of the head (P1)). The head position was found approximately vertically above the shoulder joint centre of rotation when the head is held upright. This angle (γ) was equivalent to zero when the hip and shoulder centres of joint rotation and head marker were in alignment, as shown in Figure 7.4(b). This segmental angle was positive when the head was rotated in an anti-clockwise direction and negative when rotated in a clockwise direction from the neutral position, as shown in Figures 7.4(a and c) respectively. These respective segmental angles were equivalent to head extension and flexion.



(a) Head extension (b) Neutral position (c) Head flexion

Figure 7.4 Diagram to illustrate the definition of the head segmental angle

The ankle segmental angle (δ), as shown in Figure 7.5(a), was defined between a line extended perpendicularly from the shank segment (P1), and the foot segment (P2). The shank segment (P1) was determined as being from the ankle lateral malleolus (A1) to the approximate joint centre of rotation of the knee (A2). The foot segment end points were defined as being from the third metatarsal (toe) (B1) to the back of the heel of the foot (B2). The ankle angle (δ) was positive when the foot is in dorsiflexion, as shown in Figure 7.5(a), and negative when in plantarflexion, as shown in Figure 7.5(c). The ankle angle was considered to be in a neutral position, i.e. equivalent to the zero, when the two segments are perpendicular to each other, as shown in Figure 7.5(b), again defined by the neutral zero method by Heck et al (1965).

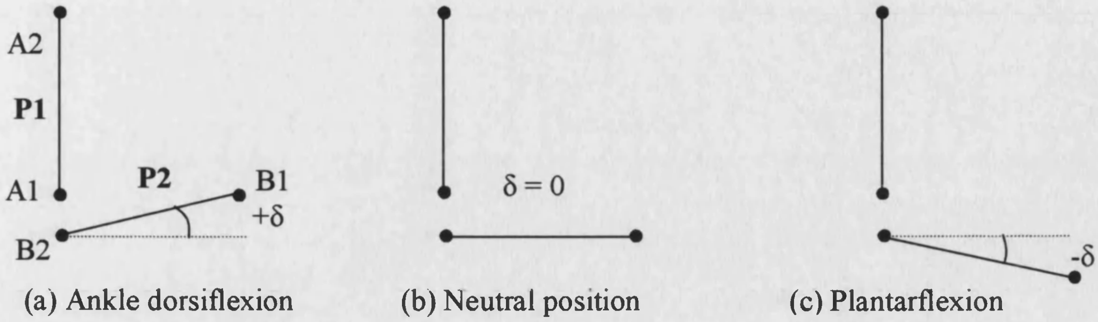


Figure 7.5 Diagram to illustrate the definition of the ankle segmental angle

The trunk angle (ε), which was calculated to make comparisons with equivalent measurements made in literature, was defined as the angle produced between the horizontal X-axis (P1), and the approximate joint centres of rotation of both the shoulder (P2) and the hip (V), as shown below in figure 7.6. All trunk angles were measured in the anti-clockwise direction from the horizontal axis to the trunk segment and are considered positive.

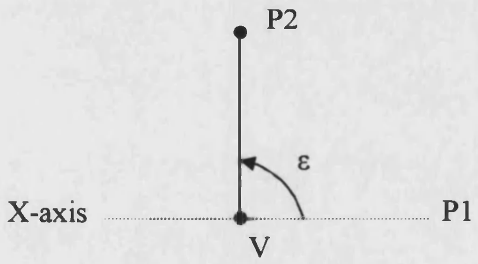


Figure 7.6 Diagram to illustrate the definition of the trunk segmental angle

7.4 Results

The sequence of the gross body movements used by all three subjects was analysed to define the movement phases when rising and reclining to a sitting posture. The gross body movements were determined through the analysis of the segmental angles produced during the five trials carried out by each subject. Comparisons of these findings were then made with similar published studies reviewed in section 5.1.

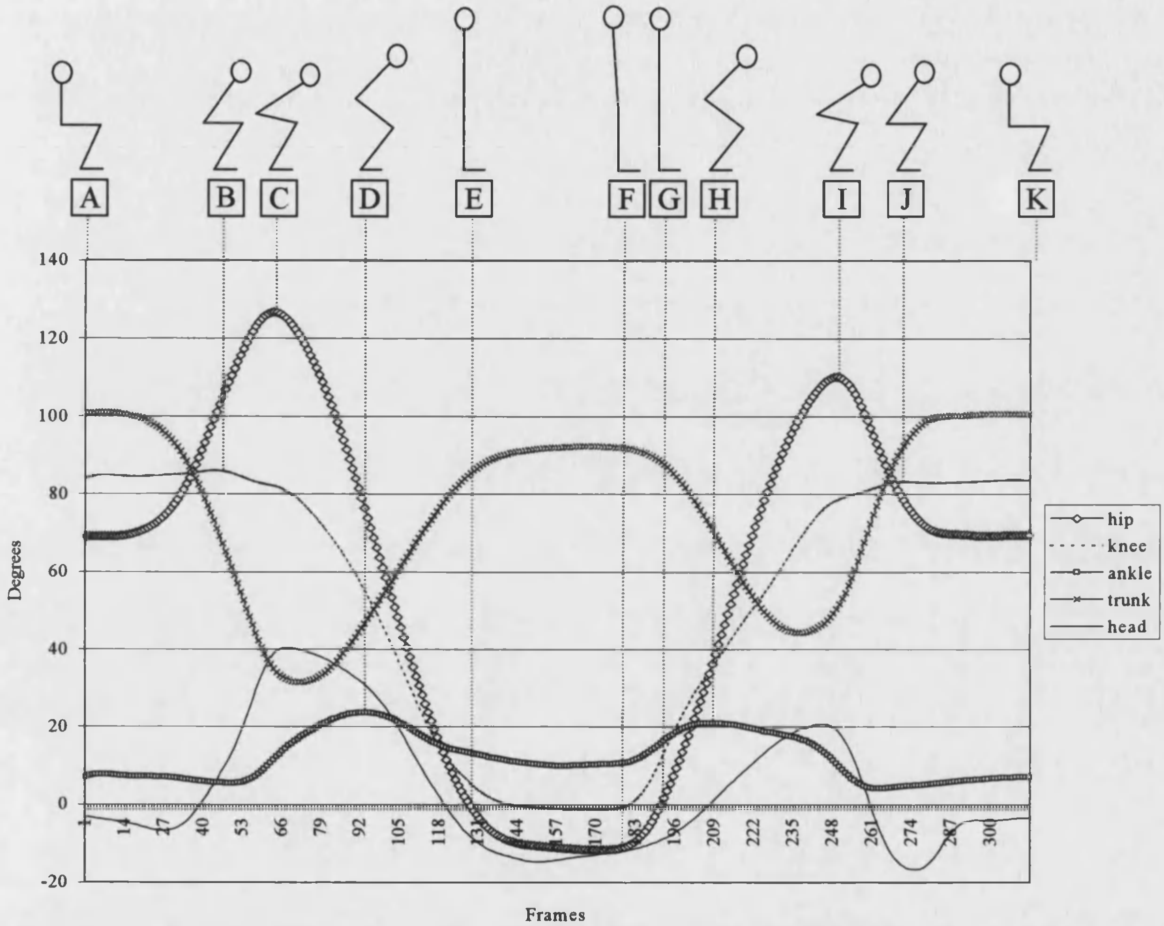
7.4.1 Movement phases employed when rising from a chair

Comparisons of the movement phases employed by all three subjects analysed in this experiment when rising, were found to be very similar to the results published by authors Schenkman et al (1990) and Jeug et al (1991), previously discussed in section 4.1. The movement phases for each subject are defined and illustrated in Figures 7.7 to 7.9. The initial movement phase began with the sitting posture, and all three subjects started the movement task by swaying the upper body forwards. The first phase ends and the second begins just before the gross movement of the knees began to extend and the buttocks were lifted off the seat of the chair, as shown by illustrations 'B'. The second phase was terminated when maximum hip flexion was reached, as shown by illustrations 'C'. This phase was then followed by an almost sequential movement of maximum head extension and trunk flexion, followed by a maximum ankle dorsiflexion, which terminated the third phase, as shown by illustrations 'D'. The erect stance was then attained through the extension of the knees and hips, as shown by illustrations 'E'. During the erect stance the three subject's movement varied slightly. It was thus decided to define the erect stance as beginning when the hip angle was equal to zero degrees, which terminates the end of the task of rising from a chair. After this position was gained, 'Subject A' (Figure 7.7) hyper-extended the hip, i.e. moves the upper torso further backwards than the neutral upright postion, whereas subjects B and C (Figures 7.8 and 7.9, respectively) extended, flexed and again extended both the knees and hips before sitting back down, as shown in illustrations 'F'. All these variations found during the erect stance, after rising, were typical of the slight swaying movements that people make to maintain stability, and can be thus classified as occurring during the 'stabilisation phase' by Schenkman et al (1991), described in section 5.3.1.

7.4.2 Movement strategies employed when reclining onto a chair

All three subjects employed an almost identical pattern of movement when reclining to a sitting posture from standing erect. This was illustrated by the symmetry of the curves shown in Figures 7.7 to 7.9. This pattern of symmetry was also recognised by Anglin and Wyss (1999), during a similar study published in the literature of six healthy subjects over the age of 50 years. The experiment, reported here, showed that in all five trials subjects A and B (Figures 7.7 and 7.8 respectively) flexed both the hip and the knees until maximum dorsiflexion of the ankles were reached, as shown by illustrations 'H'. The hips and knees proceeded to continue flexion, until maximum hip flexion was found, shown by illustrations 'I', knee flexion was terminated and the buttocks were placed back down onto the seat of the chair, as shown by illustrations 'J'. The hip is then extended until the sitting posture was found, shown by illustrations 'K'. Subject C followed a similar pattern of movement, but in all five trials initially swayed backwards, during the flexion of the hips, and then forwards about the ankle joint before maximum ankle dorsiflexion was reached (illustrated as 'Ga' in Figure 7.9). It was thus speculated that subject C initially tried to control the positioning of the buttocks above the seat of the chair, mainly through rotations of the body segments about the hip and ankle alone. To prevent himself from 'falling' backwards onto the chair, the movement was corrected by rotating the body about the ankles in the opposing direction towards maximum dorsiflexion in a similar manner to that of the other subjects. All subjects tended to flex the head slightly more forwards after sitting back down, before extending the their heads backwards onto the backrest of the chair, than when rising upwards. It was speculated that the subjects needed to find the position of the backrest with their upper body first before they regained the initial sitting posture, by placing the back of their heads against the backrest.

Figure 7.7 A typical graphical representation of the sit-to-stand-to-sit movements of subject A

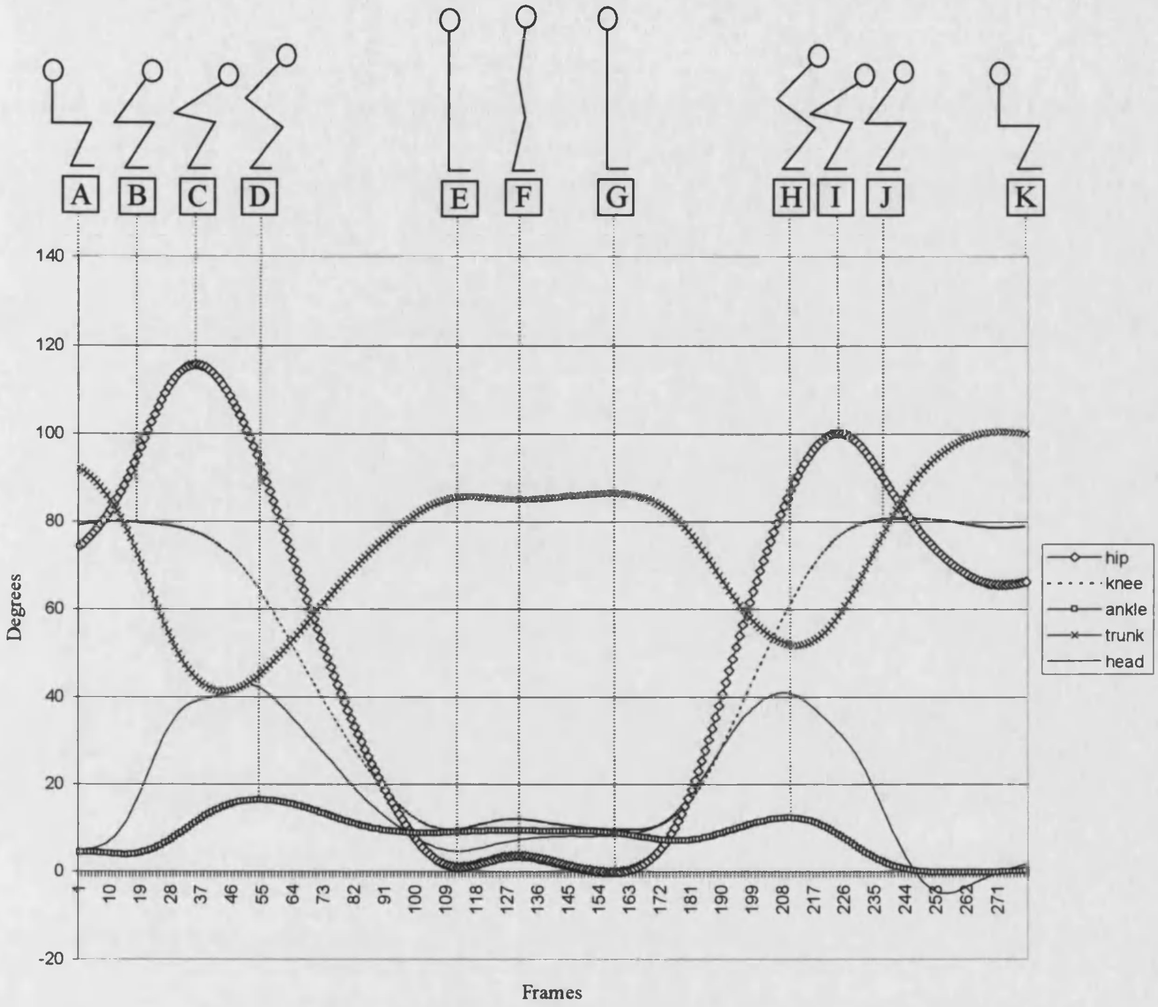


KEY

SIT-TO-STAND
A: Sitting posture
B: Before seat off
(Start of knee extension)
C: After seat off
(Maximum hip flexion)
D: Squat position
(Maximum ankle dorsiflexion)
E: Initiation of erect stance
(Neutral hip position)
F: Erect stance
(hip hyperextension)

STAND-TO-SIT
G: Initiation of erect stance
(Neutral hip position)
H: Squat position
(Maximum ankle dorsiflexion)
I: Before sitting down
(Maximum hip flexion)
J: After sitting down
(End of knee flexion)
K: Sitting posture

Figure 7.8 A typical graphical representation of the sit-to-stand-to-sit movements of subject B

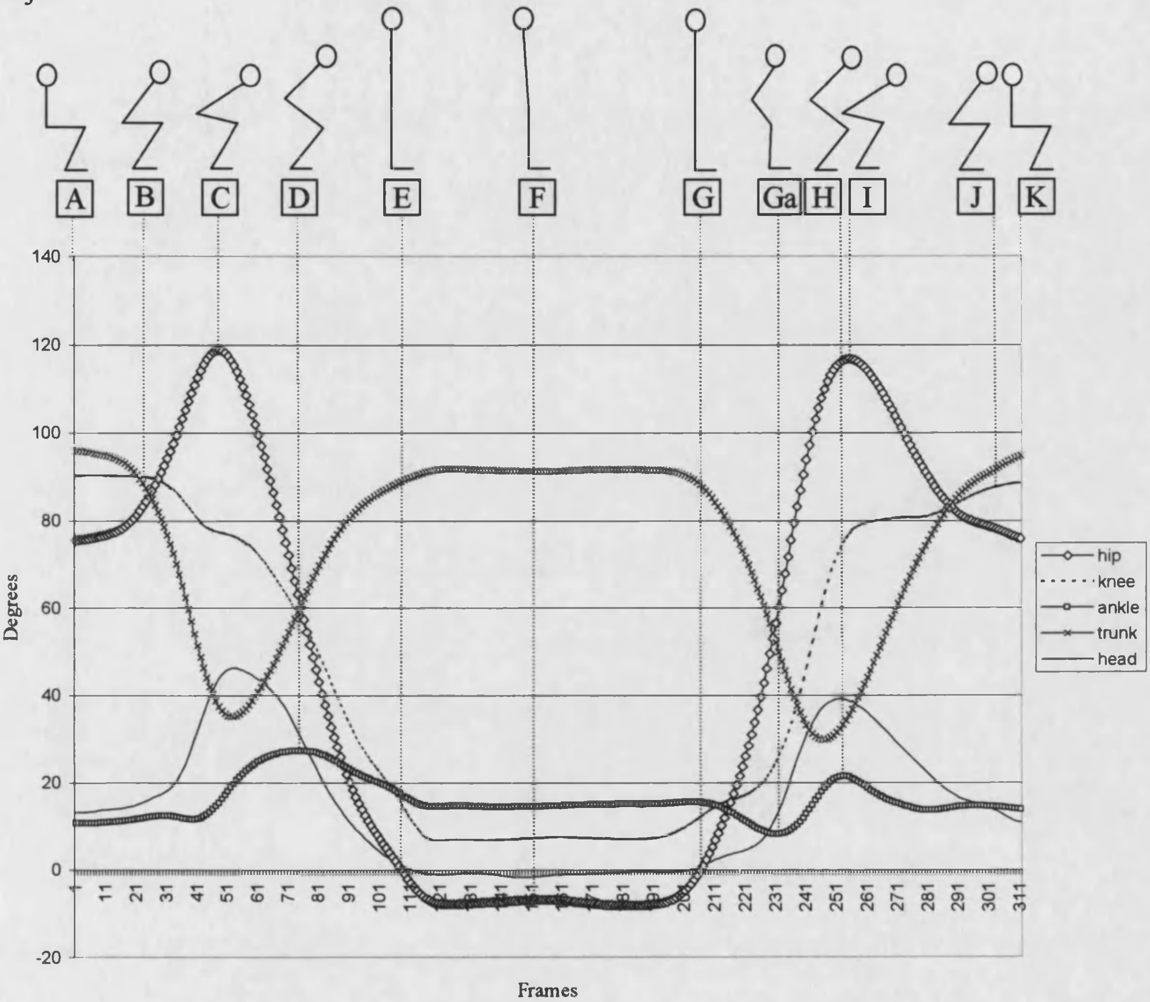


KEY

SIT-TO-STAND
A: Sitting posture
B: Before seat off
(Start of knee extension)
C: After seat off
(Maximum hip flexion)
D: Squat position
(Maximum ankle dorsiflexion)
E: Initiation of erect stance
(Neutral hip position)
F: Erect stance
(hip/knee flexion)

STAND-TO-SIT
G: Initiation of erect stance
(Neutral hip position)
H: Squat position
(Maximum ankle dorsiflexion)
I: Before sitting down
(Maximum hip flexion)
J: After sitting down
(End of knee flexion)
K: Sitting posture

Figure 7.9 A typical graphical representation of the sit-to-stand-to-sit movements of subject C



KEY

SIT-TO-STAND
A: Sitting posture
B: Before seat off
(start of knee extension)
C: After seat off
(maximum hip flexion)
D: Squat position
(maximum ankle dorsiflexion)
E: Initiation of erect stance
(neutral hip position)
F: Erect stance
(hip hyperextension)

STAND-TO-SIT
G: Initiation of erect stance
(neutral hip position)
Ga: Reclining to sitting posture
(ankle plantarflexion)
H: Squat position
(maximum ankle dorsiflexion)
I: Before sitting down
(maximum hip flexion)
J: After sitting down
(end of knee flexion)
K: Sitting posture

7.5 Consistency of movement strategies

This section aims to show that the segmental body movements employed by an individual, when carrying out a prescribed task, are repetitive. The gross movements employed by subject A, during five trials of the sit-to-stand and stand-to-sit task, were thus compared. The gross movements employed during this task were considered to be the hip, knee and head flexions and extension. For comparative purposes the termination of the sit-to-stand movement and the initiation of the stand-to-sit movement was defined by the attainment of the theoretical zero position, for each body segment measured, as defined by Heck et al (1965) This is achieved when the hip, knee and head segmental angles are individually equal to zero. All five trials were also scaled to fit the same number of frames required to complete one of the five trials. An example of this is shown in Figure 7.10, where all five trials were scaled to fit the time duration of 140 frames of 'Trial 1', at a frequency of 50 frames per second. The angle between each body segment, plotted along the y-axis, was not altered so as to enable comparisons of the angular movements produced for trails with variable time scales. This is illustrated graphically in Figures 7.10 to 7.15 below.

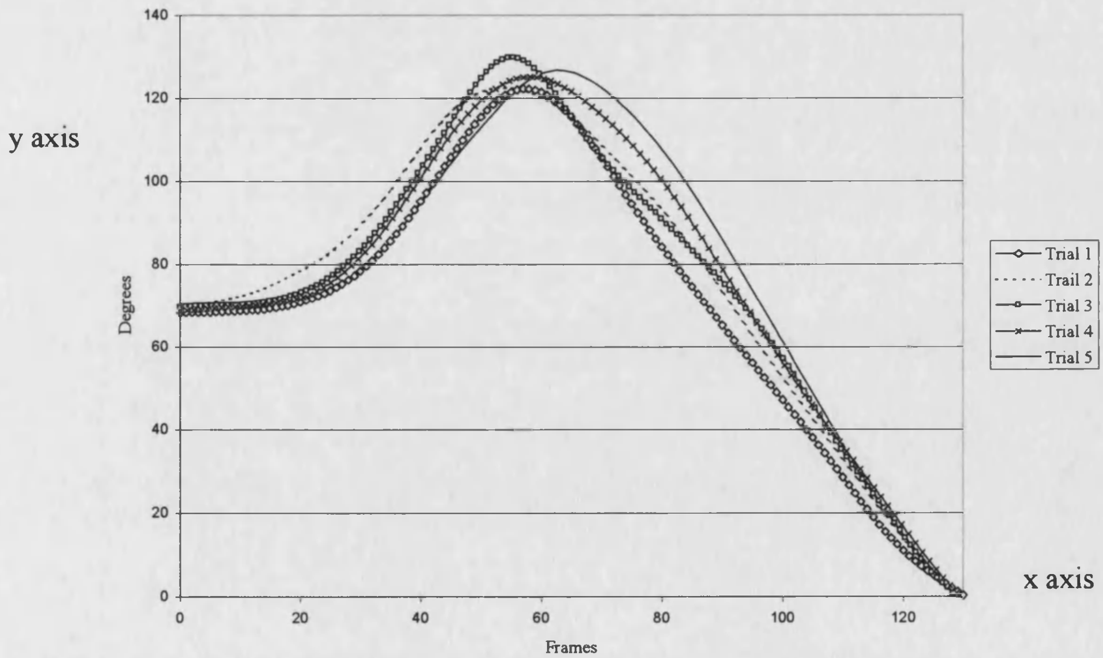


Figure 7.10 Graph of hip flexion and extension produced during five repetitive trials of the sit-to-stand task carried out by subject A

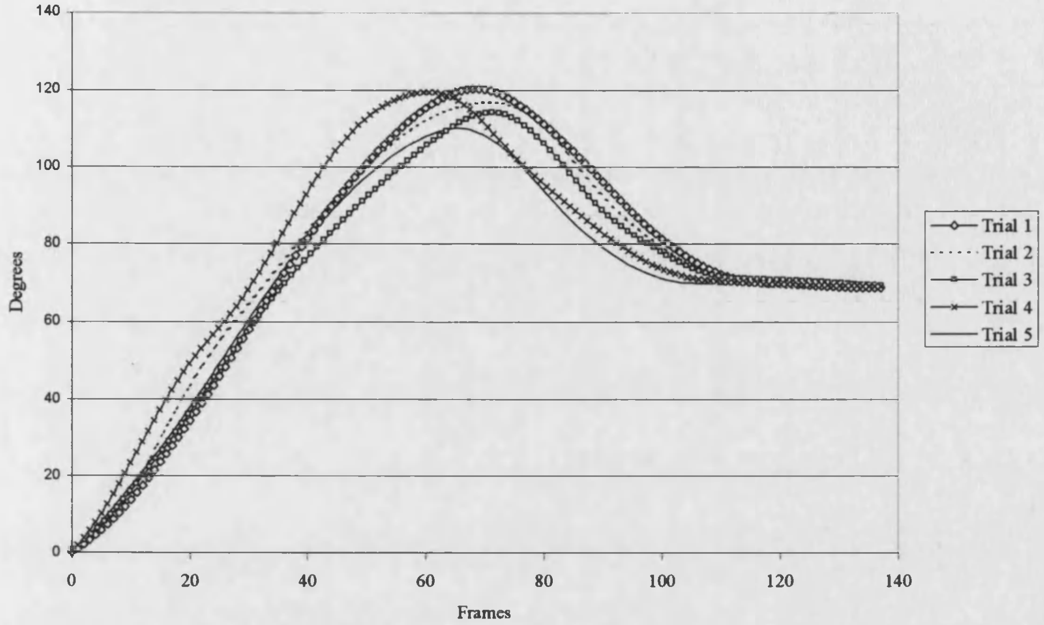


Figure 7.11 Graph of hip flexion and extension during five repetitive trials of the stand-to-sit task carried out by subject A

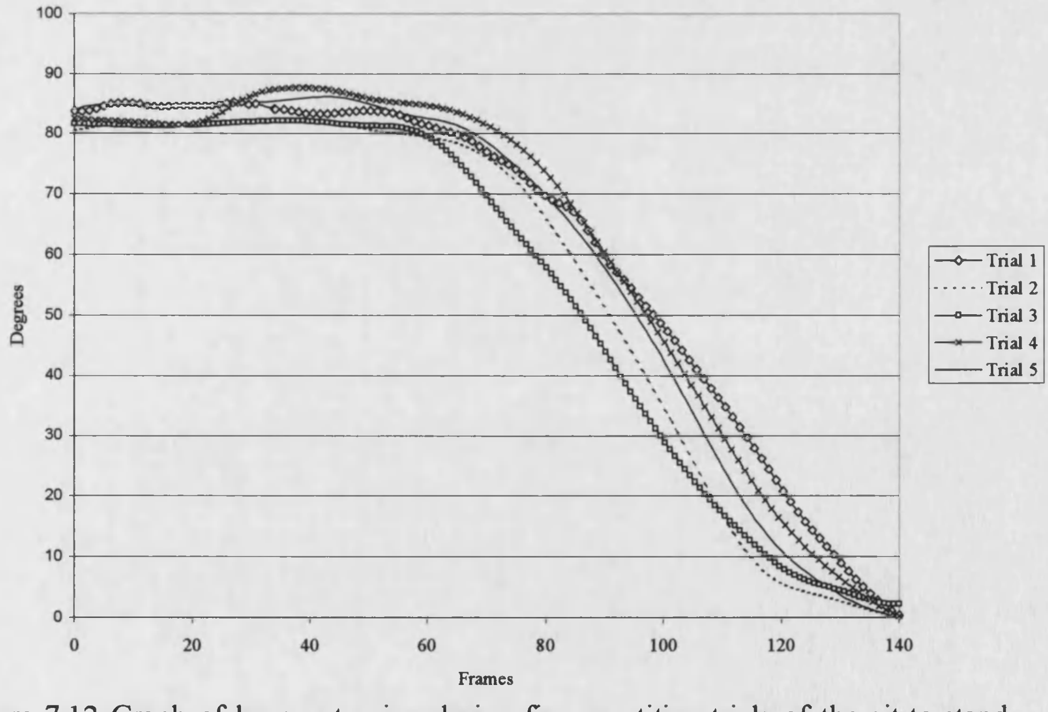


Figure 7.12 Graph of knee extension during five repetitive trials of the sit-to-stand task carried out by subject A

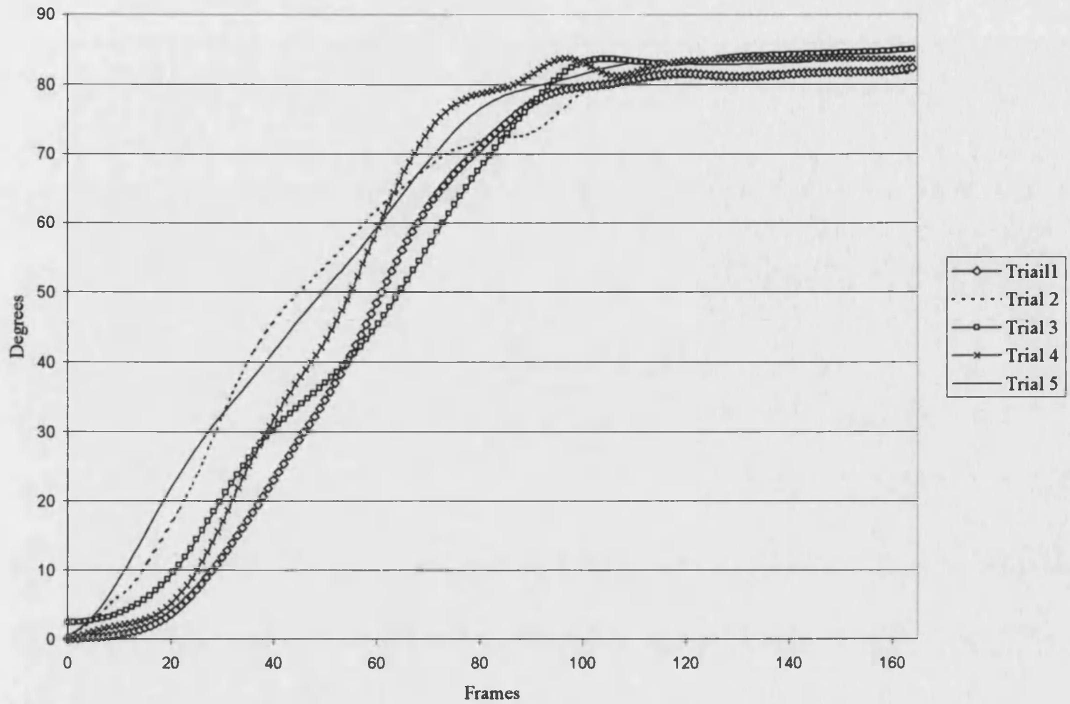


Figure 7.13 Graph of knee flexion during five repetitive trials of the stand-to-sit task carried out by subject A

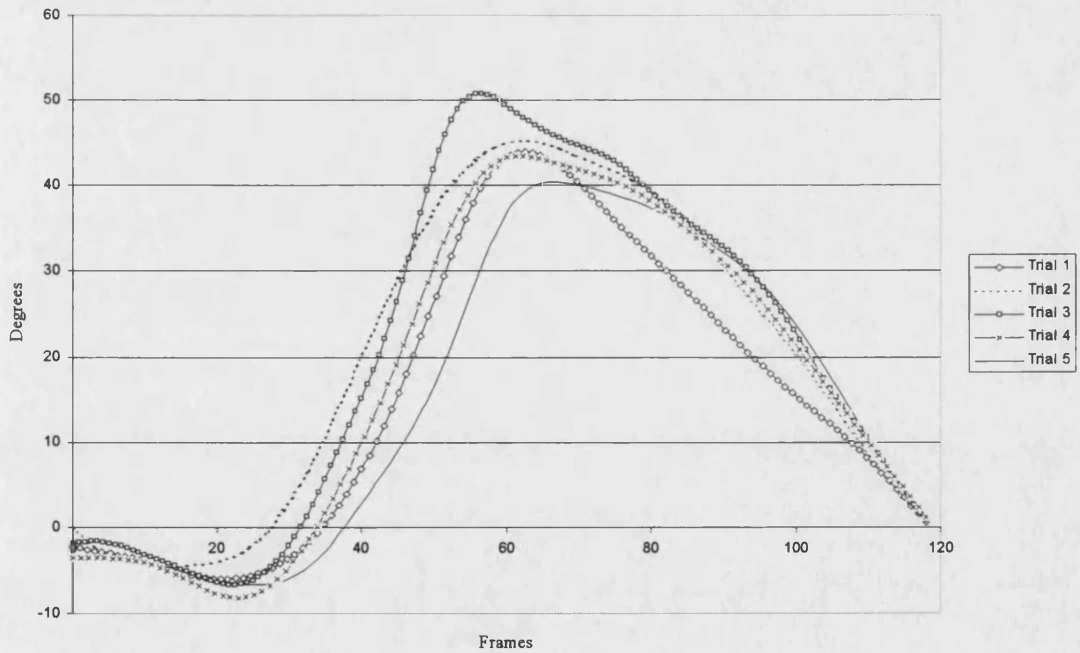


Figure 7.14 Graph of head extension and flexion during five repetitive trials of the sit-to-stand task carried out by subject A

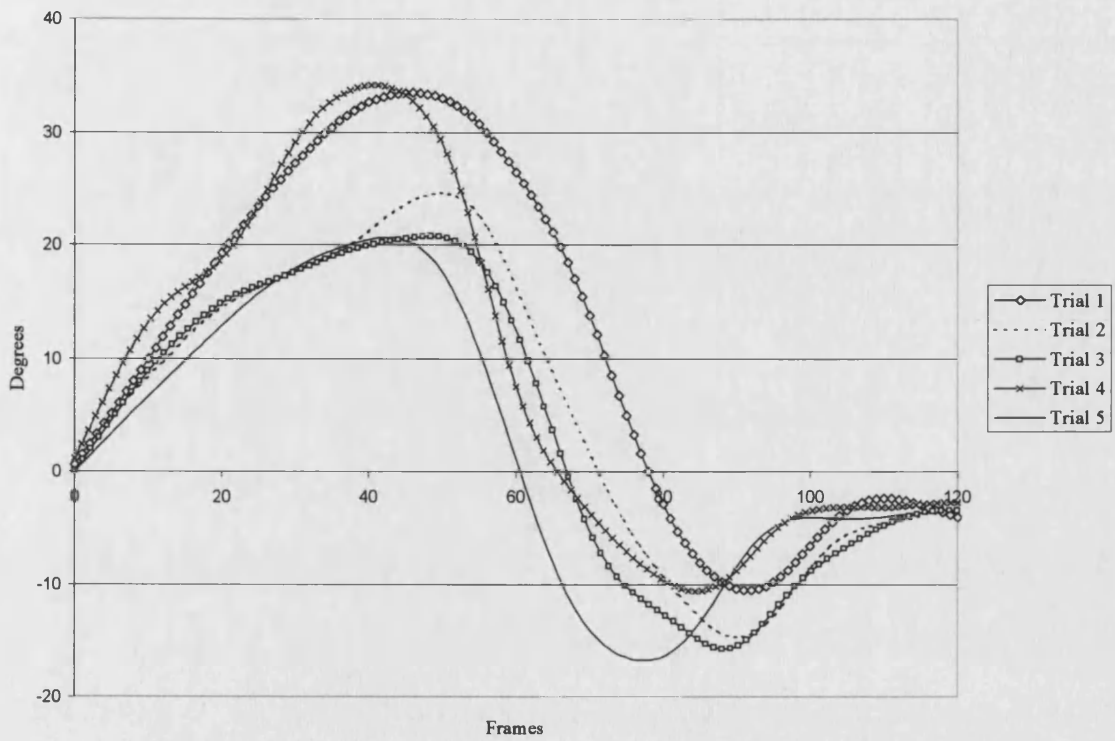


Figure 7.15 Graph of head extension and flexion during five repetitive trials of the stand-to-sit task carried out by subject A

7.5.1 Discussion of results

The graphical results of the five trials carried out by subject 'A' clearly showed that the gross movements employed were repetitive. This was particularly evident in the flexions and extensions of the hip during the task of standing up from and sitting down onto a chair, as shown in Figures 7.10 and 7.11, respectively and are discussed as follows:

- The largest percentage deviation from the mean of the five trials of the maximum hip flexion measured was 3.36% and 5.78% when standing up from, and reclining onto a chair, respectively

However, the graphical representations of the head extension, shown in Figures 7.14 and 7.15, show relatively variable movements and is discussed as follows:

- The head extension during trials 4 and 1, shown in Figure 7.15 of the stand-to-sit movement, deviate 27.82% and 25.29% respectively, from the mean of the maximum extension measured during the five trials.

- The head extension variation also occurred during trial 3, shown in Figure 7.14, during the sit-to-stand movement, where the deviation is 13.53% from the mean.

- During the same trials, as mentioned above, the greatest hip flexions occurred, i.e. during trial 3 (as shown in Figure 7.10) and trials 4 and 1 (in Figure 7.11).

The hip flexion was the only gross movement that reached its maximum flexion at approximately the same time as the head extension, as shown in Table 7.3. It was thus speculated, similarly to Ikeda et al (1991), that the head, in this case, was used as a compensatory body segment for the hip flexion to maintain balance.

The graphical representations of the knee angles during the sit-to-stand (Figure 7.12) and stand-to-sit (Figure 7.13) movement showed slight variations, even though the gradients of the curves of all five trials were similar. This indicates that the same segmental angles were produced, i.e. the same movement employed, over the same time period, except that they were initiated at slightly different intervals when the buttocks were lifted off or placed onto the seat of the chair.

These graphical representations of the gross movements of the hip, knee and head clearly showed that when a subject was required to carry out a given task, such as rising from and reclining onto chair, their movement patterns were consistent. This consistency proved that an identifiable repetitive movement strategy was employed by young adult able-bodied people to undertake a given task.

7.6 Comparisons of sequential movements

Comparisons of the means of the maximum flexion and extension of the body segments, during the five trials carried out by the three subjects, were made during the sit-to-stand-to-sit movement. These angles, shown in Tables 7.1 and 7.2, are the gross segmental movements that define the sequential phases of the sit-to-stand-to-sit movement task previously described in section 7.4. These results showed good comparison to similar studies carried out by Schenkman et al (1990) and Jeug et al (1991) for young able-bodied adults.

Comparisons of the occurrence of the means of the maximum and minimum angles produced between each body segment during the five trials undertaken by all subjects are shown in Table 7.3. This table enables individual comparisons of the sequential movements employed to carry out the sit-to-stand-to-sit movement, to be made. To ensure consistency, it was decided to terminate the sit-to-stand and initiate the stand-to-sit movements with the attainment of the theoretical zero position of the hip extension, defined by Heck et al (1965).

The results, in Figure 7.3, showed that each subject repeatedly attains the maximum hip flexion, head extension, trunk flexion, ankle dorsiflexion, hip and knee extension sequentially when rising to an erect stance from a sitting posture. This sequence was almost identical as those reported in literature by Schenkman et al (1990) and Ikeda et al (1991), except that the sequence reported by these authors show the trunk flexion to occur slightly before the head extension. Considering that the trunk flexion and head extension occurred almost simultaneously, i.e. within a mean of 0.03 seconds, and was not used to determine the end of a movement phase, these differences are not considered substantial when defining the movement strategies when rising from a chair.

Table 7.3 also showed that the occurrence of the maximum segmental angles, measured during the task of sitting down from a standing posture, were slightly different from each other due to a minor variation of ankle movement. Subject C illustrated this, where maximum hip flexion occurred slightly before the ankles were rotated to a position of maximum dorsiflexion. The maximum hip flexion of subject B, when reclining into a sitting posture, occurred just before maximum head extension. Again due to these events occurring almost simultaneously, i.e. within a mean of 0.03 seconds and that they also do not define the end of a movement phase, they were not considered substantial when defining the movement strategies when reclining onto a chair. The mean values of these three subjects however, show that the sequence of sitting down was reversed to that found when rising., which was in agreement with the findings presented by Anglin and Wyss (1999). This sequential movement strategy was found to be maximum ankle dorsiflexion, maximum hip flexion and finally the sitting posture.

Subject	Maximum hip flexion		Maximum head extension		Maximum trunk flexion		Maximum Ankle dorsiflexion		Maximum trunk hyper/extension	
	$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$	Range
A	125.35	122.3 129.9	44.75	40.4 50.8	34.71	31.6 40.3	23.75	22.3 26.2	92.37	-1.0 -4.2
B	113.35	110.3 115.9	44.28	40.1 49.9	39.19	37.1 41.3	16.65	16.2 17.5	86.74	85.9 -1.9
C	114.87	109.8 119.1	46.56	38.7 54.8	37.49	30.4 47.4	26.93	22.7 30.1	92.81	-1.9 -4.2
$\bar{x}$ of all subjects	**117.85**	109.8 129.9	**45.2**	38.7 54.8	**37.13**	30.4 47.4	**22.44**	16.2 30.1	**90.64**	85.9 -4.2
Schenkman et al (1990)	104	90 129	39	Not reported	40	Not reported	27	Not reported	Not reported	Not reported
Jeug et al (1991)	103								94.37	

Table 7.1 The mean and ranges of the maximum segmental angles of the experimental analysis of five trials carried out by subjects rising from a chair, compared to similar studies reported in literature

Subject	Maximum hip flexion		Maximum head extension		Maximum trunk flexion		Maximum Ankle dorsiflexion		Maximum knee hyper/extension	
	$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$	Range	$\bar{x}$	Range
A	116.37	110.2 120.7	26.74	20.7 34.8	40.45	36.2 44.4	20.34	16.7 23.2	-1.36	-0.6 -2.3
B	102.27	95.2 107.9	43.39	40.2 40.7	47.41	44.3 51.7	12.81	12.2 13.3	9.62	9.6 11.2
C	114.12	107.9 116.9	40.28	32.1 48.4	32.81	30.9 39.6	20.94	18.7 22.7	6.34	4.7 7.7
$\bar{x}$ of all subjects	**110.92**	95.2 120.7	**36.80**	20.7 48.4	**40.22**	30.9 51.7	**18.03**	12.2 23.2		

Table 7.2 The mean and ranges of the maximum segmental angles of the experimental analysis of five trials carried out by subjects reclining onto a chair

Sit-to-stand

Subject	Hip flexion		Head extension		Trunk flexion		Ankle dorsiflexion		Hip flexion = 0	
	% Time	Order	% Time	Order	% Time	Order	% Time	Order	% Time	Order
A	14.7	1	20.2	2	20.7	3	25.0	4	40.6	5
B	13.4	1	15.3	2	15.5	3	17.8	4	46.3	5
C	13.1	1	13.9	2	14.8	3	23.2	4	33.3	5
All	13.73		16.47		17		22		40.07	

Standing

Subject	Knee hyper-extension		Hip hyper-extension	
	% Time	Order	% Time	Order
A	44.2	*	50.7	*
B	47.5	*	none	*
C	45.6	*	43.2	*
All				

Stand-to-sit

Subject	Ankle dorsiflexion		Trunk flexion		Head extension		Hip flexion		Final sitting posture	
	% Time	Order	% Time	Order	% Time	Order	% Time	Order	% Time	Order
A	21.8	1	42	2	45.2	3	49.5	4	100	5
B	32.2	1	40.9	3	39.7	2	45.8	4	100	5
C	42.3	2	36.3	1	46	4	44.7	3	100	5
All	32.1	1	39.73	2	43.63	3	46.67	4	100	5

Table 7.3 The order and mean percentage of time taken for each subject to attain maximal flexion and extension of body segments that define the movement phases when rising from, standing and reclining onto a chair.

7.7 Conclusions

Comparisons of the mean and range of the segmental angles (produced by subject A in section 7.5) showed that the movements of an individual are repetitive when carrying out a predefined task. The mean of the segmental angles produced by subjects A, B and C (shown in Table 7.1) also show good comparison to those reported by similar studies carried out by Schenkman et al (1990) and Jeug et al (1991). The sequence of these movements, of these subjects also showed good concurrence with the those described by Schenkman et al (1990), Jeug et al (1991), Alexander et al (1991, 1996 and 2000) and Bahrami et al (2000). These results demonstrate that the phases of movement employed by adult able-bodied people are distinct, repeatable and can be determined through the employment of the techniques described in sections 7.2 to 7.4.

The following chapter involves the employment of the computer manikin created within SWORDS, as described in chapter 6, to mimic the distinct movement patterns found from this experimental study. The results of the following study have been compared with this experimental study and those found in the literature.

Chapter 8

Simulation of the sit-to-stand strategy using SWORDS

8.0 Introduction

The aim of this study was to simulate the movement strategy identified in the experimental analysis in Chapter 7, during the task of rising from a sitting posture, using the constraint-based modeller SWORDS. Anthropomorphic and range of joint motion measurements taken of the three able-bodied subjects, studied in Chapter 7, were used as part of this simulation to determine the individual segmental angles of these subjects during each intermediate posture. Comparisons of these results were subsequently made between each subject's measurements taken during the experimental study, and with data published in the literature. These comparisons were employed to evaluate the application of the constraint based modeller SWORDS for the simulation of intermediate postures of individual able-bodied people when rising from a sitting posture.

8.1 The movement strategy

Many published authors have concentrated their experimental analyses on the task of rising from a chair alone, rather than include the task of reclining back onto the chair. This was due to the task of rising from a chair as being identified as one of the essential tasks to independent daily living by Ikeda et al (1991). It is also one of the transfer functions used to assess the assistance of a carer for older people, as stated by Alexander et al (2000). Through numerous visits to rehabilitation clinics and from the experimental study carried out in Chapter 7, the movement of rising from a sitting posture was considered to be more difficult than that of reclining onto a chair. This is probably because the confidence of being able to sit down onto a chair is far greater than rising, due to the seat and backrest of a chair being perceived as being able to support the user if they should fall. Whereas, when standing from a chair, without the support of armrests, the user has to depend totally on their own body strength and ability to maintain stability to prevent any possible fall and physical injury. This study therefore concentrated on modelling the movement strategies employed when rising from a chair only.

8.2 Modeling the sit-to-stand movement strategies

The simulation of the sit-to-stand task, using the constraint based modeller SWORDS, was achieved by translating the intermediate strategies identified into constraint rules that invoke specific variables. These variables were model spaces that contained the geometric data pertaining to the anthropomorphic and joint range of motion measurements of, in this case, the three able-bodied subjects employed for the experimental study discussed in Chapter 7. If the movement strategy involves the use of an artefact to carry out a given task, then a geometric representative of, for example a chair, can be modelled in SWORDS and an interface with the manikin created using constraint rules. This section will describe the how this was achieved.

8.2.1 Geometric representation of artifacts

The chair used for the experimental study, described in Chapter 7, was modelled using a separate file for each individual subject, within the constraint modeller SWORDS. This enabled the geometric model of the chair to resemble the individual chair design and the variable dimensions, such as the seat height, use by each subject. The geometric entities representing the seat and the backrest of the chair were placed within their own model spaces within SWORDS. This enabled them to be to rotated or translated through the manipulation of the units shown in bold in Figure 8.1. The height of the chair, for example, represented as 'wb_p[1_6]' shown in Figure 8.1, could then be altered to suit the same height used by each individual subject as defined in the experimental study in Chapter 7.

```
wb_p[1,1] = 41;      Width along x axis (positive P direction)
wb_p[1,2] = 20;      Length [n] along y  axis (positive Q direction)
wb_p[1,3] = 6;       Depth along z axis (along negative R direction)

wb_p[1,4] = 0;       Position of model space along x axis (negative P direction)
wb_p[1,5] = 0;       Position of model space along y axis (positive Q direction)
wb_p[1,6] = 42.5 ;   Position of model space along z axis (positive R direction)

wb_p[1,7] = 0;       Rotation of model space about x axis
wb_p[1,8] = 0;       Rotation of model space about y axis
wb_p[1,9] = 0;       Rotation of model space about z axis
```

Figure 8.1 Coding written in the SWORDS program to manipulate the geometric entities representing the chair seat

To enable the manikin to be placed in a given position upon the chair, geometric grids were positioned on the surface of geometric entities representing the backrest and seat, as shown in Figure 8.2. This grid formed by lines were placed 25%, 50% and 75% along the length and width of both the seat and backrest. The lines shown in bold were used to represent the interface with the manikin and the chair. To enable the inner feet of the manikin to be placed 15cms apart, directly below the front of the seat, three lines were placed in front of the chair, at zero height along the horizontal plane, to represent the ground plane. A ball, which each subject was requested to look at during the whole of the sit-to-stand movement, was placed at the same height and distance from the chair, as in the experimental study described in Chapter 7.

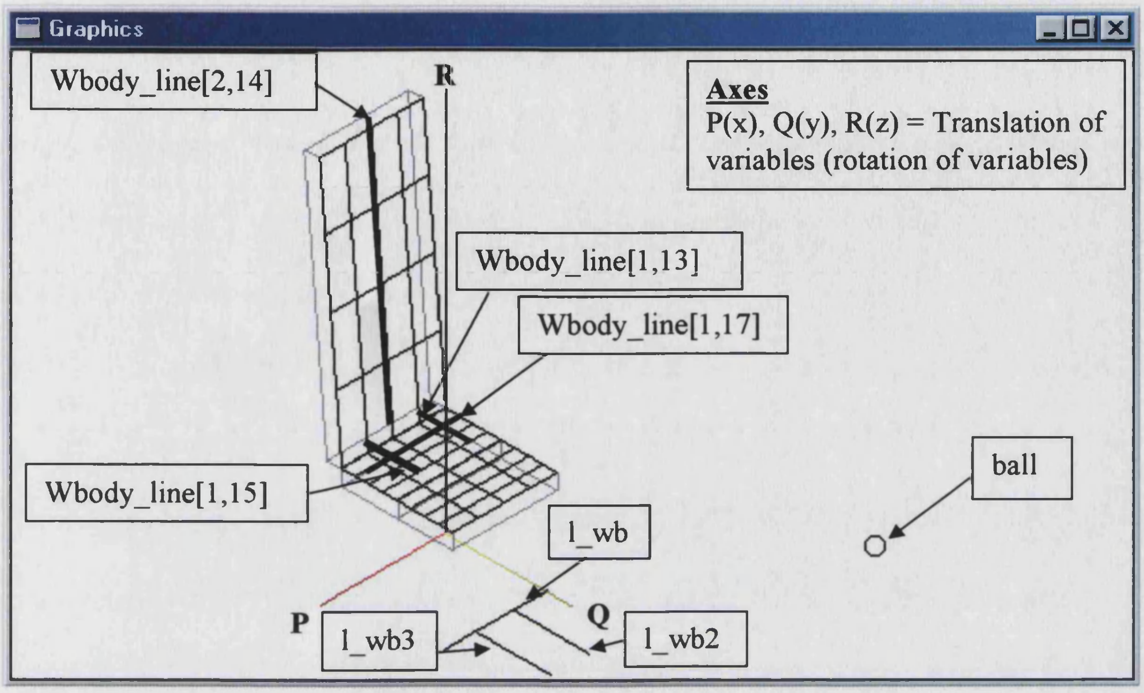


Figure 8.2 Diagram of chair graphically represented using the constraint based modeller SWORDS

8.2.2 Subject measurements

The measurements of the subjects employed to carry out the experimental analysis, described in Chapter 7 were carried out according to the following descriptions:

- The measurements of the appendages were made according to the segmental lengths corresponded to the link lengths of the manikin developed in SWORDS, defined in Chapter 6. Where each body segment was measured using the observed points of joint rotation.

- The clavicular and shoulder link were combined as one link and measured from the middle of the thorax to the centre of joint rotation of each shoulder.

- The pelvis was measured from the observed joint centre of rotation of the hip to a point observed to be vertically above and in line with the illiac crest.

To enable the manikin to emulate the segmental lengths of the people employed for the experimental study, the lumbar and the torso, and the neck and head were combined respectively as two separate link lengths.

- The combined link length of the lumbar and torso was measured from the top of the illiac crest to the observed joint centre of rotation of the shoulder.

- The neck and head were measured from the observed vertical distance between the joint centre of rotation of the shoulder and the corner of the right eye. These two measurements were taken when each subject was stood upright looking directly forwards.

The joint range of motion of each subject was measured in accordance to the method as defined by Heck et al (1965). To ensure that this procedure of measurement was undertaken in accordance to this method, the measurements were observed and verified by a qualified clinician (Dr Lisa Leonard, Royal United Hospital, Bath, UK). The lumbar and torso, and neck and head were measured as combined link lengths acting about a fulcrum found at the top of the illiac crest (i.e. the pelvis) and the shoulder, respectively. The measurements of the appendages were taken from the right side of the body only, as comparisons were to be later made with the experimental study carried out in Chapter 7, which was also restricted to the right side of the body

The external body measurements (in centimetres) were taken to correspond with the body part which came into contact with the external environment during the experimental study of rising from a chair, undertaken in Chapter 7, and are listed in Figure 8.3. The measurements for each individual subject can be found in Appendix A. These measurements are an addition to the ADAPS model and are measured in respect to the joint centres of rotation for reasons of clarity and simplification.

Description of body measurements	**Corresponding measurements**
Vertical distance from corner of right eye to top of head	l[61] = 9.5
Horizontal distance from corner of the eye to furthest point at the back of the head	l[62] = 8.9
Horizontal distance from joint centre of rotation of shoulder to furthest point of back	l[63] = 10
Horizontal distance from hip joint centre of rotation to furthest point measured on buttocks (during sitting posture)	l[64] = 12
Vertical distance from hip joint to bottom of buttocks (during sitting posture)	l[65] = 11
Vertical distance from knee joint centre of rotation to underside of knee (during sitting posture)	l[66] = 7
Half the width of the heel	l[67] = (5/2)
Half the width of front of foot (from most distal end of first to fifth digits of feet, measured perpendicular to the rigid stick length representing the feet)	l[68] = (9.5/2)
Horizontal distance from the rigid stick length representing the feet to distal end of 5th digit on right foot	l[69] = 10.8
Horizontal distance from the rigid stick length representing the feet to distal end of 1st digit of right foot	l[70] = 14.3
Horizontal distance from top of illiac crest to most posterior point of pelvis	l[71] = 11

Figure 8.3 Example of external measurements encoded in SWORDS, taken from female subject

These individual subject measurements were then incorporated into the model spaces containing the geometric entities of each body segment, with respect to the joint centre of rotation from which the measurement was made and are defined in Figure 8.4.

Description of external body measurements	**Body points representing external body measurements in SWORDS**
Top of head (vertical to corner of eye)	body_points[1] = pnt(0,0,(l[15]+l[61]),head_s)
Most posterior point of head	body_points[2] = pnt(0,-l[62],l[15],head_s)
Most posterior point of torso	body_points[3] = pnt(0,-l[63],l[4],torso_s)
Most posterior point of buttocks *	body_points[4] = pnt(0,-l[64],0,zpelvis_s)
Underside of right buttocks *	body_points[5] = pnt(0,-l[65],0,right_ts)
Underside of left buttock *	body_points[6] = pnt(0,-l[65],0,left_ts);
Underside of left knee *	body_points[7] = pnt(0,-l[66],-l[23],left_ts);
Underside of right knee *	body_points[8] = pnt(0,-l[66],-l[19],right_ts);
Outer heel of right foot	body_points[9] = pnt(-l[67],-l[27],-l[25],right_fs);
Inner heel of right foot	body_points[10] = pnt(l[67],-l[27],-l[25],right_fs);
5th digit of right foot	body_points[11] = pnt(l[68],l[69],-l[25],right_fs);
1st digit of right foot	body_points[12] = pnt(-l[68],l[70],-l[25],right_fs);
Outer heel of left foot	body_points[13] = pnt(-l[67],-l[27],-l[25], left_fs);
Inner heel of left foot	body_points[14] = pnt(l[67],-l[27],-l[25], left_fs);
1st digit of left foot	body_points[15] = pnt(l[68],l[70],-l[25], left_fs);
5th digit of left foot	body_points[16] = pnt(-l[68],l[69],-l[25], left_fs);
Furthest most point posterior of pelvis	body_points[17] = pnt(0,-l[71],l[2],zpelvis_s);

* Measured during the sitting posture

Figure 8.4 The external body points incorporated into the computer manikin in SWORDS

8.3 Modelling of the intermediate postures

The intermediate postures identified in Chapter 7 were interpreted into constraint rules by determining the relationship between CoM of the total body, the external points placed on the body segments (defined in Figure 8.4) and the external environment (i.e. the ground plane and the chair). The intermediate postures and their corresponding constraint rules are described in the following sections.

8.3.1 The sitting posture

The modelling of the sitting posture was interpreted into constraint rules mainly through the use of the 'on' function, which can be used to determine the distance between two entities. When the 'on' function is used within a constraint rule, the constraint modeller will try to resolve the equation as being as close to zero as possible and thus find a solution where two entities are brought together, i.e. zero distance apart. The 'on' function was therefore used to place the 'body_points' defining the buttocks, pelvis, torso, head and feet of the manikin, previously described in Figure 8.4, onto the geometric grids placed on the seat and backrest of the chair, and the ground (shown in Figure 8.2). The constraint rules listed in Figure 8.5 were thus used to constrain the manikin into a sitting posture.

Description of constraint rules	Rules as written in SWORDS
Placement of buttocks on seat	
left underside buttock on seat grid	Rule(body_points[6]on wbody_line[1,13])
right underside buttock on seat grid	Rule(body_points[5]on wbody_line[1,15])
left underside buttock on seat grid	Rule(body_points[6]on wbody_line[1,17])
right underside buttock on seat grid	Rule(body_points[5]on wbody_line[1,17])
Placement of upper body on backrest	
back of pelvis on middle backrest grid	Rule(body_points[17]onwbody_line[2,14])
back of torso on middle backrest grid	Rule(body_points[3] on wbody_line[2,14])
back of head on middle backrest grid	Rule(body_points[2]on wbody_line[2,14])
Placement of feet on lines placed on ground plane	
right 1st digit of foot on right ground line	Rule(body_points[12] on l_wb3)
right inner heel on right ground line	Rule(body_points[10] on l_wb3)
right inner heel on back ground line	Rule(body_points[10] on l_wb)
left 1st digit of foot on left ground line	Rule(body_points[15] on l_wb2)
left inner heel on left ground line	Rule(body_points[14] on l_wb2)
left inner heel on back ground line	Rule(body_points[14] on l_wb)
Placement of eye sight on ball	
left sight ball, on ball	Rule(l_sight_ball on ball)
right sight ball, on ball	Rule(r_sight_ball on ball)

Figure 8.5 Rules that constrained the manikin to a sitting posture on the chair modelled in SWORDS

Two geometric entities 'l_ball' and 'r__ball' , that constrain the sight of the manikin to the ball, were two geometric points that were placed within the model space of the eye ray, representing the line of sight of a subject. These points were constrained to move along the line of the sight only, such that when the rules for the placement of the eye sight on the ball was resolved, the points could be seen to be in the same position as the ball.

It should be noted that the constraint rules and functions, defined in Table 8.1, and all similar Excel spreadsheets, are confined to columns A and B alone, where the remaining columns pertain to the model space variables of the manikin. The variables invoked to be resolved along with the constraint rules previously described are as follows:

The model spaces 'l_eye' and 'r_eye', containing the geometric entities representing the line of sight of the eyes, were allowed to rotate about the x-axis. This was to allow the back of the head to be in contact with the backrest of the chair and the line of sight to be aligned with the 'ball' placed in front of the chair.

- The 'man_space' model space, which was the root of the hierarchy of all the model spaces, was allowed to translate along all three global axes (p, q, r) to enable the manikin to translate from the initial default function 'set2()' position, towards the sitting posture.

The function 'set2()' was where all translations or rotations of the model spaces that contain the segmental geometric entities were equal to zero, with the exception of the left and right arm model spaces which was rotated 2.5 degrees laterally about their local 'q' axes.

- The right and left feet 'left_fs and right_fs', thighs 'right_ts and left_ts, shanks 'right_ls and left_ls', pelvis 'zpelvis_s', and neck 'neck_s', were allowed to rotate about the 'x-axis' (i.e. about the sagittal plane), as shown in column H, of Table 8.1.

- The head model space, however, was not invoked so that it would rotate as one link in accordance with the 'neck' model space in which it was embedded.

- The right and left thighs were also allowed to rotate 'ay' about the 'q' axis (i.e. the frontal plane), and the shanks were allowed to rotate 'az' about the 'r' axis (i.e. transverse plane). This was to allow the legs to open and rotate in order to position the inner feet 15cms apart on the lines ‘wb_2’ and ‘wb_3’ located on the ground plane in front of the chair, as shown in Figure 8.2.

	A	B	C	D	E	F	G	H	I	J
1	**title:**	sit								
2	**manikin:**	general								
3										
4	**RULES:**		**VARIABLES:**							
5	**total no.**	**active.**	**total no.**	**active.**						
6	15	15	22	13						
7	**rules:**	**state:**	**variables:**	**null**	**p**	**q**	**r**	**ax**	**ay**	**az**
8	rule (body_points[5] on wbody_line[1,13]);	on	man_space		on	on	on			
9	rule (body_points[6] on wbody_line[1,15]);	on	lumbar_s							
10	rule (body_points[5] on wbody_line[1,17]);	on	right_fs					on		
11	rule (body_points[6] on wbody_line[1,17]);	on	left_fs					on		
12	rule (body_points[17] on wbody_line[2,14]);	on	right_ts					on	on	
13	rule (body_points[3] on wbody_line[2,14]);	on	left_ts					on	on	
14	rule(body_points[2] on wbody_line[2,14]);	on	right_ls					on		on
15	rule(body_points[12] on l_wb3);	on	left_ls					on		on
16	rule(body_points[10] on l_wb3);	on	zpelvis_s					on		
17	rule(body_points[10] on l_wb);	on	torso_s							
18	rule(body_points[15] on l_wb2);	on	neck_s					on		
19	rule(body_points[14] on l_wb2);	on	head_s							
20	rule(body_points[14] on l_wb);	on	l_eye					on		
21	rule(l_sight_ball on ball);	on	r_eye					on		
22	rule(r_sight_ball on ball);	on	l_ball			on				
23			r_ball			on				

Table 8.1 Excel spreadsheet containing the rules and variables invoked to constrain the manikin to a sitting posture

Once resolved the manikin representation of subject A was found to be sitting on the geometric representation of the chair used for the experimental analysis, as shown in Figure 8.6. A video frame of subject ‘A’ is also shown in Figure 8.6. Comparisons of the angles measured both in SWORDS and in the experimental analysis are discussed later in this chapter.

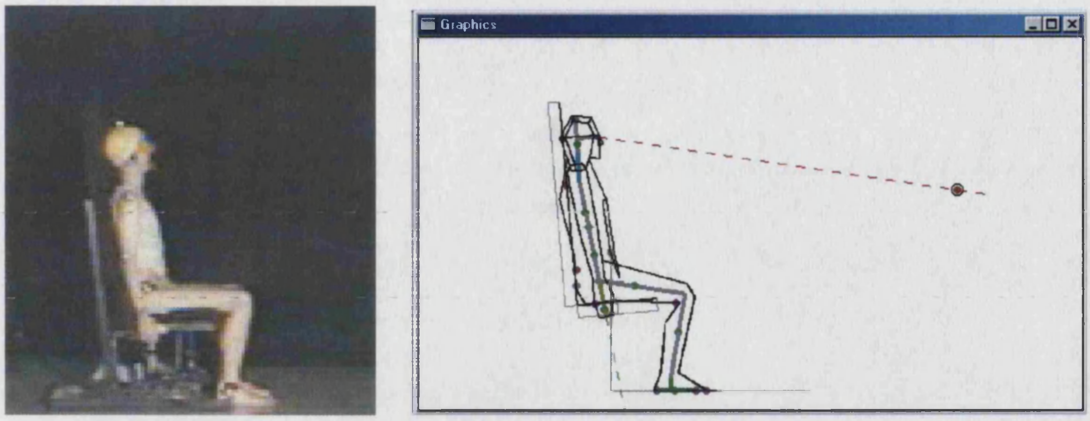


Figure 8.6 Video frame of sitting posture carried out by subject A in Chapter 7 and manikin representation of subject A constrained to the sitting posture using constraint rules and variables defined in Table 8.1

8.3.2 Maximum hip flexion

The intermediate postures that immediately followed the initial sitting posture were identified, in the experimental study in Chapter 7, as the maximum sway of the upper body (before the knees extend to bring the buttocks off the seat of the chair), followed by maximum hip flexion. It was, however, decided to model the second intermediate posture as that of maximum hip flexion, and to neglect the trunk sway intermediate posture for the following reasons:

- The greatest change of total gross body movement occurred when the hip reached its maximum flexion.

- The movement of the knees and hips were relatively small between these two intermediate postures, in comparison to their total rotational movement as shown in Table 8.2.

A direct consequence of this decision was that computational efficiency was improved for the sit-to-stand movement.

Intermediate posture	Hip angle	Range	Knee angle	Range	Ankle angle	Range	Head angle	Range
Trunk sway	**120**	113.76 129.90	**82.33**	81.15 84.03	**12.11**	5.99 19.15	**35.90**	22.78 48.92
Max hip flexion	**125.2**	122.3 129.9	**82.24**	80.1 84.8	**12.7**	6.8 19.1	**41.84**	37.8 48.9

Table 8.2 Segmental angles (mean values shown in bold) of the five trials carried out by subject A when rising from a chair

The rules that previously constrained the buttocks, pelvis, torso and head to be in contact with the chair, when modelling the sitting posture, were abandoned when modelling maximum hip flexion. Whereas, the rules that constrained the feet to the lines defined on the ground plane, however, were still invoked and weighted by a multiplication of 10, as shown in Table 8.3, thus imposing a priority when being solved above the other rules invoked. This priority was applied to ensure that the feet always remained in contact with the ground, thus modelling the real situation where the feet must remain on the ground to enable a person to rise out of a chair. These rules are explained in further detail as follows:

Description of constraint rules/functions	Rules as written in SWORDS
Rules to place feet on lines on ground plane	
1st digit of right foot on right line on ground	rule(body_points[12] on l_wb3)*10
Right inner heel on right line on ground	rule(body_points[10] on l_wb3)*10
1st digit of left foot on left line on ground	rule(body_points[10] on l_wb) *10
Left inner heel on left line on ground	rule(body_points[15] on l_wb2)*10
Left inner heel on line on ground under chair	rule(body_points[14] on l_wb2)*10
Left inner heel back ground line	rule(body_points[14] on l_wb)*10
Function to calculate base of support of feet	
Function to calculate base of support of feet	footprint();
Functions to calculate CoM	
Function to transform segmental CoM coordinates	balance_mapping();
Function to calculate total body CoM	balance_cofs()
Rules to place vertical line from CoM into base of support of feet	
X coordinate of total body CoM greater than minimum x coordinate of footprint calculation	rule(b_array[0,2].gt.c_xmin)
X coordinate of total body CoM less than maximum x coordinate of footprint calculation	rule(b_array[0,2].lt.c_xmax)
Y coordinate of total body CoM greater than minimum y coordinate of footprint calculation	rule(b_array[0,3].gt.c_ymin)
Y coordinate of total body CoM less than maximum y coordinate of footprint calculation	rule(b_array[0,3].lt.c_ymax)
Functions for CoM	
Function to define CoM for graphical display	cofg_vectors()
Function to transform local segmental CoM coordinates to global coordinates	transform()
Placement of eye sight on ball	
Left sight ball on ball	rule(l_sight_ball on ball)

Right sight ball on ball	rule(r_sight_ball on ball)
Rules to constrain hip joint an specified distance above seat	
Z coordinate of right joint centre of hip equal a given height 'h' above the height of the seat of the chair	rule(righthipjoint:z.eq.(wb_p[1,6]+h))
Rule(lefthipjoint:z .eq. (wb_p[1,6]+ h))	z coordinate of right joint centre of hip equal a given height 'h' above the height of the seat of the chair

Table 8.3 Description of rules used to transform the manikin into maximum hip flexion after the sitting posture was obtained

- To enable the manikin to move forward and upwards out of the seat of the chair, the 'man_space' 'root' model space, was allowed to translate along both the 'q' and 'r' axis. Whereas, the rest of the model spaces were allowed to rotate about the 'x' axis to simulate the movement about the sagittal plane.

- The rules invoked to manipulate a vertical line projected from the total body CoM of the manikin to move forwards, within the base of support formed by the feet, as shown in Table 8.3, had the effect of moving the manikin in an anterior direction.

- To enable the resolution of the previous rules described, the calculation of the total body CoM and base of support of the feet were made by invoking the functions shown respectively in Table 8.3

- The rules to constrain hip joint a specified distance above the seat, as shown in Table 8.3, were invoked to prevent the manikin from standing up. Also maximum hip flexion occurs just after the buttocks are lifted only slightly from the seat, as found in the experimental analyses published by Ikeda et al (1991) and Schenkman et al (1990), and shown in the experimental study in Chapter 7. These rules were written such that the 'z' coordinates of the joint centres of rotation of both left and right hips are to equal the height 'h', above the height of the seat of the chair 'wb_p[1,6]'. The height 'h' was calculated as the mean of the vertical distance calculated between the joint centre of rotation of the right hip and the seat of the chair, for each individual undertaking the task of rising from a chair 5 times, as described in Chapter 7. This value was calculated to be 11.66cm for subject A, 13.4cm for subject B and 14.21cm for subjects C.

- The rules to constrain the geometric points embedded within the sight rays, onto the ball in front of the seat, were again invoked. However, the model spaces representing the line of sight 'l_eye' and 'r_eye' were not invoked. This was to force the 'neck' model space to rotate in an anterior direction to simulate the movement of the head and neck, when the individual subjects were requested to direct their line of sight at the ball placed in front of them when rising, as shown in Table 8.3.

The functions, rules and variables were manipulated using the excel spreadsheet shown in Table 8.4. The resulting manikin representative of subject A is shown in Figure 8.8, where the rules previously described are resolved.

	A	B	C	D	E	F	G	H	I	J
1	**title:**	seatoff								
2	**manikin:**	individual								
3										
4	**RULES:**		**VARIABLES:**							
5	**total no.**	**active.**	**total no.**	**active.**						
6	19	19	16	11						
7	**rules:**	**state:**	**variables:**	**null**	**p**	**q**	**r**	**ax**	**ay**	**az**
8	rule(body_points[12] on l_wb3)*10;	on	man_space			on	on			
9	rule(body_points[10] on l_wb3)*10;	on	lumbar_s					on		
10	rule(body_points[10] on l_wb)*10;	on	right_fs					on		
11	rule(body_points[15] on l_wb2)*10;	on	left_fs					on		
12	rule(body_points[14] on l_wb2)*10;	on	right_ts					on		
13	rule(body_points[14] on l_wb)*10;	on	left_ts					on		
14	footprint();	on	right_ls					on		
15	balance_mapping();	on	left_ls					on		
16	balance_cofs();	on	zpelvis_s					on		
17	rule(b_array[0,2].gt.c_xmin);	on	torso_s							
18	rule(b_array[0,2].lt.c_xmax);	on	neck_s					on		
19	rule(b_array[0,3].gt.c_ymin);	on	head_s							
20	rule(b_array[0,3].lt.c_ymax);	on	l_eye							
21	cofg_vectors();	on	r_eye							
22	transform();	on	l_ball			on				
23	rule(l_sight_ball on ball);	on	r_ball			on				
24	rule(r_sight_ball on ball);	on								
25	rule(righthipjoint:z .eq. (wb_p[1,6]+ h));	on								
26	rule(lefthipjoint:z .eq. (wb_p[1,6]+ h));	on								

Table 8.4 Excel spreadsheet containing rules and variables used to invoke the manikin into maximum hip flexion

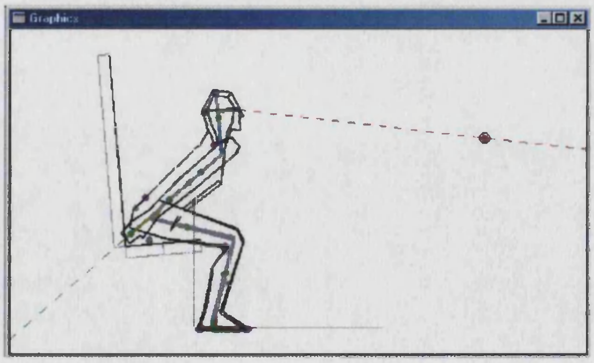


Figure 8.7 Video frame of 'subject A' during maximum hip flexion that occurred during sit-to-stand trail, carried out in Chapter 7, and manikin representation of 'subject A' using constraint rules and variables defined in Table 8.4

To enable the constraint rules to be applied when mimicking the maximum flexion posture for the variable dimensions of any subject or chair design, it was decided to alter the rules to be generic rather than individually tailored. To enable the buttocks to be constrained close to the chair, the outer body of the manikin and the chair were considered to be rigid structures. This meant that the dimension measured vertically from the centre of the hip rotation to the underside of the buttocks, when the subject was in a sitting posture, was considered to remain the same, even when the buttocks were lifted off the seat of the chair. This also meant that the seat of the chair would be considered to not experience any compression.

It was thus calculated that maximum hip flexion occurred when the three subjects, studied in Chapter 7, lifted their buttocks of the seat by a mean height of 1cm, when all structures were considered to remain rigid. The rules 25 and 26 of Table 8.4, that forced the hip joint to be equal to a specific height above the seat, were thus modified as follows: Body points 'body_points[5] and 'body_points[6] (placed on the underside of the buttocks) were transformed into global co-ordinates and constrained to be 1cm above the height of the chair seat, as shown in Figure 8.8 to model the occurrence of maximum hip flexion.

It was also decided not to invoke the model spaces containing the geometric entities representing the left and right shanks. This was due to the movement of these segments being considered to be insignificant when compared to the gross movement of the hip, when the buttocks had only risen such a small distance from the seat of the chair. Comparisons of these results are presented and discussed further in section 8.5.2.

rule(underbottom[1]:z .eq. (wb_p[1,6]+ 1));
rule(underbottom[2]:z .eq. (wb_p[1,6]+ 1));

Figure 8.8 Modification of the rules applied to attain maximum hip flexion

8.3.3 Maximum ankle dorsiflexion

The intermediate posture, identified in both the experimental study described in Chapter 7, and by authors Schenkman et al (1990) and Ikeda et al (1991), that occured after the attainment of maximum hip flexion was maximum ankle dorsiflexion. The constraint rules developed for this posture were similar in nature to that of maximum hip flexion and are described as follows:

- The rules that constrain the feet to the three lines placed on the ground plane were modified such that they were given a priority of 100. The rules that constrained the vertical projection of the total body CoM within the base of support formed by the feet, were given a priority of 10. This was done to simulate the hierarchical requirement of the feet being placed on the ground when rising.

- The rules that constrained the vertical projection of the total body CoM within the base of support formed by the feet were also modified. The vertical projection from the total body CoM was constrained to lie within 95% of the total perimeter of the base of support formed by the feet. This was done to force the total body segments to again move in an anterior direction towards a more stable posture.

- The rules that constrained the hip joint centre of rotation to a height above the seat of the chair were modified. Where the hip centre of joint rotation was forced to be greater than, instead of equal to, the individual height specified for each subject in the previous section, when maximum hip flexion occurs.

To prevent the legs of the manikin to be fully extended, an addition of the constraint rule numbered 23 was made, shown in the excel spreadsheet in Table 8.5. This rule constrained the joint centre of hip rotation to rise not more then 90% of the total height, from the ground plane to the hip joint, i.e. the summation of the ankle, shank and upper leg link lengths of each individual. This arbitrary value was chosen to prevent the knees from extending fully, as sometimes found when a standing posture is obtained. The outcome of this using the manikin representative of subject A can be seen in Figure 8.9.

	A	B	C	D	E	F	G	H	I	J
1	**title:**	riseup								
2	**manikin:**	individual								
3										
4	**RULES:**		**VARIABLES:**							
5	**total no.**	**active.**	**total no.**	**active.**						
6	20	22	16	12						
7	**rules:**	**state:**	**variables:**	**null**	**p**	**q**	**r**	**ax**	**ay**	**az**
8	rule(body_points[12] on l_wb3)*100;	on	man_space			on	on			
9	rule(body_points[10] on l_wb3)*100;	on	lumbar_s					on		
10	rule(body_points[10] on l_wb)*100;	on	right_fs					on		
11	rule(body_points[15] on l_wb2)*100;	on	left_fs					on		
12	rule(body_points[14] on l_wb2)*100;	on	right_ts					on		
13	rule(body_points[14] on l_wb)*100;	on	left_ts					on		
14	footprint();	on	right_ls					on		
15	balance_mapping();	on	left_ls					on		
16	balance_cofs();	on	zpelvis_s					on		
17	rule(b_array[0,2].gt.(c_xmin +(0.05*c_xmin)))*10;	on	torso_s							
18	rule(b_array[0,2].lt.(c_xmax-(0.05*c_xmax)))*10;	on	neck_s					on		
19	rule(b_array[0,3].gt.(c_ymin+(0.05*c_ymin)))*10;	on	head_s							
20	rule(b_array[0,3].lt.(c_ymax-(0.05*c_ymax)))*10;	on	l_eye							
21	cofg_vectors();	on	r_eye							
22	transform();	on	l_ball			on				
23	rule(midhipjoint:z .lt. ((l[21]+l[20]+l[19])*0.90));	on	r_ball			on				
24	rule(righthipjoint:z .gt. (wb_p[1,6]+ h));	on								
25	rule(lefthipjoint:z .gt. (wb_p[1,6]+ h));	on								
26	rule(l_sight_ball on ball);	on								
27	rule(r_sight_ball on ball);	on								

Table 8.5 Excel spreadsheet of constraint rules and variables used to simulate maximum ankle dorsiflexion

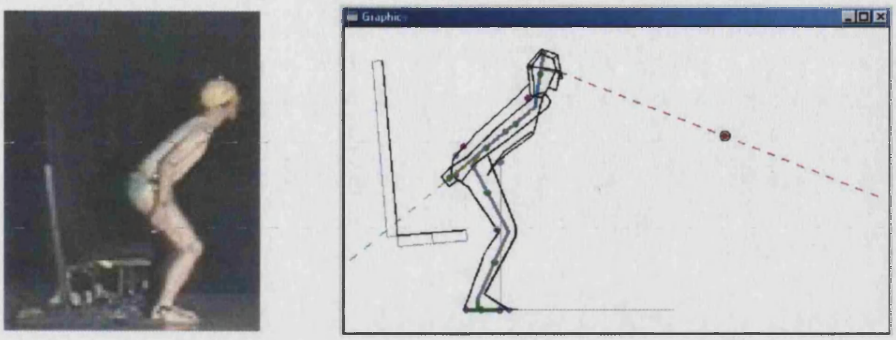


Figure 8.9 Video frame of 'subject A' attaining maximum ankle dorsiflexion during sit-to-stand trail carried out in Chapter 7, and manikin representation of 'subject A' using constraint rules and variables defined in Table 8.5

8.3.4 The erect stance

The erect stance was defined, in the experimental study described in Chapter 7, as being when the hip angle had reached a neutral position, i.e. zero degrees. Thus the constraint rules to simulate this posture were resolved such that the shoulder, hip and knee joint centres of rotation were aligned.

It was observed that the knee angle reached zero degrees when subjects A and C rotated their upper body further, after the neutral zero position had been reached, into hyper-extension while standing erect. This posture was similar to that of the erect stance described by Kuaffman et al (1997) in Chapter 2 and the final standing 'stabilisation' phase described by Schenkman et al (1990), where during 'quiet' standing the body acts as an inverted pendulum that sways about the ankle joint. To attain the alignment of the joint centres of rotation it was decided to write the rules such that each joint centre obtained the same 'y' co-ordinate as the ankle joint, which the body as a whole, in reality, would sway about, (see rules 26 to 29 of Table 8.6).

The final modification to the rules described in Table 8.6 was to the shoulder joint centre of rotation (rule23), to attain the total vertical height of the summation of all the segmental lengths from the bottom of the feet to the shoulder, as shown in Figure 8.10.

	A	B	C	D	E	F	G	H	I
1	**title:**	stand							
2	**manikin:**	individual							
3									
4	**RULES:**		**VARIABLES:**						
5	**total no.**	**active.**	**total no.**	**active.**					
6	22	23	16	12					
7	**rules:**	**state:**	**variables:**	**null**	**p**	**q**	**r**	**ax**	**ay**
8	rule(body_points[12] on l_wb3)*100;	on	man_space			on	on		
9	rule(body_points[10] on l_wb3)*100;	on	lumbar_s					on	
10	rule(body_points[10] on l_wb)*100;	on	right_fs					on	
11	rule(body_points[15] on l_wb2)*100;	on	left_fs					on	
12	rule(body_points[14] on l_wb2)*100;	on	right_ts					on	
13	rule(body_points[14] on l_wb)*100;	on	left_ts					on	
14	footprint();	on	right_ls					on	
15	balance_mapping();	on	left_ls					on	
16	rule(b_array[0,2].gt.(c_xmin +(0.05*c_xmin)))*10;	on	zpelvis_s					on	
17	rule(b_array[0,2].lt.(c_xmax-(0.05*c_xmax)))*10;	on	torso_s						
18	rule(b_array[0,3].gt.(c_ymin+(0.05*c_ymin)))*10;	on	neck_s					on	
19	rule(b_array[0,3].lt.(c_ymax-(0.05*c_ymax)))*10;	on	head_s						
20	balance_cofs();	on	l_eye						
21	cofg_vectors();	on	r_eye						
22	transform();	on	l_ball			on			
23	rule(midshoulderjoint:z .eq. (l[21]+l[20]+l[19]+l[2]+l[3]+l[4]));	on	r_ball			on			
24	rule(l_sight_ball on ball);	on							
25	rule(r_sight_ball on ball);	on							
26	rule(midshoulderjoint:y .eq. rightanklejoint:y);	on							
27	rule(rightkneejoint:y .eq. rightanklejoint:y);	on							
28	rule(leftkneejoint:y .eq. rightanklejoint:y);	on							
29	rule(midhipjoint:y .eq. rightanklejoint:y);	on							

Table 8.6 Excel spreadsheet of constraint rules and variables used for the erect stance

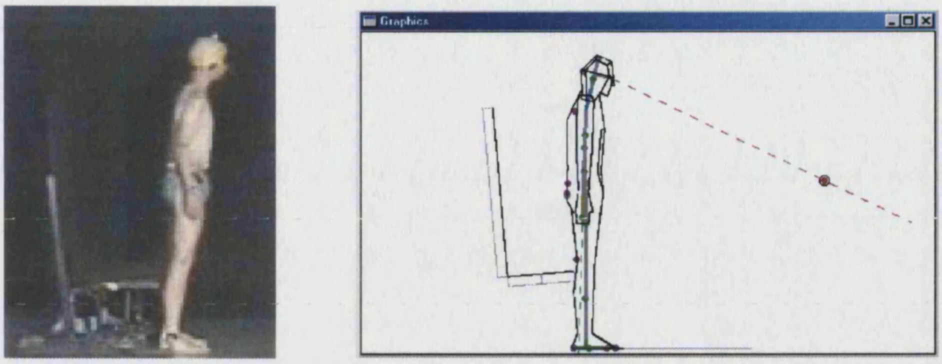


Figure 8.10 Video frame of ‘subject A’ attaining erect stance during sit-to-stand trial carried out in Chapter 5, and manikin representation of ‘subject A’ using constraint rules and variables defined in Table 8.5

8.4 Presentation and discussion of results

The following results were determined from the constraint rules, functions and variables, defining the intermediate postures described in section 8.3, when resolved sequentially using the anthropomorphic data and limitations of joint range of motion for subjects ‘A, B and C’, found in Appendix A. The resulting segmental angles defined in Chapter 5 (of the hip, knee, ankle and head) were evaluated and compared to the resulting segmental angles taken from the same three subjects during the experimental study of five trials of the sit-to-stand movement, also described in Chapter 7.

8.4.1 The sitting posture

Comparisons of the actual hip and head segmental angles (in degrees) attained by each subject during the experimental study described in Chapter 7 and those determined using SWORDS during the sitting posture, as shown in Table 8.7, were generally in good agreement.

Although the knee segmental angle determined in SWORDS for subject C was in good agreement with the actual knee flexion attained, the results determined in SWORDS for subjects A and B are closer to the actual expected knee flexion angle of approximately 100°.

The results for the knee flexion attained in SWORDS were also reflected in the values of the ankle dorsiflexion angles shown in Table 8.6. The result of 10° and 8° ankle dorsiflexion using SWORDS for the individual subjects A and B, and subject C, respectively, showed that each subject could attain the intended initial ankle dorsiflexion of 10°. However, the results of the experimental study showed that even though the height of the chair was adjusted so that each subject should attain 100° knee flexion, and hence 10° ankle dorsiflexion, their actual range of ankle dorsiflexion varied from 1.5° to 15.7°. This was possibly due to their feet and buttock placements being slightly altered every time each subject sat back down onto the seat of the chair after each trail that were performed simultaneously, as knee flexion was not re-measured at the beginning of each trial.

Sitting posture								
Subject	**Hip**	Range	**Knee**	Range	**Ankle**	Range	**Head**	Range
A	69.12	68.3	82.46	80.5	5.89	4.3	-2.16	-0.1
Swords	**70**	70.2	**91.18** **91.18**	84	**9.55** **9.53**	7.9	**7**	-3.5
B	75.27	74.3	81.97	79.2	3.23	1.5	4.83	1.8
Swords	**79**	75.7	**97.07** **97.05**	86.1	**10** **9.94**	4.3	**0**	6.1
C	72.84	68.6	86.92	80.6	10.81	6.9	10.07	5.3
Swords	**64**	77.2	**84.24** **84.25**	93.7	**7.38** **7.39**	15.7	**9**	16.2

Table 8.7 Results of segmental angles determined in SWORDS (shown in bold) and experimental study during the sitting posture (mean and ranges given)

8.4.2 Maximum hip flexion

Comparisons of the hip and head segmental angles determined during the attainment of maximum hip flexion in SWORDS using the rules for each individual subject as described in Figure 8.8, and the experimental study in Chapter 7, also showed good agreement (see Table 8.8).

The actual knee flexion measured during the experimental analysis for subjects B and C reduced when those subjects attained maximum hip flexion, whereas subject A shows negligible change. This indicates that subject A has hardly lifted the buttocks from the seat of the chair and subjects B and C only slightly. The knee flexion, and consequently the ankle dorsiflexion results, determined from the manikin model in SWORDS, indicates that the model space representing the shank, which was allowed to rotate in this instance, has rotated further forwards than that of the experimental values measured for each subject.

Max hip flexion -A								
Subject	**Hip**	Range	**Knee**	Range	**Ankle**	Range	**Head**	Range
A	125.28	122.3	82.24	80.1	12.7	6.8	41.84	37.8
Swords	**122**	129.9	**100.13** **100.17**	84.8	**20** **20.04**	19.1	**52**	48.9
B	113.37	110.3	74.52	73.2	12.79	11.1	43.03	39.1
Swords	**112**	115.7	**104.22** **104.23**	77.7	**20.12** **20.17**	14.6	**48**	49.3
C	114.87	109.8	75.59	66.1	15.32	10.4	44.73	35.69
Swords	**114**	119.1	**88.69** **88.74**	80.4	**16.78** **16.80**	18.7	**48**	53.9

Table 8.8 Results of segmental angles determined in SWORDS (using subject specific rules) and experimental study during maximum hip flexion (mean and ranges given)

The results of the hip and head segmental angles determined by SWORDS using the generic rules described in section 8.4.2, where a given point on the underside of the buttocks, constrained to being 1cm above the height of the seat of the chair, also shows comparatively good agreement with the actual experimental results, as shown in Table 8.9.

Due to the model space representing the shanks being fixed, when solving these generic rules, the results of the ankle dorsiflexion on this occasion in SWORDS show an improvement, when compared to the previous results determined (see Table 8.7 and 8.8).

The segmental knee angle modelled in SWORDS hardly changes in comparison to the value determined during the sitting posture, due to the movement of the shank model space being fixed. Even though the knee segmental angle did not lie within the range of the actual results measured during the experimental analysis, they were considered acceptable. This was due to the results of the hip segmental angle, which was the gross movement employed for this movement, being within close agreement to the actual segmental angles measured for each subject.

The segmental values of greatest interest, due to the gross movement of the trunk towards the attainment of the maximum hip flexion posture, is the maximum hip flexion angle. This segmental angle, when modelling maximum hip flexion using SWORDS, was found to lie within the ranges of all subjects, as shown in Table 8.9.

Max hip flexion -B								
Subject	**Hip**	Range	**Knee**	Range	**Ankle**	Range	**Head**	Range
A	125.28	122.3	82.24	80.1	12.7	6.8	41.84	37.8
Swords	**122**	129.9	**91.11** **91.11**	84.8	**14.2** **13.6**	19.1	**52**	48.9
B	113.37	110.3	74.52	73.2	12.79	11.1	43.03	39.1
Swords	**112**	115.7	**97.07** **97.06**	77.7	**19.36** **20**	14.6	**48**	49.3
C	114.87	109.8	75.59	66.1	15.32	10.4	44.73	35.69
Swords	**114**	119.1	**84.23** **84.25**	80.4	**19.9** **20.38**	18.7	**53**	53.9

Table 8.9 Results of segmental angles determined in SWORDS (using generic rules) and experimental study during maximum hip flexion (mean and ranges given)

8.4.3 Maximum ankle dorsiflexion

The results obtained during the maximum ankle dorsiflexion posture are presented in Tables 8.10 and 8.11. Where the results determined by SWORDS in Table 8.10 were for the initial constraint rules and functions, described in section 8.4.3, and the results for the modified rules were presented in Table 8.11. Comparisons of the SWORDS results shown in these two tables are very good for subjects A, but deviate somewhat for subjects B and C. However, the results of the segmental angles measured from the experimental study shows great variability of the hip and knee segmental angles, when compared to the SWORDS results (see Tables 8.10 and 8.11). Due to the arbitrary nature in defining constraint rules to model the maximum ankle dorsiflexion intermediate posture for each of the individual subjects, and for that matter, also the definition of the modified generic rules. It was proposed that it was not possible to directly compare the experimental and SWORDS data for this particular posture.

Maximum ankle dorsiflexion –A								
Subject	**Hip**		**Knee**		**Ankle**		**Head**	
A	95.31	76.4	68.33	55	23.75	22.3	38.17	30.6
	74	125.9	**53.21** **53.20**	80.3	**24.29** **24.33**	26.2	**37**	50.7
B	101.13	93.1	68.76	63.9	16.64	16.2	42.69	38.62
	79	106.9	**52.37** **52.34**	72.5	**20.11** **20.11**	17.5	**45**	46.2
C	54.87	46.8	55.52	51.7	26.93	22.7	29.69	25.9
	88	60.5	**38.13** **38.10**	59.3	**0** **0**	30.1	**46**	34.4

Table 8.10 Results of segmental angles determined by SWORDS (using initial rules) and experimental study during maximum ankle dorsiflexion (mean and ranges given)

Maximum ankle dorsiflexion -B								
Subject	hip		Knee		ankle		head	
A	95.31	76.4	68.33	55	23.75	22.3	38.17	30.6
	74	125.9	**53.67** **53.70**	80.3	**24.73** **24.70**	26.2	**45**	50.7
B	101.13	93.1	68.76	63.9	16.64	16.2	42.69	38.62
	79	106.9	**52.34** **52.38**	72.5	**20.01** **20.01**	17.5	**38**	46.2
C	54.87	46.8	55.52	51.7	26.93	22.7	29.69	25.9
	88	60.5	**52.43** **52.44**	59.3	**20.99** **20.98**	30.1	**40**	34.4

Table 8.11 Results of segmental angles determined by SWORDS (using modified rules) and experimental study during maximum ankle dorsiflexion (mean and ranges given)

8.4.4 The erect stance

The resolution of the rules to simulate the erect stance (as shown in Table 8.12) provided a neutral hip angle of zero, and shown that the erect stance defined in section 8.4.4 can be attained by each subject.

The head angle determined by SWORDS indicates that each subject was able to look downwards at the ball while standing erect. However, the actual segmental angles measured for subjects A, B and C showed that the knee extension and ankle dorsiflexion had not reached the neutral position, defined in section 8.4.4. This was because subjects A and C extend their knees further after the neutral hip position was reached, whereas subject B did not extend her knees fully, as shown by postures 'E to F' in Figures 7.7 to 7.9.

Erect stance								
Subject	**Hip**		**Knee**		**Ankle**		**Head**	
A	0.46	0.2	5.04	2.8	10.47	7.9	-6.14	-9.6
	0	0.8	**0**	6.6	**0**	13.3	**-14**	-2.9
B	2.02	0.2	10.02	9.8	8.4	7.1	7.07	4.4
	0	5.2	**0**	11.2	**0**	9.4	**-11**	9.3
C	0.65	0.4	15.84	12.3	17.5	16.4	3.72	1.3
	0	0.9	**0**	18.8	**0**	18.9	**-13**	6.2

Table 8.12 Results of segmental angles determined by SWORDS and experimental study during the erect stance (mean and ranges given)

8.5 Conclusions

The comparisons of the results provided by the SWORDS modeller, when simulating the sit-to-stand movement, were believed to be generally good when compared to the experimental study described in Chapter 7. A comparison of the maximum ankle dorsiflexion intermediate posture, shows the hip and knee angles to be too variable and thus not suitable for comparisons.

However, this study has shown that it was possible to mimic the intermediate postures determined when rising though the use of i.e. the sitting posture, the maximum hip flexion and the erect stance, using generic rules and measurements taken from individual subjects. It was thus concluded that these generic rules could be used to model other individuals using the same movement strategy commonly used by able-bodied subjects when rising from a chair.

The following chapter will describe a case study carried out to validate the design methodology proposed in chapter 3. This case study involved three people with osteoarthritis, who wished to stand from a sitting posture using normal movement patterns, without experiencing pain.

Chapter 9
Case Study

9.0 Introduction

This chapter describes a case study, undertaken to show that the proposed design methodology, described in chapter 3, could be used to design appropriate devices to improve the mobility of people. It was also undertaken to enable these people to gain optimal function while carrying out a movement task in a normal manner, without experiencing pain. The novel part of the proposed this design methodology was focused around the development of the concept design for the user, thus the case study will conclude before the Embodiment Phase. Finally conclusions have been provided.

9.1 Case Study

This case study was aimed at creating a device to improve the mobility of three people with osteoarthritis during the task of rising, from a sitting to a upright standing posture. The following sections will describe how this was carried out.

9.2 Phase 1 Define problem and user needs

The initial design phase, shown in Figure 9.1, involved defining the user attributes and the movement task they wished to carry out. It also involved an observational study and subjective questioning of potential users and able-bodied people using a chair simulating a typical design commonly used by both groups, as well as existing designs created to aid the task of rising. These tasks were carried out to enable the understanding of the physical attributes of the user; to distinguish whether the movement strategies of both the potential user and able-bodied people were similar; and to study the advantages and disadvantages of using existing designs. Subjective questioning of the user group was also carried out during these observational studies to understand the specific problems of the users when carrying out the task. Other user needs related to the device to be designed, such as material choice, were established and defined in the design specification document.

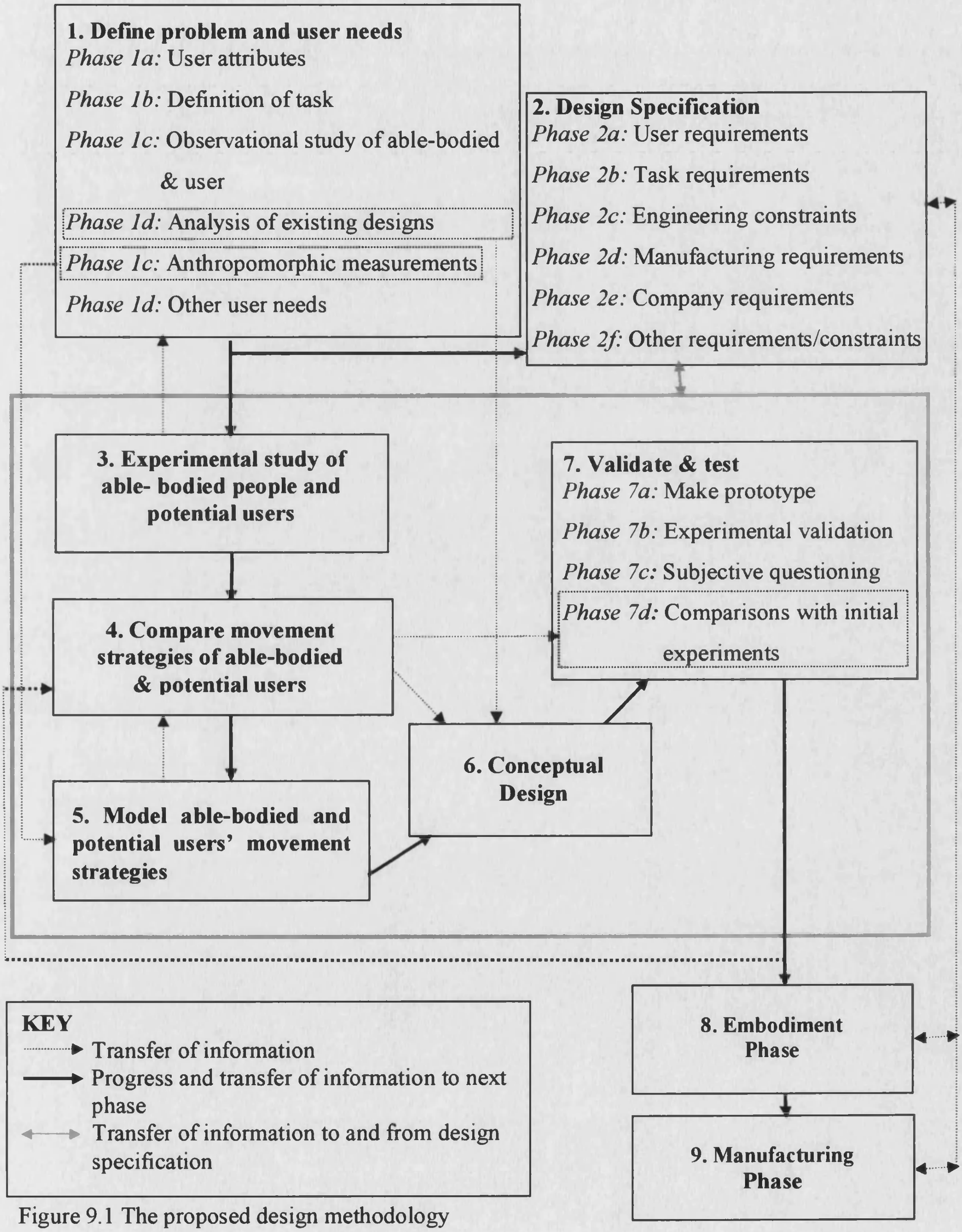


Figure 9.1 The proposed design methodology

9.2.1 *Phase 1a* User attributes

Three people with osteoarthritis were chosen according to their availability. They were all living independently at home and thus wished for a device that would not require any physical aid from another person. All three people claimed to experience slight stability problems when rising. The general attributes of the three subjects D, E and F, are shown in table 9.1.

Subject	Age (years)	Weight (kg)	Height(m)	Gender
D	36	55	1.67	female
E	54	101	1.65	female
F	74	72	1.78	male

Table 9.1 User attributes

9.2.2 *Phase 1b* Definition of task

The task carried out by the subjects D, E and F was to rise from a sitting posture to a standing one using a stable natural movement strategy similar to that employed by able-bodied people.

9.2.3 *Phase 1c* Observational study of able-bodied and user

The objective of the initial observational study was to determine whether the movement strategies employed by the potential users were similar to those used by able-bodied people.

The three subjects with osteoarthritis and the same three able-bodied people that took part in the experimental study described in Chapter 7, were employed to rise from a chair used to simulate the design most commonly used by both able-bodied people and the potential users. This chair had a seat height of 440mm without arm rests or moving parts. While being video recorded each subject was requested to begin the movement task using the same initial posture, i.e. both feet on the ground and arms placed at their sides, and to stand up, with no other movement or time constraints. All subjects were questioned subjectively on their comfort and stability.

9.2.3.1 Results

The video recordings taken of the subjects using a chair design commonly used by the two groups, showed that the movement strategy, illustrated in Figure 9.2, of the two groups studied were essentially similar. The only exception was that of subject F, with osteoarthritis. He employed a slightly different movement strategy, due to not being able to rise from a sitting posture without the use of both arms, as illustrated in Figure 9.3. This subject experienced limited range of motion of the right hip joint, and hence it was speculated that the arms were rotated forwards in an attempt to move the body's CoM forwards to gain stability and to also generate enough momentum to stand up. Even though the use of the arms was a slightly different strategy to aid rising, subject 'F' still employed similar gross movements of the trunk and legs to that commonly employed by both the able-bodied subjects. Also the design intent was to focus on being able to rise without arm support (to accommodate subject D who had limited arm strength) and therefore should have enabled this subject to rise without swinging his arms forward.

Figure 9.2 Common movement strategy employed by able-bodied and subjects with osteoarthritis

Figure 9.3 Movement strategy employed by subject F with osteoarthritis

9.2.4 *Phase 1d* Analysis of Existing designs

The analysis of existing designs enabled the understanding of the advantages and disadvantages of devices that were specifically designed for the purpose of aiding the task of rising. This involved observational studies and the subjective questioning of both able-bodied people and the potential user groups using existing designs.

There were currently numerous devices available on the market to aid the task of rising from a chair. There were many armchairs that were designed to automatically lift upwards and tilt forwards, requiring very little mobility of the user when rising from a chair. However, there were also two typical types of design that were aimed towards the more independent user. The two that were considered to be most popular and effective, by the orthopaedic therapists employed at the Independent Living Centre in Bristol, were used for the analysis of existing designs. The first, called the 'Arran Riser' (produced by A.J. Way and Co. Ltd) was a seat, integral to an armchair, that pivoted about the front edge and tilted forwards, that pushed the user out of the chair, as shown in Figure 9.4. The other design, called the 'Easy stand' (produced by Grimstead Medical Ltd), where the user had to pull themselves to a standing position using a hand grips positioned in front of them, as shown in Figure 9.5. The chair with the pivoting seat, shown in Figure 9.4, was used in combination with the device with hand grips, with its seat remaining in an horizontal position, and on its own, with the seat being allowed to tilt forwards.

Figure 9.4 The 'Arran' spring operated lifted seat used for observational analysis

Figure 9.5 The 'Grimstead Easy Stand' device used for observational analysis

9.2.4.1 Results

All subjects (i.e. both able bodied and those with osteoarthritis) found that the seat that raised upwards and pivoted forwards, shown in Figure 9.4, tended to give them a feeling that they were being 'pushed' or 'propelled forwards'. Most of the subjects also felt that they were 'out of control' and that they were being 'pushed into an unstable posture after standing up'. Observational studies showed that half of the subjects needed to take a step forwards to maintain stability, after they acquired a standing posture.

The majority of the subjects, including the able bodied people, found that the 'Grimstead Easy Stand' aid where the user had to pull themselves out of the chair, shown in Figure 9.5, required too much arm strength. They also found that their movements were restricted and that 'more pain than usual', was felt in the knee joint of subject E, with osteoarthritis. Observational studies showed that each subject was prevented from swaying their upper body forwards, when rising, due to the position of the hand grips. This resulted in the upper body being kept vertical and the subjects pivoting about their knee joints to rise to a standing posture, as shown in Figure 9.6. This forces the user to employ an intermediate posture that they would not commonly use.

Figure 9.6 Movement strategy employed when using 'Grimstead easy stand'

It was concluded that due to the difficulties observed and reported by the users studied, using existing aids to rise, that a device was required to enable the potential user group to employ the natural stable movement strategy similarly used by able-bodied people.

9.2.5 *Phase 1e* Anthropomorphic measurements

Anthropomorphic measurements of the body segmental lengths, the external body measurements and the joint range of motion, described in section 8.2.2, were taken of both groups. This information shown in appendix A was later input into the constraint based modeller SWORDS, to enable the computer manikin to mimic each individual's body sizes and joint movement limitations, carried out in Phase 5.

According to Weller and Wells (1982) osteoarthritis is 'a degenerative condition attacking the articular cartilage and aggravated by an impaired blood supply', 'mainly affecting weight bearing joints and causing pain'. Therefore the measurements of the three subjects were taken to the limit of joint rotation, before they experienced discomfort. The joint range of motion that was found to be limited, when compared to able-bodied people measurements, and caused pain or discomfort for the people with osteoarthritis, are shown in the design specification.

9.2.6 *Phase 1f* Other user needs

This was documented as part of the design specification.

9.3 Phase 2 Design Specification

This phase involved the development of the design specification document that defined the requirements of device by the user, company and production. This case study, however, was aimed at designing a conceptual device for only three subjects without the inclusion of the usual constraints imposed by a company or production. Therefore focus was placed upon specific user and task requirements as follows:

9.3.1 *Phase 2a* User requirements

To prevent the user experiencing discomfort or pain when rising, the design solution was required to prevent the user's joint range of motion from exceeding the limits listed in Table 9.2 below.

Subject	Joint with limited range of motion	Flexion (degrees)	Extension (degrees)
D	Wrist (right)	Fused (i.e. no movement)	
	Knee (left)	19-110	
	Knee (right)	11-90	
	Ankle (right)	5 (dorsiflexion)	
E	Knee (left)	Limited range (28-86)	
F	Hip (right) ankle (right)	86 0 (dorsiflexion)	0

Table 9.2 User joint range of motion measured before discomfort was experienced

Environment where the device is used:

- Home environment, used for watching television, reading and relaxing
- Attributes of device normally found in context of environment used:

A lounge chair would normally have a seat height slightly lower than average, e.g. 44cm, with a reclining backrest. Both seat and backrest should be cushioned with, for example, foam. The chair would also include armrests usually cushioned and covered in a material to suit the interior decoration of the lounge.

It was decided to exclude armrests from the design of the concept device due to the limited arm strength and range of joint movement of subject D, which negated the use of armrest to aid rising. The device should thus not rely on the use of arms to rise from a sitting posture but instead use the trunk flexion and leg extension to aid rising. However, it is recognised that the addition of armrests should be considered for further development, as described in Chapter 10, to create a chair that is suitable for use in a lounge environment.

Comfort requirements

- The user should feel no pain when rising and be able to use the device as an aid to carrying out the activities described in 9.4.3.

Attributes of artefacts that were incorporated or discarded in the design solution, from analysis of existing devices:

- The design solution should not include any object, such as a handrail or hand grips that are placed directly in front of the user, that may prevent them from carrying out the movement strategy defined in section 9.3.2.

- The design solution should not depend on the use of the arms to aid the subject in rising.

- The design solution should not force the user into an unstable position after rising. The user should thus not need to take a step forwards after standing erect to maintain stability.

Safety requirements

- To prevent a possible fall the user should not be forced into an unstable posture.
- The surface of the seat should be made of a material that would prevent the user slipping, while sitting or rising.

Other requirements

- A device that does not require any physical aid from another person to enable the user to rise.

9.3.2 *Phase 2b* Task requirements

Definition of the task:

- To rise up from a sitting to a standing posture.

Movement strategy employed to carry out task:

- The initial sitting posture was found to be where both feet are placed on the ground, and the head and buttocks are supported by the backrest and seat, respectively. The upper body should then be swayed in an anterior direction, bringing the CoM forwards close to the base of support formed by the feet, before the subject rises upwards to a standing posture.

Problems experienced while carrying out task:

- Subject D had a lack of strength in the hands and limited range of movement of the left wrist.
- Subject E had a limited range of movement of the left knee and experienced severe pain in this joint when the buttocks were lifted from the seat, when rising.
- Subject F had a limited range of movement of the right hip and experienced discomfort in this joint when rising from a sitting posture

Reasons for instability when carrying out task:

- The people observed with osteoarthritis were able to perform similar stable intermediate postures and movement strategy employed by able-bodied people. However, due to their physical disability they required a device that would aid them in maintaining these stable intermediate postures, rather than force them into unstable ones.

9.3.3 *Phase 2c* Engineering constraints

There are no specific engineering constraints

9.3.4 *Phase 2d* **Manufacturing requirements**

There are no specific manufacturing requirements

9.3.4 *Phase 2e* **Company requirements**

There are no company requirements

9.3.3 *Phase 2f* **Other requirements/constraints**

Cost constraints

- No cost constraints for the purpose of this project

Material requirements

- Non slip surface on seat of chair

Other functional requirements of device

- Attainment of a reclined posture for relaxation purposes

9.4 Phase 3 Experimental study of able-bodied people and potential users

The aim of the experimental study was to measure the joint angles produced during rising of the young healthy able-bodied people and the potential user group. The same three people with osteoarthritis and the three able-bodied people used for the observational study, described in section 9.2.3, were employed for this purpose.

The movement task of rising was undertaken in a laboratory setting using the same chair described for the experimental study described in section 7.1.1 and followed the same procedures described in section 7.2. Therefore to avoid repetition and experimental laboratory time the results for the able-bodied people, described in the experimental study in Chapter 8, were used to make comparisons for the following phase 3. Armrests were not used for this study to enable the design to be developed to support a movement strategy that would not require arm movement to aid rising.

All subjects were requested to rise using the same movement constraints also described in section 7.2. However, two of the people with osteoarthritis were not able to obtain the same feet placement as the able-bodied people due to the limited joint range of motion and pain experienced in the knee and ankle joints. Therefore, instead of requesting them to obtain 10° ankle flexion, similarly to the able-bodied group which resulted in the adjustment of the seat height to approximately 100% popliteal height. To enable them to rise more comfortably, the seat height was adjusted to approximately 120% of their individual popliteal heights. Their individual heel placement is listed, in respect to a line placed on the floor directly underneath the front of the seat, as follows:

- Subject D 4.5cms in front of the line
- Subject E Placed on the line with some discomfort
- Subject F 2cms behind the line

The results of this study are discussed in the following section.

9.5 Phase 4 Compare able-bodied and potential user movement strategies

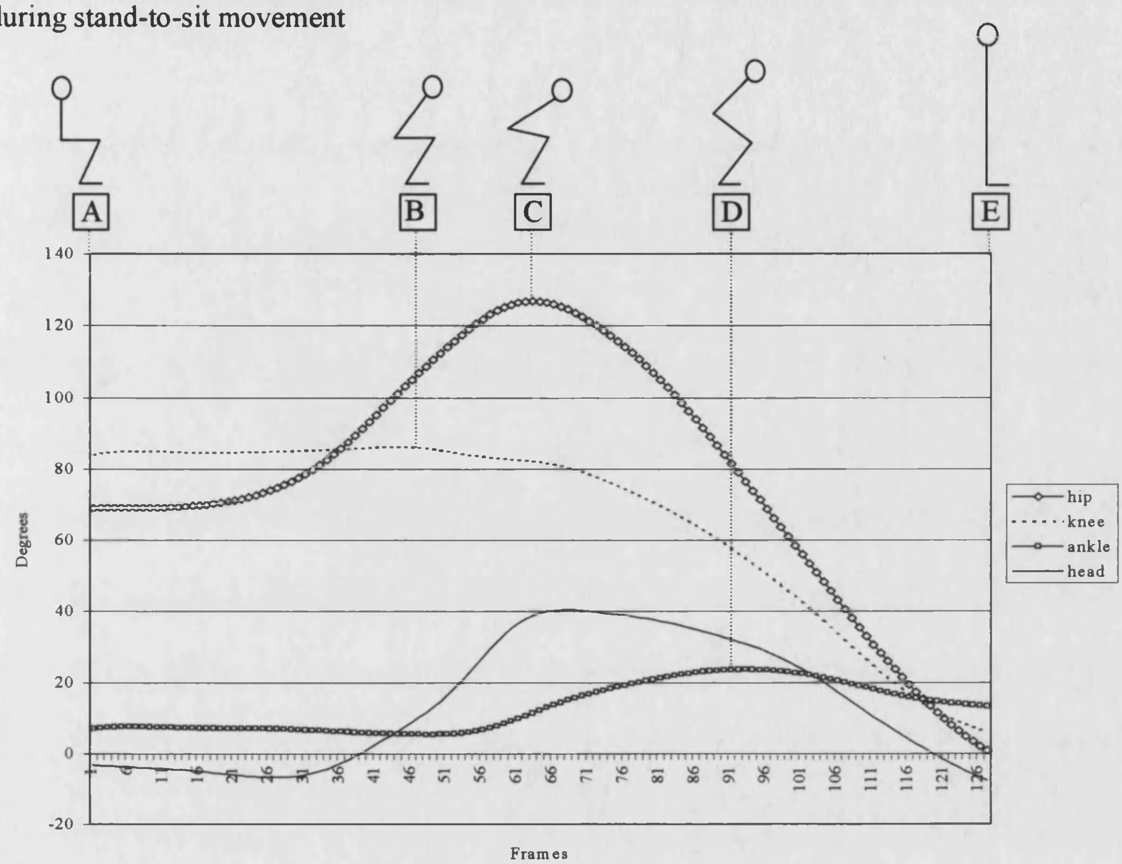
Initial comparisons of the graphs, shown in Figures 9.7 to 9.10, illustrated that both groups employed essentially the same movement strategy during the stand-to-sit movement. Further analysis of the angles produced between the body segments of the subjects with osteoarthritis, measured during the stand-to-sit movement, show that their range of movement exceeded that initially measured when determining their joint range of motion. The reason for this was perhaps twofold. The joint range of motion of the subjects with osteoarthritis was specifically measured passively before the subjects experienced any pain or discomfort during extension or flexion. Also that the 'flexibility of one joint may be influenced by the posture of adjacent joints' (Pheasant (2001)), hence the range of motion of any joint may alter when carrying out a different movement. Even though during subjective questioning the users reported that pain was experienced from these joints during rising. The limitation of joint range of motion constraining the manikin representative of these subjects within SWORDS was later modified according to these limits, which were rounded up to the nearest whole number and is showed in bold in Table 9.3, to enable their movements to be mimicked more accurately.

Subject	Joint with limited range of motion	Flexion/dorsiflexion (degrees)		Extension (degrees)	
D	Wrist (right)	Fused			
	Knee (left)	19-110			
	Knee (right)	11-90			
	Ankle (right)	5	**23**		
E	Knee (left)	28-86			
F	Hip (right)	86	**109**		
	ankle (right)	0	**19**		

Table 9.3 Joint range of motion of subjects measured during the STS movement shown in bold

Comparisons of the ankle segmental angle showed that both subjects D and E tended to maintain almost the same degree of ankle angle after maximum ankle dorsiflexion was attained, as graphically illustrated in Figures 9.8 and 9.9. Subject F, who also followed a similar movement pattern to subjects D and E, shown in Figure 9.10, did not attain maximum ankle dorsiflexion, which was thought to be due to a slight change in movement strategy caused by the subject's arms being swayed forwards. The limited neck and head flexion and extension of subject D showed an expected reduced range of movement when rising from a chair in comparison to the other subjects, as shown in Figure 9.8. The hip extension of subject D was also slightly reduced when compared to the other subjects. This could be the result of this subjects limited neck extension, which was not a consideration of the design specification, as it was thought that this movement was not a prerequisite to rising. The results of the angles measured between their body segments during the sitting, maximum hip flexion and standing posture will be shown in the following section.

Figure 9.7 Graphical illustration of segmental angles produced by able-bodied subject 'A' during stand-to-sit movement

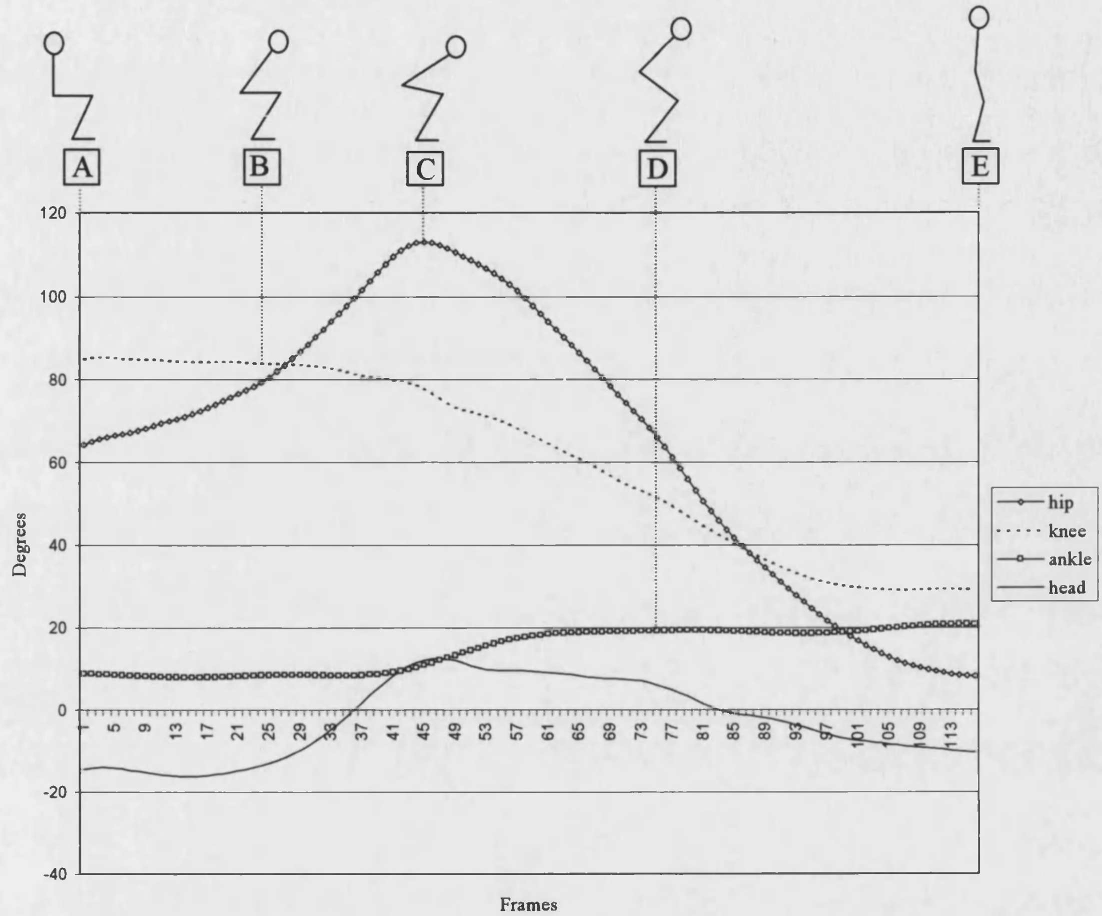


KEY

STAND-TO-SIT

A: Sitting posture
B: Before seat off
(Start of knee extension)
C: After seat off
(Maximum hip flexion)
D: Squat position
(Maximum ankle dorsiflexion)
E: Initiation of erect stance
(Neutral hip position)

Figure 9.8 Graphical illustration of segmental angles produced by able-bodied subject 'D' during stand-to-sit movement

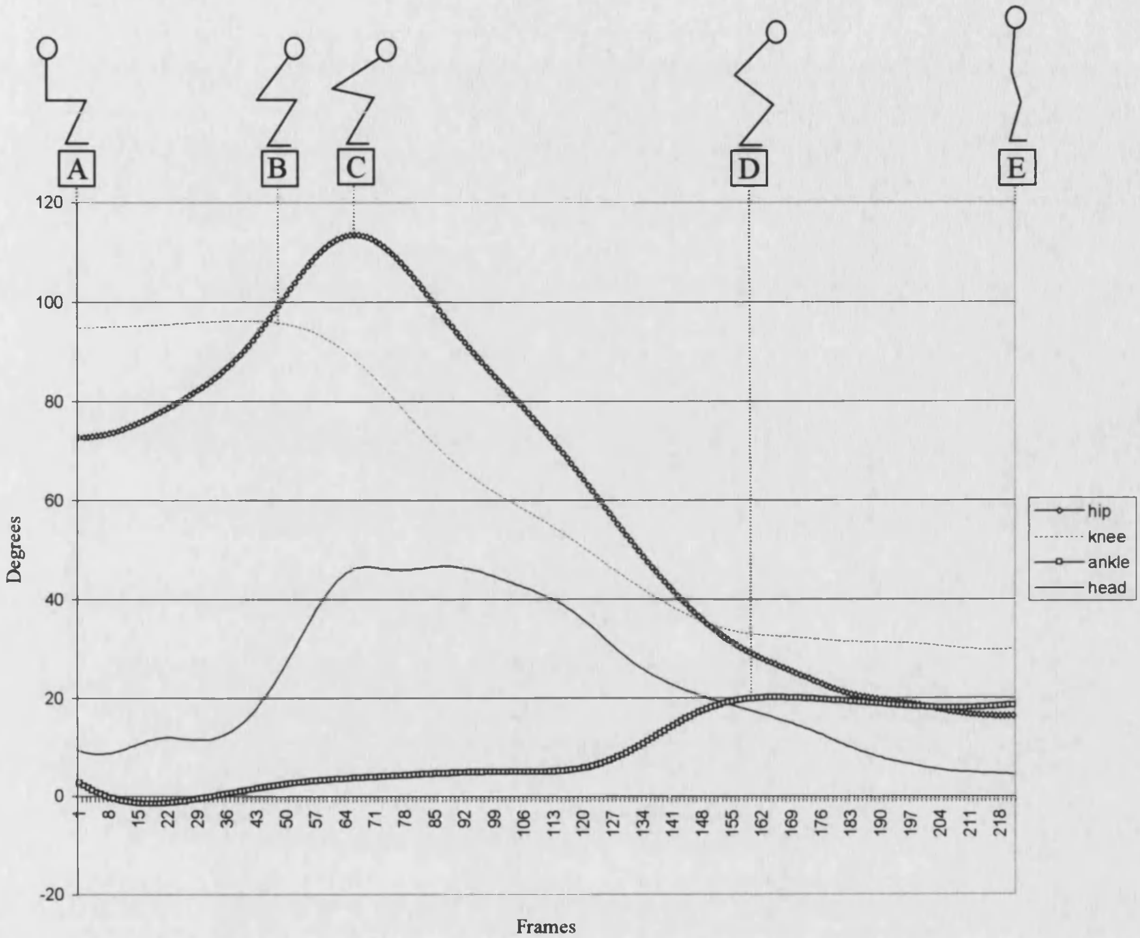


KEY

STAND-TO-SIT

A: Sitting posture
B: Before seat off
(Start of knee extension)
C: After seat off
(Maximum hip flexion)
D: Squat position
(Maximum ankle dorsiflexion)
E: Initiation of erect stance

Figure 9.9 Graphical illustration of segmental angles produced by able-bodied subject 'E' during stand-to-sit movement

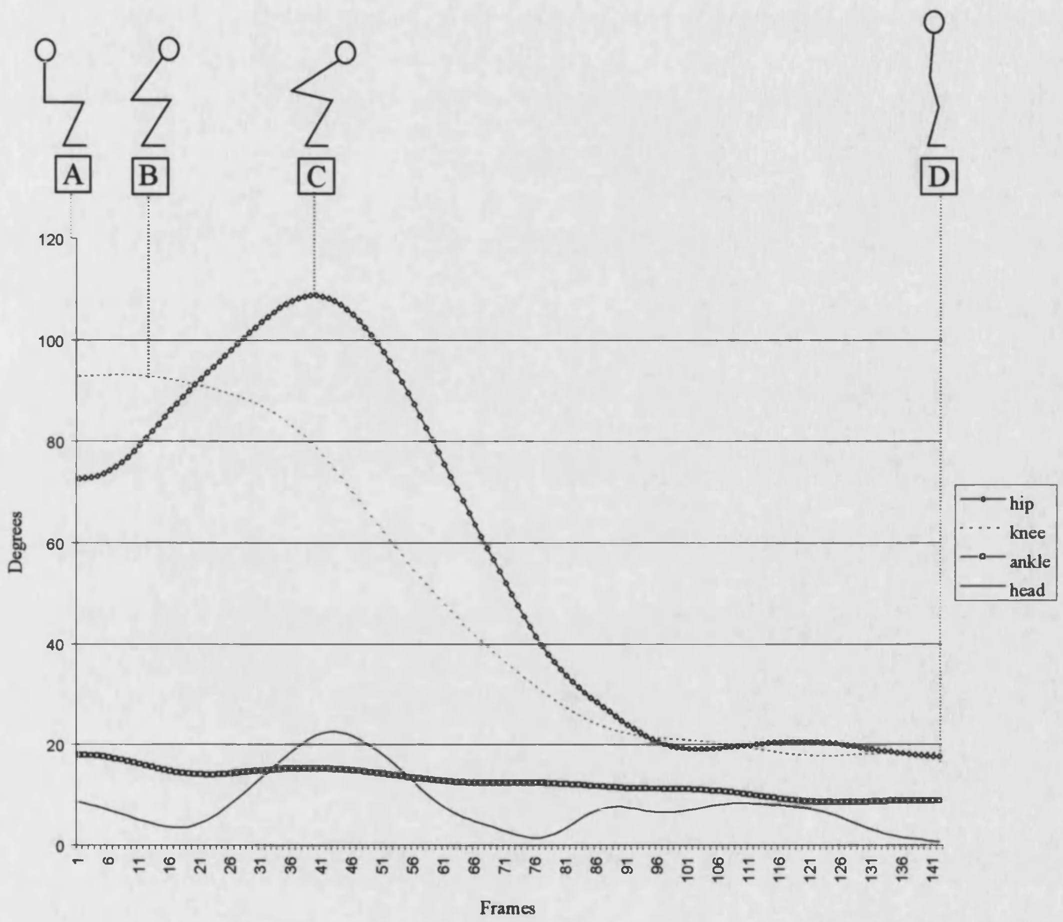


KEY

STAND-TO-SIT

A: Sitting posture
B: Before seat off
(Start of knee extension)
C: After seat off
(Maximum hip flexion)
D: Squat position
(Maximum ankle dorsiflexion)
E: Initiation of erect stance

Figure 9.10 Graphical illustration of segmental angles produced by able-bodied subject 'F' during stand-to-sit movement



KEY

STAND-TO-SIT

A: Sitting posture
B: Before seat off
(Start of knee extension)
C: After seat off
(Maximum hip flexion)
D: Initiation of erect stance

9.6 Phase 5 Model able-bodied and potential user movement strategies

The movement strategy employed by both groups was mimicked using the same rules and body segment variables used and comprehensively described in chapter 8. The external body measurements, segmental lengths and range of joint motion of each individual subject, represented by the manikin developed in SWORDS, were also used to model the intermediate postures when rising. It was decided not to model the movement strategies for comparative purposes employed by subject F due to the variation of the movement strategy caused by the arm movement employed.

The results of the hip, knee, ankle and head segmental angles (defined in section 5.3), measured while modelling the sit-to-stand intermediate postures, are shown in bold type in Tables 9.4 to 9.6. The corresponding mean and range of the segmental angles measured during the experimental study are also shown for comparative purposes. The video frames of typical postures employed by subject D during the experimental study are shown in Figures 9.11 to 9.13. The following sections discuss and compare these results.

9.6.1 The sitting posture

The results of the segmental angles measured during the sitting posture for able-bodied subjects A, B and C, and subjects D and E with osteoarthritis, were comparatively similar to those modelled using the equivalent manikin representative, as shown in Table 9.4.

The actual knee flexion of subject E, however, was found to be slightly more that the other subjects, even though the heel of this subject was placed on the same line marked on the ground for the able-bodied subjects. This could be due to the following reasons:

- A larger body mass of the upper thighs which could have altered the placement of the buttocks on the seat, which could have in turn affected the knee flexion, even when the same foot placement had to be maintained.

- The variable placement of the buttocks on the seat of the chair after each stand-to-sit trial was completed may have also attributed to the small discrepancies between the results of those found using the manikin representative and those of each subject.

Similarly, it was believed that the variable position of the head and eye range of movement to view the ball, placed in front of each subject, was accountable for the variable head flexion and extension during the sitting posture found both experimentally and through the use of the manikin.

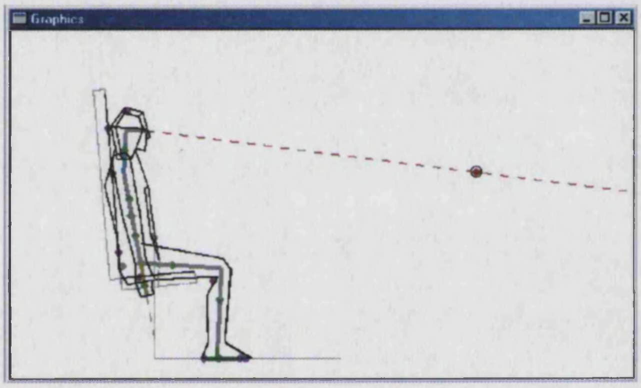


Figure 9.11 Video frame of 'subject D' during sitting posture that occurred during stand-to-sit trail and manikin representation of 'subject D' using constraint rules and variables defined in section 7.3.1

Standard chair Sitting posture									
Subject	**Hip**	Range	**Knee**	Range	**Ankle**	Range	**Head**	Range
A	69.12	68.3	82.46	80.5	5.89	4.3	-2.16	-0.1
	70	70.2	**91.18** **91.18**	84	**9.55** **9.53**	7.9	7	-3.5
B	75.27	74.3	81.97	79.2	3.23	1.5	4.83	1.8
	79	75.7	**97.07** **97.05**	86.1	**10** **9.94**	4.3	**0**	6.1
C	72.84	68.6	86.92	80.6	10.81	6.9	10.07	5.3
	64	77.2	**84.24** **84.25**	93.7	**7.38** **7.39**	15.7	**9**	16.2
D	64.72	63.6	85.37	84.3	7.28	6.3	-13.52	-11.9
	79	65.7	**91.03** **91.08**	86.8	**3.01** **3.09**	8.9	**6**	14.6
E	75.36	73.3	96.21	94.9	11.22	7.8	8.49	5.2
	68	75.5	**87.87** **87.86**	97.4	**10** **9.96**	14.7	**6**	11.8
F	70.81	68.5	91.89	91.3	16.83	15	4.73	1
		72.8		92.3		18.9		7.4

Table 9.4 Results of segmental angles determined in SWORDS and experimental study during the sitting posture (mean and ranges given)

9.6.2 Maximum hip flexion

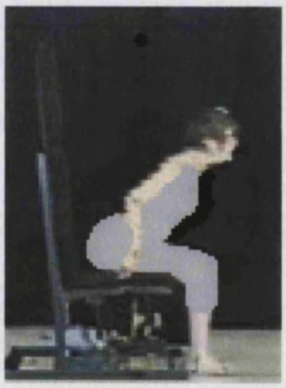
Comparisons between the hip segmental angle found using the individual manikin representatives show good agreement and are discussed as follows:

- The hip flexion measured within SWORDS was 2% outside the movement range for subject D and 5% for subject E.

- This was reflected in the head extension measured using the manikin for subject D, which hi-lights the compensatory nature of this body segment during hip sway. However, the results of the head extension measured for the other subjects show comparatively good agreement.

- The knee segmental angles of some of the subjects did not lie within the range of the actual results measured during the experimental analysis. They are however considered acceptable due to the results of the other segmental angles being within close agreement to the actual segmental angles measured for each subject.

- The measurements of the right and left ankle angle found in SWORDS are within range of those found experimentally. It was speculated that the small discrepancies between the right and the left ankle angles of subjects A and B were due to the SWORDS modeller trying to solve two possibly conflicting rules. One rule constrained the heels of the feet to be placed on the line directly underneath the seat of the chair, and the other forcing the total body CoM to be placed within the base of support formed by the feet.



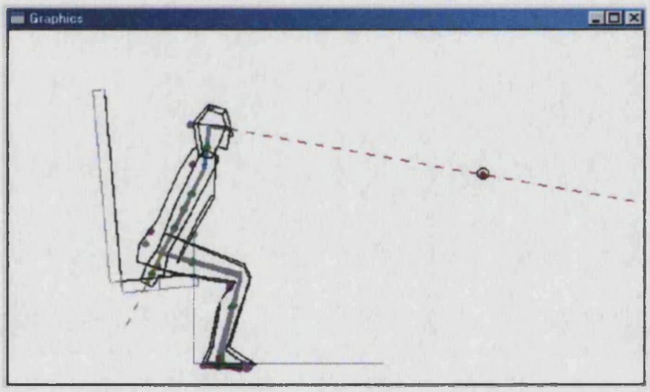


Figure 9.12 Video frame of 'subject D' during maximum hip flexion that occurred during stand-to-sit trail and manikin representation of 'subject D' using constraint rules and variables defined in section 7.3.2

Standard chair Max hip flexion								
Subject	**Hip**	Range	**Knee**	Range	**Ankle**	Range	**Head**	Range
A	125.28	122.3	82.24	80.1	12.7	6.8	41.84	37.8
	122	129.9	**91.11** **91.11**	84.8	**14.2** **13.6**	19.1	**52**	48.9
B	113.37	110.3	74.52	73.2	12.79	11.1	43.03	39.1
	112	115.7	**97.07** **97.06**	77.7	**19.36** **20**	14.6	**48**	49.3
C	114.87	109.8	75.59	66.1	15.32	10.4	44.73	35.69
	114	119.1	**84.23** **84.25**	80.4	**19.9** **20.38**	18.7	**53**	53.9
D	109.38	104.8	78.31	77.9	11.8	10.91	9.22	3.4
	102	113.1	**90.08** **91.86**	78.9	**11.03** **11.56**	12.49	**20**	12.1
E	115.87	113.5	89.05	88.68	11.82	3.6	43.59	41.1
	107	117.2	**87.88** **87.86**	90.68	**18.8** **18.8**	18.8	**44**	46.3
F	105.26	102.9	83.5	78.7	15.08	14.7	11.37	4.5
		108.8		87.1		15.4		21.9

Table 9.5 Results of segmental angles determined in SWORDS (using generic rules) and experimental study during maximum hip flexion (mean and ranges given)

9.6.3 The erect stance

The results from the segmental angles measured using the individual manikin representatives of the people with osteoarthritis reflect the limited range of motion of these subjects during the erect stance. This could be seen by the variation of the knee and ankle segmental angles measured in SWORDS of subjects D and E.

The hip and head segmental angles of subject E modelled show good agreement with the experimental results:

- The head segmental angle of subject D also lies within range of the experimental results.

- The hip segmental angle of subject D however was found to be 36% more than the highest range of values. The reason was thought to derive from the flexion of the trunk of the manikin representative to enable the line of sight to be directed though the ball placed in front. Whereas it was thought that subject D kept her head straight as if looking forwards, which is a tendency during the erect stance, and used eye movement to look at the ball, as shown in Figure 9.12.

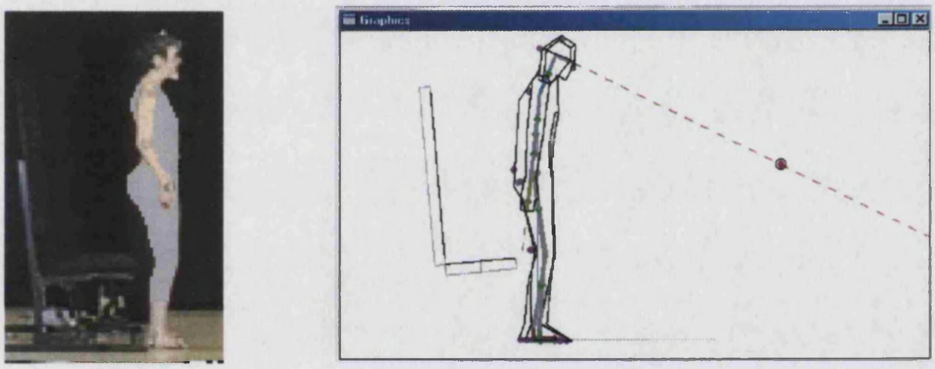


Figure 9.13 Video frame of 'subject D' attaining erect stance during stand-to-sit trial, and manikin representation of 'subject D' using constraint rules and variables defined in section 6.3

Standard chair Erect stance								
Subject	**Hip**	Range	**Knee**	Range	**Ankle**	Range	**Head**	Range
A	0.46	0.2	5.04	2.8	10.47	7.9	-6.14	-9.6
	0	0.8	**0**	6.6	**0**	13.3	**-14**	-2.9
B	2.02	0.2	10.02	9.8	8.4	7.1	7.07	4.4
	0	5.2	**0**	11.2	**0**	9.4	**-11**	9.3
C	0.65	0.4	15.84	12.3	17.5	16.4	3.72	1.3
	0	0.9	**0**	18.8	**0**	18.9	**-13**	6.2
D	8.39	8.2	29.85	29.3	20.39	19.7	-11.87	-16.3
	12	8.8	**11.04** **19.08**	30.4	**5.43** **12..63**	20.8	**-16**	-9.1
E	10.2	5.5	30.5	29.2	19.83	18.5	-1.66	-6.9
	9	16.3	**5.4** **28**	32.3	**2.2** **10**	21.1	**-8**	4.6
F	20.08	18.9	22.28	20.4	11.51	10.7	1.82	-3.3
		22.3		25.7		12.9		7.4

Table 9.6 Results of segmental angles determined by SWORDS and experimental study during the erect stance (mean and ranges given)

9.6.4 Conclusions

It was considered that the comparisons of the results provided by the SWORDS modeller, when simulating the stand-to-sit movement, were generally good when compared to the experimental study, carried out in phase 3. This study showed that the SWORDS constraint modeller was able to model the intermediate postures, i.e. the sitting posture, the maximum hip flexion and the erect stance, of both the able bodied people and the two subjects with osteoarthritis. It was thus concluded that these generic rules could be used to develop a conceptual design using the manikin created within the SWORDS modeller.

9.7 Phase 6 Conceptual design

Some authors have found that older people found rising from a seat of approximately 140% of popliteal height to be the least challenging, when compared to seats of lesser height, as discussed in section 2.3. However experimental studies, such as those carried out by Alexander (1996 and 2000), have found that peripheral circulation can be compromised if the feet are not in contact with the floor. This problem, according to Alexander (2000) can be overcome by employing a seat of 20cm depth, where only the ischial tuberosities (sitting bones) are in contact with the seat. According to Alexander (2000) this places the user in a perched position, presumed to be similar to the intermediate posture where maximum ankle dorsiflexion is found. The following diagrams show the iterative procedures that were used to develop a concept design, which was based upon these findings. The rules and variables developed to mimic the stand-to-sit movement within SWORDS were used as part of these procedures and are illustrated through the use of the manikin representation of subject D (i.e. one of the female subjects with osteoarthritis).

A separate file, created in SWORDS, representing the geometric entities of the chair used for the experimental analysis, described in section 7.2.1, was employed to create a device to fulfil the design intent of the specification, detailed in section 9.3. The intention of using this file was to either modify the existing design or to use the geometric entities, already constructed, to create a new concept.

The movement analysis, carried out using the manikin, was focused on the attainment of maximum hip flexion due to the pain experienced during knee flexion of subject E, during this posture. It was also the most challenging phase, according to Schenkman et al (1991), of transferring the body's CoM from the base of support of the buttocks, thighs and feet, to the feet alone.

The aim of the design, according to the design specification was to decrease both the knee and hip flexion to 86°, to suit the limited joint range of motion of subjects E and F respectively. The manikin representative of Subject D was initially used for this purpose and later validated using the manikin representatives of all subjects involved in the case study.

9.7.1 Design Iteration 1

The initial design iteration was to increase the height of the chair, represented by the geometric entities used for the experimental study carried out in phase 5, to 140% of the popliteal height of subject D (i.e. 491mm). This was with the intention of decreasing the knee flexion required during the sitting posture and during maximum hip flexion. Hence reducing the amount of torque on the knee joint when rising and thus reducing the pain experienced.

The geometric representative of the seat of the chair was rotated to be horizontal (i.e. with no recline), to be able to visually estimate the interference of the upper leg with the front of the chair. The feet were positioned in the same position as that used by subject D in the experimental analysis. Where the backs of the heels were positioned 45mm in front of the line placed on the ground directly underneath the front of the seat. The rules that invoked the sitting and maximum hip flexion of the manikin representing subject D were invoked, as shown in Figure 9.14.

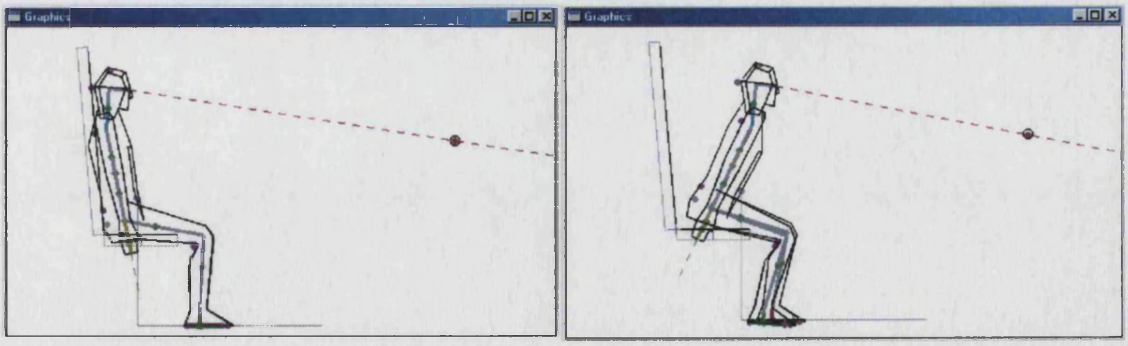


Figure 9.14 140% of popliteal height (49.1cm), feet placement 4.5cm in front of seat

When the chair height was increased from 430mm to 491mm the segmental angles measured while modelling the maximum hip flexion posture were as follows:

- Maximum hip flexion was reduced from 102° to 95°
- Right knee flexion was reduced from 90° to 82.62°
- Left knee flexion was reduced from 89° to 82.69

9.7.2 Design Iteration 2

The target of reducing the knee flexion had reduced to 82.69°, which was less than the design specification target of less than 86°. The hip flexion of 95° however needed to be reduced further to become less than the design specification requirement of 86°. It was thus decided to further increase the height of the chair to 160% of the popliteal height of subject D with the intention of decreasing both the hip flexion further, when maximum flexion occurred, as shown in Figure 9.15.

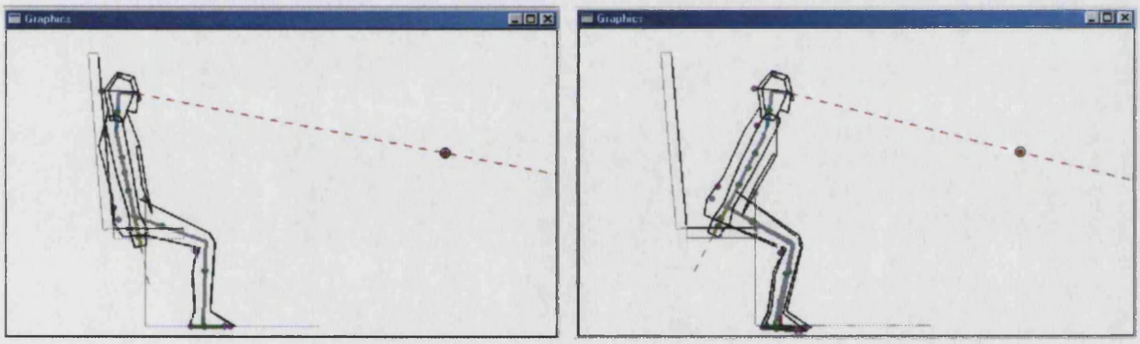


Figure 9.15 160% of popliteal height (562mm), feet placement 45mm in front of seat

The results of modelling the sitting and maximum hip flexion posture when the seat height was increased from 140% to 160% of the popliteal of subject D (i.e. 562mm) are as follows:

- Reduction of hip flexion from 95° to 87°
- Reduction of right knee flexion from 82. 62° to 72.23°
- Reduction of left knee flexion from 82.69° to 72.32

Even though these results were closer to the requirements of the design specification. It was visible that the seat could cause discomfort on the underside of the upper leg, as shown in Figure 9.15, and that possible peripheral circulation could be compromised.

9.7.3 Design Iteration 3

To avoid the discomfort that could be caused by the front of the seat 'digging' into the upper leg it was decided to split the seat into two segments both of 200mm depth. This would require a chair with adjustable height, where the front half of the seat would pivot downwards as the chair rose in height. The diagram in Figure 9.16 shows the design to be 160% of the popliteal height of subject D, where the front half of the seat is rotated 40° from the horizontal.

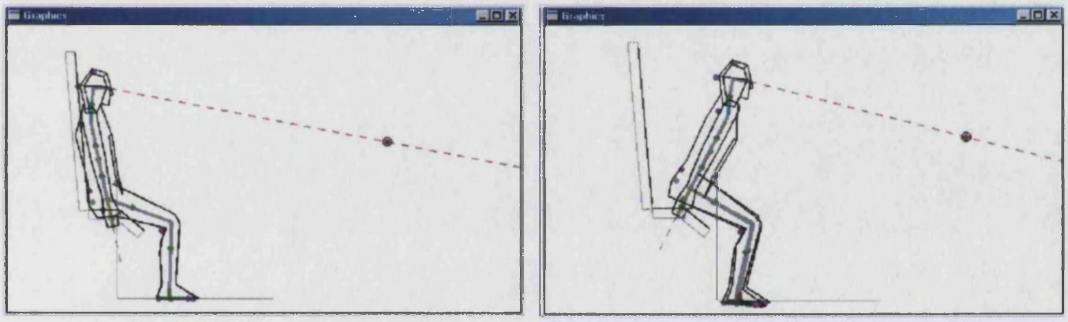


Figure 9.16 160% of popliteal height (562mm), feet placement 4.5cm in front of seat, rotation of front seat 40°

The rotation of 40 ° to the horizontal of the front half of the seat, as shown in Figure 9.16, should have prevented the front of the seat causing discomfort to the underneath of the upper leg. However, the calculation of the total body CoM, when vertically projected from the ground plane, showed the manikin to be unstable during maximum hip flexion, due to the manikin not being in contact with the seat or the base of support formed by the feet.

9.7.4 Design Iteration 4

The seat height of the chair was further increased to 175% of the popliteal of subject D (i.e. 614mm), to further decrease the hip flexion. The segmental angles of the manikin mimicking maximum hip flexion are as follows:

- Reduction of hip flexion from 87° to 82°
- Reduction of right knee flexion from 72.23° to 63.21°
- Reduction of left knee flexion from 72.32° to 63.3°

The hip flexion was thus reduced to 82°, on the attainment of maximum hip flexion, which meant that the design specification of reducing the hip flexion to less than 86° had been met. The calculation of the CoM vertical line projected on the ground during maximum hip flexion showed the manikin to be unstable, as shown in Figure 9.17.

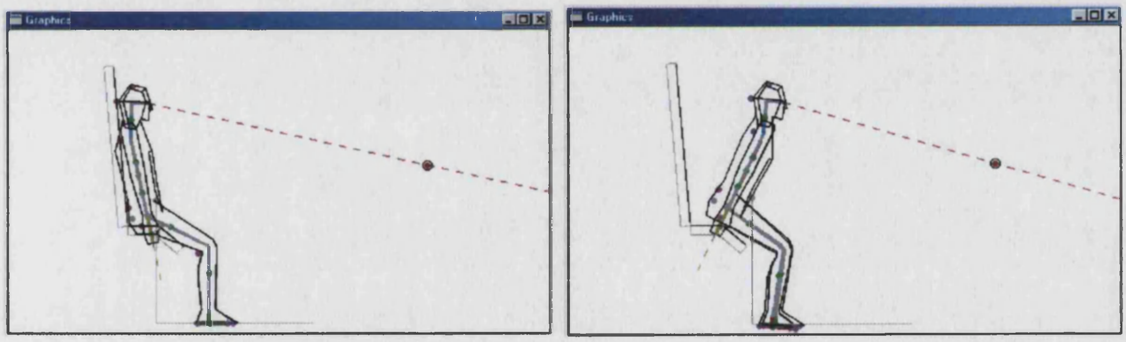


Figure 9.17 175% of popliteal height (61.4cm), feet placement 4.5cm in front of seat, rotation of front seat 40°

9.7.5 Design Iteration 5

To enable the vertical line projected from the CoM to be placed within the base of support formed by the feet, the heels of the feet of the manikin were constrained to be positioned on the line placed directly underneath the front seat of the chair, 45mm further back. This would require a slight increase in ankle dorsiflexion flexion that was deemed possible due to the decrease in knee flexion.

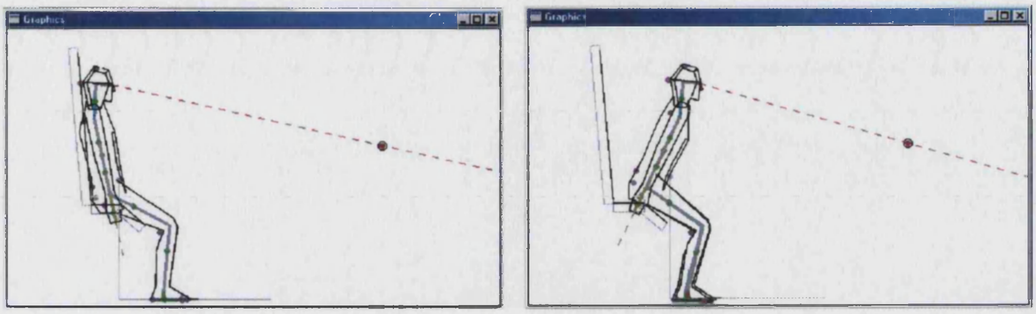


Figure 9.18 175% of poptilea height (61.4cm), feet placement directly under front of seat. Rotation of front seat 40°

This iteration, shown in Figure 9.18, had the following effect on the manikin representative of subject D during maximum hip flexion:

- Reduction of hip flexion from 82° to 79°
- Increase right knee flexion from 63.21° to 68.82°
- Increase left knee flexion from 63.32° to 68.95°

This design iteration brought the feet closer to the vertical line projected from the total body CoM, which lay 25.5mm behind the base of support formed by the feet.

9.7.6 Design Iteration 6

To increase stability when the user reached maximum hip flexion, when the buttocks had just started to lift off from the seat. The rotation of the front half of the seat was decreased from 40° from the horizontal to 30°. It was intended that the front half of the seat was to be used as a support, during transition from the base of support formed by the seat of the chair and the feet, to the feet alone, as shown in Figure 9.19.

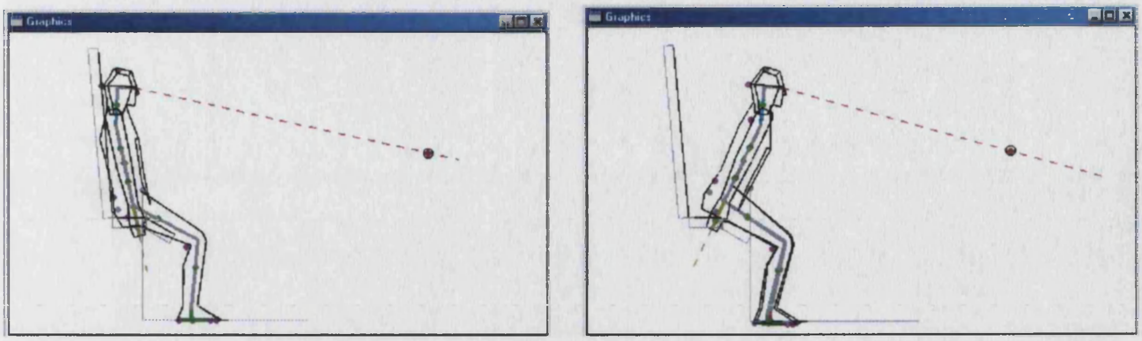


Figure 9.19 75% of poptilea height (61.4cm), feet placement directly under front of seat
Rotation of front seat 30° from the horizontal

9.7.7 Design Iteration 7

Part of the design specification required a chair that could also be used for relaxing purposes, such as watching television or reading. It was thus decided to fix the seat and the backrest of the chair to form a 90° angle and pivot the chair backward to an estimated 25°. This design required a lower leg rest that could be adjustable in height and distance from the seat of the chair to suit the variable leg lengths of users. It would also have to be able to rotate to according the comfort of the user.

Two extra body points were placed upon the back of the shanks of the manikin which were constrained to be placed upon a geometric representative of the lower leg rest that was encoded within SWORDS. Similar rules written to position the buttocks on the seat of the chair, were written to constrain the shanks on the lower leg rest. The rules to constrain the feet on the ground plane were discarded and the same rules employed to constrain the manikin to the sitting posture were invoked. The placement of the lower leg rest was then modified until a suitable position was found to suit the limited range of motion of the knee joint, as shown in Figure 9.20.

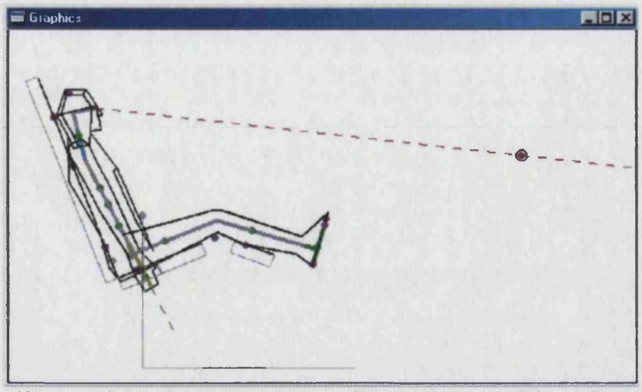


Figure 9.20 Recliner, with additional lower leg rest to enable relaxation

9.7.8 Design Iteration 8

Finally the whole of the chair, consisting of the seat and the backrest, now considered fixed at a 90° angle to each other, was tilted to a 5° recline, thought to aid user comfort, and the three sit-to-stand intermediate postures were again invoked. The total body CoM was shown to lie within the base of support of the seat, 25mm behind the base of support formed by the feet, as shown in Figure 9.21. A summary of the maximum flexion intermediate posture only is shown in Table 9.7. To avoid repetition the results of representative manikins of each subject simulating the intermediate postures using the final design iteration are later shown in section 9.8.4.1 to 9.8.4.3.

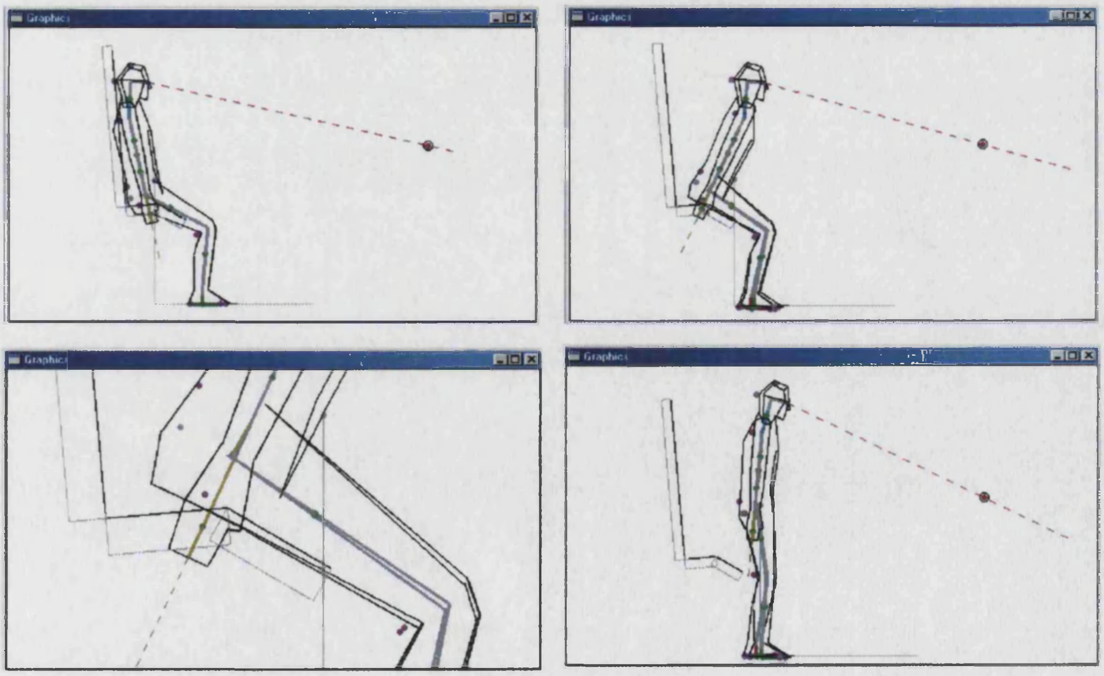


Figure 9.21 Final chair design

Design iteration	Rotation of front seat section	% Popliteal height/ seat height	Heel placement*	Hip	Knee	Ankle	Head
0	0°	123 (430mm)	45mm FoL	**102**	**90.18 (91.86)§**	11.03 (11.56) §	20
1	0°	140 (491mm)	45mm FoL	95	82.62 (80.69)	8.13 (10.64)	21
2	0°	160 (562mm)	45mm FoL	87	72.23 (72.32)	7.66 (9.82)	20
3	40°	160 (562mm)	45mm FoL	87	72.23 (72.32)	7.66 (9.82)	20
4	40°	175 (614mm)	45mm FoL	82	63.21 (63.3)	6.5 (5)	21
5	40°	175 (614mm)	On line	79	68.82 (68.95)	12.61 (12.44)	19
6	30°	175 (614mm)	On line	79	68.82 (68.95)	12.61 (12.44)	19
8	30° 5° recline of whole chair	175 (614mm)	On line	**82**	**67.03 (67.36)**	10.23 (9.16)	21

Table 9.7 Segmental angles measured in SWORDS during iterative development of conceptual design, whilst mimicking subject D undertaking the maximum hip posture

The hip and knee flexion during maximum hip posture was reduced to less than 86°, shown in bold in Table 9.7.

** Heel placement in respect to line placed directly under the front edge of the seat, where FoL is 'in Front of Line'*

§ Left knee and ankle segments are shown in brackets

9.7.9 Remarks

The measurements of the final design iteration, in Table 9.7, when compared to the original measurements of the chair design employed for the experimental study carried out in phase 3, were shown to positively reduce the hip and knee flexion when maximum hip flexion was obtained. The hip flexion for subject D when mimicked in SWORDS was decreased by 19.6% and the right, and left knee flexion by 25.8% and 26.7% respectively. The left ankle dorsiflexion was decreased by 20.76% and the right decreased by 7.3%. This could possibly be associated to the limited joint range of motion of the right knee of subject D.

The decrease of the hip and knee flexion to 82° and 67.36 respectfully, was less than the 86° design specification requirement. It was speculated that this reduction in flexion should have decreased the torque that occurred about the knee and hip joints when maximum hip flexion was obtained. This should have reduced the pain and discomfort experienced by the subjects with osteoarthritis.

Further analysis of the final design was undertaken through the employment of manikin representations of both groups. Comparisons of the results using these manikin representatives were made with the experimental measurements, which are discussed in the following section.

9.8 Phase 7 Validation and test

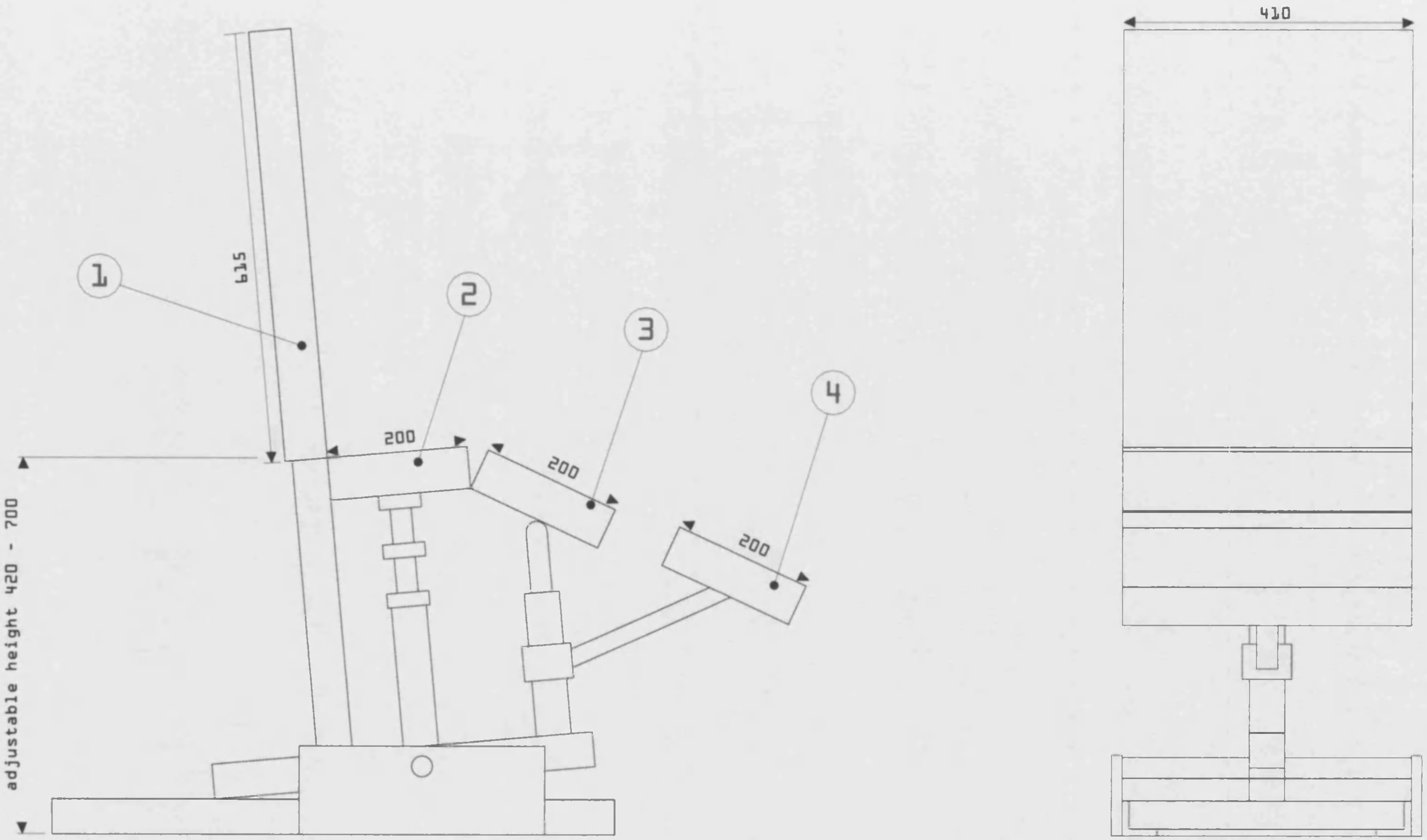
The following section describes the validation and testing phase, which involved making a simple prototype of the conceptual design solution. The same user groups were employed to carry out an experimental analysis of the task of rising using the prototype and comparisons were made with the initial experimental study, carried out in phase 3. Comparisons of the segmental measurements found using the manikin representative of the individuals and the experimental results are also discussed.

9.8.1 *Phase 7a* Make prototype

A prototype of the final conceptual design was made according to the dimensions defined in the previous section 9.8, and in the general assembly drawing shown in Figure 9.22. Due to time constraints it was decided that the prototype be made from as many existing standards parts available. A picture of the prototype is shown in Figure 9.23. The user can rotate the lower leg rest (once a comfortable height was determined) into the desired position and tilt the seat backwards to recline, as shown in Figure 9.23a. Also from the typical seating position, shown in Figure 9.23b, the user was able to increase the height of the seat according to their preference, as shown in Figure 9.23c, and rise up to a standing posture.

There are certain modifications that could be made to improve the usability of the chair design, which would be carried out during the embodiment phase and used for further user validations. Some of the suggested modifications would be as follows:

- The back of the seat becomes integral rather than being made from backrests from existing chairs, as shown in 'A' in Figure 9.23.
- An electric motor that could be used to activate the mechanism to enable the user to automatically adjust the height of the chair as indicated in 'B' in Figure 9.23. This would be encased and hidden from the user for both safety and aesthetic purposes.
- Modify the design of the base support of the chair to negate the heavy industrial appearance and become more in keeping with being used within a 'living room' environment, as shown in 'C' in Figure 9.23.
- An alternative design for the foot rest which would negate the user having to bend down and swing the arm to which the footrest was attached, as shown in 'D' in Figure 9.23.



ITEM	DESCRIPTION
1	BACK REST
2	SEAT
3	FRONT OF SEAT
4	LEG REST

PROJECTION

DRAWN MAW

DATE 23 09 01

SCALE 1:10

ALL DIMENSIONS IN mm

PROTOTYPE CHAIR

Figure 9.22 General assembly drawing of prototype

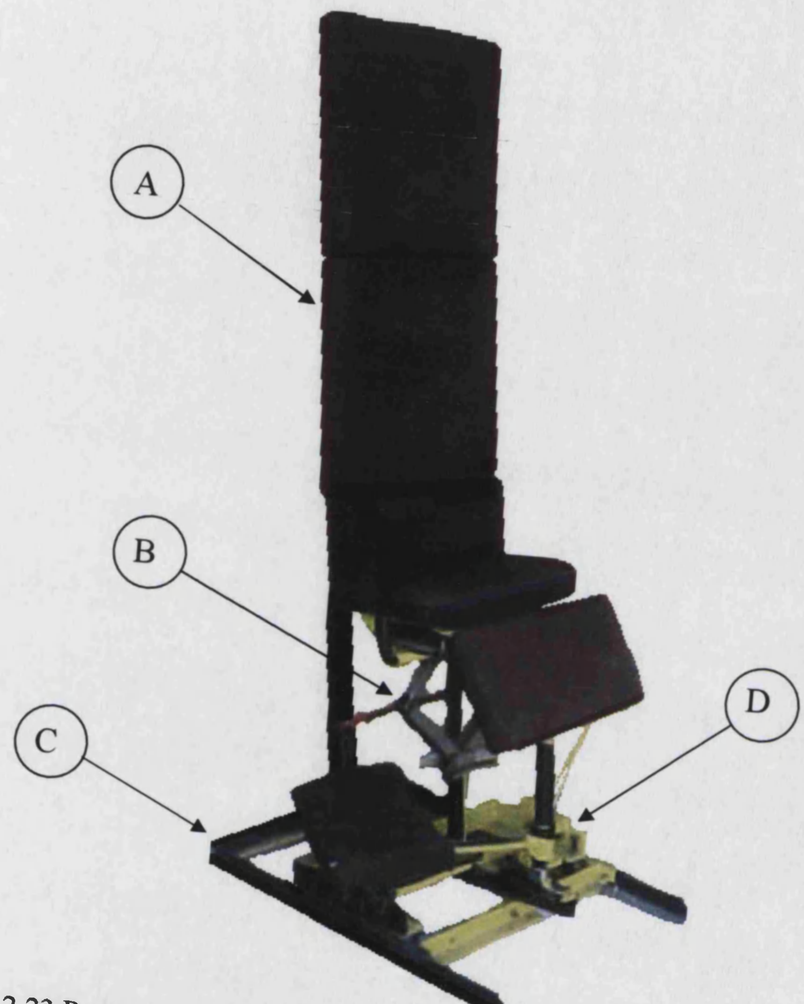


Figure 2.23 Prototype made to carry out experimental validation of conceptual design

Figure 9.23a
reclined posture

Figure 9.23b
Common sitting
posture

Figure 9.23c
Sitting posture
before rising

9.8.2 *Phase 7b* Experimental validation

An experimental study was carried out to measure the segmental angles produced during the initial sitting, the intermediate maximum flexion posture and erect stance, while using the prototype chair. The same groups were used for this purpose.

The subjects, employed in section 9.6 to analyse the typical chair design, were requested to follow the same procedures to rise up from a sitting posture using the prototype developed. The height of the chair and front half of the seat was adjusted according to a preferred height and decline, respectively, as shown in Table 9.8. The decline of the front of the seat was preferred to be a decline of 60° for all subjects.

Subject	Prototype height cms	Prototype height (% of popliteal height)
A	67.5	151
B	61	173
C	61.5	173
D	62.5	152
E	61	177
F	66.5	153

Table 9.8 Preferred seat height of prototype and corresponding % of popliteal height

The experimental measurements were used to ensure that the users were able to carry out the same movement strategy, as that of the able bodied people, originally defined. This was carried out by comparing the movement patterns of the two groups. Comparisons with the initial experimental study, carried out in phase 4, also aided the determination of whether the design improved the problems experienced by the individual users and that that the requirements of the design specification were met. Comparisons between the two groups using the prototype and the standard device also enabled the analysis of whether any difficulties were experienced by the user group were due to their physical disability or the device alone. The following sections discuss these findings.

9.8.3 *Phase 7c* Subjective Questioning

All subjects were questioned on the comfort and possible pain experienced while rising to an erect stance from the prototype chair in a raised position. Their comments are described as follows:

- Subject D, who was not able to use arm support when rising due to her right wrist joint being fused, found that the front sloping part of the seat a particularly good aid when rising to a standing posture.

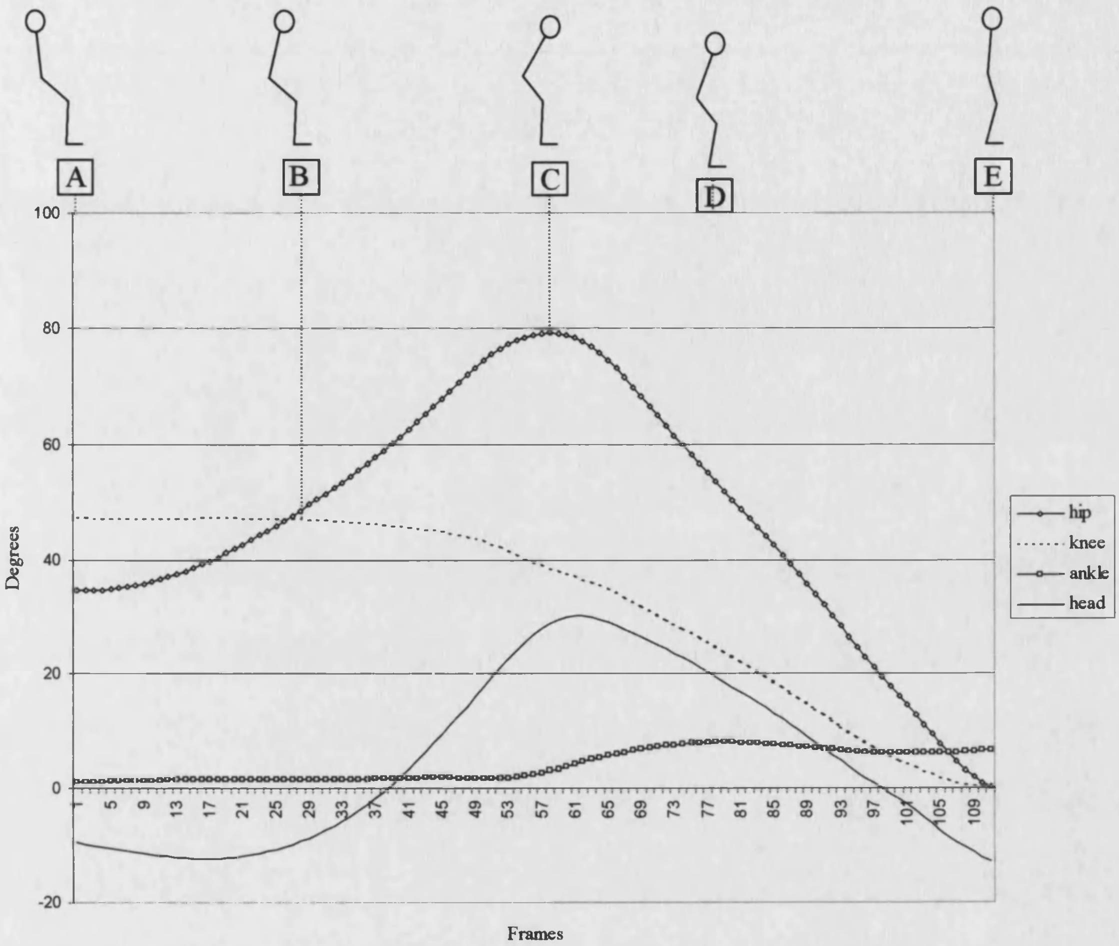
- Subject E, who normally experienced severe pain in the right knee when rising from a sitting posture, commented that it was the first time that she had felt no pain when rising from a chair.

- Subject F was requested to rise from the prototype chair while employing the same procedures carried out in the experimental study i.e. without the use of arms. Results showed that subject F did not feel any discomfort in his left hip joint on rising and was able to use the same movement strategy used by able-bodied people, without having to use his arms to gain momentum to enable him to stand up, as shown in Figure 9.24.

Figure 9.24 Video picture frame of subject F able to employ able-bodied strategy while using prototype

9.8.4 *Phase 7d* Comparisons with initial experiments

The results of the experimental analysis carried out to analyse and compare the movement strategy of both groups using the prototype showed that the movement strategies used by both groups were essentially the same as those originally defined. This can be seen by comparing the graphical representations of the segmental angles produced by both groups throughout the stand-to-sit movement. Typical graphical representations of the movement patterns employed by subject A, D, C and F are shown in Figures 9.25 to 9.28, illustrate these similarities. The only differences were that the maximum segmental angles reached throughout this movement strategy were greatly reduced, as predicted in the development of the conceptual design through the use of the manikin representations of each subject within the constraint modeller SWORDS.

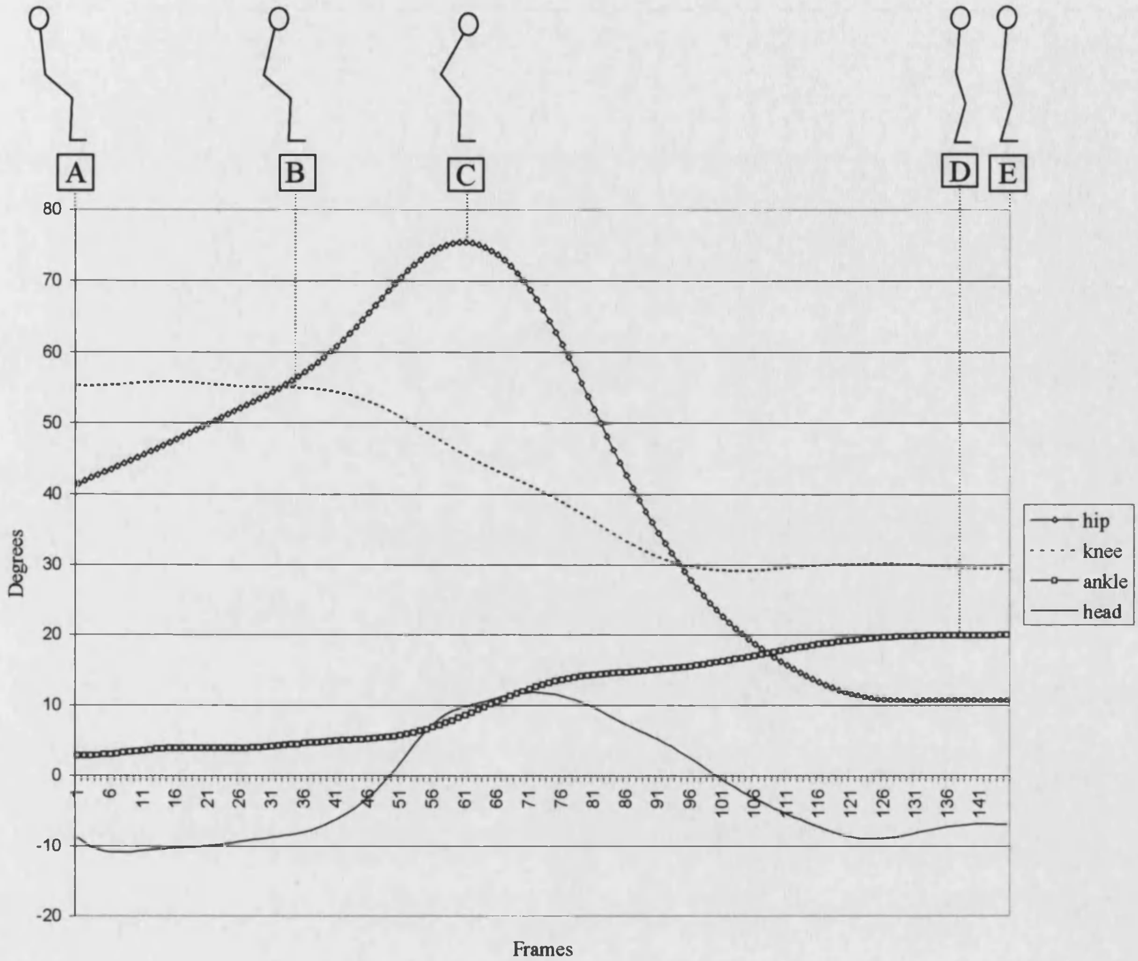


KEY

STAND-TO-SIT

A: Sitting posture
B: Before seat off
(Start of knee extension)
C: After seat off
(Maximum hip flexion)
D: Maximum ankle dorsiflexion
E: Initiation of erect stance

Figure 9.25 Graphical representation of able-bodied subject 'A' during stand-to-sit movement using prototype

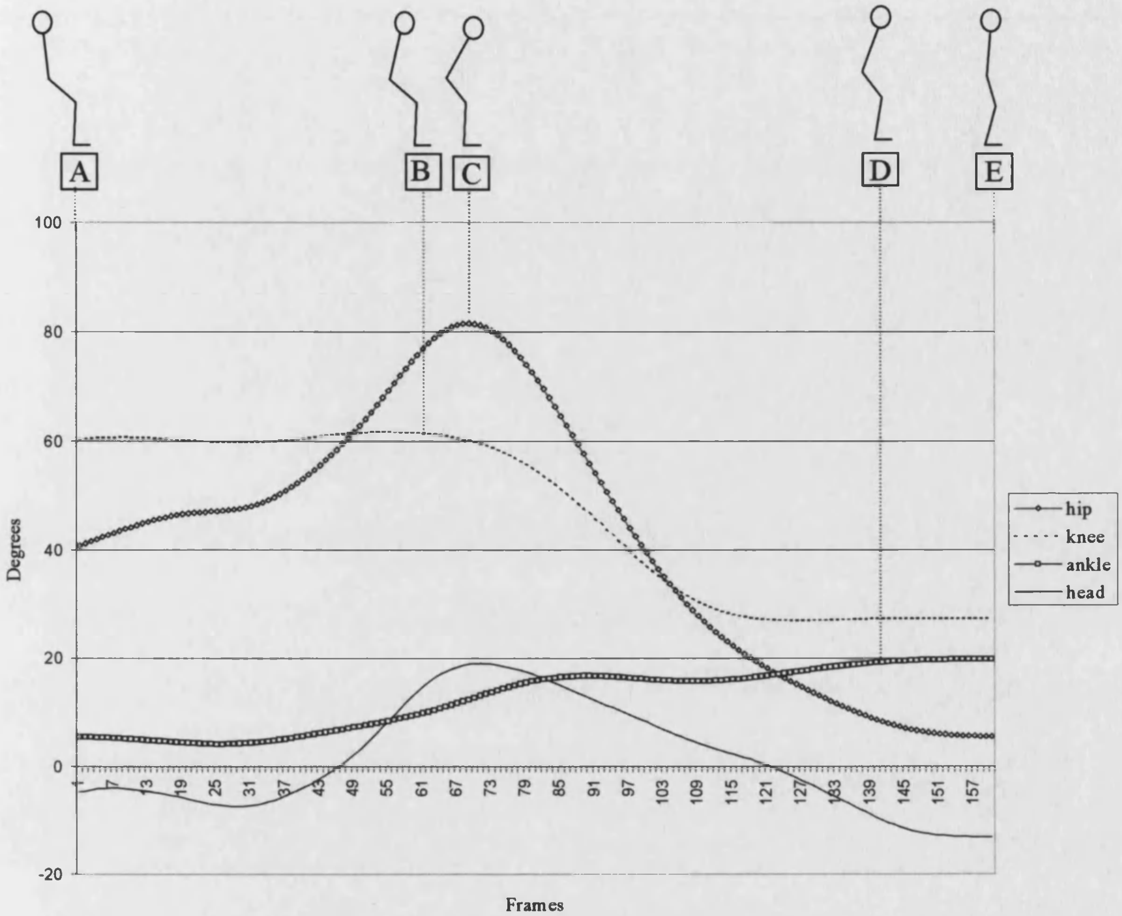


KEY

STAND-TO-SIT

A: Sitting posture
B: Before seat off
(Start of knee extension)
C: After seat off
(Maximum hip flexion)
D: Maximum dorsiflexion
E: Initiation of erect stance

Figure 9.26 Graphical representation of able-bodied subject 'D' during stand-to-sit movement using prototype

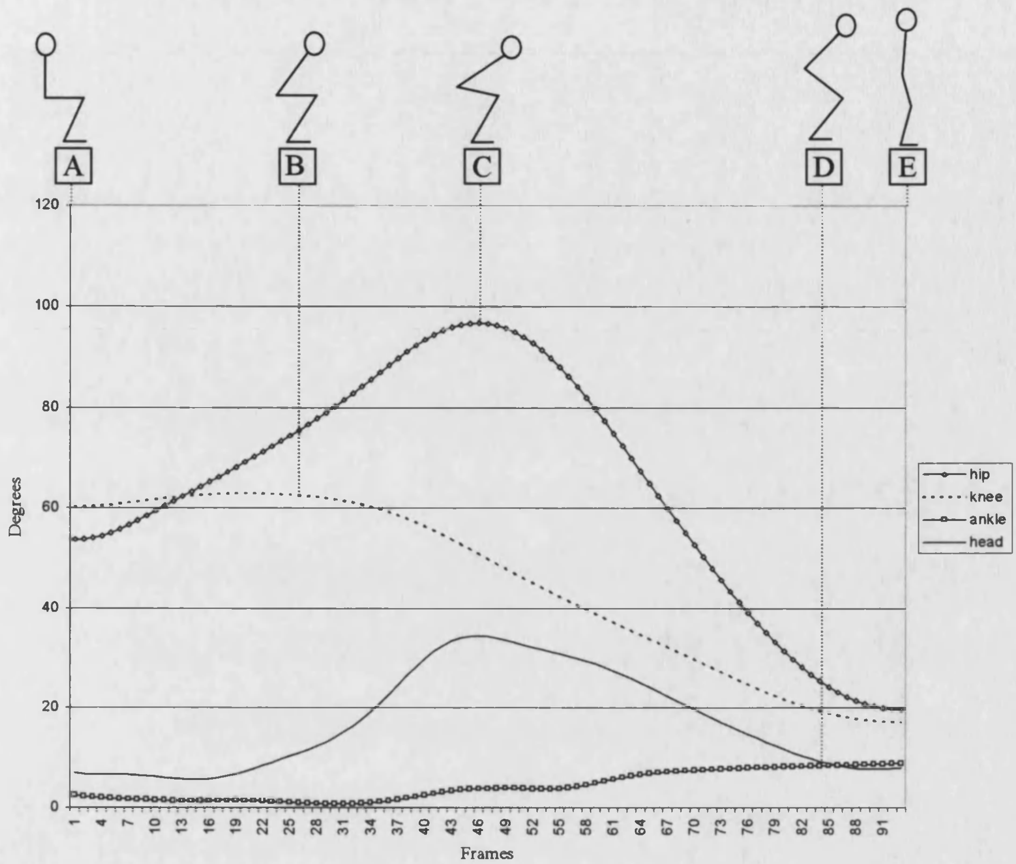


KEY

STAND-TO-SIT

A: Sitting posture
B: Before seat off
(Start of knee extension)
C: After seat off
(Maximum hip flexion)
D: Maximum ankle dorsiflexion
E: Initiation of erect stance

Figure 9.27 Graphical representation of able-bodied subject 'E' during stand-to-sit movement using prototype



KEY

STAND-TO-SIT

A: Sitting posture
B: Before seat off
(Start of knee extension)
C: After seat off
(Maximum hip flexion)
D: Squat position
(Maximum ankle dorsiflexion)
E: Initiation of erect stance

Figure 9.28 Graphical representation of able-bodied subject 'F' during stand-to-sit movement using prototype

Comparisons of the segmental angles measured during the sitting posture, the intermediate maximum hip flexion posture and the erect stance during the experimental study and those found using the manikin were made. The actual seat heights of the prototype chosen by each subject during the experimental study, shown in Table 9.8, were used to mimic the stand-to-sit movement strategy in SWORDS. The results of these comparisons are shown and discussed in the following sections.

9.8.4.1 The sitting posture

The results measured using both the manikin representative, shown in bold in Table 9.9, and those taken during the experimental study of both able-bodied and the subjects with osteoarthritis during the sitting posture, also shown in Table 9.9, were relatively similar, as shown in Figures 9.29 and 9.30.

Prototype Sitting posture								
Subject	**Hip**	Range	**Knee**	Range	**Ankle**	Range	**Head**	Range
A	34.12	33.9	47.4	46.8	1.38	1.2	-9.48	-10.5
	37	34.6	**54.19** **53.11**	48	**2.52** **1.78**	4.1	**10**	-8.4
B	31.98	31	40.24	38.6	-5.44	-7.6	-2.44	-2.6
	49	32.9	**63.75** **62.77**	41.8	**5.19** **4.44**	-3.3	**1**	-2.2
C	44.13	43.7	50.71	49.2	2.38	1.8	5.54	4.3
	34	44.5	**49.5** **48.29**	52.2	**-0.64** **-1.47**	3	**14**	6.8
D	39.88	38.8	55.56	55.3	3.13	2.4	-11.69	-13.2
	51	41.4	**68.54** **68.75**	55.7	**5.17** **5.27**	4.2	**-14**	-8.9
E	44.14	40.2	59.72	58.9	5.46	4.7	-4.34	-4.7
	46	42.4	**63.04** **63.27**	60.4	**-5.6** **-5.43**	6.3	**2**	-3.7
F	55.87	53.6	61.21	60.9	2.9	1.8	8.6	4.2
		57.8		61.5		3.5		12.5

Table 9.9 Results of segmental angles determined in SWORDS and experimental study during the sitting posture (mean and ranges given)

The measurements within SWORDS for the ankle and head segmental were generally in good agreement. The variability of the actual hip and knee flexion actually measured, when compared to SWORDS, is shown in table 9.10. It was assumed that this was due to the variability of the placement of the buttocks on the comparatively high seat height, after each subject sat back down onto the seat after rising 5 times. The amount of movement of the feet, after the heels of the feet were placed in a given position on the ground, may have also added to this variability. Also the placement of the markers denoting the joint centre of rotation of each subject's body segments may have been slightly different to that of the manikin representative, due to skin movement during the sitting posture.

Subject	Hip flexion % *	Knee flexion % *
A	7	11
B	33	43
C	22	Within range
D	19	19
E	8	4

Table 9.10 Results of the hip and knee flexion found using the manikin model, shown as a * percentage outside the range of the actual hip and knee flexion measured

Even though the results calculated using the manikin representatives within SWORDS do not all lie close to segmental angles measured for all subjects. These results show a significant reduction in the overall average of each subjects hip and knee flexion, when compared to the prototype to the typical chair design, described in section 9.7.1, as shown in table 9.11.

Reduction of:	SWORDS Manikin	Actual measured
Average hip flexion	40%	46%
Average knee flexion	34%	42%

Table 9.11 Comparisons of the average reduction in hip and knee flexion found using the manikin and the actual flexion measured

The comparisons of the average hip and knee flexion shown in Table 9.11, showed that the computer manikin representative could be used to provide a general trend of how a posture can be modified, through the use of generic procedures that interact with the conceptual design being created.

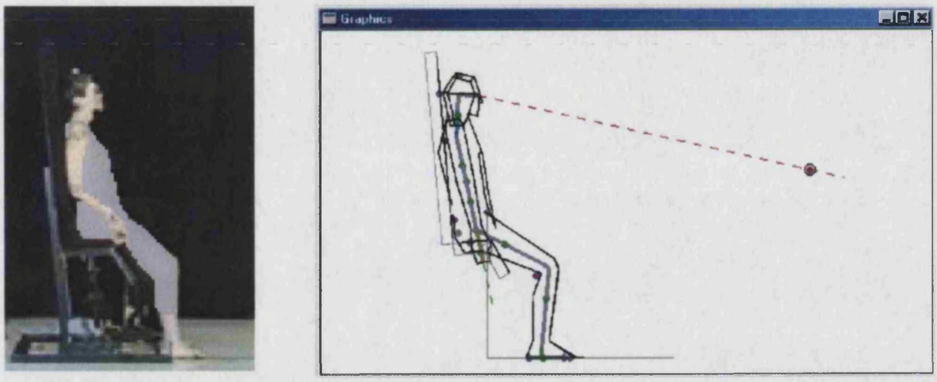


Figure 9.29 Video picture frame of subject D and corresponding manikin representative during the initial sitting posture using the prototype

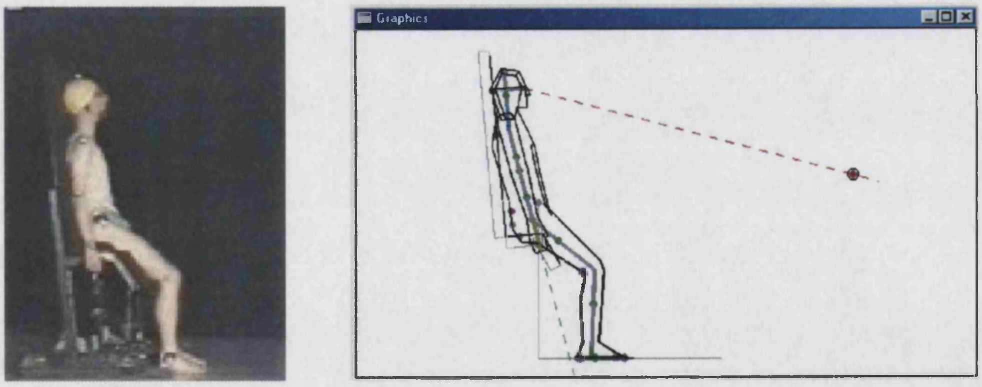


Figure 9.30 Video picture frame of subject A and corresponding manikin representative during the initial sitting posture using the prototype

9.8.4.2 Maximum hip flexion

Comparisons of the hip flexion between the intermediate maximum hip flexion posture modelled within SWORDS and measured experimentally showed relatively good agreement, as shown in Table 9.12.

Prototype Max hip sway								
Subject	**Hip**	Range	**Knee**	Range	**Ankle**	Range	**Head**	Range
A	81.13	79.3	41.62	38.7	4.81	3	28.83	26.2
	80	83.6	**54.19** **53.11**	44.2	**12.79** **12.09**	7.2	**39**	31.4
B	74.82	73.6	36.74	36.2	2.62	1.8	35.9	34.8
	86	76	**63.75** **62.78**	37.3	**14.5** **12.01**	3.5	**45**	37
C	81.84	80.1	40.84	40.8	8.21	8	28.8	27.1
	89	83.6	**49.5** **48.29**	40.9	**8.97** **7.63**	8.4	**51**	30.5
D	74.23	71.5	46.16	45.6	6.66	4.8	7.24	2.8
	82	75.8	**68.05** **68.15**	46.4	**10.58** **9.95**	8.5	**21**	9.8
E	81.63	79.6	60.16	56.8	12.1	9.4	22.75	18.9
	73	83.7	**62.85** **61.9**	63.5	**10** **10**	14.6	**28**	26.8
F	94.75	92.9	52.75	50.9	2.36	0.4	33	29.8
		96.7		54.7		2.9		34.7

Table 9.12 Results of segmental angles determined in SWORDS and experimental study during maximum hip flexion (mean and ranges given)

The knee flexion calculated in SWORDS did not change significantly from that measured during the sitting posture. This was due to the model space containing the geometric entities of the lower leg not being allowed to rotate and the height that the buttocks were constrained to rise vertically above the seat of the chair being fixed. The knee flexion, shown in Table 9.13, was calculated as a percentage outside the range of flexion measured experimentally. Although these results, in some cases, lie significantly outside the range of measured during the experimental study, they were considered to be acceptable due to the results of the hip flexion, which are in good agreement and are the predominate motion of this intermediate posture.

Subject	Hip flexion % *	Knee flexion % *
A	Within range	18
B	12	41
C	6	15
D	8	32
E	8	1

Table 9.13 Results of the hip and knee flexion found using the manikin model, shown as a * percentage outside the range of the actual hip and knee flexion measured

The results measured in SWORDS, similarly showed a significant decrease in the average hip and knee flexion when maximum hip flexion was gained, when rising from the prototype design, when compared to the typical chair design, as shown in table 9.14 below.

	SWORDS Manikin	Actual measured
Average hip flexion	26%	32%
Average knee flexion	33.6%	44%

Table 9.14 Comparisons of the average reduction in hip and knee flexion found using the manikin and the actual flexion measured

The ankle dorsiflexion, measured empirically when maximum hip flexion was gained, was shown to reduce when compared to both the empirical results (using the original chair) and those found while modelling the manikin rising from the prototype. This reflects the slight change in movement strategy when using the prototype. Observations and subjective questioning found that the subjects used the front part of the seat as a support for the underside of their upper legs to enable them to gain maximum hip flexion.

The subjects also felt that the front of the seat provided them with a support before they changed their support base the feet alone. Further questioning found that the subjects felt stable during this phase of transition, as shown in Figures 9.31 and 9.32.

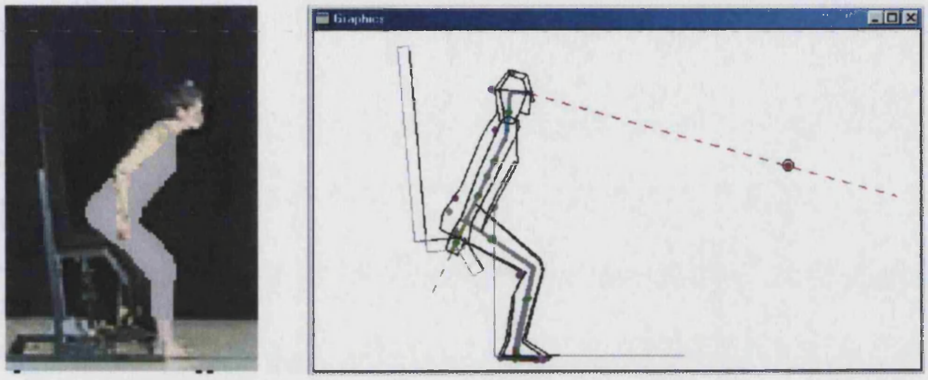


Figure 9.31 Video picture frame of subject D and corresponding manikin representative during the intermediate posture of maximum hip flexion using prototype

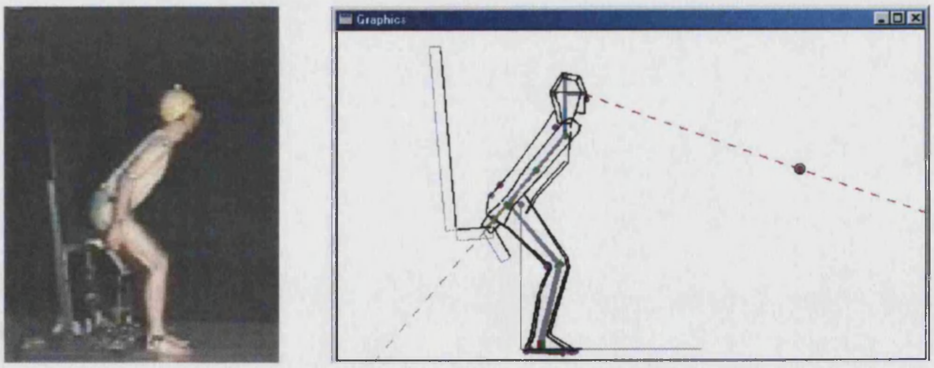


Figure 9.32 Video picture frame of subject A and corresponding manikin representative during the intermediate posture of maximum hip flexion using the prototype

9.8.4.3 The erect stance

The results of the segmental angles measured in SWORDS during the erect stance of subject A, B and C, shown in Table 9.15, are the result of the rules written to define the erect stance. This was where the shoulder, hip and knee joint range of rotation were vertically aligned with the right ankle joint.

Prototype Erect stance								
Subject	**Hip**	Range	**Knee**	Range	**Ankle**	Range	**Head**	Range
A	0.58	0.2	1.13	-0.4	7.37	6.7	-11.48	-10.5
	0	0.9	**0**	3.7	**0**	8.7	**14**	-12.6
B	2.15	0.4	8.06	7.7	9.02	7.8	4.92	3.6
	0	3.9	**0**	8.5	**0**	10.3	**11**	6.3
C	0.71	0.7	19.46	18.3	19.25	18	-3.55	-5.1
	0	0.7	**0**	20.7	**0**	20.5	**13**	-2
D	10.43	8.9	29.02	27.3	18.58	17.4	-7.56	-8.6
	25	11.7	**31** **19**	30.1	**10.05** **7.8**	19.8	**-9**	-6.9
E	9.6	5.6	29.94	27.3	19.07	18.6	-11.8	-17
	10	16.3	**6.32** **28**	35.1	**1.43** **10**	19.7	**2**	-5.3
F	20.83	19.4	17.65	15.7	8.49	6.9	7.91	6.8
		23.5		20.2		9.7		8.9

Table 9.15 Results of segmental angles determined in SWORDS and experimental study during erect stance (mean and ranges given)

The variation of knee flexion and ankle dorsiflexion, shown in Table 9.15 demonstrate that a zero neutral hip position was first attained before the knee and ankle segmental angles reached their maximum extension. The value of 31° extension of the right lower leg of subject D and 28° extension of the left lower leg of subject E was found using the corresponding manikin representative within SWORDS. This illustrates the limitations placed on the rotation of the model space of the lower leg in order to mimic to joint range of motion of these subjects, which can also be seen in the experimental results, shown in Table 9.15 and Figure 9.33 below.

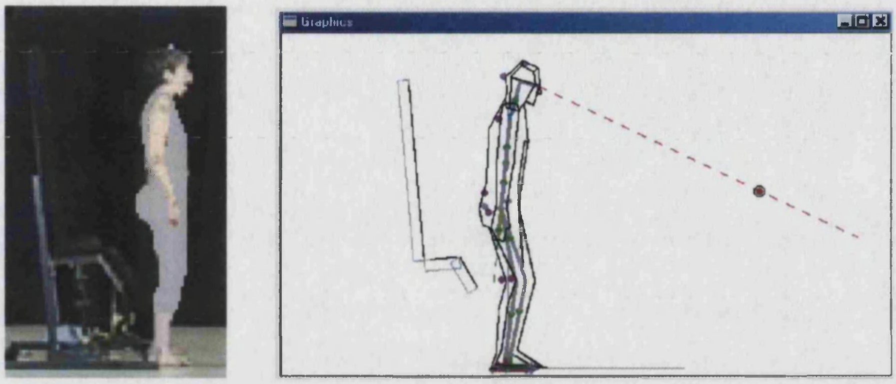


Figure 9.33 Video picture frame of subject D and corresponding manikin representative during erect stance using prototype developed

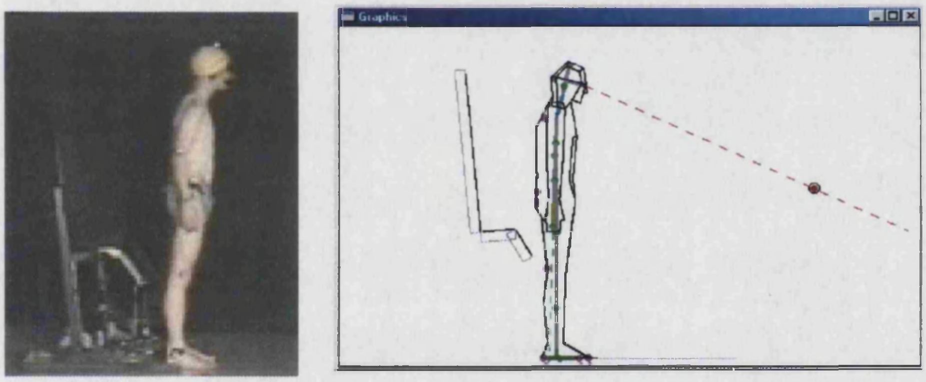


Figure 9.34 Video picture frame of subject A and corresponding manikin representative during erect stance using the prototype developed

9.9 Discussion

The aim of this research was to produce a design methodology to help improve the mobility of older people and people with physical disabilities by enhancing functional movement and enabling them to continue using normal movement patterns. The subjects with osteoarthritis involved in this case study were already able to carry out movement patterns similar to those used to by able- bodied people. However in carrying out the task of rising, as performed by able bodied people, they experienced pain and discomfort in their hip and knee joints and in one case subject F had to modify his movements by swinging his arms forward to stand up, as shown in Figure 9.3. The design thus focused on reducing the range of movement in the hips and knees to eliminate pain and to also enable the people with osteoarthritis to continue using movement patterns similar to those employed by the able-bodied people.

Subjective questioning of the subjects with osteoarthritis using the prototype chair created showed that they experienced no pain when rising and that subject F did not need to swing his arms forwards to gain momentum, as shown in Figure 9.24. The comparative study of the able bodied group and the group with osteoarthritis showed that they both used similar movement strategies using the prototype chair. Comparisons with the initial experimental study showed that the same sequence of movements was used by both groups. The only difference was that the initial sitting position before rising was a perched posture rather than a normal sitting one, which had the affect of reducing the joint range of motion while rising, as required by the design specification. This initial perched position was considered acceptable because there are existing chair designs commonly used where the height of a chair can be increased vertically to improve posture. Also that the option of attaining a normal sitting posture if required could be attained by decreasing the height of the prototype chair during occupancy. The slight modification to the movement strategy and initial sitting posture when using the prototype created were thus not considered to hi-light the disability of the user. The mobility and functional performance of the people with osteoarthritis using the prototype design were considered to be improved due to the ease of rising, the lack of pain that they experienced and that they were still able to carry out the task of rising using normal movement patterns. Referral to the design specification described in section 9.4 thus showed that all requirements of the design were met when using the methodology.

The aim of this research project was to focus on the functional design of the product rather than its aesthetic appearance. This was considered a limitation of this design methodology and will be discussed in the following chapter.

The next stage of the design methodology after the phases carried out in this case study would be the embodiment stage where the design would be further refined. The mechanisms to enable the chair design to be fully adjustable would be further developed until a satisfactory solution for the users was found. This could be further evaluated by observational and subjective studies of the user group with osteoarthritis, during the embodiment phase and later developed into detailed production drawings for manufacture.

It is recognised that there are also many other considerations that need to be addressed to enable this design to be realised as a marketable commodity. This usually involves a compromise between the design intent and the resources available. Some of these considerations are discussed as follows:

- Manufacturing constraints need to be considered while 'firming up' the conceptual design, i.e. during the embodiment phase before detail drawings are carried out. These can be, for example, the use of standard components and how the design has to be modified to suit the manufacturing processes available.

- The technology to solve a design function needs to be considered. For example, of the type of mechanism or electronic device available for the task intended.

- Cost constraints must be met. The saleable commodity has to be priced accordingly for the market sector defined by the design specification.

- The company image and existing products sold by a company should also be considered. Products are usually made to fit within a range of existing items that can be, for example, stylised to look similar.

- The aesthetic design of a product also needs to be addressed. This should be developed to suit the environment in which the design is to be used and should be evaluated through subjective user questioning.

These considerations mentioned above are not exhaustive and should be carried out before detailed drawings are made for manufacture.

9.10 Conclusions

The results of this case study have shown that the proposed design methodology has enabled a device to be designed that improved mobility and enhanced the functional ability of people with osteoarthritis. The case study has also shown that this group was able to continue using movement strategies commonly used by able-bodied people. Furthermore it has shown that through the understanding of the physical limitations and problems of people with osteoarthritis a device can be developed to eliminate the pain they experience when carrying out the task of rising. The strengths and limitations, along with the further work required to enhance the design methodology are discussed in the following chapter.

Chapter 10
Conclusions and Recommendations

10.0 Introduction

This final chapter summarises the findings relating to the objectives of this research project, identifies their limitations and finally makes recommendations for further work.

10.1 Stability required for mobility (Chapter 4)

Objective

- To review how stability was defined in the literature.

The review of published literature found that the maintenance of stability is a complex system incorporating the proprioceptive (i.e.sensory), musculoskeletal, and visual senses, as stated by Kuaffman et al (1997). If any of these systems are affected then an individuals capability to maintain balance can be affected. It was decided that the propreioceptive (i.e. the internal labyrinth of the inner ear) and the visual systems were both complex and thus any impairments of this nature would require further study beyond this research. This research has therefore only concentrated on people with musculoskeletal or physical impairments and not those with any sensory or visual impairments.

Limitations and recommendations for further work

The design methodology, proposed in Chapter 3, was constrained to designing for people with physical impairments alone, which had the effect of excluding people with psychological and visual impairments. This of course does not concur with the current trend of 'inclusive design'. It is thus recommended that this design methodology be developed to enable people with psychological and visual impairments to benefit from carrying out tasks using normal movement strategies, similar to those generally employed by able-bodied people.

Objective

- To review how stability was mechanically, mathematically and experimentally determined. This was to establish a method to be used to calculate stability of the human manikin model.

The review found that stability was mechanically defined as being when a vertical line projected from the CoM of the whole body to the ground floor and lay between the base of support defined as the convex hull.

The review of the experimental methods to define stability, such as the balance plate and reaction board methods, were found to be limited in that the CoM could only be derived from a given static posture, which had to be maintained by the subject of interest. Also, the subject has to be present throughout the whole measurement process which was considered to be time consuming. These methods were therefore not considered to be practical for the purpose of this research.

Theoretical mathematical definitions of calculating the CoM, required to define stability, were found to be limited due to the small number of cadavers used and little data for women subjects. It was decided that the calculation of the CoM of the individual body segments using the manikin representative, would be based upon the data published by De Leva (1996). This was due to the method not requiring extensive anthropomorphic measurement, which could be time consuming when numbers of subjects are large. Also, the data produced by De Leva (1996) was based upon a larger number of subjects than other authors reviewed and took both genders into consideration. The calculation of the CoM of the whole body was computationally calculated using the segmentation method within the SWORDS program while using the manikin.

Also that the base of support was defined by a two dimensional convex hull which would lie on the ground surface alone. A vertical line projected from the CoM could then be projected down to the ground plane. If this line was found to be within this convex hull then the person was considered stable. Conversely, if it was found to lie outside the convex hull then instability was determined. However, stability can not be theoretically calculated using the manikin alone. A person's ability to maintain balance is highly variable due to their many different physical and mental attributes as previously discussed. It was thus concluded that even though a person may be theoretically considered to be stable, user involvement and subjective questioning of individuals stability must be carried out.

This research project was focused on improving the mobility of people who wish to carry out common daily tasks, instead of more complex high speed tasks, such as running. It was thus decided that this analysis of human movement would focus on the stable static postures that were employed when moving slowly from one intermediate posture to another.

Limitations and recommendations for further work

Although the calculation of the stability, where the convex hull was calculated as being on the ground floor was sufficient for the task of rising from a sitting posture. It could be considered to be limited when a movement strategy may incorporate the support of other surfaces on different planes, such as walls or work surfaces. It is thus suggested that the stability calculation could be modified to include various parts of the body used to form a base of support on various surfaces other than the ground plane. This would enable a more detailed analysis of the base of support that may be required for stability when, for example, creating a support aid such as a handrail used for walking.

This research project has focused on movement tasks that involved intermediate postures that an individual may carry out in a relatively slow manner, such as walking or getting out of bed. It may be a possibility that a user would wish to carry out a task at higher speeds, for example, for exercise or to be able to gain momentum to carry out certain movements. It would thus be advantageous for this research to also incorporate analises and comparisons of velocity and momentum when a user carries out a physical task.

10.2 The sit-to-stand movement (Chapter 5)

Objective

- To review the distinct movement strategies commonly employed by able-bodied people, when rising from a sitting posture.

A literature review of published clinical studies, described in section 5.1, found that young able-bodied adults employed distinct, repeatable movement strategies when rising from a sitting posture. These phases were generally described to begin with the initial sitting posture where upper body sways forwards until the buttocks are brought off the seat of the chair. Maximum hip and trunk flexion is then obtained, before the knees and hips begin to extend and maximum ankle dorsiflexion occurs and before the trunk and hip are extended to produce the erect stance.

Objective

- To review the comparisons made between the movement strategies employed by able bodied people, older people and people with physical disabilities, when rising from a sitting posture.

A review of clinical studies, comparing the movement strategies employed by able-bodied people, older people and people with physical disabilities found that the movements of the latter groups were slightly more exaggerated, for example, when they flexed their trunks further to gain postural stability before they stood up. However, it was found that they employed a similar movement strategy used by able-bodied people.

Objective

- To understand the effect of the variance of chair design upon the movement strategies that older people and people with disabilities may employ.

It was found that the design of a chair altered the movement strategy employed, which could either hinder or aid the task of rising. For example, the majority of the authors reviewed in section 5.3 found that the higher the seat placement the easier the task of rising. This was due to the user being initially positioned in an intermediate posture used to rise, which decreased the joint range of motion and presumably the reduction of the torque about the knee joint.

10.2.1 Experimental study to define the sit-to-stand movement (Chapter 7)

Objectives

- To review the experimental techniques employed to define the sit-to-stand movement
- To carry out an experimental study to determine the movement patterns employed by able-bodied people when rising from and declining into a sitting posture.
- To determine the consistency of the movement patterns employed during the experimental study previously carried out.
- To compare these findings with experimental results published in literature.

An experimental study to define the movement strategies employed when rising, as described in Chapter 7, showed that the phases of movement employed by adult able-bodied people were repeatable and could be determined through the employment of specific experimental techniques. Comparisons of these results with published literature, reviewed in Chapter 5, found that able-bodied people employ similar distinct and repeatable strategies when carrying out the prescribed physical task of rising from a sitting posture.

These results showed that it was possible to study, define and understand the movement strategy employed by able-bodied people through specific experimental techniques and observation analysis.

Limitations and recommendations for further work

People with physical disabilities are sometimes able to carry out the same movement patterns as those commonly used by able-bodied people, however they may not always move predominantly in the sagittal plane. Many motion analysis and human movement simulation software packages have the capability to study three-dimensional movement. It would thus be useful to develop the experimental study and the modelling of the user movement strategy to carry out a three dimensional analysis rather than two dimensional.

10.3 Computer based human models (Chapter 6)

Objective

- To review the computer manikin models employed to simulate human movement.

Although packages such as SAMMIE and SAFEWORK were considered to provide a useful tool when evaluating conceptual designs, their approach was thought to restrict the designer into using the animated movements of the manikin predefined in the program. If a modification was made to the design a new animation of the human movement may be required to re-evaluate the design, which can be time consuming due to subject involvement. JACK had the advantage of being able to constrain certain body segments to either be attached to the external environment or to constrain the movement of the CoG relative to the feet, which would be useful when simulating human movement during the creation of a conceptual design. However, this option was limited in the amount of segments and variables that the user was able to activate or constrain.

Objective

- To determine and describe the model that would be used for this research project.

The constraint modelling program SWORDS was chosen to model stable intermediate movement strategies, to evaluate and develop a conceptual design to improve mobility for the following reasons:

- The option to modify the geometric representative of a conceptual design without having to manipulate the individual body segments into what could be both a complicated posture, which could be time consuming.

- The ability to apply constraints to any part of the human model to enable the new body movements to be analysed without having to reiterate subject involvement could reduce the conceptual design development time.

- The choice of being able to incorporate the stability calculation into the rules being resolved enables stable postures to be sought when designing and evaluating.

Objectives

- To replicate the movement patterns determined from the experimental study carried out in the Chapter 7, while employing the computer human model chosen in Chapter 6.
- To compare these results with both the findings in the literature described in section 5.1, and the experimental results found in Chapter 7.

Comparisons of the measurements taken from the subjects analysed during the experimental study and the results using generic procedures to enable the manikin to mimic the movement of rising were provided in Chapter 7. It was found that these generic rules were suitably interpreted and could be successfully used to model individuals using the same movement strategy commonly used by able-bodied subjects when rising from a chair.

Limitations and recommendations for further work

The proposed design methodology was limited to designing for gross movements of the human body only. It is thus proposed that further work should include the finer movements to be considered and, therefore, a more complex manikin be developed to include a more detailed model such as the hands and fingers.

To further reduce the time taken to interpret the movement strategies employed by a specific user group, it is suggested that further research be carried into the common daily tasks that people carry out. These tasks could then be stored within a library of movement strategies that a designer could choose to mimic and also modify if desired to aid the creation of a conceptual design.

10.4 Existing, proposed design methodology and case study (Chapters 2, 3 and 9)

Objective

To review existing design methodologies and processes published in the literature for their strengths, and limitations in the context of the aims of this project, as defined in Chapter 1.

Many of the authors of existing design methodologies, described in Chapter 2, have recognised the need to satisfy the functional and psychological requirements of the user, throughout various phases of the design process to varying degrees. They did not, however, prescribe a procedure to enable designers to understand the normal movement patterns employed by able-bodied people, to thus enable them to create a device or devices to improve users mobility by continuing to use normal movement strategies. The effect of this could result in the designer creating a device that would force the user into using a movement strategy that they would not commonly use, which may later result in the user abandoning the design.

Objective

- To present a design methodology, aimed at improving the mobility of older people and people with physical disabilities, and to enable them to continue using the movement patterns, similar to those commonly used by able-bodied people.

A design methodology was proposed that analysed the common movement strategies employed by able-bodied people and by a user group, before and after the conceptual design stage. This was to enable the designer to understand the similarities and the shortcomings of the physical capabilities of the potential users compared to able-bodied people using existing designs, as well as evaluating the conceptual design proposed.

Reiterative subject involvement to validate conceptual prototypes was considered to be both time consuming and costly. It was thus proposed that the movement strategies of both groups be mimicked by a computer human model, through the understanding gained from the analysis of the movement strategies used. It was the intention that this would enable the designer to simultaneously develop a conceptual design to enable optimal function at the very beginning of the conceptual design and thus possibly prevent costly and time consuming redesigns.

Objective

- To carry out a case study to validate the design methodology proposed, when designing a chair. This was to improve the mobility of a group of subjects with osteoarthritis and to enable them to use similar movement patterns to those employed by able-bodied people.

The case study, described in the previous chapter, showed that through the use of the experimental techniques advocated in the design methodology proposed, the commonalties and variances of a common movement strategy used by the two groups studied were able to be identified. It also showed that they could be successfully mimicked, using the manikin developed in the constraint based modeller SWORDS, and used to create a chair design for three people with osteoarthritis.

Experimental results also showed that the prototype of the chair design enabled the osteoarthritic group to successfully rise up in a manner, similarly employed by the able-bodied group. Subjective questioning of this group also showed that this prototype design enabled them to rise with far greater ease, comfort and also without experiencing physical pain, previously acknowledged when using existing designs.

Limitations and recommendations for further work

This research project was limited in that the case study was centred around creating devices for a small group of individuals with the same disabilities i.e. osteoarthritis. It is estimated however, as stated by Weller and Wells (1992), that 20 million people in Britain had rheumatic disease, of whom between 6 and 8 million were seriously effected. Also the problem of a limited joint range of motion experienced by people with osteoarthritis, is also a common problem for people with large body sizes, pregnant women, older people and people with other physical disabilities, which means that this approach could be useful for much larger user groups.

This research project was also restricted to a kinematic analysis of users. This means that a movement strategy, the body sizes, body parts and limited joint range of motion of individuals, are the only variables that were employed to mimic a user's physical attributes. This kinematic analysis could, however, be used as an aid in creating devices, for users with reduced strength, that wish to carry out a task using a natural stable movement strategy commonly used by able-bodied people. Also, if an analysis of the external force exerted by the user interacting with a design were to be carried out during the experimental analyses, designers would then be able to understand the limited strength of the user and develop their concepts accordingly.

This research project has also been limited by the case study that involved creating a device only for the movement task of rising. However, considering that the task of rising from a sitting posture is an important function towards independent living, it was felt that the case study provided enough detailed analysis to show the benefits of the design methodology proposed

There are many tasks required to be carried out by people of various physical capabilities who are employed within various industries, one for example being the manufacturing industry. The use of the proposed design methodology could be further developed to aid in the understanding and design of devices to enable people to undertake natural stable movement strategies to be carried out and to prevent possible physical injury and increase their physical comfort at work.

The aim of this research project was to focus on the functional design of the product rather than its aesthetic appearance. This was considered a limitation of this design methodology, as the appearance of an assistive aid could attract unwanted attention and also cause the user to discard a device. It was thus suggested that the aesthetic appearance of the device could be either developed in parallel or towards the end of the conceptual design phase to enable comparisons and subjective questioning be carried out before the embodiment phase. This would hopefully lead to a design that would be functionally used and as well as being aesthetically accepted.

There are documented mechanisms for introducing a design methodology for people who are physiologically or psychologically disabled into industry, such as the British Standard BS7000: Part 6, 2005, entitled 'Managing inclusive design'. This standard advocates that the initial acceptance of such a design methodology should begin at executive level before it can be filtered through to the whole of the company. It was recognised that the prototype made as part of this case study was considered to be unrefined, in that it was suitable for the purpose of experimental evaluation but not yet completely developed as a final saleable commodity. To gain the interest of investors within industry it is thought that a fully working prototype should be developed while taking into consideration the cost, aesthetic and manufacturing requirements stipulated by the design specification. This may also include some of the design features normally found in a lounge environment such as armrests and soft foam coverings. This would be carried out with the aim of producing a prototype that would be seen as a saleable commodity and show the benefits of investing in such a design methodology to create devices for those who wish to continue using normal movement strategies.

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Appendix A

This appendix provides details of the body segmental lengths, the external body measurements and the joint range of motion of subjects A to E taken during the experimental and case study found in Chapters 6 and 9 respectively.

Measurements made for skeletal link lengths Subject A

Description of body measurements	**Corresponding body length**
Fixed measurement	l[1] = 0
Pelvis	l[2] = 7.4
Lumbar (along z axis)	l[3] = 6.5
Torso	l[4] = 35.8
Right shoulder	l[5] = 15.7
Right upper arm	l[6] = 25.4
Right lower arm	l[7] = 25
Right hand	l[8] = 17.5
Left shoulder	l[9] = 15.7
Left upper arm	l[10] = 25.4
Left lower arm	l[11] = 25
Left hand	l[12] = 17
Fixed measurement	l[13] = 1.3
Neck	l[14] = 15.1
Head	l[15] = 7.8
Eye (along y axis)	l[16] = 9.9
Eye ray *	l[17] = 300
Right hip (along x axis)	l[18] = 11.55
Right upper leg	l[19] = 43.9
Right lower leg (shank)	l[20] = 42.9
Right foot (along z axis)	l[21] = 5.9
Left hip (along x axis)	l[22] = 11.55
Left upper leg	l[23] = 43.9
Left lower leg (shank)	l[24] = 42.9
Left foot (along z axis)	l[25] = 5.9
Eye (along y axis)	l[26] = 6.3

Measurements made for skeletal link lengths Subject B

Description of body measurements	**Corresponding body length**
Fixed measurement	l[1] = 0
Pelvis	l[2] = 10
Lumbar (along z axis)	l[3] = 6.5
Torso	l[4] = 34.8
Right shoulder	l[5] = 17.5
Right upper arm	l[6] = 26
Right lower arm	l[7] = 25.5
Right hand	l[8] = 14.5
Left shoulder	l[9] = 17.5
Left upper arm	l[10] = 26.4
Left lower arm	l[11] = 25.5
Left hand	l[12] = 14.5
Fixed measurement	l[13] = 1.3
Neck	l[14] = 15
Head	l[15] = 8
Eye (along y axis)	l[16] = 9.9
Eye ray *	l[17] = 300
Right hip (along x axis)	l[18] = 13
Right upper leg	l[19] = 40
Right lower leg (shank)	l[20] = 36
Right foot (along z axis)	l[21] = 6.5
Left hip (along x axis)	l[22] = 13
Left upper leg	l[23] = 40
Left lower leg (shank)	l[24] = 36
Left foot (along z axis)	l[25] = 6.5
Eye (along y axis)	l[26] = 6.3

Measurements made for skeletal link lengths Subject C

Description of body measurements	**Corresponding body length**
Fixed measurement	l[1] = 0
Pelvis	l[2] = 7
Lumbar (along z axis)	l[3] = 6
Torso	l[4] = 44.5
Right shoulder	l[5] = 21.5
Right upper arm	l[6] = 31
Right lower arm	l[7] = 27.5
Right hand	l[8] = 20
Left shoulder	l[9] = 21.5
Left upper arm	l[10] = 31
Left lower arm	l[11] = 27.5
Left hand	l[12] = 20
Fixed measurement	l[13] = 1.3
Neck	l[14] = 15.5
Head	l[15] = 9.5
Eye (along y axis)	l[16] = 9.9
Eye ray *	l[17] = 300
Right hip (along x axis)	l[18] = 13
Right upper leg	l[19] = 45
Right lower leg (shank)	l[20] = 43
Right foot (along z axis)	l[21] = 8.5
Left hip (along x axis)	l[22] = 13
Left upper leg	l[23] = 45
Left lower leg (shank)	l[24] = 43
Left foot (along z axis)	l[25] = 8.6
Eye (along y axis) ?	l[26] = 6.3

Measurements made for skeletal link lengths Subject D

Description of body measurements	**Corresponding body length**
Fixed measurement	l[1] = 0
Pelvis	l[2] = 12
Lumbar (along z axis)	l[3] = 5.5
Torso	l[4] = 26.7
Right shoulder	l[5] = 15.5
Right upper arm	l[6] = 25.9
Right lower arm	l[7] = 21
Right hand	l[8] = 15.8
Left shoulder	l[9] = 15.5
Left upper arm	l[10] = 25.9
Left lower arm	l[11] = 21
Left hand	l[12] = 15.8
Fixed measurement	l[13] = 1.3
Neck	l[14] = 17.3
Head	l[15] = 6
Eye (along y axis)	l[16] = 9.9
Eye ray	l[17] = 300
Right hip (along x axis)	l[18] = 12.5
Right upper leg	l[19] = 46.9
Right lower leg (shank)	l[20] = 37.9
Right foot (along z axis)	l[21] = 4.5
Left hip (along x axis)	l[22] = 12.5
Left upper leg	l[23] = 46.9
Left lower leg (shank)	l[24] = 37.9
Left foot (along z axis)	l[25] = 4.5
Eye (along y axis)	l[26] = 6.3

Measurements made for skeletal link lengths Subject E

Description of body measurements	**Corresponding body length**
Fixed measurement	l[1] = 0
Pelvis	l[2] = 6.6
Lumbar (along z axis)	l[3] = 7.3
Torso	l[4] = 35.8
Right shoulder	l[5] = 15.7
Right upper arm	l[6] = 25.4
Right lower arm	l[7] = 25
Right hand	l[8] = 17.5
Left shoulder	l[9] = 15.7
Left upper arm	l[10] = 25.4
Left lower arm	l[11] = 25
Left hand	l[12] = 17.5
Fixed measurement	l[13] = 1.3
Neck	l[14] = 15.1
Head	l[15] = 7.8
Eye (along y axis)	l[16] = 9.9
Eye ray	l[17] = 300
Right hip (along x axis)	l[18] = 11.55
Right upper leg	l[19] = 43.9
Right lower leg (shank)	l[20] = 42.9
Right foot (along z axis)	l[21] = 5.9
Left hip (along x axis)	l[22] = 11.55
Left upper leg	l[23] = 43.9
Left lower leg (shank)	l[24] = 42.9
Left foot (along z axis)	l[25] = 5.9
Eye (along y axis)	l[26] = 6.3

Measurements made for skeletal link lengths Subject F

Description of body measurements	**Corresponding body length**
Fixed measurement	l[1] = 0
Pelvis	l[2] = 12.5
Lumbar (along z axis)	l[3] = 7
Torso	l[4] = 30.5
Right shoulder	l[5] = 20
Right upper arm	l[6] = 25
Right lower arm	l[7] = 28
Right hand	l[8] = 18
Left shoulder	l[9] = 20
Left upper arm	l[10] = 25
Left lower arm	l[11] = 28
Left hand	l[12] = 18
Fixed measurement	l[13] = 1.3
Neck	l[14] = 14.5
Head	l[15] = 7.5
Eye (along y axis)	l[16] = 9.9
Eye ray	l[17] = 300
Right hip (along x axis)	l[18] = 15.5
Right upper leg	l[19] = 43
Right lower leg (shank)	l[20] = 40.5
Right foot (along z axis)	l[21] = 7.5
Left hip (along x axis)	l[22] = 15.5
Left upper leg	l[23] = 43
Left lower leg (shank)	l[24] = 40.5
Left foot (along z axis)	l[25] = 7.5
Eye (along y axis)	l[26] = 6.3

External body measurements Subject A

Description of body measurements	**Corresponding measurements**
Vertical distance from corner of right eye to top of head	l[61] = 9.5
Horizontal distance from corner of the eye to furthest point at the back of the head	l[62] = 7
Horizontal distance from joint centre of rotation of shoulder to furthest point of back	l[63] = 6.8
Horizontal distance from hip joint centre of rotation to furthest point measured on buttocks (during sitting posture)	l[64] = 11.5
Vertical distance from hip joint to bottom of buttocks (during sitting posture)	l[65] = 11.5
Vertical distance from knee joint centre of rotation to underside of knee (during sitting posture)	l[66] = 5.3
Half the width of the heel	l[67] = (5.1/2)
Half the width of front of foot (from most distal end of first to fifth digits of feet, measured perpendicular to the rigid stick length representing the feet)	l[68] = (10/2)
Horizontal distance from distal end of the rigid stick length l[21], representing the feet, to distal end of 5th digit on right foot	l[69] = 12.8
Horizontal distance from distal end of rigid stick length l[21], representing the feet, to distal end of 1st digit of right foot	l[70] = 18
Horizontal distance from top of illiac crest to most posterior point of pelvis	l[71] = 10

External body measurements Subject B

Description of body measurements	**Corresponding measurements**
Vertical distance from corner of right eye to top of head	l[61] = 9.5
Horizontal distance from corner of the eye to furthest point at the back of the head	l[62] = 8.9
Horizontal distance from joint centre of rotation of shoulder to furthest point of back	l[63] = 10
Horizontal distance from hip joint centre of rotation to furthest point measured on buttocks (during sitting posture)	l[64] = 12
Vertical distance from hip joint to bottom of buttocks (during sitting posture)	l[65] = 11
Vertical distance from knee joint centre of rotation to underside of knee (during sitting posture)	l[66] = 7
Half the width of the heel	l[67] = (5/2)
Half the width of front of foot (from most distal end of first to fifth digits of feet, measured perpendicular to the rigid stick length representing the feet)	l[68] = (9.5/2)
Horizontal distance from distal end of the rigid stick length l[21], representing the feet, to distal end of 5th digit on right foot	l[69] = 10.8
Horizontal distance from distal end of rigid stick length l[21], representing the feet, to distal end of 1st digit of right foot	l[70] = 14.3
Horizontal distance from top of illiac crest to most posterior point of pelvis	l[71] = 11

External body measurements Subject C

Description of body measurements	**Corresponding measurements**
Vertical distance from corner of right eye to top of head	l[61] = 9.5
Horizontal distance from corner of the eye to furthest point at the back of the head	l[62] = 7
Horizontal distance from joint centre of rotation of shoulder to furthest point of back	l[63] = 6.8
Horizontal distance from hip joint centre of rotation to furthest point measured on buttocks (during sitting posture)	l[64] = 11.5
Vertical distance from hip joint to bottom of buttocks (during sitting posture)	l[65] = 11.5
Vertical distance from knee joint centre of rotation to underside of knee (during sitting posture)	l[66] = 5.3
Half the width of the heel	l[67] = (5.1/2)
Half the width of front of foot (from most distal end of first to fifth digits of feet, measured perpendicular to the rigid stick length representing the feet)	l[68] = (10/2)
Horizontal distance from distal end of the rigid stick length l[21], representing the feet, to distal end of 5th digit on right foot	l[69] = 12.8
Horizontal distance from distal end of rigid stick length l[21], representing the feet, to distal end of 1st digit of right foot	l[70] = 18.3
Horizontal distance from top of illiac crest to most posterior point of pelvis	l[71] = 10

External body measurements Subject D

Description of body measurements	**Corresponding measurements**
Vertical distance from corner of right eye to top of head	l[61] = 9.7
Horizontal distance from corner of the eye to furthest point at the back of the head	l[62] = 9.8
Horizontal distance from joint centre of rotation of shoulder to furthest point of back	l[63] = 6.4
Horizontal distance from hip joint centre of rotation to furthest point measured on buttocks (during sitting posture)	l[64] = 9.6
Vertical distance from hip joint to bottom of buttocks (during sitting posture)	l[65] = 7.7
Vertical distance from knee joint centre of rotation to underside of knee (during sitting posture)	l[66] = 7.3
Half the width of the heel	l[67] = (5.5/2)
Half the width of front of foot (from most distal end of first to fifth digits of feet, measured perpendicular to the rigid stick length representing the feet)	l[68] = (11.6/2)
Horizontal distance from distal end of the rigid stick length l[21], representing the feet, to distal end of 5^{th} digit on right foot	l[69] = 11.8
Horizontal distance from distal end of rigid stick length l[21], representing the feet, to distal end of 1^{st} digit of right foot	l[70] = 15.2
Horizontal distance from top of illiac crest to most posterior point of pelvis	l[71] = 10.5

External body measurements Subject E

Description of body measurements	**Corresponding measurements**
Vertical distance from corner of right eye to top of head	l[61] = 8.5
Horizontal distance from corner of the eye to furthest point at the back of the head	l[62] = 8.9
Horizontal distance from joint centre of rotation of shoulder to furthest point of back	l[63] = 9
Horizontal distance from hip joint centre of rotation to furthest point measured on buttocks (during sitting posture)	l[64] = 16
Vertical distance from hip joint to bottom of buttocks (during sitting posture)	l[65] = 14
Vertical distance from knee joint centre of rotation to underside of knee (during sitting posture)	l[66] = 7.1
Half the width of the heel	l[67] = (6/2)
Half the width of front of foot (from most distal end of first to fifth digits of feet, measured perpendicular to the rigid stick length representing the feet)	l[68] = (9.5/2)
Horizontal distance from distal end of the rigid stick length l[21], representing the feet, to distal end of 5th digit on right foot	l[69] = 12.2
Horizontal distance from distal end of rigid stick length l[21], representing the feet, to distal end of 1st digit of right foot	l[70] = 15.5
Horizontal distance from top of illiac crest to most posterior point of pelvis	l[71] = 11

External body measurements Subject F

Description of body measurements	**Corresponding measurements**
Vertical distance from corner of right eye to top of head	l[61] = 9.6
Horizontal distance from corner of the eye to furthest point at the back of the head	l[62] = 9.8
Horizontal distance from joint centre of rotation of shoulder to furthest point of back	l[63] = 10.5
Horizontal distance from hip joint centre of rotation to furthest point measured on buttocks (during sitting posture)	l[64] = 11.2
Vertical distance from hip joint to bottom of buttocks (during sitting posture)	l[65] = 10.4
Vertical distance from knee joint centre of rotation to underside of knee (during sitting posture)	l[66] = 7
Half the width of the heel	l[67] = (5.5/2)
Half the width of front of foot (from most distal end of first to fifth digits of feet, measured perpendicular to the rigid stick length representing the feet)	l[68] = (9/2)
Horizontal distance from distal end of the rigid stick length l[21], representing the feet, to distal end of 5th digit on right foot	l[69] = 20.2
Horizontal distance from distal end of rigid stick length l[21], representing the feet, to distal end of 1st digit of right foot	l[70] = 23
Horizontal distance from top of illiac crest to most posterior point of pelvis	l[71] = 8.4

Limits of rotation of body parts imported into SWORDS

The following tables are the limited range of motion measured for subjects A-F to simulate the sit-to-stand movement:

- The limits shown in bold are the joint angles measured during the sit-to-stand movement.
- The lumbar and torso, and neck and head were measured as combined link lengths acting about a fulcrum found at the top of the illiac crest (i.e. the pelvis) and the shoulder, respectively.

Subject A

Rotation of body part about sagittal plane	**Corresponding model space contained within manikin**	**Flexion/ dorsiflexion**	**Extension/hyperextension Plantar-flexion**
Pelvis	zpelvis_s:ax	30	15
Lumbar & torso	lumbar_s:ax	60	20
Neck & head	neck_s:ax	50	55
Right hip	right_ts:ax	90	25
Left hip	left_ts:ax	90	25
Right knee	right_ls:ax	130	0
Left knee	left_ls:ax	130	0
Right ankle	right_fs:ax	26	74
Left ankle	left_fs:ax	26	74

Subject B

Rotation of body part about sagittal plane	**Corresponding model space contained within manikin**	**Flexion/ dorsiflexion**	**Extension/hyperextension Plantar-flexion**
Pelvis	zpelvis_s:ax	30	10
Lumbar & torso	lumbar_s:ax	50	22
Neck & head	neck_s:ax	45	50
Right hip	right_ts:ax	97	15
Left hip	left_ts:ax	97	15
Right knee	right_ls:ax	115	0
Left knee	left_ls:ax	115	0
Right ankle	right_fs:ax	20	50
Left ankle	left_fs:ax	20	50

Subject C

Rotation of body part about sagittal plane	**Corresponding model space contained within manikin**	**Flexion/dorsi flexion**	**Extension/hyperextension Plantar-flexion**
Pelvis	zpelvis_s:ax	40	20
Lumbar & torso	lumbar_s:ax	55	35
Neck & head	neck_s:ax	50	55
Right hip	right_ts:ax	97	25
Left hip	left_ts:ax	97	25
Right knee	right_ls:ax	110	0
Left knee	left_ls:ax	110	0
Right ankle	right_fs:ax	20	55
Left ankle	left_fs:ax	20	55

Subject D

Rotation of body part about sagittal plane	**Corresponding model space contained within manikin**	**Flexion/dorsi flexion**	**Extension/hyperextension Plantar-flexion**
Pelvis	zpelvis_s:ax	30	12
Lumbar & torso	lumbar_s:ax	18	32
Neck & head	neck_s:ax	16	20
Right hip	right_ts:ax	96	14
Left hip	left_ts:ax	96	13
Right knee	right_ls:ax	11(zero start position) 90	0
Left knee	left_ls:ax	19(zero start position) 110	0
Right ankle	right_fs:ax	5 **23**	15
Left ankle	left_fs:ax	23	14

Subject E

Rotation of body part about sagittal plane	**Corresponding model space contained within manikin**	**Flexion/dorsi flexion**	**Extension/hyperextension**
Pelvis	zpelvis_s:ax	30	11
Lumbar & torso	lumbar_s:ax	30	11
Neck & head	neck_s:ax	26	46
Right hip	right_ts:ax	86	14
Left hip	left_ts:ax	92	13
Right knee	right_ls:ax	114	0
Left knee	left_ls:ax	28 (zero start position) before experiencing pain - 86	0
Right ankle	right_fs:ax	19	30
Left ankle	left_fs:ax	18	30

Subject F

Rotation of body part about sagittal plane	**Corresponding model space contained within manikin**	**Flexion/dorsi flexion**	**Extension/hyperextension**
Pelvis	zpelvis_s:ax	18	14
Lumbar & torso	lumbar_s:ax	50	36
Neck & head	neck_s:ax	30	12
Right hip	right_ts:ax	86 **109**	14
Left hip	left_ts:ax	50	0
Right knee	right_ls:ax	26	0
Left knee	left_ls:ax	24	0
Right ankle	right_fs:ax	0 **19**	38
Left ankle	left_fs:ax	20	35