Workforce Challenges: 'Inclusive Design' for Organizational Sustainability

By

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Abstract

Today’s challenge for workforce management lies in providing a healthy, safe and productive working culture where people are valued, empowered and respected. Workforce diversity is becoming an essential aspect of the global workforce, and ageing is the most prominent and significant factor in this regard. Diversity brings many opportunities and challenges, as workers with different backgrounds, cultures, working attitudes, behaviours and age work together, and in future, the key to organizational effectiveness and sustainability will heavily depend on developing and sustaining inclusive work environments where people with their differences can co-exist safely and productively. Manufacturing organizations expect the highest levels of productivity and quality, but unfortunately the manufacturing system design process does not take into account human variability issues caused by age, skill, experience, attitude towards work etc.

This thesis focuses on proposing an inclusive design methodology to address the design needs of a broader range of the population. However, the promotion and implementation of an inclusive design method is challenging due to the lack of relevant data and lack of relevant tools and methods to help designers. This research aims to support the ‘inclusive design’ process by providing relevant data and developing new design methodologies.

The ‘inclusive design methodology’ suggested in this thesis is a three step approach for achieving a safe and sustainable work environment for workers, with special concern for older workers. The methodology is based on the provision of relevant human capabilities data, the capture and analysis of difference in human behaviour and the use of this knowledge in a digital human modelling tool. The research is focused on manual assembly through a case study in the furniture manufacturing industry and joint mobility data from a wide-ranging population has been analysed and the task performing strategies and behaviours of workers with different levels of skills have been recorded and analysed.

It has been shown that joint mobility significantly decreases with age and disability and that skilful workers are likely to adopt safer and more productive working strategies. A digital human modelling based inclusive design strategy was found to

be useful in addressing the design needs of older workers performing manufacturing assembly activities. This strategy validates the concept of using human capabilities data for assessing the level of acceptability of any adopted strategy for older workers, and suggests that the strategies adopted by skilful workers are more likely to be equally acceptable for older and younger workers – keeping in view differences in their joint mobility.

The overall purpose of this thesis is to present a road map towards the promotion and implementation of the inclusive design method for addressing workforce challenges and in future the same strategies might be implemented within a variety of other industrial applications. The proposed three step inclusive design methodology and getting a reasonable understanding of human variability issues along with the use of human capabilities data (joint mobility in this case) in a human modelling system for design assessment at a pre-design stage can be considered as the major contributions of this research.

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Chapter 1

Introduction

1.1. Research Motivation

Workforce demographics are changing dramatically. Organizations are witnessing the emerging trends of workforce diversity, and the issue is becoming a business case for 21st century organizations, as all want to attract and retain the very best employees available. It is evident that the trend towards a diverse workforce is prominent in most parts of the world. Workforce diversity covers a wide range of dimensions such as age, gender, race, skill, cultural background, marital status etc. (Williams and O'reilly, 1998). Because of this, workers share different attitudes, working behaviours, needs, desires and values; along with variations in physical, physiological and cognitive capabilities, that directly or indirectly affect work performance at individual and organizational levels. Workforce diversity comes with a number of potential benefits but also brings challenges as it increases work performance inconsistencies because of human variability. Effective diversity management can provide an opportunity of better work performance by utilizing more diverse ideas in decision-making, increasing creativity, competitiveness and innovation along with a greater variety of perspectives and a broad range of task-related knowledge and skills (Roberge and van Dick, 2010; Childs, 2005; Bassett-Jones, 2005; Richard, 2000; De Dreu and West, 2001). However, failure to manage a diverse workforce may lead to an environment of conflicts, frustration and a sense of insecurity that can promote absenteeism, high turnover, job dissatisfaction and lower work commitment (Shore et al., 2009; Richard, 2000). So, it becomes very important to understand the relationships between different dimensions of diversity and their potential impact on work performance of individuals and organizations. Moreover, diversity management demands the implementation of working methods and strategies that might promote positive outcomes and prevent negative outcomes.

The most prominent and challenging fact is the ageing population (U.N.O., 2009). Over the last few decades, the proportion of older people has been significantly increasing in almost all parts of the world, including the UK, USA, Canada, Japan and Australia; however, most of the increase is taking place in the developing world. According to the United Nations Organization statistics (U.N.O., 2009), the average age of the population is increasing. Approximately, one of every ten persons is now 60 years or above and by 2050, one out of five will be 60 years or older. The UK population is also ageing and there has been an increase of 1.7 million people aged 65 and over in last 25 years (O.N.S., 2010). However, the percentage of the population aged less than 16 decreased from 21% to 19% between 1984 and 2009. This trend is predicted to continue together with a marked increase in those over 85 and a decrease in the ratio of women to men in the over-65 years age group. The UK population trends show an ageing population, but that it is ageing less rapidly than other European countries such as Germany and Italy. In common with other European countries life expectancy in the UK is increasing, but the UK has higher fertility and immigration rates. In Europe, the median age of the population was 29.7 in 1995, had risen to 39 years by 2005, and is forecast to be approximately 47.1 years in 2050. Similarly, The United States Bureau of Labor Statistics (B.L.S) identied that the proportion of the workforce over 55 years of age is rapidly increasing whereas that of younger workers aged 16-19 years old is decreasing (B.L.S, 2011). The higher the number of older people in the population means simply that there is a greater number of older workers available in the workforce as compared with the younger. One way to manage the workforce shortage problem is to retain skilled and experienced workers for a longer time and increase their retirement age. Furthermore, the current global economic crisis also demonstrates the need for effective utilization of this valuable human capital.

Accommodation and retention of older workers demands several critical factors to be addressed, which are challenges for managers, planners, designers, ergonomists, engineers and human resources personnel. Many changes occur with age and these changes affect humans in different ways including physical, physiological, psychological, cognitive, attitudinal and cognitive aspects. Functional capacity to perform work decreases with age in a number of ways and is considered to be significant after the age of 50. For example, decreases in muscular strength, flexibility, joint mobility, aerobic capacity and vision. affect the work performance capability of individuals and increase the level risk of exposure to injuries, illnesses and mistakes at work (Sturnieks et al., 2008; Wanger et al., 1994; Chung and Wang, 2009; Chiacchiero et al., 2010; Falkenstein et al., 2006; Hultsch et al., 2002; Der and Deary, 2006; Sue, 2008; Boyce, 2008). Development of a proper understanding of all these changes is very important so that they can be accommodated so as to effectively utilize this skilful and experienced resource. There is a necessity to understand the effects of ageing in the context of work performance, so that the needs' of older workers might be addressed properly.

The foregoing discussion has centred on areas where the older worker has inferior capabilities when compared with their younger counterparts. Gerontologists consider 75 to be a milestone beyond which the effects of ageing become very significant but the "younger" old from 50 to 75 have many advantages over younger workers. These advantages are predominantly cognitive and social and include sagacity, prudence, strategy, wisdom, decision-making, logical reasoning, critical thinking, experience, better product knowledge, loyalty, greater motivation, better engagement with work and more quality consciousness (Posthuma and Campion, 2009; Dychtwald et al., 2004; Tillsely and Taylor, 2001). Strategies for coping with or benefitting from an older workforce should therefore concentrate on utilising and enhancing these positive characteristics whilst providing support and assistance (for example through workplace design) to ameliorate the physical aspects of ageing. It should also be noted that the continuous migration of work from the physical to the cognitive is an extremely powerful reason for adopting this strategy. In this way the challenges of an ageing workforce can actually be seen as an opportunity to adopt strategies to take full benefit of the older workers' capabilities.

Ergonomics is a scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theoretical principles, data and methods to design in order to optimize human well-being and overall system performance (International Ergonomics Association (I.E.A), 2012). These days, organizations are facing challenges in economic and occupational health because of immense market pressure for achieving the highest level of work productivity and sustained product quality. In common with other organisations, manufacturing organizations have to fulfil highly competitive market demands for high product quality and reliability at the lowest price. In spite of highly automated manufacturing systems, a considerable proportion of manufacturing assembly activities are still carried out manually where work performance is directly affected due to variations in work performing strategies and capabilities that might be influenced by age, skill, experience, motivation, commitment etc. To achieve productivity and quality objectives, companies have to provide and maintain risk-free working environments where people feel themselves safe, productive, valued and empowered. Good ergonomics results in improved product quality, better work productivity, and a more productive work environment, that develops a sense of belonging, safety, satisfaction and being valued in the organization (Eklund, 1995; Vink et al., 2006). Few workplaces and organizations have been designed to accommodate the needs of a diverse workforce, especially older workers. Certainly, organizations will need a committed and motivated workforce for achieving organizational performance excellence. The key to organizational effectiveness and sustainability is to develop and sustain inclusive work environments where people feel valued, empowered and safe – and this can be achieved by putting ergonomics into action. Despite the inclusive design research agenda, there is little knowledge about how to design or modify workplaces and what can help organizations in addressing the needs of a diverse workforce; especially older workers.

'Inclusive design' methods aim to address the design needs of a broader range of the population where efforts are made to understand existing differences among humans because of their age, anthropometry, background and working capabilities and to address these variations in the design process. However, 100 percent design inclusion is not possible as it becomes difficult for designers, engineers and ergonomists to accommodate all varying design needs into a single design solution. Nevertheless, inclusive design methods significantly contribute in the development of such design solutions that are equally acceptable for a broad range of the population, despite their existing differences. Undeniably, the inclusive design process can address the issue of designing such workplaces and work practices that are equally acceptable for a broad range of population. Despite this reality, promotion and implementation of an inclusive design strategy becomes challenging due to the lack of relevant data and unavailability of appropriate tools and methods that can help the designers during the design process (Vanderheiden and Tobias, 2000; Keates et al., 2000; Sims, 2003; Goodman et al., 2006).

1.2. Research Aim and Objectives

In order to address the issues highlighted above, this research aims to "*support the 'inclusive design' process by providing relevant data and developing new methodologies that can conceptually support design processes*".

The following research objectives are set to achieve the above stated research aim:

Objective 1: To explore current global workforce challenges and their relationship with individual and organizational work performance;

Objective 2: To identify the research gap in the literature relating to the promotion of the inclusive design method for addressing global workforce challenges, especially a safe and healthy accommodation and retention of older workers;

Objective 3: To understand human variability issues in terms of work performance capabilities and strategies, and their implications for 'inclusive design' in general and for older workers in particular;

Objective 4: To investigate how experience and level of skill affect work performance strategy, in terms of productivity and risk exposure;

Objective 5: To validate the usefulness of digital human modelling based approach for the implementation of an inclusive design strategy for addressing the design needs of older workers;

Objective 6: To develop a guideline methodology for the promotion of an 'Inclusive Work Environment'; where people with their existing differences can coexist productively.

1.3. Thesis Structure

This thesis consists of 8 chapters. A brief description of each chapter is given below, and figure 1.1 shows the relationships between the chapters. Table 1.1 shows the relationships between the research objectives and the thesis chapters.

Chapter 1

This chapter mainly gives an overview of the research, together with the research aims and objectives.

Chapter 2

In this chapter, a literature review concerning workforce challenges, ageing and work performance, computer-aided ergonomics using digital human modelling and the inclusive design method are presented. The chapter also highlights a need for the promotion and implementation of an Inclusive Design method for workplace design to address the design needs of a diverse workforce, with a special focus on older workers.

Chapter 3

In the light of the research aims and objectives, this chapter focuses on discussing how this research has been carried out to achieve the set goals. The chapter also highlights the research strategy, data collection and data analysis techniques used in this research.

Chapter 4

This chapter explains the importance of the concept of design exclusion and how it relates to the inclusive design process. The Office of National Statistics (ONS) conducted a 1996/1997 disability follow-up survey that was aimed at collecting information on the extent of disability in UK population and the characteristics of those with disabilities. This chapter describes how the disability follow-up survey (DFS) data explains different levels of disability severity and the use of this data in a simple design exclusion process. It also explains how the severity scores determined in the DFS relate to the HADRIAN database (HADRIAN is described in chapter 2). Similarities between the HADRIAN and DFS severity assessment criteria enable an estimation of the acceptability of different design scenarios for the entire UK population. It is shown that the HADRIAN database represents the wider UK population on the basis of the similarities in working capabilities, and can be used for the estimation of 'design exclusion' where its human modelling based task evaluation capabilities enhance its effectiveness. (HADRIAN is the digital human modelling tool that has been the focus of the research).

Chapter 5

The importance of designing workplaces and equipment by considering the joint mobility constraints of individuals is discussed in this chapter and the effects of age, gender and disability on joint range of motion are analysed. The trends in the joint mobility capabilities of different people and how exceptional data variations affect the design process are explored in terms of the challenges for designers, ergonomists and engineers.

Chapter 6

This chapter focuses on the investigation and comparison of ergonomics-based risk assessment of a diverse workforce, aiming to understand the effects of skill and experience on work performance and how much risk is involved with any adopted working strategy in manufacturing assembly work. The Ovako Working posture Analysis System (OWAS) and Rapid Entire Body Assessment (REBA) methods have been used for this purpose..

Chapter 7

Assembly activities are the major manual activities in manufacturing industry and this chapter validates the concept of using a digital human modelling based inclusive design strategy (HADRIAN) for manufacturing workplace design. The working capability data such as joint constraints data (discussed and presented in chapter 5) and task performing strategies captured at a furniture manufacturing company (discussed in chapter 6) are used for analysis purposes. The main focus of this case study was to investigate the acceptability of any adopted strategy for older workers, as age significantly affects joint mobility (concluded in chapter 5).

Chapter 8

The aim of this chapter is to draw all the key research findings together and to discuss the key findings, research contributions, limitations and recommendations, so that a better understanding can be developed. The discussion is mainly focused on the key research contributions and how these are linked with the research aims and objectives. Table 1.1 summarises which research objective is discussed and addressed in which chapter. Finally, this chapter discusses how the current research can be extended in future.

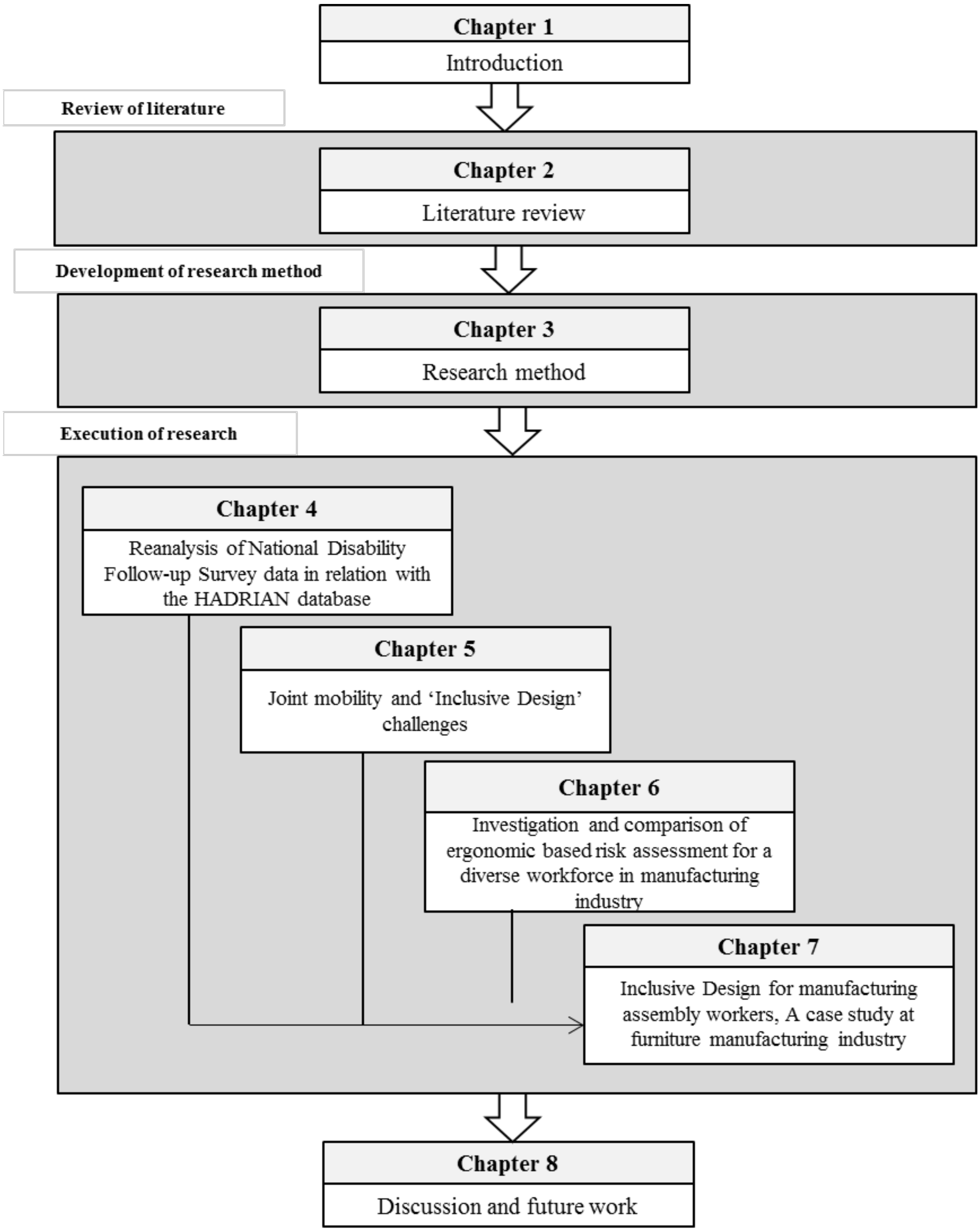


Figure1.1: Thesis Structure

Table1.1: Relation between research objectives and thesis chapters

		Chapters							
Research Objectives		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	1	**Introduction**	✓						**Discussion and Future Work**
	2		✓						
	3				✓	✓			
	4						✓	✓	
	5							✓	
	6			✓					

Chapter 2

Literature Review

2.1. Introduction

This chapter mainly presents background literature on three key research themes:

- Workforce challenges;
- Computer-aided ergonomics and digital human modelling;
- Inclusive design.

The overall discussion will be made from the perspective of global workforce challenges like workforce diversity, especially the ageing population and its impact on future workforce trends; use of computer-aided ergonomics tools to address workplace design issues; and the promotion of an inclusive design strategy to address these issues for achieving a more sustainable workforce – by providing a safe, healthy and productive working environment where individuals are valued and their differences are respected at all levels.

Section 2.2 discusses the global workforce challenges like the increase in workforce diversity and the proportion of older workers and their potential impacts on individual and organizational work performance. Moreover, background literature about the significance of experienced and older workers and issues related to their decline in capabilities are discussed. Inadequate responses to the challenges identified in section 2.2, directly or indirectly influence individual and organizational work performance and paying no attention to these issues will affect future organizations. These human factors related issues and their significance for achieving sustainable future organizations are also discussed at the end of this section.

Section 2.3 highlights the significance of using computer-aided ergonomics tools and more specifically digital human modelling tools for product, process or environment design. However, the focus of the discussion is to highlight the usefulness of these tools in addressing human related issues in workplaces, with special emphasis on manufacturing workplace design. The next section (section 2.4) deals with the importance of the inclusive design method which can address the design needs of a broad range of the population and attempts to accommodate all people with their existing differences. Furthermore, this section also discusses the implementation challenges faced by this strategy and the need for highly relevant and useful data to ensure success. It is important to mention that the reviewed literature is mainly focused on the human factors/ergonomics relevance of these review themes, with a prime concern of how the highlighted workforce challenges might be addressed during a design process.

2.2. Workforce Challenges

This section discusses global workforce challenges like workforce diversity, ageing population trends, ageing effects, work related issues and finally how these issues affect organizational effectiveness.

2.2.1. Diversity and work performance

Diversity refers to differences between individuals because of their gender, age, functional capability, cultural background, experience and education (Williams and O'Reilly, 1998). There are multiple dimensions of diversity mentioned in the literature; however, some dimensions are mentioned in the literature very frequently, including age, race, gender, disability and national origin. (Shore, et al. 2009). In the US, 42% of the workforce will be over the age of 45 by 2015; people of colour are expected to be 36% in 2025 with an increase of 4% as compared with 2010; people with disabilities comprise 12% of the workforce and women comprise 47% of the labour force and their participation is expected to increase (Ragins et al., 2007).

Workforce diversity comes with a number of potential benefits and challenges as it increases work performance inconsistencies because of human variability issues. Effective diversity management can provide an opportunity for better work performance by utilizing more diverse ideas in decision making. However, failure to manage a diverse workforce may lead to an environment of conflicts, frustration and sense of insecurity that can promote absenteeism, high turnover, job dissatisfaction and lower work commitment (Richard, 2000; Shore et al., 2009). So, it becomes very important to understand relationships between different dimensions of diversity and their potential impact on work performance of individuals and organizations. Moreover, diversity management demands the implementation of working methods and strategies that might promote positive and prevent negative outcomes.

Practitioners acknowledge the sustained competitive advantage of having a diverse workforce, as variations in skills, experiences, backgrounds etc. increase creativity, competitiveness and innovation (Childs, 2005; Bassett-Jones, 2005; Richard, 2000). There is also evidence of increased performance effects of diversity because of improved creativity and innovation arising from a greater variety of perspectives, broad range of task relevant knowledge, skills and abilities (Roberge and Van Dick, 2010; De Dreu and West, 2001; McLeod et al., 1996). However, it's very important to identify the conditions in which diversity may increase group performance. Pettigrew (1998) describes many studies that have been conducted for finding a relationship between different variables and group performance. These studies reveal that positive effects of diversity are facilitated by four key conditions: intergroup cooperation, common goals, equal group status within the situation and the support of the authorities, law, or custom. Recently, researchers have started paying attention to explain when diversity may lead to increased group performance. Some moderating variables like task interdependence, task complexity, organizational culture, and openness to a diverse work environment have been found effective for explaining when diversity leads to increased group performance (Bacharach et al., 2005; Chatman et al., 2005; Ely and Thomas., 2001; Mohammed and Angell, 2004; Jehn et al., 1999; Pelled et al., 1999; Jehn and Bezrukova, 2004; Hobman et al., 2004). Recently, Homan et al. (2008) further broadened the understanding of diversity and work performance by taking different moderators into account. It was found that the highest performing teams were highly open to experience and the lowest performing teams were lower on openness, when differences among the individuals were prominent.

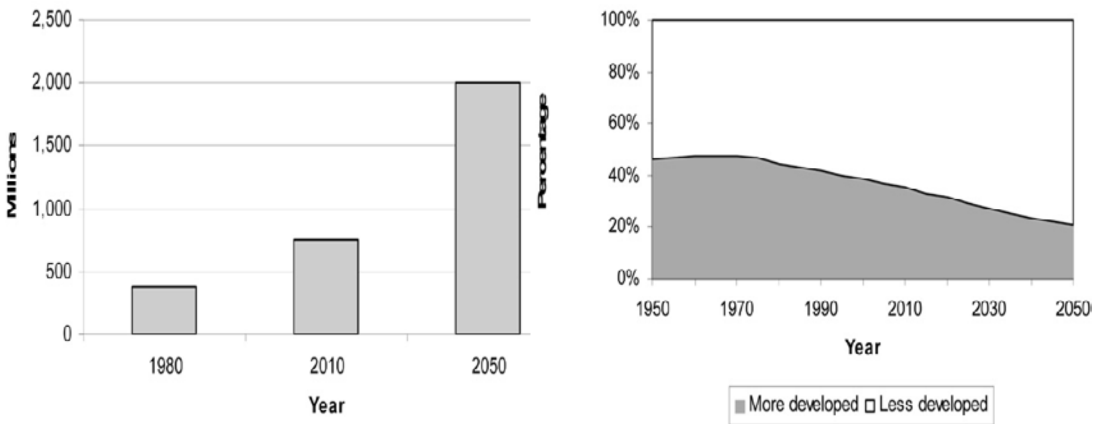
Roberge and Van Dick (2010) reviewed literature for recognizing the benefits of diversity and finding about when and how diversity can increase group performance. It was recognized that the available literature on diversity management suggests that heterogeneity in teams can reduce intra-group cohesiveness that can ultimately lead to lower satisfaction, mutual understanding and citizenship behaviour with increased turnover. Similarly, some studies conclude that like group performance, diversity at the individual level (dissimilar individuals) also affects work performance, as individuals have less trust, less frequent communication, lower group commitment, lower task contribution and lower perceptions about organizational inclusiveness

(Chatopadhyay, 1999; Zenger and Lawrence, 1989; Tsui et al., 1992; Kirchmeyer and Cohen, 1992; Mor-Barak et al., 1998). Research findings about the outcome of diversity are not consistent although many studies have been focused on this issue. Moreover, Shore et al. (2009) further concluded that the research findings draw conclusions by considering single dimension of diversity; whereas, in reality diversity has multiple dimensions that exist in the system at the same time.

2.2.2. Ageing demographics and work related issues

For the purposes of this research, the focus is on a well-known dimension of diversity that is ‘age’.

It is evident in the literature that the world is experiencing a significant increase in the proportion of the older population. Figure 2.1 (a) shows that there were about 759 million people aged 60 or above in 2010; where it is further projected that this figure will increase to 2 billion by 2050. Moreover, figure 2.1 (b) shows that this trend is more prominent in the developing world. It is estimated that one out of 5 persons will be of age 60 years or above by 2050 and this will ultimately increase the dependency ratio (the proportion of economically inactive versus active population). Moreover, the median age of the population is increasing in almost all parts of the world. Figure 2.2 shows this trend, where it is clear that the median age of the world population will increase by 34.5% (to 37.8 years) between 2005 and 2050; and the same trend will be followed in most parts of the world.



(a) (b)

Figure2.1: Percentage aged 60 and over: 1980, 2010, and 2050 (U.N.O., 2009)

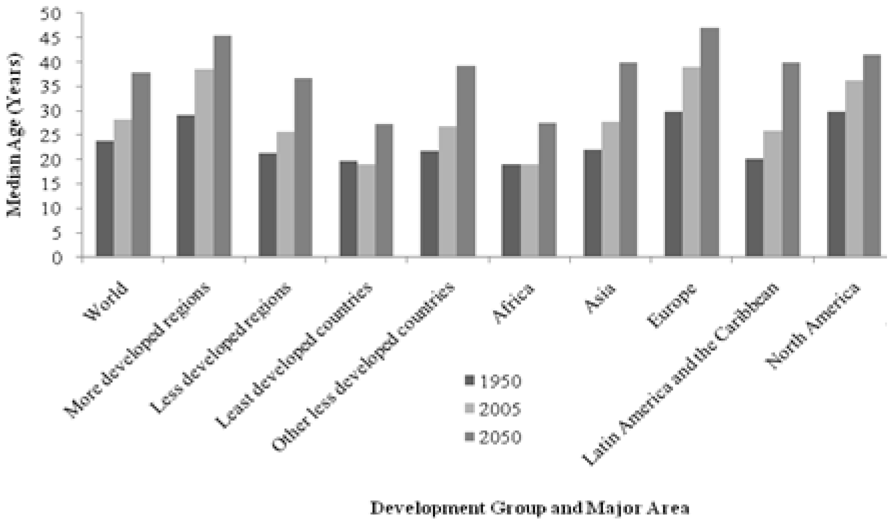
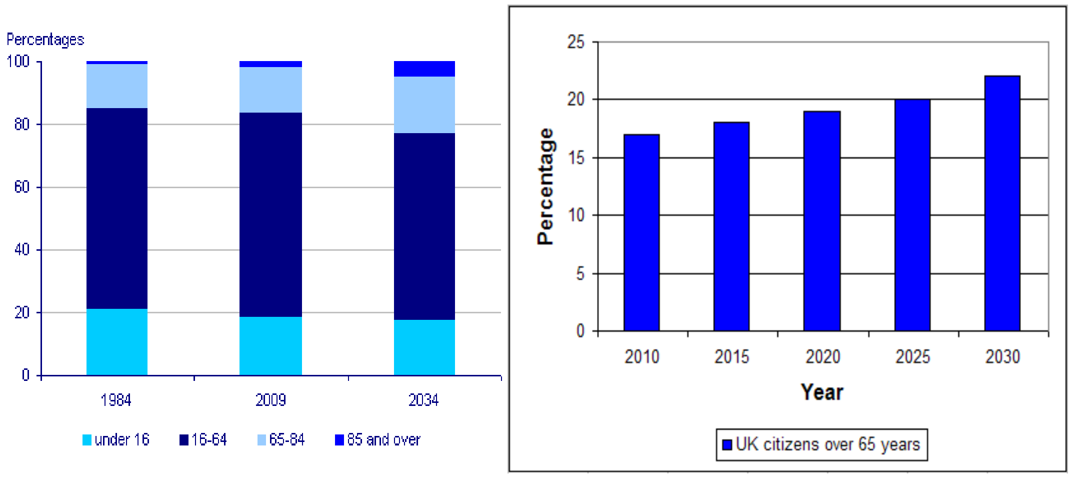


Figure 2.2: Median age of the population by development group, 1950, 2005 and 2050 (U.N.O., 2009)

Like other parts of the world, the UK population is also ageing (O.N.S., 2010). There has been an increase of 1.7 million people aged 65 and over in last 25 years. On the other hand, the percentage of the population aged less than 16 years has decreased from 21 percent to 19 percent from 1984 to 2009 (figure 2.3 (a)). Figure 2.3 (b) shows the continuing trend that by 2030, will result in the percentage of people aged more than 65 years being approximately 23 percent, whereas the percentage of the population under 16 years will further decrease to 18 percent. There are other noticeable trends in the UK population which will be continued in the coming years. These are that the fastest percentage increase in the population will be in those who are more than 85 years old and a decrease in the ratio of women to men in the over-65 age group. In comparison with other European countries, relatively the UK has higher birth rate, which makes it less alarming. In 2008, Japan was the most aged country in the world and 22% of the population was aged 65 and over (O.N.S., 2010). Similarly, the United States Bureau of Labor Statistics (B.L.S) identifies that the proportion of the workforce over 55 years of age is rapidly increasing whereas that of younger workers aged 16-19 years old is decreasing (B.L.S., 2011).



(a) (b)

Figure 2.3: UK population trends (O.N.S. UK, 2010)

The above demographics clearly identify the need for the effective utilization of valuable human capital. The current global economic crisis also attracts attention for accommodating and holding older and experienced workers for a longer time, so that this resource might be utilized for national and global economic growth. However, retention of older workers comes with potential benefits and challenges for the organizations. Experience, knowledge and skills of older workers are considered prominent factors that attract positive inclination of employers and older workers are considered as an asset for the organization. However, decline in their physical and physiological capabilities, and differences in psychological attitudes and behaviours create many challenges. There is a need for understanding the effects of ageing and the potential impact on work performance. A realistic understanding of both positives and negatives about older workers can provide an opportunity for designers to address the design needs of this part of the workforce. Otherwise, unrealistic and over ambitious production targets create a mismatch between job demands and working capabilities of older workers. Such situations ultimately result in an unsatisfied, over-stressed, frustrated and less loyal workforce that results in a decrease in individual and organizational work performance.

2.2.3. Ageing effects and challenges

Age affects humans in different ways including the physical, physiological, cognitive, psychological, attitudinal and psychosocial aspects. There is a need to understand all these changes so that the challenges faced by older workers might be addressed in a logical way. However, physical, physiological and cognitive issues are the primary concern for designers, ergonomists, managers, engineers and human resources personnel. They must be able to understand the effects of ageing and their implications in actual working environments. In this respect, it becomes essential to have an in-depth knowledge and understanding of the working capabilities of older people and job demands, so that more productive and safe working environments for an older workforce might be ensured.

The functional capacity of workers declines with age in a number of ways and becomes critical for workers aged 50 years and more. The musculoskeletal strength of the body plays a vital role in the determination of functional capacity in the context of work performance and it starts declining after the age of 30. Wanger et al. (1994) concluded that a 60 year old person has muscular strength which is approximately 70% of a person 30 years old. Balance disorders are a major cause of falls and injuries among older people and are serious and costly. It is noticeable that one in three persons aged 65 and more, fall at least once a year and about 15% of these falls cause serious injuries. Moreover, these balance disorders and risks of falls and injuries lead to a decline in work performance in sitting, standing, walking, leaning and stooping positions (Sturnieks et al. 2008). Flexibility also decreases with an increase in age and is also closely related to balance. Chung and Wang (2009) found that joint mobility reduces considerably with age; however, its severity and level depends on the joint and type of motion. Recently, Chiacchiero et al. (2010) investigated the link between decreased joint mobility and falls in the elderly. Eighteen 60 year-old subjects were studied and it was concluded that falls in older people are linked with a decline in joint range of motion. Like many other responses, reaction time increases with age whilst the speed of performing a task also decreases. It has been noted that all behavioural responses to simple and complex stimuli slow down with age and similarly reaction time also increases. The results suggest that overt response is needed at a higher activation level in older adults as compared with younger people, which ultimately increases reaction time with ageing (Falkenstein et al. 2006). Reaction time variability becomes more challenging when designers are required to design workplaces, products and tasks for older people. Different measures of reaction time like diversity (variability between persons), dispersion (variability within persons across tasks), and inconsistency (variability within persons across time) were measured for younger and older people to assess the reaction time variability. It was found that reaction time variability is higher in older people and directly affects work performance (Hultsch et al. 2002). Der and Deary (2006) further concluded that this decline in reaction time is more prominent in older women as compared to men. Similarly, Sue (2008) found a relationship between functional capacity, vision and type of task performed by older workers. This is why older workers are thought to be unsafe in working environments.

People with higher aerobic capacity are more productive than those with lesser capability, as it directly relates to the ability to accommodate variations in job demands. Ageing results in maximal heart rate decreasing proportionally by about one beat per year, which might be a prominent factor responsible for a decline in cardiac output and eventually a decrease in aerobic capacity. Due to variations in maximal heart rate, it is difficult to establish job adequacy on the basis of aerobic capacity for older workers (Boyce, 2008). It has been found that task complexity also influences aerobic capacity which demands a comprehensive physiological investigation of a task before assigning it to an older worker (Ilmarinen and Rutenfranz, 1980; Ilmarinen, 1984). McArdle et al. (2001) also reported that physically active older people are better able to perform physically demanding jobs as the decline in their capacity is half as compared to that of sedentary older people. More specifically, Astrand et al. (2003) documented that physically active older people are better able to maintain their aerobic capacity. Physical involvement of aged people plays an important role in the determination of their suitability against the maximum aerobic capacity and oxygen consumption criteria.

There are a number of other performance factors including fatigue, memory deterioration and thermoregulation problems faced in extreme environmental conditions, which are influenced by age and affect work performance. A detailed discussion on the relationship between work related musculoskeletal disorders and individual factors like age, demographics, lifestyle, past history and social background, is made in chapter 6. To conclude, in the light of above discussion, it is very important to understand all physical, physiological, psychological and cognitive changes that result from ageing. Retention of the older workforce in today’s globally competitive organizational culture can only be made possible if designers, ergonomists and planners have a good understanding of ageing effects and challenges.

On the other hand, there are a number of other factors like experience, decision-making, loyalty to the organization, sense of responsibility and critical thinking which make older people a real asset for organizations. The removal of an experienced and skilful older worker is not simply the loss of one person; it is also a drainage of skills, knowledge, experience and relationships and to regain these attributes, needs resources in the form of money and time (Dychtwald et al., 2004).

Where there is a need to retain older employees in the workforce for a longer time, there are many age stereotypes that act as barriers to their employment and retention. Gordon and Arvey (2004) provided the evidence that younger applicants are considered more positively as compared to older ones. Furthermore, Tillsely and Taylor (2001) said when management avoids hiring and retention of older workers, they miss an opportunity of employing and retaining the most skilled, efficient and productive workers. Older workers can also contribute in economic growth and retirement systems (Feyrer, 2007; Walker, 2007). There is a need to understand and address these stereotypes as these discourage and frustrate older workers from remaining in the workforce (Brooke and Taylor, 2005). There are many common stereotypes mentioned in the literature; like poor performance, resistance to change, lower ability to learn, shorter job tenure, more costly and more dependable etc. Studies also show that there is a weak correlation between these stereotypes and age. However, performance often improves with age as workers get more experience and skill (Posthuma and Campion, 2009). Chiu et al. (2001) compared how age stereotypes are related to discriminatory attitudes at work between the UK and Hong Kong. It was found that UK workers are more effective at work but less adaptable to change as compared to Hong Kong people. Moreover, stereotypical beliefs have influence over respondent perception about the effects of training, promotion and retention of older workers. Not only organizational but socio-political culture also affects behaviour towards the older workforce. As the percentage of older workers is increasing, the effects of work-related age stereotypes may become more prevalent and potentially can affect more workers (Walker, 1999).

In the 1980s, the term *work ability* was first used in Finland. The objective was to answer the question: "how good is the worker at present and in the near future, and how able is he/she to do his/her job with respect to work demands, health and mental resources?" (Ilmarinen and Tuomi, 1992). The concept of work ability is a complex and multi-dimensional issue where the main objectives of work ability assessment are: identification of decline in work ability; effectiveness assessment of preventive measures and assessment of work disability. A feasible method of work ability assessment, Work Ability Index (WAI), was constructed which takes aspects like functional capacities, job demands, health and other aspects into consideration. Many studies were conducted where it was concluded that the mean value of the work ability index was significantly reduced for active workers aged more than 51 years. It was further summarized that physical work load and age are critical factors which influence work ability of older workers (Ilmarinen et al. 1997). High physical demands, stressful and dangerous working environments and poor organization of work are the key factors that cause deterioration of work ability of older workers (Ilmarinen et al. 1991).

The Finnish Institute of Occupational Health (FIOH) designed action programs in 1990-1996 called Finn Age-Respect for the ageing (Ilmarinen and Louhevaara, 1999), where the objective was to promote work ability of ageing workers based on these findings. The basic concept was based on four actions: (i) adjustments in the physical work environment, (ii) adjustments in the psychosocial environment, (iii) health and life-style promotion and (iv) updating professional skills and knowledge. Figure 2.4 shows a concept diagram of this program (Ilmarinen and Rantenan, 1999). Later, it was emphasized that work ability of an individual is a process of human resources in relation to work (Ilmarinen, 2001). It was further emphasized that the concept of work ability is a dynamic process which changes throughout one's work life, however the main factor is ageing that affects human performance. Human resources can be described by: health and functional capacities (physical, mental and social); education and competence; values and attitudes and motivation. Work ability is found by relating all these comprehensive individual factors with work demands, work management and work environment.

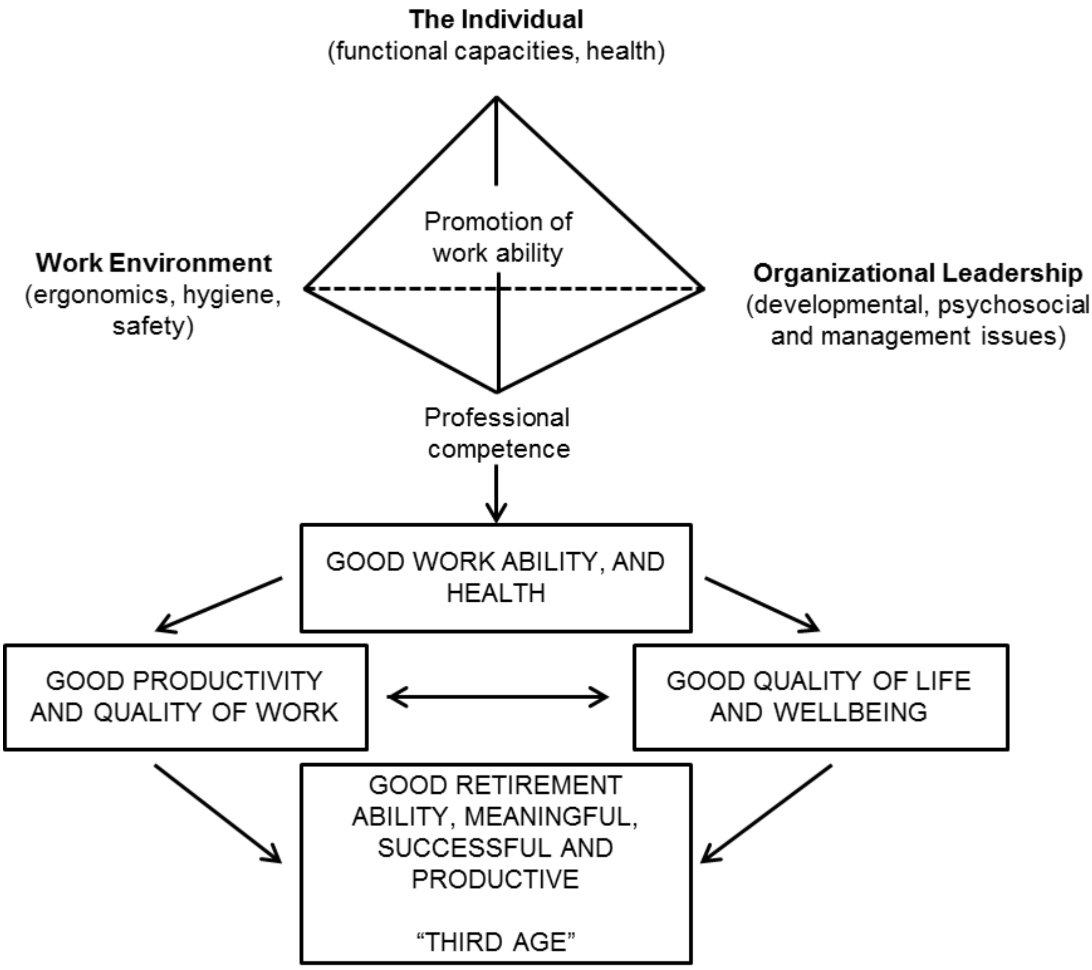


Figure 2.4: Concept of promotion of work ability during ageing (Ilmarinen and Rantanen, 1999; Ilmarinen, 2001)

Several important organizations have taken initiatives to promote retention of their older workforce. For example, Toyota introduced a concept of 'New JIT' to address the needs of 21st century customers. The optimized use of the older workforce was identified as being very important in a continuously changing market. Along with many other strategies, they also launched an 'ageing and work development' project to promote strategies for the ageing workforce. It was found that strategies like motivation, reduction in physical strength, redesign of tools and equipment and control of suitable temperature conditions were very useful for older workers and the strategies were implemented in local and overseas plants. It was also concluded that manufacturers have to shift from work-oriented to people-oriented shop designs, especially for assembly workers where job demands are relatively high (Amasaka 2002; Amasaka 2007). BMW has also taken up the issue of the ageing workforce and figured out how it can make its workplaces easier, more comfortable and more efficient for older workers. They simply analysed the behaviour of assembly line workers and made very simple modifications like wooden floors, fitting of unique chairs on the assembly lines, ergonomically designed tools and computer monitors. Surprisingly, productivity went up seven percent, attendance increased and the assembly line's defect rate dropped to zero (BMW, 2010). Moreover, the literature identifies a list of strategies that might be useful for improvement in productivity of older workers. Improvements in work task design, work organization, physical work environment, and improvements in peoples' performance capacities might lead to productive and safe working environments for all workers and specifically for older ones.

2.2.4. Human Factors and organizational sustainability

Much has been written on the concept of sustainability in the last few years and the debate is still going on. This might be due to the varying conceptual roots of defining the term 'sustainability'. Indeed, the sustainability concept has inherent positive meanings that can appeal to everybody at individual and organizational levels. There are two very common perspectives of sustainability mentioned in the literature. The first is conceptually based on Brundlandt's definition of sustainability, where sustainability is defined as, "meeting the needs of the present generation without compromising the ability of future generations to meet their needs" (World Commission on Environment and Development (WCED), 1987). Later on, Dyllick and Hockerts (2002) conceptualized the definition again from the perspective of organizational stakeholders, where it was defined as, and "meeting the needs of firm's direct and indirect stakeholders (such as employees, shareholders, clients, pressure groups and communities) without compromising its ability to meet the needs for future stakeholders as well. The second popular concept of sustainability was defined by Elkington (1997), where the triple-P perspective was introduced. The Ps stand for people, planet and profit. An organization might be considered sustainable, if a certain minimum performance can be achieved in these areas. In practical terms, organizational sustainability can be achieved by finding and achieving a balance between financial or economic goals (profit), social goals (people), and ecological or environmental goals (planet). The core of the organizational sustainability concept lies in the understanding of the fact that multiple stakeholders share different objectives of sustainability as it is directly related to the needs and the extent to which these needs are fulfilled. Moreover, it is a continuous process where relative needs of different stakeholders might change with the passage of time. It is interesting to note that the effects of organizational work arrangements on the physical and psychological well-being have been discussed in the literature; however, the human dimension of sustainability remains largely in the background (Pfeffer, 2010).

As mentioned previously, organizational workforces are becoming increasingly diversified. Hence it becomes important for organizations to understand the changing needs of their future diverse workforce, so that they can retain their experienced, skilful and committed workforce. Organizational sustainability can be promoted by achieving a safe, friendly, productive and healthy working environment for the workforce. Diversity management demands a working environment where people with different backgrounds, races, age, working capabilities and behaviours can co-exist happily in the presence of all these differences. So, the objective of organizational sustainability in workforce diversity management can only be achieved by establishinging a working environment where differences among the workers are recognized and their job needs are fulfilled according to their capabilities.

The above literature review concludes the following:

- The workforce is ageing;
- An ageing workforce brings many challenges and opportunities;
- Variations and declines in human working capabilities, become a real challenge for organizations;
- Healthy accommodation, effective utilization and long-term retention of diverse, experienced and ageing workforces might be achieved by promoting an ‘inclusive work environment’ where people are valued and empowered;
- Some organizations have taken initiatives to promote retention of their older workforce;

- Organizational sustainability can only be achieved by providing a working environment where differences among the workers are recognized and valued;
- There is still a need to conceptualize human differences and develop comprehensive and effective methodologies to address these issues, especially for older workers.

Section 2.2 briefly describes the challenges and opportunities attached with ageing workforce. Many times, the assessment of any design is based on the effective use of the fundamental ergonomic principles. Section 2.3 will discuss how computer-aided ergonomics can be used to address the design needs of working population

2.3. Computer-aided Ergonomics and Digital Human Modelling (DHM)

The International Ergonomics Association (IEA) defines Ergonomics (or human factors) as "a scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theoretical principles, data and methods to design in order to optimize human well-being and overall system performance". It is broadly divided into three main domains; physical, cognitive and organizational ergonomics which shows its multi-disciplinary nature. Organizations are facing challenges in economic and occupational health because of enormous market pressure for achieving optimal productivity with sustained product quality and the complexity created due to latest systems and product variety. Moreover, companies also have to provide and maintain a risk-free working environment because of the laws made in most industrial countries (Zink, 2005). Furthermore, as discussed in the previous section, it becomes more important because of the fact that the average age of the working population is increasing and this increases the risk for musculoskeletal disorders which directly influence work performance. It becomes very prominent when people are involved in physically demanding activities like manual material handling, heavy lifting and repetitive overhead work (De Zwart et al., 1997; Bernard and Putz-Anderson, 1997).

It has been shown that good ergonomics can significantly improve occupational health and have a positive economic impact. Therefore, it is necessary to design workplaces by using fundamental ergonomic principles, so that healthy, safe and more productive working environments might be achieved and sustained, where workers feel themselves safe, satisfied, valued and empowered. Good ergonomics also assures good product quality. Eklund (1995) investigated the relationship between quality and ergonomics at a car assembly plant. It was found that quality deficiencies are strongly linked with bad ergonomics and it has a great economic impact as these quality problems are three times more likely with activities linked with bad ergonomics. Evidence suggests that ergonomics interventions in assembly work can increase productivity and workplace safety along with reducing worker's discomfort (Eklund, 1995; Vink et al., 2006). It becomes very important to assess designs of products or workplaces as early as possible, as redesigning activity substantially increases the overall product cost. Hence, a proactive workplace design approach is needed so that any design scenario can be assessed and modified easily with minimum economic impact.

The use of computers in the creation and modification of any design is inevitable as it assists designers through graphical visualizations at early design stages. The assessment of human performance, prediction of risk elements and non-productive scenarios through computer-aided ergonomics tools is quite common (Feyen et al., 2000; Sanjog et al., 2012; Brennan and Fallon, 1990). The evaluation of ergonomic aspects of any design by using computer-aided tools and techniques is an established methodology (Porter and Porter, 1999). These tools have the ability to develop a three-dimensional model of products, equipment or workplaces, to develop a three-dimensional human model for its assessment and an interactive user interface with evaluation techniques (Porter et al., 1995). Computer-aided simulation tools, such as digital human modelling (DHM) are considered extremely useful in proactive ergonomic based design investigations (Demirel and Duffy, 2007). Furthermore, Chaffin (2007) argued that integration of digital human models with other computer-aided engineering methods significantly reduces overall cost, that includes design, engineering and ergonomic evaluation costs. These facilitate designers by providing them the option of constructing and evaluating a virtual prototype design before actual production. Different design options can be developed, and alternatives can be compared before physical mock-ups and production trials. The availability of different design options and their visualization at some earlier design stage, enhance cooperation and understanding between designers, engineers, ergonomists and workers, and promote a participatory ergonomic approach (Sundin et al., 2004; Sundin and Örtengren, 2006; Chaffin, 2005; Chaffin, 2007)

SAMMIE-CAD (System for Aiding Man-Machine Integration Evaluation) is considered as the earliest digital human modeling (DHM) tool that can evaluate human model fitness in a workplace by using different criterion like reach, fit, move, different body postures and comfort with the help of joint angles (Porter et al., 1999) (Figure 2.5).

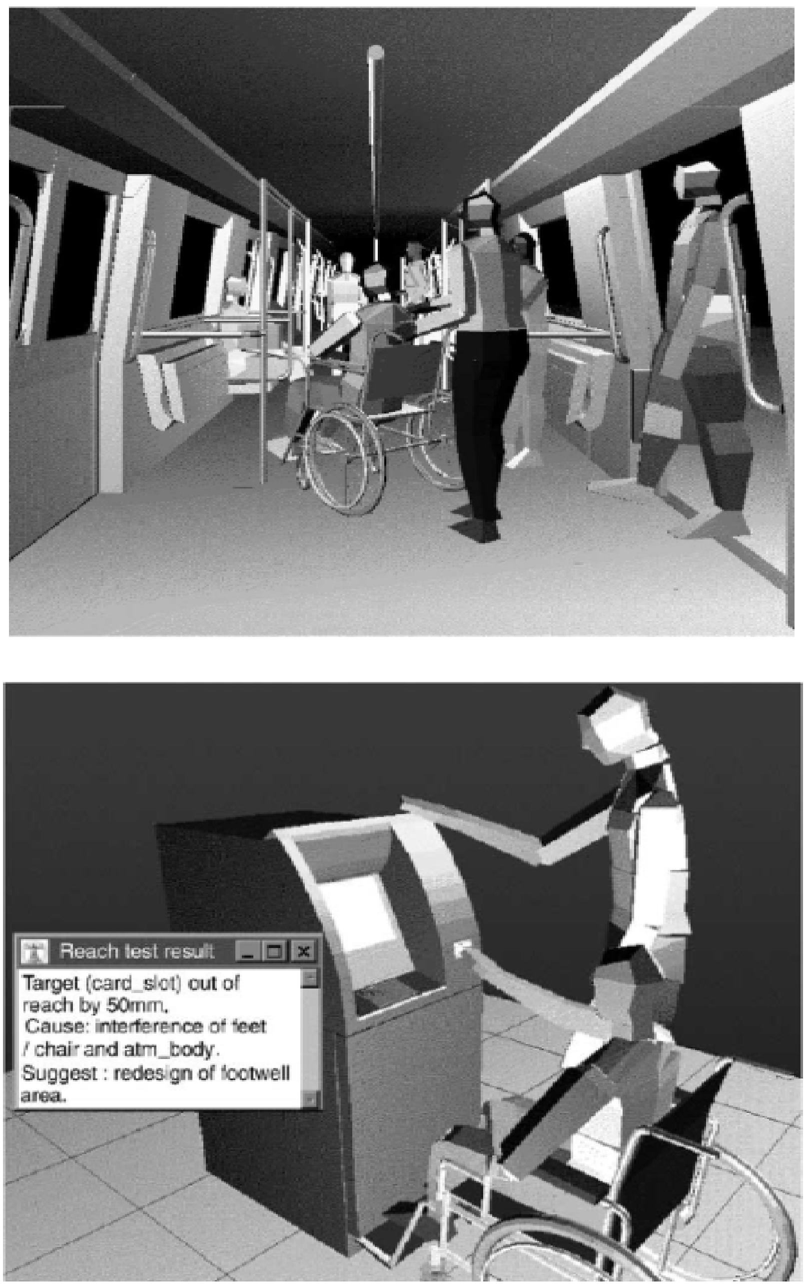


Figure 2.5: Use of human modeling system SAMMIE-CAD (Case et al., 2001)

Realistic representation of a human model in any digital human modelling tool is a key element for achieving best design evaluations. However, it has always been a challenge for the designers. Initially, 2D templates were used for design evaluation but these were upgraded with 3D-CAD systems, as any 2D template does not support the analysis of postures and comfort in a realistic way. On the other hand, accurate dimensionality of any human model is also a great challenge. To overcome all these difficulties and address the challenges, the RAMSIS (Rechnerunterstützes Anthropometrisches Mathematisches System zur Insassen Simulation) human modelling system was introduced in 1980. It uses real humans for measurement purposes and sophisticated cameras are used to capture the three dimensional geometry of the subjects. The RAMSIS human model is processed at two levels; one is internal and the other is external. The external level is just the representation of the body surface that contains 1200 anchor points attached to the internal model. The internal model is a human skeleton that provides a base for kinematic characteristics and restricts the number of joints and their degrees of freedom (Seidl, 1997). Human Solutions Gmbh provides many specialized products as digital human modelling systems against a variety of applications like RAMSIS Automotive, RAMSIS Industrial Vehicles, RAMSIS Bus and Truck, and RAMSIS Aircraft etc. (Bubb et al., 2006; Bubb, 2002; RAMSIS, 2012).

Another digital human modelling tool called JACK was developed at the University of Pennsylvania, USA, where researchers used a number of data sources so that the human model representation could be made more realistic (Gallwey and O'Sullivan, 2005; Phillips and Badler, 1988). It also has a task analysis toolkit that can be used to perform a variety of ergonomics analyses like lifting analysis, fatigue and estimated time for recovery, low back analysis and predetermined times. It is widely used in industrial organizations and many success stories have been described in the literature. In one case, it has been successfully used to perform ergonomics analysis where 640 different activities were analysed for different requirements like body posture, reach, space requirement and viewing an object. Results show that only nine out of four thousand requirements are not found suitable for JACK analysis. These facts show the importance of its use in such typical applications where all analysis was performed according to NASA zero gravity specifications (Sundin et al., 2000a). Moreover, successful use in the evaluation of assembly working positions and sequences was carried out by analysing workload, reach and visual constraints (Sundin et al., 2000b). Figure 2.6 shows the use of the digital human modelling system JACK.

Some other tools like 3D Static Strength Prediction Program (3DSSPP) for manual material handling, Dassault system's SAFEWORK model, and SANTOS for military applications have been mentioned in the literature (Chaffin, 1997; Fortin et al., 1990; Abdel-Malek et al., 2006). Furthermore, Chaffin (2001), Landau (2000), and Duffy (2009) have provided a detailed discussion of digital human modelling basics and its application and effectiveness in product and workplace design assessment (Chaffin, 1997; Landau, 2000; Duffy, 2009)

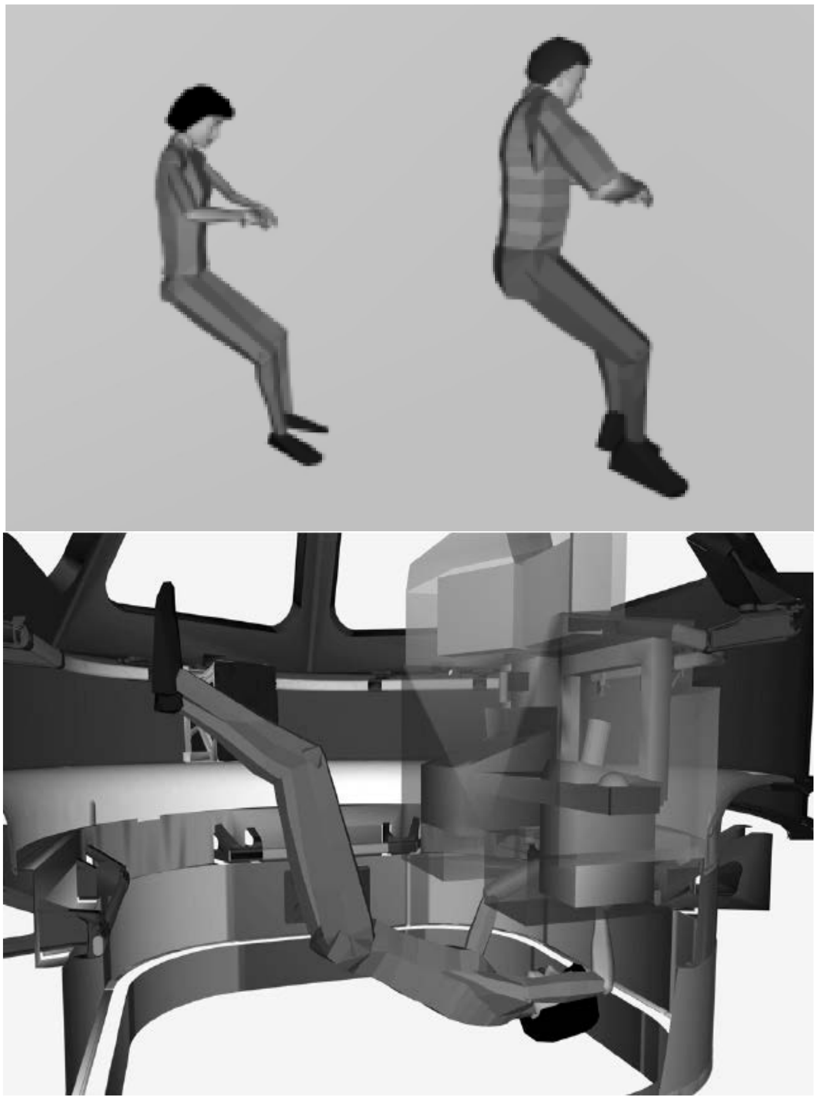


Figure 2.6: Use of digital human modeling systems JACK (Sundin et al., 2000a)

2.3.1. Digital Human Modeling and Workplace Design

Digital human modelling and ergonomics based workplace assessment has been a major research topic and its contribution in terms of workplace design, human well-being, and work satisfaction has been recognized. Manufacturing industry has also benefited from DHM based workplace/workstation evaluations, especially in the designing and planning of human intensive manual activities like assembly activities, manual material handling and heavy weight lifting. Conventional ergonomics analysis of any workplace requires a significant effort for physical mockups for conceptualizing interactions between products, environments and workplaces with real workers. Results show that such practices are time consuming and costly and become challenging in modern manufacturing industries as changing the developed systems costs huge additional expenditure in terms of money and time (Chaffin, 2009; Mavrikios et al., 2007a; Helin et al., 2007; Karmakar et al., 2012).

Published literature highlights the effective use of digital human modelling tools for workplace/workstation design evaluation. Mavrikios et al. (2007b) conducted a posture based ergonomics analysis in a virtual environment to improve working environment of assembly workplace for a commercial refrigerator manufacturing industry. Investigations helped in redesigning actions that result in reduced worker’s fatigue and task completion time. DHM systems use human capabilities data to investigate the acceptability of any design for the population, and anthropometric variations play a key role in addressing reachability concerns at manufacturing workplaces, especially in the designing of production assembly workplaces. It can also be used to make assessments of existing working situations regarding human motion and lifting behaviours where recommendations can be made for people with different stature and the suitability of different alternative workstation geometries can be investigated. These investigations might propose modified workstation design and optimal workplace layouts (Bubb, 2007; Rider et al., 2003). Cimino et al. (2009) and Santos et al. (2007) proposed a methodology for industrial workstation design, supported by a simulation model where different working scenarios can be created and analysed in a 3-D virtual environment along with human models. It was found that these investigations provide an opportunity to create a broad range of workplace scenarios and ergonomics analysis of these scenarios considerably reduces idle time.

DHM tools have also been successfully used in the automobile industry. Peacock et al. (2001) at the General Motors Corporation observed that sheet metal handling is a complex process because of the demanding spatial characteristics of workplace and physical parameters of tasks that need to be optimized. In this case study, a sheet metal handling process was investigated by using digital human modelling tools for achieving a safe and collision free environment between people, equipment and parts. These investigations helped in conducting sophisticated ergonomics analysis that finally helped in making policy decisions. Similarly, a participatory ergonomics approach in collaboration with DHM has been used for carrying out ergonomics analysis of assembly activities in the automotive industry. Analysis resulted in design changes, which decreased assembly times, work related physical stress and rework that finally facilitated an increase in productivity and quality (Sundin et al., 2004). It was further argued by Demirel and Duffy (2007) that DHM contributes in terms of cost savings by integrating manufacturing, design, management, training and marketing departments with product life cycle management software. Lämkull et al. (2009b) reported the reasons why DHM tools are frequently used in automotive manufacturing industry, and argued that there is a strong relationship between ergonomics and manufacturing quality, time to market, workplace safety and musculoskeletal disorders; where these aspects have direct implications for organizational productivity. These tools are frequently used to predict harmful working postures and ergonomic stresses for manual assembly tasks (Lämkull et al., 2009a). It was revealed in a review regarding the use of digital human modelling and simulation tools for industrial workplace design that the majority of the case studies conducted have ergonomics objectives followed by workplace safety and operational requirements. Most of the time such investigations result in layout re-arrangement, changes in hazardous movements and organizational changes (Longo and Monteil, 2011). On the other hand, an ergonomically deficient workplace can cause serious issues with the workforce like physical and mental stress, low productivity, less job satisfaction and poor quality of work. Neglect of ergonomics fundamentals is also the main cause of high turnover, sick leave and work injuries. These issues can be due to lack of ergonomics knowledge, training in ergonomics and resources (Lämkull et al., 2009a; Shikdar et al., 2002; Ayoub, 1990)

Barnes (1980) emphasized that mass production of many standardized products is considered highly acceptable as this form of manufacturing is found to be cost effective. Effort is made to standardize the working procedures where the overall task is divided into smaller task elements and workers are trained to achieve their optimum. Workers with their existing differences in anthropometry, age, shape, experience, and capabilities, repeat these standard tasks thousands of times a day and this may result in a number of problems like musculoskeletal disorders, repetitive motion syndromes and cumulative trauma disorders (Ostrom, 1993). These issues can be addressed by integrating ergonomics considerations into the planning process which is often not the case in reality. Therefore, there is a need to change organizational perceptions about these issues and the people with ergonomics knowledge should be brought into the production planning process (Jensen, 2002). It is very clear that the goal of achieving human-centred design of products, processes and environments can only be achieved by focusing and eliminating mismatches between human capabilities and task requirements, where special consideration should be given to physical constraints (Mavrikios et al., 2007b; Longo and Monteil, 2011).

There is a need to consider the knowledge, characteristics, needs, capabilities and limitations of the workers while designing manufacturing systems. More precisely, a human-centred design approach should be promoted where humans are valued and considered the most valuable and critical constituent of the manufacturing system. In this context, productivity, quality, human health and safety, and satisfaction should be considered along with human capabilities and limitations (Shahrokhi and Bernard, 2009; Licht et al., 1989). Hence, DHM based proactive ergonomics assessment of workplaces can bring immense benefits for organizations in terms of improved performance, reduced design and manufacturing costs, greater job satisfaction and improved productivity. In future, such tools and techniques will be moving into the mainstream design process and bring about a standard ergonomic evaluation methodology (Gabriel, 2003; Chaffin, 2009; Chaffin, 2005; Chaffin et al., 2001; Hanson et al., 2006).

As discussed in section 2.2, the global workforce is becoming more diverse where the proportion of older workers is significantly increasing in coming years. Organizations will be facing the challenge of the accommodation and retention of older workers. This trend will bring many challenges and opportunities for the organizations and demand the effective utilization of this valuable resource. As discussed in this section, DHM based proactive ergonomics assessment can potentially highlight the work related issues faced by the workers. However, no literature exists about the use of this technique for addressing the design needs of older workers at workplaces. HADRIAN (Human Anthropometric Data Requirements Investigation and Analysis) is the only available human modelling based ergonomics assessment tool that works with SAMMIE and addresses the needs of a broad range of the population that includes background, capabilities, and task performing strategies data for the younger, older and disabled (wheelchair users, arthritis patients) which is effectively exploited during the design process. However, HADRIAN's automated task evaluation strategy has only been used for addressing the design needs of older and disabled people for daily living activities like kitchen activities, transport activities, use of ATMs etc. (Marshall et al., 2010; Marshall et al., 2002).

The above literature review concludes the following:

- Ergonomics can significantly contribute to improving occupational health and economic benefits for organizations;
- Digital human modeling based proactive ergonomics design investigations effectively address human-related design issues at manufacturing workplaces;
- This strategy brings immense benefits for organizations by providing a healthy, safe and productive work environment, which leads to an increase in overall productivity of manufacturing system;
- This strategy has not been used to address the design needs of older workers at manufacturing workplaces.

2.4. Inclusive Design

"Design is the process of converting an idea or market need into the detailed information from which a product or system can be made" (Royal Academy of Engineering, 2005)

The British Standards Institute (2005) defined inclusive design as "The design of ***mainstream*** products and/or services that are accessible to, and ***usable*** by, ***as many people*** as reasonably possible ... without the need for special adaptation or specialised design". Later on, the inclusive design term was also referred to providing quality of life and independent living for the ageing population (Waller and Clarkson, 2009).

The terms *inclusive design, universal design, design for all, barrier-free design and accessible design* have been promoted in different parts of the world. For example, universal design was firstly introduced in the United States by Ronald L. Mace in 1985 and referred to as a design approach that could be utilized by a wide range of users. It is also used very frequently in Japan. *Inclusive design* and *design for all* are very popular terms in the United Kingdom and most parts of northern and central Europe (Ostroff, 2011). It is interesting to note that momentum towards these terms has been fuelled because of the social as well as economic interests. For example, in Japan, this thinking was emerged in response to its ageing demographics where both government and business started looking for opportunities and challenges caused by these trends (Kose, 2001). Later on, in 2002, an International Conference on Universal Design was held at Yokohama, where the International Association of Universal Design (IAUD) was formed – as a business oriented organization. Similarly, the United Kingdom has been considered an innovative place regarding providing new design solutions for an ageing population, such as developing the DesignAge programme at the Royal College of Art (RCA) in London (Coleman, 2011). Clarkson et al. (2003) found that the inclusive design method has been found as a successful business strategy and design practice in the United Kingdom . Moreover, introduction of legislation requiring companies to consider older and disabled people in mainstream design, for example the Disability Discrimination Act in the UK and the Americans with Disabilities Act in the USA have played a vital role in promoting the level of awareness and importance of inclusive design

(Disability Discrimination Act, 1995; Americans with Disabilities Act, 1990). Therefore, it can be said that the promotion of inclusive design can give both financial as well as legislative incentives.

The Commission of Architecture and the Built Environment (CABE, 2008) developed the following five key principles of inclusive design:

- People – Place people at the heart of the design process.
- Diversity – Acknowledge diversity and difference.
- Choice – Offer choices where a single design solution cannot accommodate all users.
- Flexibility – Provide for flexibility in use.
- Convenience – Design buildings and environments that are convenient and enjoyable to use for everyone.

The challenge of inclusivity is this that it is impossible to design products, processes or environments that fit everyone every time. Therefore, inclusive design is all about the acceptability or appropriateness of any design for the individual (Vanderheiden, 2009). The real challenge of inclusive design is what to include and what to exclude so that a design can match with individual's needs. There are many case studies mentioned in the literature, showing how an inclusive design method can be used for designing products and environments. These studies include the use of inclusive design in product, residential, office, healthcare and transport design. where it is concluded that inclusive design not only makes life easier and comfortable, it also creates a considerable business value and achieves market advantage as well, when its managed effectively (Eames, 2012; Saffo, 2012; Maddox, 2012; Lin, 2012; Saarinen, 2012; Gehry, 2012; Dong et al., 2007; Coleman et al., 2007, Clarkson et al., 2007b).

Despite the need to consider older people in the design process, designers still have difficulties in doing so. Inclusive design implementation becomes challenging due to the lack of relevant data and appropriate tools that can help them in designing products, processes and environments. There have been studies conducted in different parts of the world that identify some of the drivers and barriers of inclusive design. Vanderheiden and Tobias (2000) conducted telephone interviews of 26 consumer product manufacturers and identified a range of barriers and motives like government regulation, market data, training, consumer demands, technical complexity and unavailability of highly relevant knowledge, data and techniques. A similar kind of survey was conducted in Japan where 307 companies from different industrial categories were selected for the survey. Interestingly, Japanese companies also identify similar kind of results as US companies (Unpublished report, 2000).

In the UK, Keates et al. (2000) found that few industries knew about inclusive design and that there was a misconception about the fundamental understanding of this design method. Companies believed that universal design meant designing only for older and disabled people. In another survey conducted by Sims (2003) at Loughborough University, 32 design professionals working with different types and sizes of companies, were surveyed and it was concluded that 'design for all' is widely known but unfortunately not practised within the design community. The majority of designers were aware of the philosophy of 'design for all' but rarely considered the approach because of the perceived time and financial costs. Underwood and Metz (2003), and Bellerby and Davis (2003) also discussed how inclusive design methods can be promoted and design related issues could be addressed. They suggested that the provision of guidelines and standards could be important drivers, as currently these are not presented appropriately. Moreover, legislation and brand imaging can also play an effective role as generic business drivers. Later on, Dong et al. (2004a and 2004b) conducted a more comprehensive study with SMEs, where a survey was carried out with 38 manufacturing and retailer companies, along with 35 design consultancies. It was concluded that different companies perceive different factors as major barriers. However, drivers within these groups were found to be the same. For example, manufacturers and retailers mentioned key barriers because of the assumptions that inclusive design is more expensive, difficult to practice and learn and time consuming. In 2006, Goodman et al. (2006a) unlike Dong et al. (2004a, 2004b), targeted large organizations along with SMEs and used a survey method for getting a more detailed insight about the drivers and barriers for inclusive design and used the same questionnaire for comparison purposes. Complete responses were collected from 101 UK companies and organizations and a detailed analysis was carried out. Barriers most frequently identified were a lack of time and budget for supporting inclusive design, lack of knowledge and tools to practice it, and not perceived as the need of the end users. Moreover, the perception that there is no justifiable business case for inclusive design was considered extremely important by most of the respondents; whereas, it was not the most common identified barrier.

In the light of the above discussion, it’s very clear that if significant progress is to be made in the promotion of inclusive design, it is very necessary to address these barriers in a more logical and realistic way, especially through the provision of highly relevant knowledge and tools so that designers can bring the knowledge into practice. Previously, based on this understanding of design practice, some efforts had been made to develop knowledge about these issues and using it in providing tools to support and encourage inclusive design. In the UK, the inclusive design research group at the Cambridge Engineering Design Centre has developed some inclusive design materials, methods and tools to support the designer’s community. The tools and materials are:

- Inclusive design toolkit
- Impairment simulation
- Exclusion audit (Figure 2.7)
- Database for user methods

All these facilitate designers and common users to understand the importance of inclusive design and how easily variations in human capabilities can be addressed by simple modifications. Further details can be found in Cardoso and Clarkson (2006), Waller et al. (2008), Goodman et al. (2008, 2007, 2006a, 2006b, 2006c) and Clarkson et al. (2007).

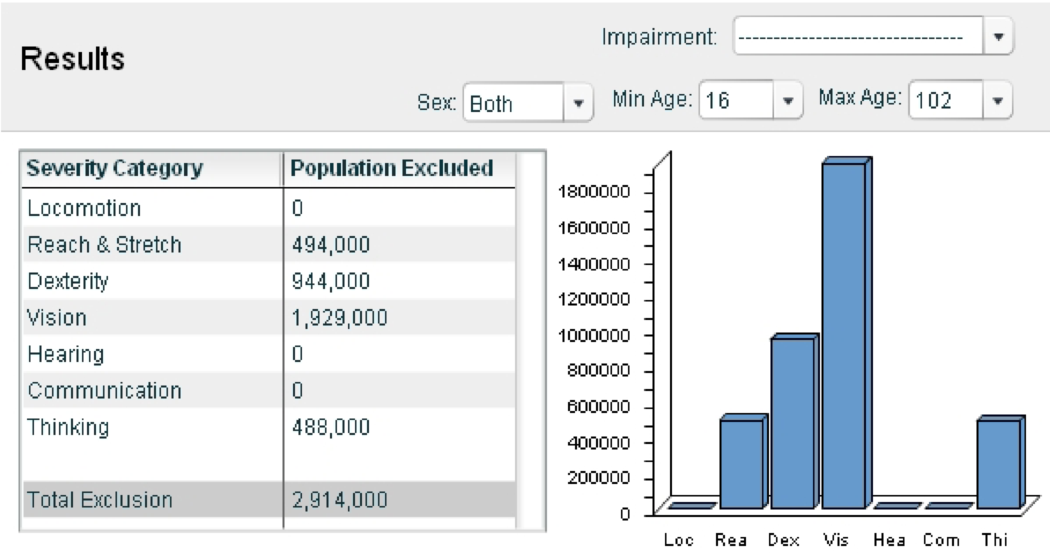


Figure 2.7: Screenshot from the exclusion calculator, showing the estimates of the total design exclusion based on various capabilities (Goodman et al., 2008)

Another inclusive design approach was supported by funding from the Engineering and Physical Sciences Research Council's (EPSRC) initiative called 'Extending QUAlity Life' (EQUAL), this initiative was designed to promote inclusive design or design for all research that could result in achieving a better quality of life for older and disabled people. Previously, a survey of 50 designers had been carried out, where the aim was to identify the situation and how the needs of older and disabled people are accounted in the design process (Gyi et al., 2000). The results clearly highlighted the issues of the unavailability of relevant data that could be easily used by the designers to make more informed and realistic design decisions. Moreover, most of the designers used computer-aided design packages where ergonomics data would be of great importance if this were presented in a format or language that could be understood and related a design process easily. Understanding these needs, efforts were made to provide ergonomic data and integrate this data with an existing computer-based design tool 'System for Aiding Man Machine Interaction Evaluation' SAMMIE (figure 2.8) (Porter et al., 2004; SAMMIE CAD, 2012). It has already been discussed in section 2.3 that digital human modelling based computer-aided

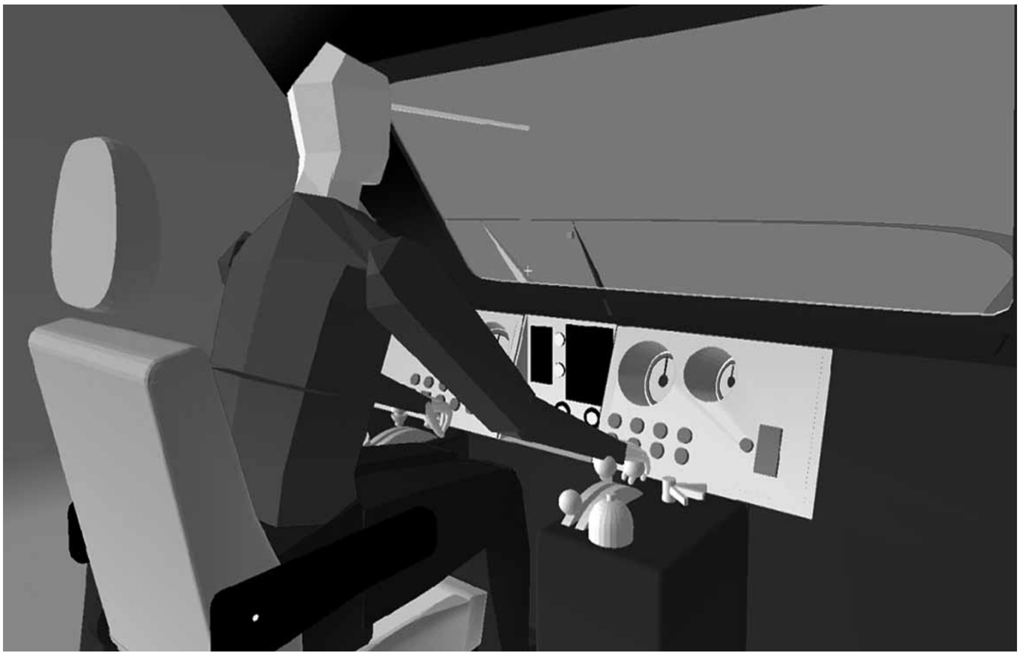


Figure 2.8: SAMMIE human modelling system used in the evaluation of train cab design (Marshall et al., 2010)

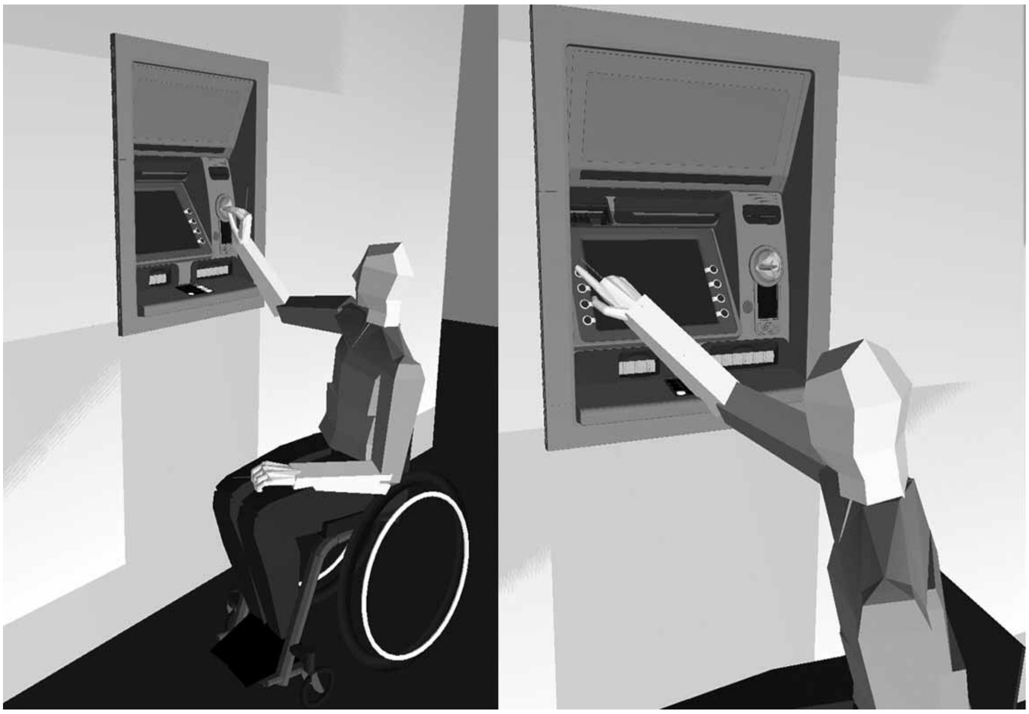


Figure 2.9: Validation of an ATM case study, performed in the SAMMIE system with HADRIAN data (Marshall et al., 2010)

ergonomics tools have been successfully used for the risk assessment of product, service and environments.

Capturing task performing strategies and behaviours and utilizing the captured data along with other human capabilities data for assessing the inclusiveness of any proposed design is a unique feature of HADRIAN task analysis system. The HADRIAN task analysis system has been designed to evaluate a product's interaction with the human and the acceptability of a proposed design is made by utilizing a variety of human capability data including younger, older, wheelchair users and arthritis patients. Further details about the development and implementation of this tool can be studied in Marshall et al. (2010, 2009, 2004, 2002), Porter et al. (2004), Gyi et al. (2000, 2004), Sims (2003), Summerskill et al. (2009, 2010) and Case et al. (2009, 2001). This literature indicates the successful utilization of the HADRIAN inclusive design tool against a variety of applications like the use of ATMs, transport facilities and activities of daily living (ADL) such as kitchen activities. (figure 2.8 and 2.9) where its task analysis system provides an opportunity to evaluate the inclusiveness of a product, process or environment at a pre-design phase (further detail will be provided in chapter 4).

The above literature review concludes the following:

- The inclusive design approach has been used for providing new design solutions for a broad range of the population, including older and disabled people;
- There is a need to address the barriers to inclusive design like the lack of knowledge and tools, lack of justifiable business case and the perception that inclusive design is not an end user need;
- Considerable efforts have been made to provide more appropriate and highly relevant data and tools for the promotion of an inclusive design strategy into the main design process. However, still there is a need to develop better tools and applicable methodologies that can put inclusive design into practice;
- There is a need to introduce the inclusive design method for the development of an industrial working environment where older workers design needs could be addressed in a more logical way.

2.5. Conclusion

The global workforce is becoming more diverse where the proportion of the older workers is significantly increasing in almost all parts of the world. Workforce diversity management, especially the accommodation and retention of older workers, brings many opportunities and challenges for future organizations. There is a need to provide an adequate response to these challenges, so that organizations can sustain their experienced and skilled workforce. Computer-aided ergonomics workplace assessments tools have been successfully used to address the issues that directly affect human well-being, workplace safety and organizational productivity. However, these tools have not been used to address the design needs of older workers at workplaces; especially manufacturing assembly activities because of the high level of physical demands. Older workers are significantly different from younger workers, in terms of their physical, physiological, and cognitive capabilities and these capabilities directly or indirectly affect human work performance. The inclusive design method is a useful strategy that successfully addresses the design needs of a broad range of population. However, still there is a great need to address barriers like the lack of knowledge and tools by providing highly relevant and useful human capabilities related data, along with appropriate inclusive design tools and methodologies, so that the upcoming workforce demographic challenges might be addressed.

The reviewed literature clearly highlights the need of understanding work related issues faced by older workers. Computer-aided ergonomics based tools have successfully been used to address the design needs at an earlier design stage but there is no such method or technique seen in the reviewed literature, that has been developed and used to address human variability challenges, especially issues faced by older workers. The analysis of the reviewed literature, clearly found the need of a new method that can be used to understand and address the issues caused due to human variability that is mainly due to the changes occurring due to age, skill, experience and background.

Chapter 3

Research Focus and Design

3.1. Introduction

This chapter focuses on the development and description of a research method that can address the global workforce challenges in terms of accommodating and retaining older workers along with other human variability issues caused due to varying levels of skill, experience and background, so that people with their existing differences can coexist productively and safely.

3.2. Research Method

The research method proposed in this research is a novel three step approach (figure 3.1) that promotes the utilization of an inclusive design strategy for addressing the needs of a diverse workforce. The aim of this newly developed approach is to design working systems or workplaces that are equally acceptable, healthy, safe and productive for a broad range of the population, and this is challenging because of the differences in age, experience, capabilities, working strategies and behaviours.

The three steps are:

1. Capture of human working capabilities;
2. Capture of task performing strategies;
3. Verification of design inclusiveness by the use of appropriate tools and methods.

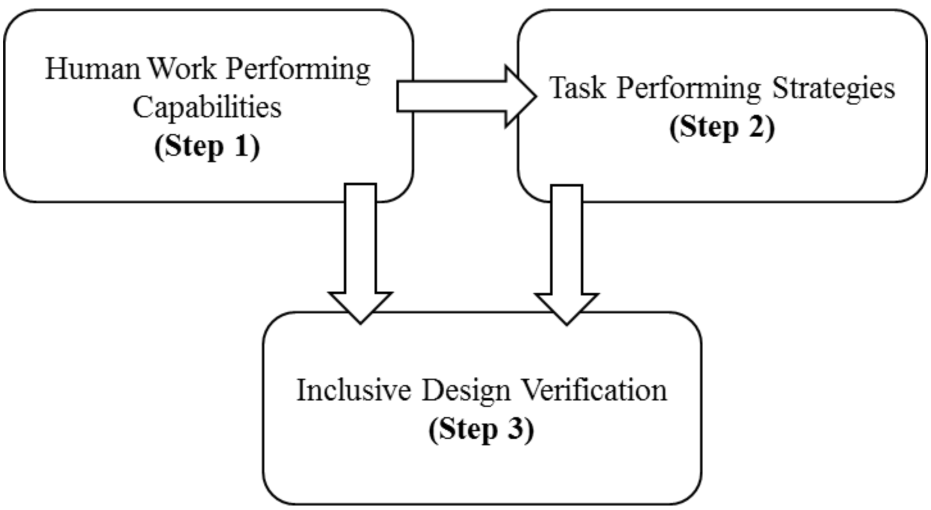


Figure 3.1: Inclusive Design Method for Workplace Design

This new three step method developed in this research is thought to be extremely useful in achieving the aim of “supporting the ‘inclusive design’ process by the provision of relevant data and new application methodologies”. The usefulness of this approach has been validated by a case study at a furniture manufacturing industry.

3.2.1. Step 1 Capturing human work performing capabilities

This step is highly important, as it is very simple to understand that a successful interaction between human and product, process, service or environment is mainly based on a good match between human capabilities and task requirements. It is equally significant to note which task needs dominate human capability. For example, manual material handling activities require physical capabilities for their completion. However, using new technology to remove or reduce the physical requirements might generate a need for new cognitive capabilities to learn and use the system. As mentioned earlier, this research focuses on manufacturing assembly activities that are highly physical capability intensive, so it is natural to focus on physical capabilities. Furthermore, simply knowing about the capabilities might not be sufficient for the promotion of the inclusive design strategy. It is also extremely important to conceptualize and evaluate human capabilities differences among the human caused by differences in age, skill and experience.

3.2.2. Step 2 Capturing task performing strategies

This stage focuses on capturing task performing strategies of a broad range of the population for a variety of tasks being carried out in industry. This provides an opportunity to understand the relationship between human variations and the impact on the adopted work strategies. Furthermore, risk assessment of these strategies on the basis of fundamental ergonomic principles highlights key areas of concern attached to them that must be addressed to make them acceptable to a broad range of the population. Working strategies can be captured through video recording of different workers accomplishing similar kinds of activities, so that the effects of age, experience, skill and background. can be observed. Moreover, ergonomics based risk assessment will provide an option to assess different working strategies in terms of human well-being and workplace safety and their comparison will clearly highlight the strengths and weaknesses attached of each.

3.2.3. Step 3 Verifying design inclusiveness by using appropriate tools and methods

Finally, this step focuses on the effective utilization of the data gathered in steps 1 and 2 for assessing the design inclusiveness of any adopted strategy by using appropriate tools and techniques. A digital human modelling based inclusive design strategy is suggested for this research where human capabilities data along with working strategies and behaviours, are used for task assessment purposes. Human capability data like joint mobility data of a broad range of the population can be used in determining the number of workers where working capability is affected by differences in joint mobility. For this research, joint mobility data of older and younger workers is used to define a sample of virtual workers with varying working capability in a virtual environment and can be used to assess the level of acceptability of any working strategy captured at stage 2. In this way, the activities or working strategies that are more acceptable and appropriate for a broad range of the population can be promoted.

3.3 Use of the three-step approach

Figure 3.2 describes how this research method is implemented and how the three step approach is used to achieve the aim and objectives of this research. Chapters 4 and 5 are about capturing human capabilities, which is step 1 of the above method research method. Chapter 4 is concerned with re-analysing the National Disability Follow-up Survey (DFS) (1995/1996) data in relation to the HADRIAN database. The chapter debates how human capabilities are linked with the level or severity of disability and establishes the relationship between the disability survey data and the HADRIAN database of 100 subjects. The HADRIAN database also uses the same severity criterion as used in the disability survey, for defining the level or severity of disability and relating it to task performing capabilities. Furthermore, the HADRIAN database also contains some more specific human capabilities data that directly affects human work performance, for example joint mobility, anthropometry and task behaviours. In this way, the analysis of this captured data clearly identifies the need for the understanding of human variability issues. More specifically, chapter 5 discusses joint mobility data of older and younger people, along with people with particular disabilities such as wheelchair users and arthritis patients. Qualitative data has been analysed statistically to explore the level of significance of variations in joint mobility due to age, gender and level and type of disability. Analysis of the data reveals the importance of understanding the differences in human capabilities and how this complicates the inclusive design process.

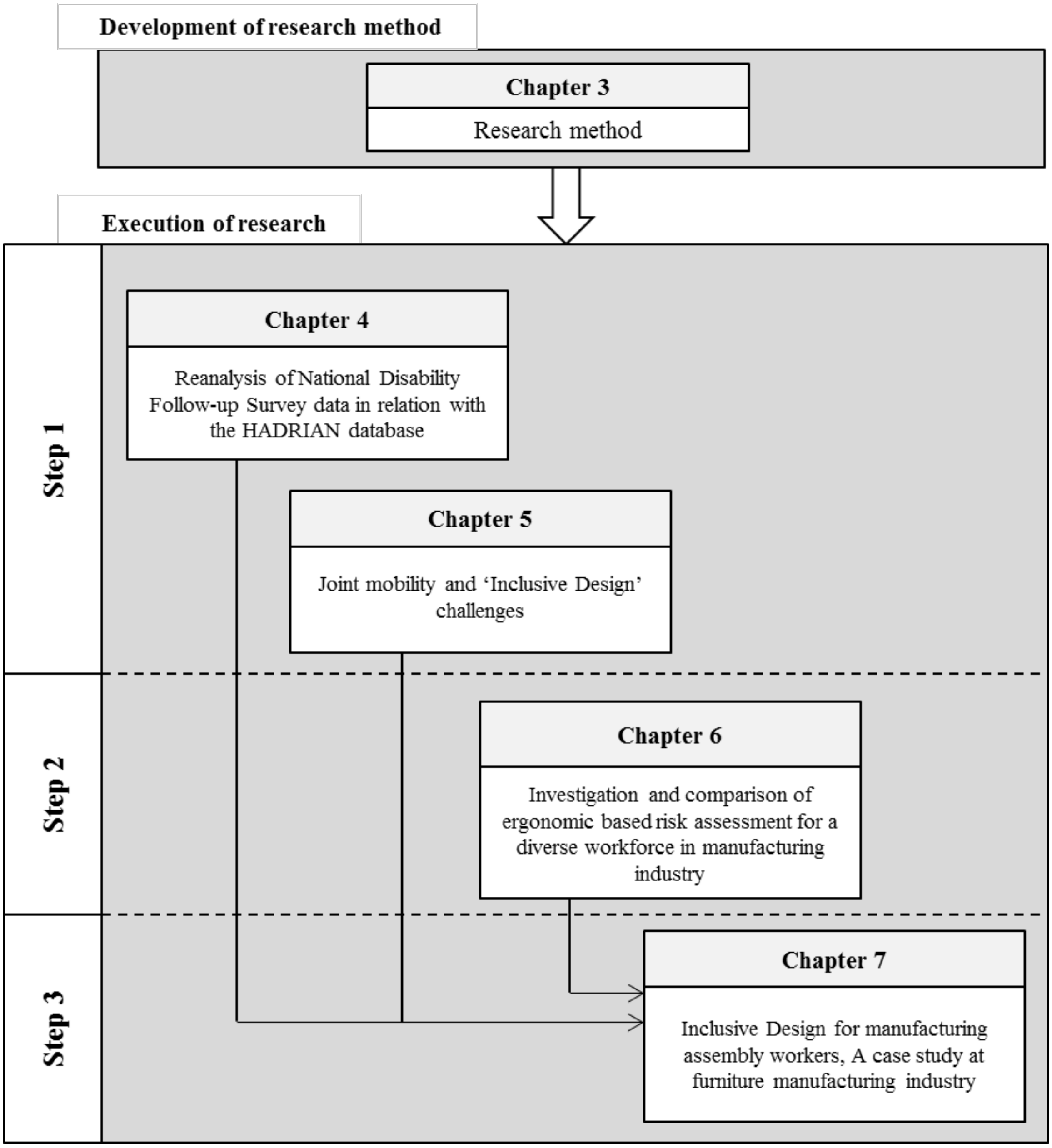


Figure 3.2: The research method

Chapter 6 describes how differences in adopted working strategies contribute to work productivity and especially how these variations are linked with the risk of musculoskeletal disorders, injuries and pain. To gain this understanding, it is extremely important to capture (video record) the working strategies of different workers for similar kinds of tasks, so that the differences can be understood and conceptualized. Age, skill, experience and background might play major roles in the adoption of any particular strategy. However, this research mainly focuses on the effects of skill and experience, in terms of adopting healthy, safe and productive working strategies. A case study method has been used for this purpose, where video recordings of different workers with varying level of skills have been made for similar kinds of manual assembly tasks at a furniture manufacturing company. Execution of this case study meets the needs of step 2 in the research method.

Chapter 7 describes how step 3 utilises the data captured at step 1 and 2, for assessing the inclusiveness of any design by using some appropriate methods and tools. For this research, a digital human modelling inclusive design strategy based on HADRIAN has been used to validate the concept. For validation purposes, a case study method has been used, where a number of working scenarios of different workers performing the same activity, along with the joint mobility data of the older and younger workers have been used to assess the level of acceptability of the adopted strategy for older and younger workers because of differences in their joint mobility capabilities. Further details will be discussed in chapters 4 to 7.

Next chapter (chapter 4) focuses on the fundamental concept of inclusive design and explains how the data collected in the Disability Follow-up Survey conducted by the Office of National Statistics (ONS) 1996/1997 can be used in the design process. Furthermore, how the HADRIAN database can be used to generate design recommendations for millions of the UK population

Chapter 4

Re-analysis of National Disability Follow-up Survey (DFS) data in relation to the HADRIAN database

4.1. Introduction

Like 'inclusive design', design exclusion is a process of evaluating different products, services, tools, equipment and working systems on the basis of potential users' capabilities. It provides guidelines for product design improvements, so that a maximum number of people can use the product. This chapter explains the importance of the concept of design exclusion and how it relates to the inclusive design process. The Office of National Statistics (ONS) conducted a 1996/1997 disability follow-up survey that was aimed at collecting information on the extent of disability in UK population and the characteristics of those with disabilities. Government and many other agencies were planning to provide appropriate support to people with disabilities, as disability substantially affects working capabilities and quality of life. This chapter explains how disability follow-up survey (DFS) data explains different levels of disability severity and the use of this data in a simple design exclusion process. It also explains how the severity scores determined in the DFS relate to the HADRIAN database. Similarities between the HADRIAN and DFS severity assessment criteria enable an estimation of the acceptability of different design scenarios for the entire UK population. The HADRIAN database consists of 102 people from different age groups, genders and with different levels of disabilities like wheelchair users and arthritis patients. It is shown that the HADRIAN database represents the wider UK population on the basis of the similarities in working capabilities, and can be used for the estimation of 'design exclusion' where its human modelling based task evaluation capabilities enhance its effectiveness. Designers can take benefit from the method, as it provides sufficient information about the individuals designed out and why they are unable to accomplish tasks successfully. Moreover, the use of an individual's actual capability data during task assessment differentiates the method from the available conventional human modelling tools.

The rest of the chapter is arranged in eight sections. The concept of design exclusion and its importance is explained in section 4.2. Section 4.3 explains the objective of the disability follow-up survey (DFS), whereas the correlation between the severity scales for the areas of disability used in disability survey and HADRIAN database is discussed in section 4.4. Section 4.5 briefly describes the HADRIAN database and section 4.6 shows how the disability follow-up survey is used for population estimation. Section 4.7 argues that how the HADRIAN database correlates with DFS on the basis of their similarities in the severity scales. Section 4.8 illustrates a step-by-step explanation of the HADRIAN inclusive design analysis system. Discussion and conclusions are included in section 4.9.

4.2. The concept of design exclusion and its importance

The concept of inclusive design or design for all is commonly accepted as a good design aim. The usefulness of the concept of design exclusion is that it identifies why and how people are unable to use any particular product, service or environment. Availability of the information about how and why people are excluded provides an opportunity for designers to counter this exclusion, as knowledge of the reason for any design exclusion gives a chance to address the problem during the design process.

It can be seen from figure 4.1 that the inclusive design cube (IDC) not only shows how many are included but also how many are excluded. Moreover, knowing who and how many are excluded highlights the necessary aspects of design improvements. Precise description of the reasons for design exclusion clearly motivates designers and provides them with possible ways to improve a design, so that the acceptability range of any design can be expanded (Keates and Clarkson, 2003).

Note: Designing for the whole population falls into three main categories as shown in figure 4.1

- User-aware design: pushing the boundaries of ‘mainstream’ products to include as many people as possible;
- Customisable/modular design: design to minimise the difficulties of adaptation to particular users;
- Special purpose design: design for specific users with very particular needs

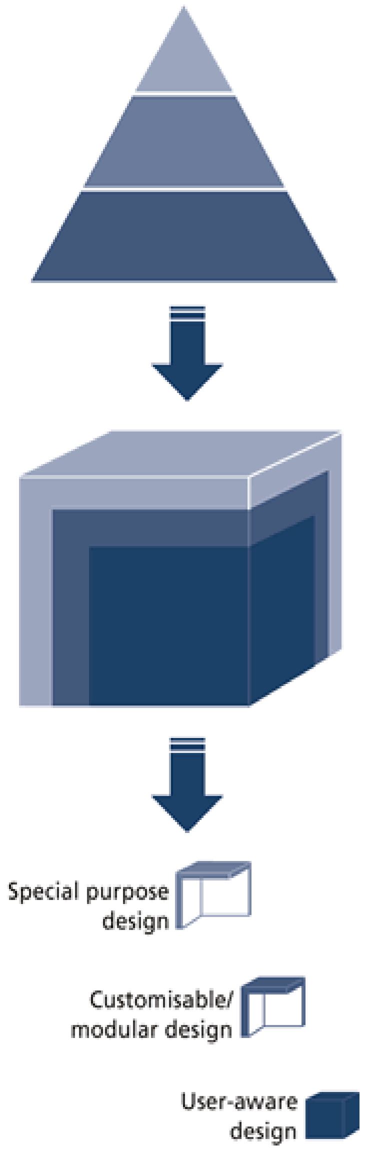


Figure 4.1: Using the inclusive design cube (IDC) to represent design exclusion (Keates and Clarkson, 2004)

The fundamental principle of design exclusion is the identification of capability demands imposed on the user by any design feature of a product during its use. In the first instance, it is possible to establish who cannot use the product and what is the particular capability demand making it difficult to use. As a result, designers can focus on that particular capability demand, where efforts can be made to change that design feature in such a way that a broad range of users can use it comfortably. Keeping in view the above discussion, it can be said the effort of countering design exclusion is very much the same as the promotion of an inclusive design strategy, as both aim for the accommodation of a broad range of the population. However, highlighting possible causes of any design exclusion additionally provides the basis for prioritizing particular design features that need to be focused on during an early design or re-design process. Finally, it is essential to access the design features of any product, system or environment design and establish the capability demands set for a user.

The next section describes how the Disability Follow-up Survey (DFS) describes population capability data and how it can be related to the HADRIAN database of 100 people belonging to different age groups, genders and levels of disability. Most interestingly, re-analysis of the HADRIAN and DFS data shows how the HADRIAN database can be used to estimate design exclusion for the wider UK population.

4.3. The Disability Follow-up Survey

The office of National Statistics (ONS) conducted a Disability Follow-up Survey (DFS) in 1996/1997. This survey was aimed at collecting information about the prevalence of disability in Great Britain and characteristics of those who were disabled so that better welfare support might be provided (Grundy et al., 1999).

The World Health Organization's (WHO) International Classification of Impairments, Disabilities and Handicaps (ICIDH) defines disability as "any restriction or lack (resulting from an impairment) of ability to perform an activity in the manner or within the range considered normal for a human being". Impairment was further defined as "any loss or abnormality of psychological, physiological or anatomical structure or function". Handicap is linked with a disadvantage for a given individual, resulting from an impairment or disability that limits or prevents the fulfilment of role (depending on age, sex and social and cultural factors) for the individual (WHO, 1980). For example, if a person has a particular impairment like diabetes, they cannot be considered as disabled if there is no effect of this impairment on their ability to perform normal activities. However, if this particular impairment (disease) results in problems like poor vision, then they will be considered as a disabled person. If any disability causes a disadvantage in life roles, then the person will be considered as handicapped. Later on, it was debated that ICIDH just provides information about the diagnosis of diseases, disorders and injuries, and is unable to cover the consequences and effects that these have on functioning. It was criticised that it should not be a classification of people with disabilities but a description of functioning capabilities across the whole population. Then ICIDH-2 was evolved where the functioning was classified for three levels – Impairment, Activity, and Participation, where a linear causal relationship between impairment, disability and handicap was replaced with a multifactorial understanding of the interactions between characteristics of individual and their environment. In 2001, the International Classification of Functioning, Disability and Health (ICF) further advanced this understanding by focusing on environmental factors that cause disability. Now, ICF is considered as universal as it covers all human functioning and takes disability as a continuum rather than categorizing people with disabilities as a separate group. In the ICF, problems with human functioning are categorized into three interconnected areas:

- Impairments – problems in body function or alternation in body structure - for example, paralysis, blindness etc.
- Activity Limitations – difficulties in executing activities - for example, walking, eating etc.
- Participation Restrictions – problem with involvement in any area of life - for example, facing discrimination in employment or transportation etc.

Some personal factors like motivation and self-esteem can also influence one's participation in the society. However, these factors are not yet conceptualized (World Report on Disability by World Health Organization (WHO), 2011)

The DFS survey was established to understand and measure the ability to perform certain tasks that were divided into many ability categories. As a first step, individuals were selected on the basis of certain criteria such as 'receipt of incapacity benefits' and age greater than 16 years. To measure the level of disability, about three hundred questions were asked covering a variety of ability categories. These questions were mainly about self-assessment of the ability to perform certain tasks, such as

Cannot walk at all

Can only walk up and down a flight of stairs if goes sideways or one step at a time

Cannot see well enough to recognise a friend across a room

Cannot see well enough to recognise a friend across a road

During this survey approximately 7200 participants were asked such questions. Some of the ability categories were locomotion, reaching and stretching, dexterity, personal care, seeing, hearing and communication. Approximately, 100 judges ranked the severity of specific limitations within each area of disability on a ten point scale. These judges included a variety of professional people so that an overall consensus on the disability scale might be achieved (Martin and Elliot, 1992). These scales were arranged in a way such that the higher the value of severity score, the greater is the severity of a particular disability. For example, a person with a reaching and stretching severity score of 9.5 (RS1- Reach and stretch severity level 1) has a more severe disability as compared with a person with a 5.5(RS6) severity score. In this way, data was used to measure the level of disability and estimate disability prevalence in the overall UK population at that time.

4.4. The Severity Scales for the areas of disability in the disability survey and the HADRIAN database

The severity of a disability is defined as the extent to which an individual's performance of activities is limited by impairments (Martin et al., 1988). During the disability follow-up survey, there were ten main areas of disability used to develop disability scores for individuals. These areas of disability were:

Locomotion

Reaching and Stretching

Dexterity

Seeing

Hearing

Personal care

Continence

Communication

Behaviour

Intellectual functioning

After developing scales for these categories, there was a need to assess the overall impact of these impairments on an individual's ability/disability. The overall severity scale was constructed according to the formula:

Worst + 0.4 (second worst) + 0.3 (third worst)

The above formula was applied to everyone in the survey to calculate an overall severity score for each person. Finally, these overall severity scores were grouped into ten severity categories; their levels and ranges are shown in the table 4.1.

Table 4.1: showing levels of severity in accordance with overall severity scores (Gundy et al., 1999; Martin et al., 1988)

Severity category	**Overall severity score**
10 (most severe)	19 or higher
9	17-18.95
8	15-16.95
7	13-14.95
6	11-12.95
5	9-10.95
4	7-8.95
3	5-6.95
2	3-4.95
1 (least severe)	0.5-2.95

In a similar way, during the HADRIAN data collection phase, similar scales were used for the assessment of level and severity of disability and all 100 individuals were placed on a ten-point severity scale. Because of this similarity in severity scales used in the HADRIAN database and the disability follow-up survey, it might be said that the individuals presented in the database, are similar in some specific ability categories with the millions of people represented by the follow-up survey. However, this similarity is simply based on a particular type of ability or disability measured through the same scale.

The common severity scales used for different areas of disability in the disability survey and the HADRIAN database; are presented in tables 4.2 to 4.5.

4.4.1. Locomotion

Table 4.2: Different levels of locomotion ability and respective severity scores (Gundy et al., 1999; Martin et al., 1988)

Level	Question	Severity Score
L1	Cannot walk at all	**11.5**
L2	Can only walk a few steps without stopping or severe discomfort/cannot walk up and down one step	**9.5**
L3	Has fallen 12 or more times in the last year	**7.5**
L4	Always needs to hold on to something to keep balance	**7.0**
L5	Cannot walk up and down a flight of 12 stairs	**6.5**
L6	Cannot walk 50 yards without stopping or severe discomfort	**5.5**
L7	Cannot bend down far enough to tough knees and straighten up again	**4.5**
L8	Cannot bend down and pick something up from the floor and straighten up again	**4.0**
L9	Cannot walk 200 yards without stopping or severe discomfort/Can only walk up and down a flight of 12 stairs if holds on and takes a rest/Often needs to hold on to something to keep balance/Has fallen 3 or more times in the last year	**3.0**
L10	Can only walk up and down a flight of 12 stairs if holds on (doesn't need a rest)	**2.5**

L11	Cannot bend down to sweep up something from the floor and straighten up again	**2.0**
L12	Can only walk up and down a flight of stairs if goes sideways or one step at a time	**1.5**
L13	Cannot walk 400 yards without stopping or severe discomfort	**0.5**

4.4.2. Reaching and Stretching

Table 4.3: Different levels of reaching and stretching ability, and respective severity scores (Gundy et al., 1999; Martin et al., 1988)

Level	Question	Severity Score
RS1	Cannot hold out either arm in front to shake hands	**9.5**
RS2	Cannot put either arms up to head to put a hat on	**9.0**
RS3	Cannot put either hand behind back to put jacket on or tuck shirt in	**8.0**
RS4	Cannot raise either arm above head to reach for something	**7.0**
RS5	Has difficulty holding either arm in front to shake hands with someone	**6.5**
RS6	Has difficulty putting either arm up to head to put a hat on	**5.5**
RS7	Has difficulty putting either hand behind back to put jacket on or tuck shirt in	**4.5**
RS8	Has difficulty raising either arm above head to reach for something	**3.5**
RS9	Cannot hold one arm out in front or up to head (but can with other arm)	**2.5**
RS10	Cannot put one arm behind back to put on jacket or tuck shirt in (but can with other arm)/Has difficulty putting one arm behind back to put jacket on or tuck shirt in, or putting one arm out in front or up to head (but no difficulty with other arm)	**1.0**

4.4.3. Dexterity

Table 4.4: Different levels of dexterity and respective severity scores (Gundy et al., 1999; Martin et al., 1988)

Level	**Question**	**Severity Score**
D1	Cannot pick up and hold a mug of coffee with either hand	**10.5**
D2	Cannot turn a tap or control knobs on a cooker with either hand	**9.5**
D3	Cannot pick up and carry a pint of milk or squeeze the water from a sponge with either hand	**8.0**
D4	Cannot pick up a small object such as safety pin with either hand	**7.0**
D5	Has difficulty picking up and pouring from a full kettle or serving food from a pan using a spoon or ladle	**6.5**
D6	Has difficulty unscrewing the lid of a coffee jar or using a pen or pencil	**5.5**
D7	Cannot pick up and carry a 5lb bag of potatoes with either hand	**4.0**
D8	Has difficulty wringing out light washing or using a pair of scissors	**3.0**
D9	Can pick up and hold a mug of tea or coffee with one hand but not with the other	**2.0**
D10	Can turn a tap or control knob with one hand but not with the other/Can squeeze the water from a sponge with one hand but not the other	**1.5**
D11	Can pick up a small object such as a safety pin with one hand but not with the other/Can pick up and carry a pint of milk with one hand but not the other/Has difficulty tying a bow in laces or strings	**0.5**

4.4.4. Personal Care

Table 4.5: Different levels of personal care ability and respective severity scores (Gundy et al., 1999; Martin et al., 1988)

Level	Question	Severity Score
PC1	Cannot feed self without help/Cannot go to and use the toilet without help	**11.0**
PC2	Cannot get into and out of bed without help/Cannot get into and out of chair without help	**9.5**
PC3	Cannot wash hands and face without help/Cannot dress and undress without help	**7.0**
PC4	Cannot wash all over without help	**4.5**
PC5	Has difficulty feeding self/Has difficulty getting to and using the toilet	**2.5**
PC6	Has difficulty getting in and out of bed/Has difficulty getting in and out of a chair	**1.0**

In the same way, similar scales were used for other areas of disability including continence, hearing, communication, behaviour, intellectual functioning and consciousness. Complete information with different levels of disability for all the above mentioned categories have been published by Martin et al. (1988), but the discussion here is limited to those which HADRIAN and the disability survey have in common.

4.5. The HADRIAN database

As mentioned about the EQUAL initiative in section 2.4, that provided an opportunity to address the challenges faced in the promotion of inclusive design practices along with the need of providing ergonomic related data, it was also initiated that there is an equally important need for integrating this ‘inclusive design’ or ‘design for all’ philosophy into currently existing computer based design tools such as SAMMIE. SAMMIE is a computer-aided human modelling system that can be used to explore ergonomics related issues in a CAD environment, where issues like fit, reach, posture and vision can be investigated at early design stages. In this way, designers can suggest design recommendations for any product, system, service or environment design, so that it can be made equally acceptable for a large proportion of the population. To assist in this, an inclusive design tool HADRIAN (Human Anthropometric Data Requirement and Analysis) was developed. The tool contains a novel database of individuals with data on anthropometry, joint constraints, capabilities and behaviours for each individual. It provides relevant, accessible and holistic information about the population of about 100 people that covers a broad range of size, shape, and ability to do a number of specific tasks. More importantly, it provides the practical means of using this data to assess the inclusiveness of a proposed design (Marshall et al., 2010). The sample consists of people ranging from 18 to 89 years old, where 46 people are over 60. A deliberate effort was made to include more older and disabled people so that the sample can represent a broad range of the population. The database is simply a catalogue of individuals where a complete set of information about individual's capabilities and behaviours is attached. A unique feature of the database is that it presents data in a visual format where the designer can pick an individual from their displayed photograph and perform a task analysis. Specific data on 28 anthropometric body measures, 18 joint mobility values, reach range; manual dexterity and grip strength were captured with some general information on occupation, age, nationality and work history etc. (Gyi et al., 2004). HADRIAN is not only a database of individuals with capabilities data, but also has the task specification and analysis system followed by the percentage exclusion – will be explained later in this chapter. Table 4.6, shows a summary of the individual's data available in the HADRIAN database.

Table 4.6: Summary of data in the HADRIAN database (Marshall et al., 2010)

1. Anthropometry (mm)	**2. Joint constraints (degrees)**	Ingress/egress: step up/step
Stature	Shoulder extension/flexion	down from maximum comfortable
Weight	Shoulder abduction/adduction	step height, two handle types,
Arm length	Upper arm extension/flexion	maximum of four handle locations
Upper arm length	Upper arm abduction/adduction	
Elbow-to-shoulder (link)	Upper arm medial/lateral rotation	**7. Additional capability**
Wrist-to-elbow (link)	Elbow extension/flexion	Bending to touch toes
Abdominal depth (standing)	Elbow pronation/supination	Getting up from lying down
Abdominal depth (sitting)	Wrist extension/flexion	Reaching to tie shoelaces
Thigh depth (standing)	Wrist abduction/adduction	Twisting upper body to left and
Thigh depth (sitting)		right
Knee-to-hip (link)	**3. Reach range (~100**	Peg test (dexterity)
Ankle-to-knee (link)	**coordinates millimetre)**	Grip strength
Ankle height	Functional reach volume	Vision
Foot length	generated by dominant arm/hand	
Sitting height		**8. Transport questionnaire**
Sitting shoulder height	**4. Somatotype (three digit number)**	**(question and answer**
Hip-to-shoulder (link)		**transcripts and videos)**
Chest height	**5. Whole body scan (VRML file)**	Transport use (frequency, etc.)
Chest depth		Issues with transport usage
Head height	**6. Task capability (encoded**	(problems, assistance required. etc.
Eye-to-top-of-head	**postures for each task plus task**	Issues with lifts, steps, escalators
Buttock–knee length	**videos)**	Issues with environment (personal
Knee height	Four pick and place tasks (high shelf,	Safety, etc.)
Shoulder breadth	work surface, oven, low shelf)	Issues with signage and timetables
Hip breadth	with three load types (cup, bag, tray)	Local issues
Hand length	each set to maximum	
Hand grip	length comfortable weight, one or two hands	**9. Background**
	as appropriate.	Age
Wheelchair length		Nationality
Wheelchair height	Seating: Two designs – high and hard,	Occupation/work history
Wheelchair width	low and soft; restricted access to	Handedness
Wheelchair seat height	single side (bus), both sides	Disability
	(toilet cubicle), no restriction.	Front and side photographs

The HADRIAN database presents an individual's data in the following domains:

Anthropometry

Joint constraints

Reach range

Somatotype

Whole body scan

Task capabilities

Additional capabilities

Transport questionnaire data

Background

Further details of this data are shown in table 4.6. Most of the data presented here, is directly linked with task performing capabilities and is used by the HADRIAN task analysis system. HADRIAN data presentation has two unique features. Firstly, provision of actually applicable and accurate data about a broad range of target users. Secondly, the ability to utilize this data for ergonomics design evaluations at early concept design stage of product, service or environment design, where the task analysis system works in combination with an existing computer-aided human modelling system SAMMIE (Marshall, 2004). Data on task related abilities have been captured for kitchen and transport related activities so that the tool might be equipped with real-world applications. An effort was made to address physical as well as cognitive and emotional issues to support design inclusiveness (Marshall, 2010).

Figure 4.2: Computerized database of individuals with their photographic presentation (Porter, et al., 2004)

The HADRIAN sample covers a broad range of the population as it represents the full range from less than 1st percentile to greater than 99th percentile for most of the anthropometric measurements (Figure 4.2).

In 1984, the Department of Health and Social Security (DHSS) commissioned the Office of Population Censuses and Surveys (OPCS) to carry out a survey of people with disabilities in Great Britain. The survey was required to estimate the number of disabled people in Great Britain according to the type and severity of their disabilities, and to provide other information about disabled people, in particular about the financial and social consequences of disability and the use of and need for health and personal social services. The information was required to help to plan policies for benefits and services for disabled people (Martin, 1992). Interestingly, the HADRIAN data also describes the level of impairment by including an OPCS score in the main data set for every individual. Here, levels of impairments are categorized from 1 to 9 (based on OPCS severity scales) representing no or minor impairments through major impairments in different areas of ability/disability like locomotion, reaching and stretching, dexterity and personal care. as described in the previous section. The designer can target a particular individual in the database to visualize the level of ability/disability. Moreover, disability data also describes the major causes and effects on different parts of the body, for example hands, legs, shoulders etc. The HADRIAN presentation of all this information is shown in Figures 4.3 and 4.4.

Figure 4.3 shows two individuals, one male (61 years of age) and other female (56 years of age). The male subject is a British, right-handed, retired plumber and heating engineer with limited vision, an OPCS score of 5 and with some disabilities because of arthritis in the knees, shoulder and elbow. The female subject is a British, right-handed, retired telephonist, with normal vision, an OPCS score of 8 and also has some disability because of arthritis in the hip (after a break), hands and shoulder. Furthermore, the individual's data set also contains functional characteristics like anthropometry, joint constraints and capabilities data (figure 4.4) that are effectively used in the task analysis system of HADRIAN. This visual presentation of the individual's data helps designers in understanding the background history of a person, possible causes of any functional disability along with the level of severity of overall disability by showing OPCS score.

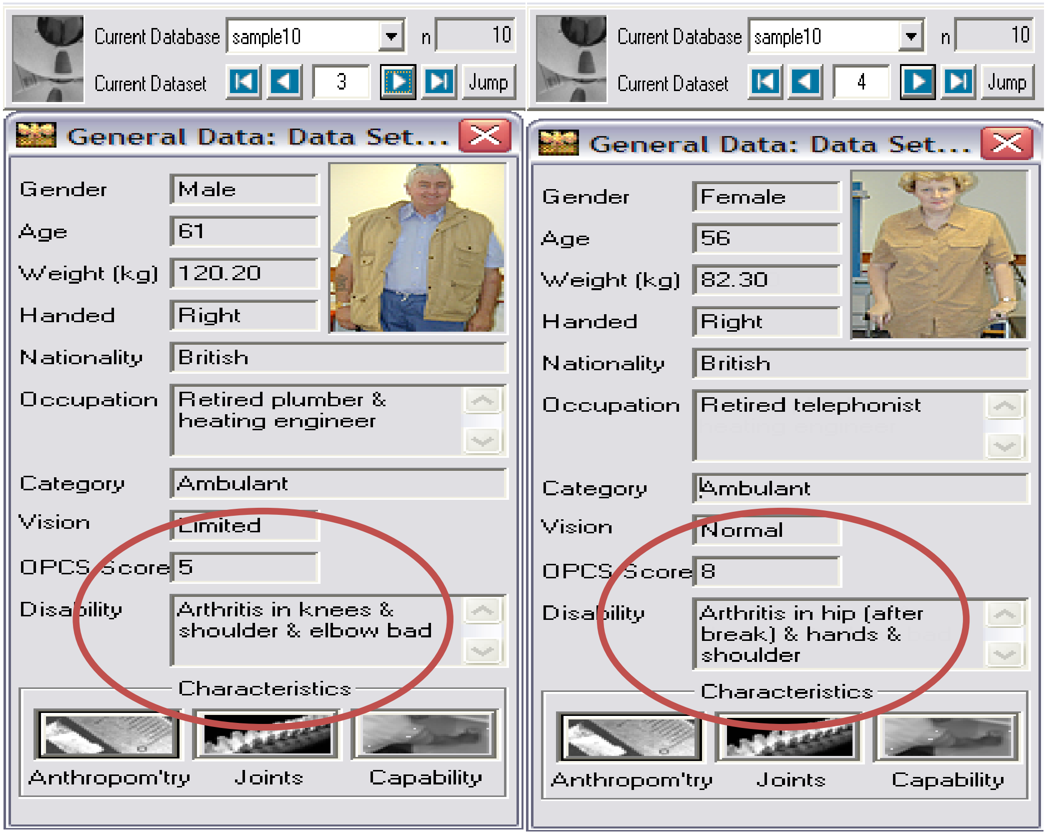


Figure 4.3: Individual presentation of OPCS severity scores in the HADRIAN database

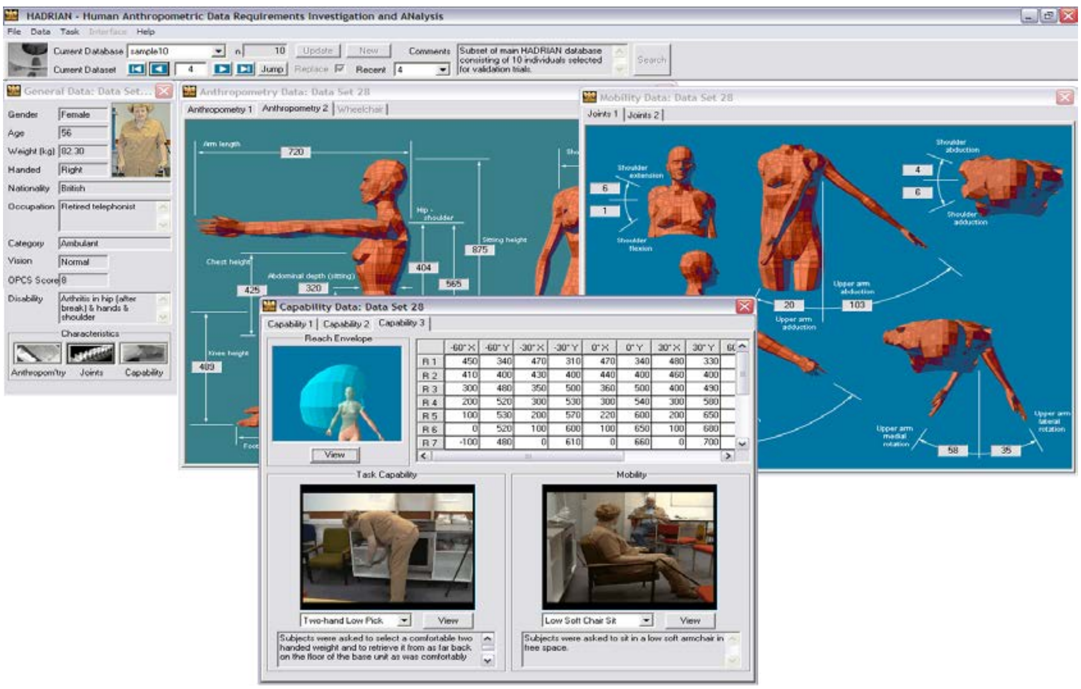


Figure 4.4: Individual's anthropometric, joint constraints and task performing capabilities data presentation within HADRIAN

Another important issue is how designers and ergonomists apply available data to address design problems. For example, anthropometric data is commonly presented as percentile values and most anthropometric databases provide data on 5^{th}, 50^{th} and 95^{th} percentiles. 5^{th} percentile stature means that only 5% of the population are shorter than that stature. Similarly 95^{th} percentile stature means that 5% of the population are taller than that stature. This method of presenting data is very much easier to present and understand, but has a number of issues when it is used for design purposes. Designing for 5^{th}, 50^{th} and 95^{th} percentile measurements encourages designers to exclude the top and bottom 5% of the population. More importantly, these percentile values are univariate, but most design problems are multivariate, where correlations between certain measures do exist either strongly or weakly. Considering these measures as independent and using them in a design process results in serious implications as a person with a fifth percentile arm length probably does not have fifth percentile sitting height, stature, weight and so on. These implications significantly increase the percentage of population excluded from any design. It is estimated that designing from 5^{th} to 95^{th} percentile for many design dimensions actually designs out nearly 50% of the population (Roebuck et al., 1975). To address these issues, the HADRIAN data is not broken down into categories of individual measures, but maintains a data set associated with a single person. Thus it is a catalogue of individuals where users can browse in the database and are able to explore the whole data about individuals.

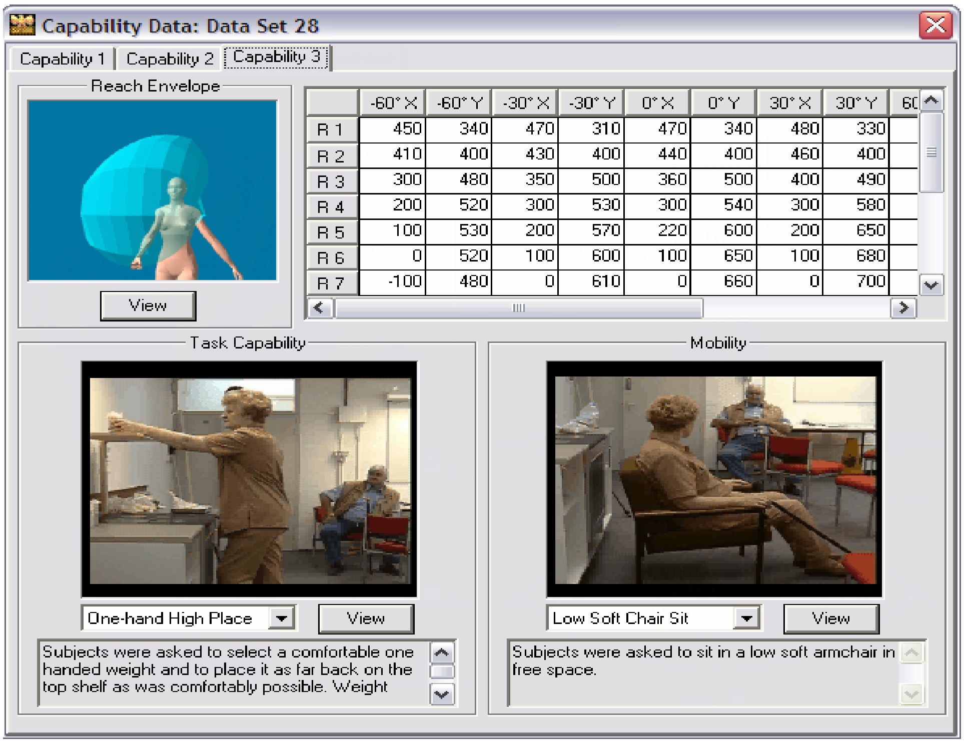


Figure 4.5: The presentation of recorded task performing capabilities data in HADRIAN

In this way, structuring the data around individuals simplifies data presentation and removes the concern of multivariate accommodation where the task analysis system utilizes all available data of individual's anthropometry with working capabilities at the same time.

Data on abilities related to tasks were captured so that the database could be used to evaluate designs based upon the task-performing capabilities of the individuals. The survey was conducted on 50 older and disabled people and data on the abilities of performing kitchen and transport related activities were captured. Very fundamental questions like whether or not one is able to prepare a meal for friends and family and able to use local transport, were explored. Figures 4.5 and 4.6 show how data was captured through recording task performing strategies and then presented in the HADRIAN inclusive design system. The objective of this study was not to design a tool for kitchen activities; it was to try to capture generic working scenarios using videos and photographs. This data record provides useful information that includes whether an individual has been successful or not and how the task was performed in terms of task behaviour (Oliver et al, 2001). Individual characteristic data (anthropometric, joint constraints and task performing capabilities data, shown in figure 4.4) and its graphical presentation further elaborates the effectiveness of using the HADRIAN inclusive design strategy in terms of the ease of understanding and use of this data during the design process. The task analysis system is based on the fundamental concept of ‘defining mismatch between job/task demands and individual capabilities’. However, a detailed discussion on the use and effectiveness of the task analysis system is given in the last section of this chapter. The next section focuses on how the disability follow-up survey’s population estimations can be correlated with the HADRIAN database, so that HADRIAN’s task analysis system can be used to address the design needs of the entire UK population.

Figure 4.6: Recording of individual’s task-based performance

4.6. Population Estimation for DFS

The DFS aimed to produce national estimates about the number of people with different levels of severity of disability in Great Britain. Each of the 7200 survey participants were questioned and severity scores were developed according to the procedure explained in the previous section. Statistical measures were used to estimate the number of people in the country with a similar level of disability. In this way, the proportions of the UK adult population (+16 years) with listed levels of disabilities were estimated. The results of this survey were first published in 'Disability in Great Britain' by the Department of Social Security in their research report number 94 (Martin et al., 1988, Grundy et al., 1999, Clarkson et al., 2007a)

Figure 4.7 provides the percentage of the UK adult population (16+ years of age) for different disability severity levels. For example, the locomotion ability level associated with question L9 (table 4.2) is very common in the population with more than 3 percent of the overall UK population with the disability.

Similarly, dexterity level D5 (table 4.4) occurs in more than 2 percent of the UK adult population.

From this percentage, it is possible to directly estimate the total number of persons in the UK population with this level of dexterity disability. By simply multiplying the percentage (D5, approximately 2.1%) with the total population (45.6M), the total number is estimated at about 1M persons in the overall UK population with this level of dexterity ability. In the same way, estimations against different areas of disability and levels of disability can be easily made. In the same way, levels for other areas of disability in reach and stretch are shown (figure 4.7) from the highest level of severity (minimum ability, maximum level of disability) to the lowest level of severity (maximum ability and minimum level of disability).

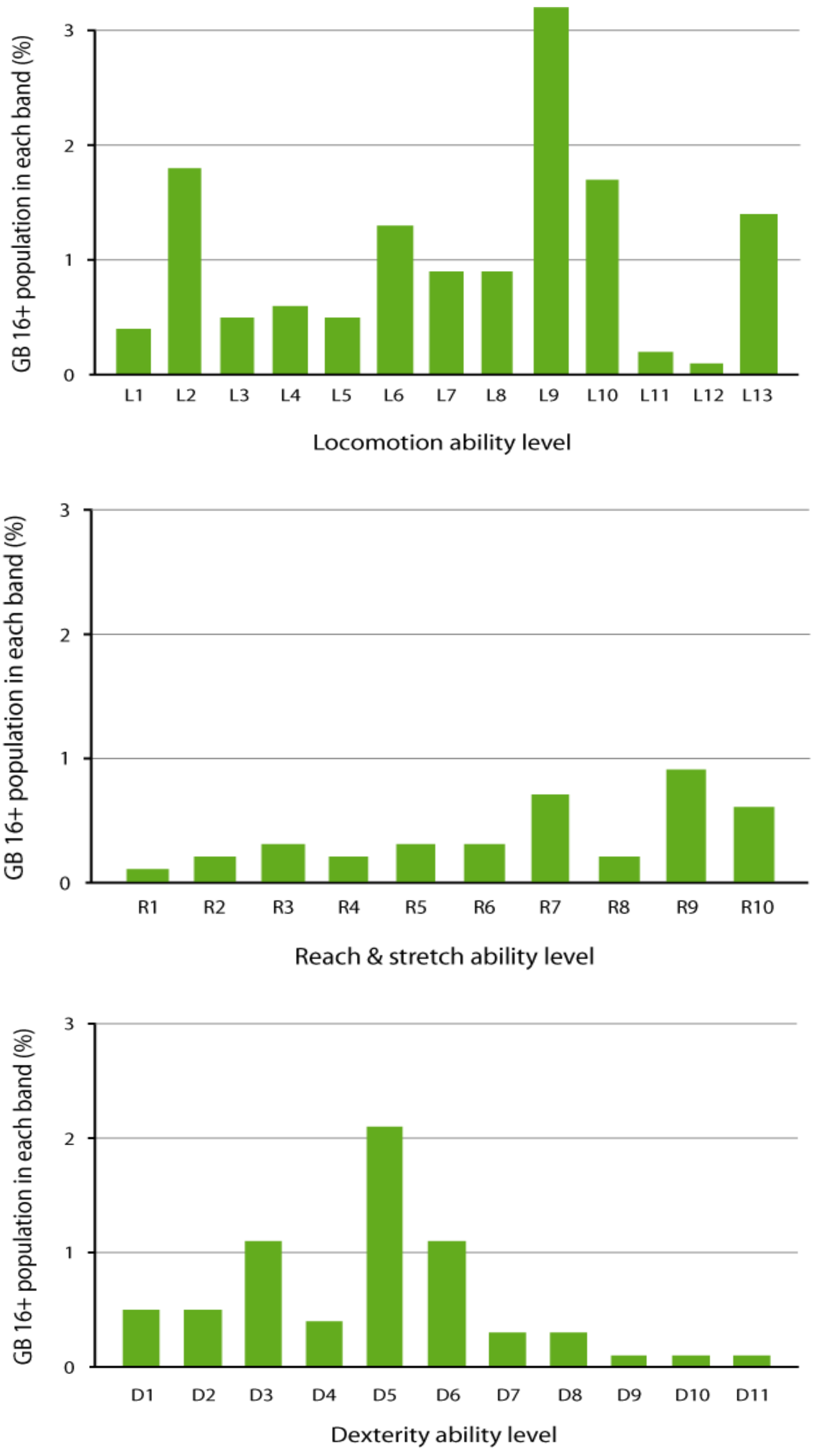


Figure 4.7: Disability prevalence data from DFS for locomotion (L1 to L13 are the questions listed in table 4.2), reach & stretch (R1 to R10 are the questions listed in table 4.3) and dexterity (D1 to D11 questions listed in table 4.4) (Clarkson et al., 2007a, Martin et al., 1988, Grundy et al., 1999)

4.7. HADRIAN Data base Correlation with DFS

As mentioned above HADRIAN has a database of about 100 individuals which represents a variety of people on the basis of their abilities, shapes, sizes and behaviours. The database also contains an OPCS score for each individual. As the method of defining the level of severity of disability is the same in both the DFS survey and the HADRIAN database, it can be said that these 103 people represent millions of people in the UK population on the basis of severity levels. It cannot be said that it is a 100 percent representation of these millions of persons; however, it exactly represents many of their abilities or disabilities because of the similarity in defining the level of severity.

Being able or unable to do some task under a specific capability category, describes an individual's ability to comfortably interact with products, services or environments. The DFS disability data was simply intended for the purpose of indicating the capability of individuals to perform certain tasks. Some of the questions also inquire about some specific product, service and environment interactions. Keeping in view all of this, a few of the same questions were put to the HADRIAN participants so that, their task behaviours, coping strategies and comfortable postures could be coded into the digital human modelling system.

The locomotion ability of the participants covered a range of tasks like walking, balancing, bending down, ascending or descending stairs etc. In the same way, reaching and stretching ability levels define the ability to perform tasks like reaching up to the head, behind the back, and the reaching and stretching abilities of both hands and arms. Similarly, dexterity ability levels provide useful information about the abilities of grasping, picking-up, holding and carrying different objects.

Table 4.7: HADRIAN severity scores and DFS-based population estimation for locomotion

Locomotion severity score (L)	Number of persons in the HADRIAN population	Disability follow-up survey estimation (Thousands)
No locomotion disability	40	40765
L10 (2.50)	6	786
L9 (3.0)	11	1438
L7 (4.50)	1	398
L6 (5.50)	1	596
L5 (6.50)	6	226
L4 (7.0)	5	255
L3 (7.50)	3	223
L2 (9.50)	1	832
L1 (11.50)	5	196
Data not available	23	
Total	102	45715

Table 4.8: HADRIAN severity scores and DFS-based population estimation for reach and stretch

Reach and Stretch severity score (RS)	Number of persons in the HADRIAN population	Disability follow-up survey estimation (Thousands)
No reach and stretch disability	58	45167
RS10 (1)	5	348
RS9 (2.50)	15	390
RS7 (4.50)	1	306
Data not available	23	
Total	102	46211

Table 4.9: HADRIAN severity scores and DFS based population estimation for dexterity

Dexterity severity score (D)	Number of persons in the HADRIAN population	Disability follow-up survey estimation (Thousands)
No dexterity disability	47	43909
D11 (0.50)	2	41
D10 (1.50)	4	33
D9 (2.00)	1	45
D7 (4.0)	12	134
D6 (5.50)	7	488
D4 (7.0)	4	191
D3 (8.0)	2	522
Data not available	23	---
Total	102	45363

For example, table 4.7 shows that there are 79 individuals in the database whose locomotion severity data are available in the HADRIAN sample population. There are 40 people who are without any locomotion disability and 17 with minor levels of locomotion disability. As we know that the HADRIAN database has used the same method for severity level assessment as used in the DFS survey, it can be said that there are 40 individuals in this database that in this respect are representative of about 40 million of the UK adult population based on the estimations made in the survey. It's much easier to justify the representation of fully able-bodied people as it confirms that all these are fully able to interact with products, services and environments with reference to their particular ability; that is locomotion in this case. In the same way, the locomotion severity score 4.5 shows that there are 6 persons with this particular level of locomotion disability. So, it might be estimated that there are over 200,000 people who are not able to 'walk up and down a flight of 12 stairs'. These individuals with a set of other information are represented in the database. The HADRIAN task analysis system will use all of the available information prior to any design decision, in combination with their incapability of being not able to 'walk up and down a flight of 12 stairs'. It can be said that a design decision made by the task analysis tool will at least produce a 'design in' or 'design out' statement for over 200,000 people who 'cannot walk up and down a flight of 12 stairs'. Additionally, because of other information available in the database, important information is provided that might help designers in understanding why they are designed out. Furthermore, there are 5 persons in the database with a locomotion severity score of 7, which shows that these people always need to hold on to something to keep balance. In the DFS dataset, there are over 250,000 people (table 4.7) with the same level of locomotion disability. We cannot say that these 7 individuals are an exact representation of those 250,000 people; but surely they represent them in relation to their specific locomotion ability. Any design decision made by the task analysis tool will represent 250,000 people in this particular aspect of ability.

From the above discussion, it can be concluded that the HADRIAN database is a representation of the millions of people that go to make up the UK adult population with regard to specific levels and severities of disability. Tables 4.8 and 4.9 give other disability categories, severity scores and DFS population estimations. There are 23 people missing in this data set whose information about severity levels is unavailable. This might be due to the participants not wishing to share personal information with others. However, the remaining 79 people cover a broad range of human capability on the basis of abilities, disabilities and their severity levels.

4.8. The HADRIAN inclusive design analysis system

The core objective of HADRIAN development was to support designers by means of utilizing captured data for inclusiveness assessment of any product, service or environment design. Unlike other conventional human modelling systems, it has useful data about the working behaviours of different individuals for some of the generic task elements recorded for kitchen and transport related activities. This research further supported the HADRAIN development by capturing, analysing and using industrial based working behaviours data of multi-skilled workers along with more realistic understanding of human variability issues and their relationship with working capabilities. Availability of such information with other capability data provides an opportunity to assess any design scenario in a virtual modelling environment where acceptability of a design can be validated for a broad range of the population. HADRIAN works in partnership with the SAMMIE human modelling system, where CAD models of products, services and environments can be developed and called into HADRIAN for task assessment purposes (Figure 4.8). The SAMMIE (System for Aiding Man-Machine Interaction) computer-based modelling system has a limitation as it is unable to adequately represent older and disabled people and variations in their functional capabilities. So, integration of the HADRIAN database with the SAMMIE human modelling system has solved this issue and individual’s capabilities and task performing strategies data can be directly used during any design evaluation process. Furthermore, this research also encouraged the use of ergonomic evaluations at the concept stage of design, so that the issue of using human modelling system at some pre-design phase - in an inclusive design perspective might be addressed

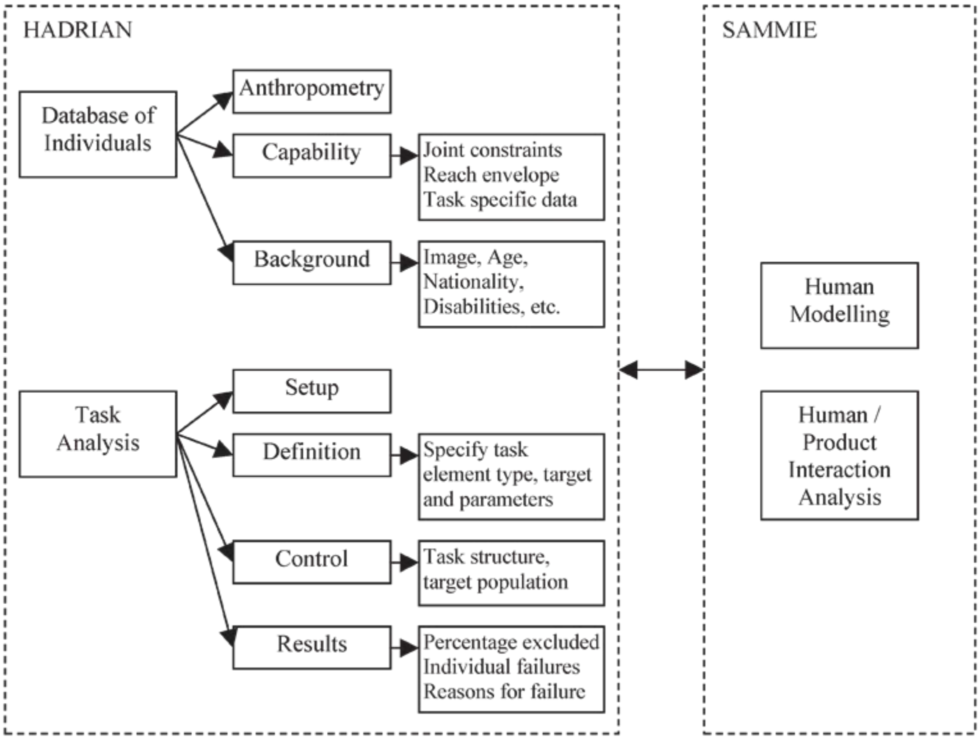


Figure 4.8: The functional layout of the HADRIAN/SAMMIE partnership (Marshall et al., 2004)

The functional partnership of the two systems has the ability of:

- modelling a product or environment and importing it to another computer-aided system
- selecting a user database which will cover a broad range of population with different shapes, sizes, age and functional capabilities – and using this for inclusive design assessment purposes
- performing task analysis by defining a task framework for selected users
- presenting results including the percentage accommodated, who is designed out for which task element and why failure occurred
- modifying the product/environment design, redefining the task parameters and re-analysing the design

The HADRIAN analysis system facilitates designers in describing how a product (in the broadest context – any object making any physical interaction) would be used. The analysis system also allows the breaking of a complex task into smaller task elements and then performing analysis of any dynamic process (task) by focusing on task element/static snapshots captured in the actual recordings. In this way, the analysis system generates results by splitting each dynamic task into static task snapshots (task elements) and performs analysis by following all task elements step by step. Successful completion of all static tasks in the sequence results in the completion of a dynamic task. On the other hand, inability to successfully interact with any product/environment during any task element results in a failure. That failure might be because of inadequate posture, high reach distance, reduced functional capabilities of an individual like joint mobility, visual impairment, inadequate height, space confines etc. Figure 4.9 shows the building a task definition by defining different task elements. As shown, the process of defining a task element mainly involves two important things. First is the definition of interaction points which are selected through the commands and targets. Secondly, setting some optional parameters that include selecting parameters like which side of the body will be used, what type of grip is required etc.? If no specific parameters are selected, the system will operate under the default set parameters. For example – if task element is ‘reach the slot’ (figure 4.9) and task parameters are not fixed, the system will automatically run the task for the nearest hand (either left or right). The importance of these optional parameters is that if designer wants to evaluate any design for a person who has some impairment like joint constraints – one has a choice to select some parameters related to the functional capabilities of an individual.

Figure 4.9: The HADRIAN task analysis system showing the building of a task definition

Furthermore, for making the task analysis as realistic as possible, the system uses the recorded task behaviour data for analysis purposes. Behaviours recorded against some generic task elements are replicated in terms of adopted postures for similar kinds of tasks. As an example, an individual's recorded behaviour for a task of reaching to the high shelf in a kitchen is taken as a generic approach and any task requiring a reach above shoulder level, is assumed to adopt a similar behaviour as that in the generic task. This behavioural data also provides very useful information about the coping strategies of older and disabled people, as many times their functional impairments hinder them in performing certain activities. The HADRIAN system breaks down the overall task into task elements where these task elements are decided by the designers; however, the designers are not required to make decisions about 'how' the task is performed. After describing task elements and defining parameters, the system simply requires a 'run' command for starting the analysis from the first task element. At the first step, the system explores information about the individual performing the task from the database and the task elements defined by the designer. Orientation of the target object and human performing that task is of great importance as it plays a vital role in the selection of different parameters that decide how a task is performed. The postures adopted for any task element are determined by the distance the target is away and the recorded behavioural coding of generic tasks associated with the individual. Figure 4.10 illustrates the use of recorded behavioural coding for two persons in the database and a similar behaviour (posture) being replicated in HADRIAN.

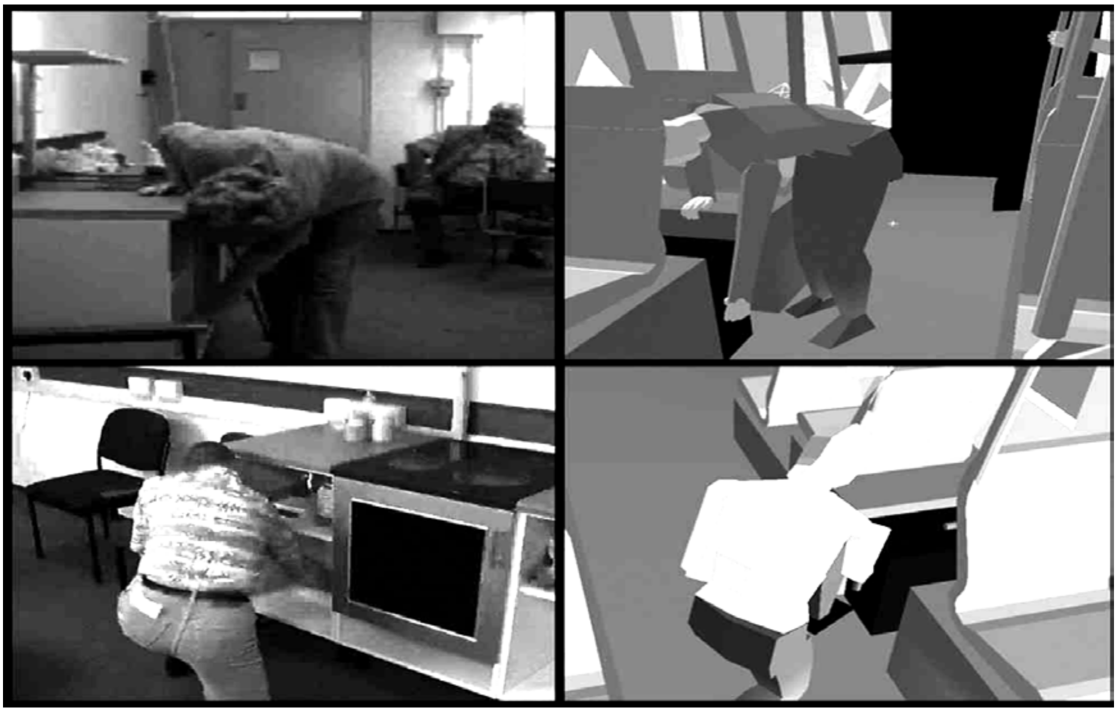


Figure 4.10: Showing adopted postures influenced by the behavioural coding recorded for individuals in the database

Further to the above discussion, Figure 4.11 illustrates the design evaluation of a simple ATM through the HADRIAN task analysis system. It shows two individuals attempting to perform a ‘reach to slot’ task element. The top row of images shows a simple ATM CAD model, a tall human and a wheelchair user attempting to perform the task. It shows that the tall individual is able to perform the task successfully. However, the wheelchair user is unable to reach the slot as it is out of reach by 2 mm (result shown in figure 4.12). When HADRIAN is used with SAMMIE for analysis purposes, its built in reach function provides an absolute solution and a reach task can show a result ‘out of reach by 2 mm’. However, in the real world 2 mm is not a significant distance and a slight move on the seat can make a success. HADRIAN is not capable of the small adjustments that real people make in the real world.

However, if the user has to adopt some coping strategy to achieve a reach task, it would be highlighted by HADRIAN and might be of designer's interest. The result of the analysis is reported to the designer in terms of a percentage excluded (unable to perform the task element). Figure 4.12 shows that 1 out of 10 is excluded, that is 10% of the overall population. The details further explain who is designed out and why – subject 40 is excluded as the target is out of reach by 2 mm. This simple feedback provides an opportunity to rethink about the task elements and the design of products or environment. As described earlier the task analysis process should be carried out at some early design stage, so it is easier to redesign and explore optimal design solutions in a short time. In this case, the ATM is lowered by 100 mm, so that a wheelchair user can use it easily. The bottom row of figure 4.11 shows a trial for a modified design, where it is clear that both individuals are able to perform the task successfully. However, the posture adopted by the tall man is significantly different as he to bend significantly to reach and see.

The HADRIAN evaluation system is not an intelligent design system. However, it can highlight major concerns needing design modification and improvement to the designers, as in the example above where the height of the ATM is highlighted as causing problems.

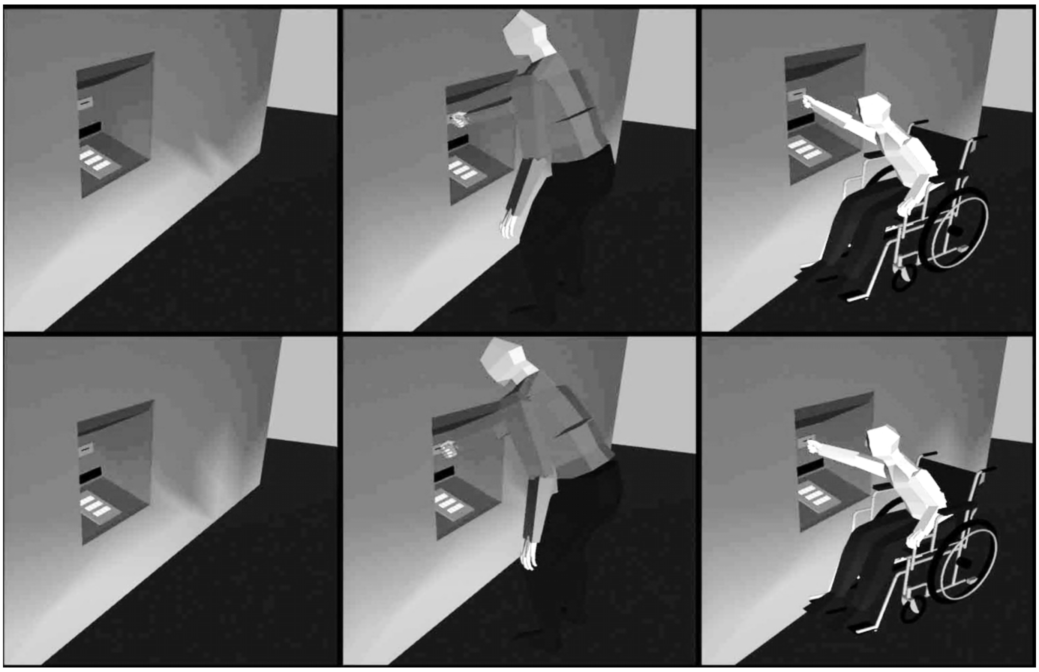


Figure 4.11: ATM model validations with the HADRIAN task analysis system

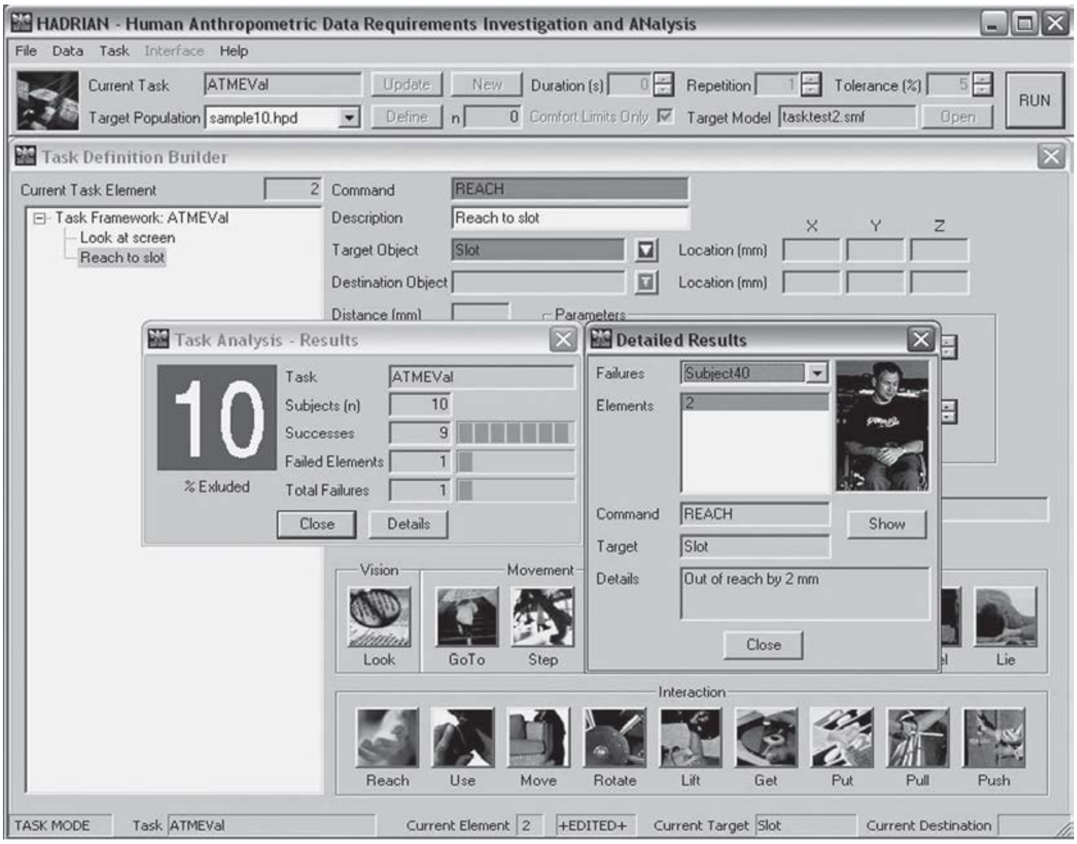


Figure 4.12: Screen shot of the HADRIAN task analysis system – showing results where 10% population is designed out

As a result of further research the scope of the HADRIAN inclusive design approach was broadened by addressing not only physical issues but also cognitive and emotional issues associated with transport related activities. Accessibility and User Needs in Transport for Sustainable Urban Environments (AUNT-SUE) was a consortium of UK academic institutions, local councils and other private and public bodies that was aiming to produce methodologies for sustainable policies and practices that can deliver socially inclusive transport design and operation and was funded as a part of the EPSRC’s Sustainable Urban Environment (SUE) programme. During this further research, data about the people with young children using pushchairs, older and disabled people using transport and their reported difficulties were recorded and integrated with the HADRIAN database. Further details about the HADRIAN capabilities, functionalities and limitations can be found in Marshall et al (2008), Marshall et al (2010), Summerskill et al (2009), Marshall et al (2004), Case et al. (2001), Porter et al (2004), Marshall et al (2002) and Gyi et al (2004).

4.9. Discussion and Conclusions

The HADRIAN task analysis system promotes an inclusive design method by accommodating the design needs of a broad range of the population including able, disabled, older and younger people. The basic principle behind the task assessment is to utilize individual's capability data to assess a success or failure of any task through a digital human modelling based inclusive design method. Task requirements within the capabilities result in a successful completion of a task, whereas high task requirements result in failure. Interestingly, severity scores that are directly linked with task performing capabilities are the same within the HADRIAN database and the Disability Follow-up Survey (DFS). The DFS shows the population estimations for the overall UK population representing the types, level and severity of different kinds of disability and their prevalence. Because of similarity in the severity scores used in the HADRIAN database and the DFS, it might be said that any design recommendation made by the HADRIAN task analysis system in likely to represent its acceptance for millions of the UK population – based on particular functional capability defined in both of the datasets. For example, a design decision recommended for an older person from the HADRIAN database who has limited joint mobility will be equally acceptable for a broad range of older or disabled people in the overall UK population, having joint mobility (constraints) equal or greater than that individual. In this way, the capability data in HADRIAN might be used to highlight and address design related issues for the wider UK population where its task performing strategies and behavioural data further enhances its relevance to reality in design.

However, the case becomes a little complex when people with different kinds of disabilities are considered at the same time, with variations in the levels and severity. It might be possible that a person countering a minor disability of one type is also facing a severe level of disability of an entirely different type. Knowing about one disability parameter does not provide realistic results in such cases. Here there is an inevitable need to use complete capability data of an individual that might directly or indirectly influence the design process. Usually, designers evaluate a design for abled bodied people or people with a specific kind of disability. Typically the aim is to address the design requirements of a particular population group like wheelchair users. All these challenges are addressed in the HADRIAN inclusive design system as it uses a complete set of data for an individual that includes anthropometric data, capability data like joint constraints, task performing strategies data and other relevant data that might affect the level of acceptability for any product or environment design. Still there is a need to link the HADRIAN database with design-relevant data about human capabilities and task performing procedures, especially for some complex tasks performed in the industrial working environment. This would enhance its capability in terms of the promotion of a digital human modelling based inclusive design strategy for industrial workplace design where people with their existing differences can perform their working activities safely and productively.

The research method proposed in section 3.2, is fundamentally based on developing an understanding of mismatches between job demands and working capabilities of the worker. As we know that most of the activities at manufacturing industries are physically intensive, so the next chapter (chapter 5) will be discussing joint mobility and its relevance with work, along with the effects of age, gender and disability on joint range of motion. It further explains the challenges faced by the designers due to varying human capabilities and these challenges might be addressed.

Chapter 5

Joint mobility and Inclusive design challenges

5.1. Introduction

It is very important to design workspaces and equipment in such a way that these should be able to accommodate the widest range of population. Joint range of motion (ROM) is one of the factors which directly influence work performance of workers. Like the general population, the worker population has different shapes, sizes, capabilities and preferences which directly or indirectly affect work ability of workers. There are many factors that influence joint range of motion. This chapter highlights the importance of joint mobility and its significance in performing different industrial activities. The aim of this study is to determine whether or not joint mobility is affected by age, gender and some specific conditions like arthritis, or the use of wheelchairs users. The importance of these variations and challenges for designers, engineers and ergonomists have also been highlighted in terms of their relevance to inclusive design. For the analysis purpose, the HADRIAN database population has been re-analysed, where joint mobility data of 66 people is used. Forty-two of the subjects were fully able-bodied whilst 24 had disabilities, of which 8 were wheelchair users and 16 arthritis patients. A total of 18 joint ranges of motion values were measured in the original study. Each value was measured twice to evaluate the influence of dominant and non-dominant sides of the body.

The research context of this study in terms of the importance of joint range of motion and its significance in inclusive design is discussed in section 5.2. Section 5.3 explains how joint mobility data was captured. Section 5.4 comprises results and discussion, where the significance of the effects of age, gender and disability is concluded. Joint mobility data variations and inclusive design challenges are debated in section 5.5. Section 5.6 includes conclusions.

5.2. Importance of joint range of motion in inclusive design

Both static and dynamic anthropometric data values are used for workplace and equipment design. Joint range of motion values with static anthropometric values are used as reference data and work-space envelopes are constructed to investigate the feasibility of any particular activity. Joint mobility is often quantified by defining the joint range of motion which is clinically defined as the “maximum range of joint angle” (American Academy of Orthopaedic Surgeons, 1965)

Carey and Gallwey (2002) investigated the effects of joint range of motion on comfort levels of workers and found that extreme joint range of motion values for the wrist cause high discomfort levels for simple repetitive exertions. It was further concluded that the combination of flexion and ulnar movements causes more discomfort as compared to other simpler and easier motions.

Joint range of motion is influenced by a number of factors like ethnicity, occupation, daily activities, age, gender and disability. The effect of age on joint ROM was observed by Stubbs et al. (1993) who found a decrease in maximal joint range of motion of between 4% and 30% for 23 different joints from a sample of 55 males ranging from 25 to 54-years of age. Chung and Wang (2009) also conducted a study on a Taiwani population of 1134 workers and measured 28 joint range of motion values and evaluated the effects of age and gender on joint ROM. It was concluded that joint ROM decreases with an increase in age; especially in the wrist joint and the cervical spine. Furthermore, female workers have greater joint ROM values than males for the upper extremities, lower extremities and cervical spine joints. The same kind of conclusions have been reached by Chaparro et al. (2000), in comparing wrist joint ROM values among different age groups and genders. The results suggest that females have more wrist joint mobility; however, an older person (age 90) will have only 60% joint ROM when compared to that of a younger person (age 30).

Doriot and Wang (2006) estimated that the highest loss in joint range of motion for 41 older male and female subjects was in the trunk and neck. However, decreases in wrist and elbow joint ranges of motion were not significant with respect to age and there was little evidence of the effect of gender on joint range of motion. Barnes, et al. (2001) studied the effects of age, gender and arm dominance on the shoulder range of motion and concluded that there is a decline in shoulder range of motion with age except for internal rotation which increases with age. As far as the effect of gender is concerned, it was again found that female subjects have a greater range of motion when compared with males. Moreover, the dominant side had greater joint ROM as compared to the non-dominant side. However, interestingly it was observed that the non-dominant side shoulder had greater joint ROM for internal rotation and extension. Moreover, there was no significant difference in shoulder joint ROM values between dominant and non-dominant sides for forward elevation of abduction.

Joint range of motion is also influenced by other factors such as ethnicity, occupation, race and daily activities, and these effects have been documented in the literature. For example, to analyse the effect of race on joint ROM, a study was conducted by Allander et al. (1974) to compare different joint range of motion values between Swedish and Icelandic people. No differences were found for shoulder joints but Swedish women have significantly greater joint mobility for the hip (five out of eight groups) and wrist (six out of eight groups) joints as compared to Icelandic women. Roach and Miles (1991) compared age-gender-race groups and found that decrease in hip joint mobility (flexion) between younger (25-39 years) and older (60-74 years) subjects for black females was twice that of other groups. Daily activities and occupation has also influence on joint ROM. Wolf et al. (1979) found that people who spent most of their time in sitting and doing less exercise, have lower lumbar joint range of motion than expected. Similarly, dancers showed greater inner hip external rotation and lesser outer hip external rotation than non-dancers (Gupta et al., 2004)

Differences in joint range of motion values between dominant and non-dominant sides of the body have been studied by a number of researchers but the results are contradictory. In some studies lower extremity joint range of motion values have been studied and no significant difference has been found due to the side of the body used (Stefanyshyn and Engsberg, 1994; Roaas and Andersson, 1982). On the other hand, Gunal et al. (1996) concluded that there was a difference in joint ROM for the right and left sides of the body and reported that joint mobility for the right side is less than the left side for upper extremity measurements. At the same time, Barnes et al. (2001) and Murray et al. (1985) tried to compare shoulder range of motion for dominant and non-dominant sides, but found no clear patterns for solid conclusions. Another study conducted by Macedo and Magee (2008), tried to find and compare ranges of motion for the ankle, knee, shoulder, wrist, hip and elbow but concluded that there were a few differences between dominant and non-dominant sides but they were very small.

The literature clearly indicates that there are number of factors that influence the joint range of motion of people. Joint mobility is an important factor that influences the work performance in working environments where a variety of people with different ethnic backgrounds, races, age, gender and capabilities work together.

There is a need for designers and ergonomists to understand these differences at pre-design phases of any product and workplace design, so that the maximum number of people can be accommodated. Many studies have been conducted to discover differences in joint mobility capabilities, but no effort has been made in highlighting the implications of these differences and variations for inclusive design. This chapter mainly focuses on the differences in joint range of motion values for a broad range of population and the potential impact on the implementation of an inclusive design strategy. The following sections of this chapter briefly describe the methodology adopted for capturing joint mobility data and analysing the data in an inclusive design perspective.

5.3. Data Capturing Methodology

. This research focuses on reanalysing joint mobility data, captured during the HADRIAN development to present a broad range of the population. A total of about 100 people participated in that study; however, only 66 subjects have been selected for this analysis. For comparison purposes, the sample was divided into two main categories of able-bodied and disabled people. Furthermore, the 42 able-bodied subjects were divided into three age groups, i.e. 20-40, 40-60, and 60-81 years for the purpose of comparing joint mobility capabilities between different age groups, where these age groups consisted of 10, 13 and 19 subjects respectively. The disabled sample, (24 subjects), were categorized into wheelchair users (8 subjects) and arthritis patients (16 subjects).

Joint constraint data was collected using a goniometer (Summerskill et al., 2010). A total of 18 joint range of motion values for the shoulder, arm, elbow and wrist were measured; each value was measured twice, firstly for the dominant side and then for the non-dominant side of the body. Descriptive statistics were computed for each joint range of motion value where means and standard deviation values for different groups (age, gender, and disability) were calculated. These values are shown in Table 5.1, 5.2 and 5.3 (mean and standard deviation values). An ANOVA test was employed to demonstrate the influence of different factors like age, gender and a specific disability on joint ROM. Post Hoc (Turkey) analysis was also performed to gain a deep insight into the significance levels and correlations between these factors. Subjects were considered as a random factor – that assumed that subjects were randomly selected from an infinite number of possible subjects, where the objective was to reach conclusions about differences among all the subjects, even the ones not included in the experiment.

Table 5.1: The means and standard deviations of joint ROM for different age groups

Joint	**20-40 years (n = 10)** *ROM degrees (std dev)*	**40-60 years (n = 13)** *ROM degrees (std dev)*	**60-81 years (n = 19)** *ROM degrees (std dev)*
Shoulder extension	40(14.4)	39.4(11.5)	44.8(10.5)
Shoulder flexion	22.7(11)	17.7(4.7)	15.2(8.4)
Shoulder abduction	28.7(13.7)	23.6(11.3)	21.3(11.2)
Shoulder adduction	27.3(11.5)	30.2(12.7)	28.1(10.6)
Arm extension	63.4(12.1)	64.4(32.5)	64.6(24.2)
Arm flexion	174.5(9)	162.2(34.1)	152.5(25.8)
Arm abduction	171.2(15.1)	158.8(18.3)	147.2(27.9)
Arm adduction	64.2(15.7)	62.6(17.4)	68.9(13.8)
Arm medial rotation	90(0)	75(18.2)	87.2(5)
Arm lateral rotation	70.7(11.9)	52.4(10.4)	59.2(14.5)
Elbow extension	1.9(1.4)	2.1(2.4)	0.8(1.2)
Elbow flexion	145.1(7.8)	135.8(9.1)	133.2(10.4)
Elbow pronation	83.9(11.7)	82.8(13.3)	83.4(11.7)
Elbow supination	93(12.5)	83.2(9.8)	88(10.5)
Wrist extension	64.8(10.2)	59.2(9.2)	56(11.8)
Wrist flexion	67(9.8)	58.3(8.6)	55.9(7.5)
Wrist abduction	12.6(7.6)	12.9(5.9)	11.6(5)
Wrist adduction	49.9(9.4)	34.9(5.9)	37.4(7.3)

Table 5.2: The means and standard deviations of joint ROM for two gender groups

Joint	**Male (n = 13)** *ROM degrees (std dev)*	**Female (n = 29)** *ROM degrees (std dev)*
Shoulder extension	37.8(12.7)	43.7(11.1)
Shoulder flexion	18.2(8.1)	17.6(8.8)
Shoulder abduction	27.1(11.7)	22.3(11.9)
Shoulder adduction	27.1(12.8)	29.2(10.7)
Arm extension	68.7(29.6)	62.3(22.2)
Arm flexion	158.6(34.5)	161.7(23.5)
Arm abduction	164.8(13.7)	152.8(26.9)
Arm adduction	64.9(16.4)	66.2(15.1)
Arm medial rotation	81.8(16.3)	85.1(9.9)
Arm lateral rotation	59.9(13.2)	59.8(14.9)
Elbow extension	1.8(2.2)	1.3(1.5)
Elbow flexion	140.1(9.2)	135.4(10.7)
Elbow pronation	81(12.5)	84.3(11.7)
Elbow supination	84.5(11.4)	89.2(11)
Wrist extension	61.8(12.2)	57.9(10.4)
Wrist flexion	60.1(8.4)	58.9(9.9)
Wrist abduction	13.8(7.1)	11.6(5.2)
Wrist adduction	39.7(8.4)	39.6(9.9)

Table 5.3: The means and standard deviations of joint ROM for people with different abilities

Joint	**Able-bodied (n = 42)** *ROM degrees (std dev)*	**Wheelchair users (n = 8)** *ROM degrees (std dev)*	**Arthritis patients (n = 16)** *ROM degrees (std dev)*
Shoulder extension	42(11.8)	42.2(8.6)	41.9(11.9)
Shoulder flexion	17.8(8.5)	11.9(10.5)	14.8(8.3)
Shoulder abduction	23.8(11.9)	20(12.3)	20.2(11.8)
Shoulder adduction	28.6(11.3)	23.5(19.9)	27.8(10)
Arm extension	64.3(24.5)	50.2(20.7)	59.6(28.3)
Arm flexion	160.7(27)	135.4(42.8)	130.8(42.2)
Arm abduction	156.5(24.2)	117.8(43.8)	114.4(43.5)
Arm adduction	65.8(15.3)	58.5(15.9)	59.8(24.4)
Arm medial rotation	84.1(12.1)	83.1(15.6)	83.6(10.1)
Arm lateral rotation	59.8(14.2)	52(23.5)	43.6(21.3)
Elbow extension	1.5(1.8)	0(0)	1(1.5)
Elbow flexion	136.8(10.4)	122.6(23.8)	123.6(34.9)
Elbow pronation	83.3(11.9)	85.5(14.8)	83.8(12.5)
Elbow supination	87.7(11.2)	68.6(23.3)	77.3(28.4)
Wrist extension	59.1(11)	48.5(28.5)	48.1(18.2)
Wrist flexion	59.3(9.3)	51.9(13.8)	52.8(10.9)
Wrist abduction	12.3(5.9)	12.4(5.9)	12.3(8.1)
Wrist adduction	39.6(9.4)	32.6(22)	32.5(15.5)

5.4. Results and Discussion

5.4.1. Effect of age on joint range of motion

Tables 5.1, 5.2 and 5.3 show the mean and standard deviation values of joint range of motion angles for the shoulder, arm, elbow and wrist for different of age, gender and disability groups. ANOVA results are shown in tables 5.4, 5.5 and 5.6, which clearly identify that there are many joint ROM values which are affected by age and disability; however, there is no evidence of significance influence of gender for any joint ROM values.

For analysing the effects of age on JROM, overall subjects (42) are divided into three subgroups. First group belongs to the age group 20-40 years, second one belongs to the age group 40-60 years; whereas, the third group belongs to the subjects from 60-80 years of age respectively. The objective of dividing these subjects into subgroups was to understand and analyse the effects of age on joint mobility. A special concern was to highlight the differences between younger and older people where the focus was to highlight the differences between younger people and people who are getting retired from workplaces; for that purpose a group of 60-81 years have been created.

Table 5.1 and figure 5.1 show that there is a decrease in joint ROM with age for most of the joints; however, its significance depends upon the type of motion and the joint itself. The difference in joint ROM values among different age groups, and is significant for arm medial rotation, arm lateral rotation, elbow flexion, wrist flexion and wrist adduction ($p<0.05$).

The greatest reductions in joint ROM between two age groups, 20-40 years and 40-60 years, was found to be approximately 14.9^o (30%) in wrist adduction, 18.3^o (26%) in arm lateral rotation, 15^o (17%) in arm medial rotation, 8.7^o (13%) in wrist flexion, 13^o (7.6%) in arm abduction and 10^o (6.9%) in elbow flexion (table 5.1).

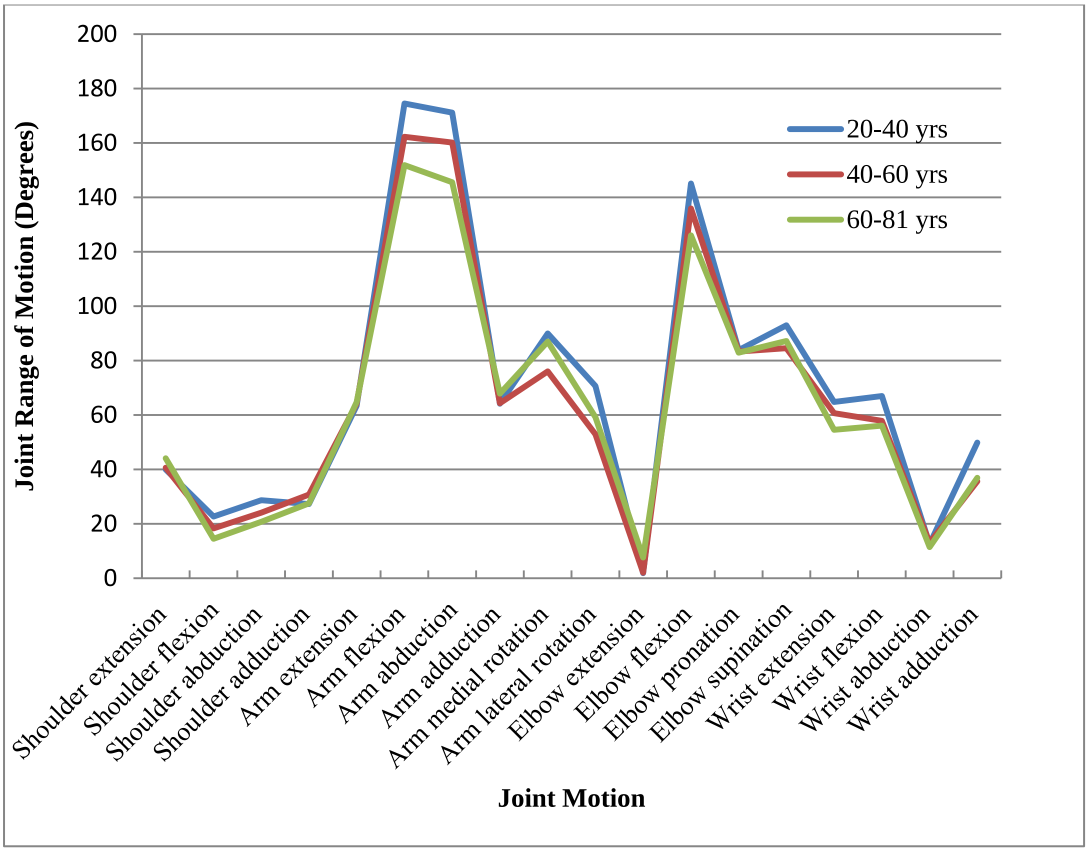


Figure 5.1: Comparison of different joint ROM for different age groups (N=42), (n1=10, n2=13, n3=19); N, n1, n2 and n3 show total number of subjects, subjects from 20-40 years age group, subjects from 40-60 years age group and subjects from 60-81 years age group respectively

Table 5.4: Effects of age on joint range of motion, ANOVA results

	Specific Joint	Degree of Freedom	F-Value*	Significance
01	Shoulder Extension	2	1	0.4
02	Shoulder Flexion	2	1.1	0.3
03	Shoulder Abduction	2	0.6	0.5
04	Shoulder Adduction	2	0.2	0.8
05	Arm Extension	2	0.3	0.8
06	Arm Flexion	2	2.1	0.1
07	Arm Abduction	2	2.1	0.1
08	Arm Adduction	2	0.2	0.8
09	Arm Medial Rotation	2	8.6	0
10	Arm Lateral Rotation	2	4.2	0
11	Elbow Extension	2	2.4	0.1
12	Elbow Flexion	2	4.4	0
13	Elbow Pronation	2	0.1	0.9
14	Elbow Supination	2	2.3	0.1
15	Wrist Extension	2	2.3	0.1
16	Wrist Flexion	2	4.9	0
17	Wrist Abduction	2	0.2	0.8
18	Wrist Adduction	2	11.2	0

* Found variation of the group averages

There are some joint ROM values, such as arm flexion, elbow flexion, elbow supination and wrist extension for which the difference is not statistically significant. The effect of age on joint ROM was also reported by different researchers in previous studies. For example, Chung and Wang (2009) tried to establish a database of joint range of motion for the worker population of Taiwan (1134 subjects), and they concluded that age reduces joint mobility with the largest reduction in joint ROM being found in the wrist joint. This decrease was 16.6^o (26%) and 10.9^o (16%) in wrist extension and wrist flexion for male subjects between the younger (16-30 years) and older (46-64 years). Furthermore, Schoenmarklin and Marras (1993) conducted a study to analyse the dynamic capabilities of the wrist joint in industrial workers and found similar joint mobility capabilities for wrist flexion and wrist extension as compared with this study. In this study, mean values of wrist extension and flexion (age 40-60 years) are 59^o and 58^o respectively, which is very similar to the 62^o and 57^o respectively (average age 41.7 years), mentioned by Schoenmarklin and Marras (1993). Moreover, a decrease in wrist joint mobility for extension and flexion was also mentioned by Chaparro et al. (2000). Allander et al, (1974) also highlighted a decrease in joint mobility with age in shoulder ROM but the decrease was only 2.2 degrees per five years for male subjects between 45-60 years old (Allander et al., 1974).

It is interesting to note that the oldest age group (60-81 years) has higher joint ROM for shoulder extension, arm adduction, arm medial rotation, arm lateral rotation, elbow supination, and wrist adduction when compared to the 40-60 years age group. Moreover, the highest percentage increase was found in arm medial rotation (16%), shoulder extension (13%), arm lateral rotation (13%) and arm adduction (10%). Chung and Wang (2009) also found a trend of increasing joint ROM with age for forearm supination and pronation.

In the light of above results and discussion, it may be concluded that age affects joint mobility. However, its significance depends upon the type of motion and specific joint. Older people are different in terms of their joint mobility and must be considered seriously during the pre-design phase of any product, service or workplace design.

5.4.2. Effect of gender on joint ROM

Table 5.2 shows a comparison between male and female joint range of motion mean values for able-bodied subjects. There is no clear pattern of increase or decrease of joint mobility found between the two gender groups, and this is also quite clear from Figure 5.2. However, the capability of joint mobility is different for both genders, and depends upon the joint and the type of motion. In this study, ANOVA tests were performed to evaluate the significance of this difference in the joint range of motion values but no statistically significant difference was noted for any of the joint motions. The results are shown in table 5.5. A total 7 out of 18 joint values show that females have greater joint mobility than male subjects, the greatest percentage increase being for shoulder extension (16%). Moreover, shoulder adduction, arm flexion, arm adduction, arm medial rotation, elbow pronation and elbow supination show approximately 8%, 2%, 2%, 4%, and 5.5% increases in joint ROM respectively for females as compared to males. On the other hand, 9 out of 18 values show that males have higher joint mobility as compared to females. Among these, elbow extension shows the greatest percentage difference of 24% between males and females. Furthermore, shoulder flexion (3.7%), shoulder abduction (17.6%), arm extension (9.3%), arm abduction (7.3%), elbow flexion (3.3%), wrist extension (6.3%), wrist flexion (1.9%), and wrist abduction (16.6%) show the same pattern of decrease in joint ROM for females. Joint range of motion for arm lateral rotation and wrist adduction are approximately the same for both genders. However, it is worth noting that statistically there is no significant difference in joint mobility between male and female subjects.

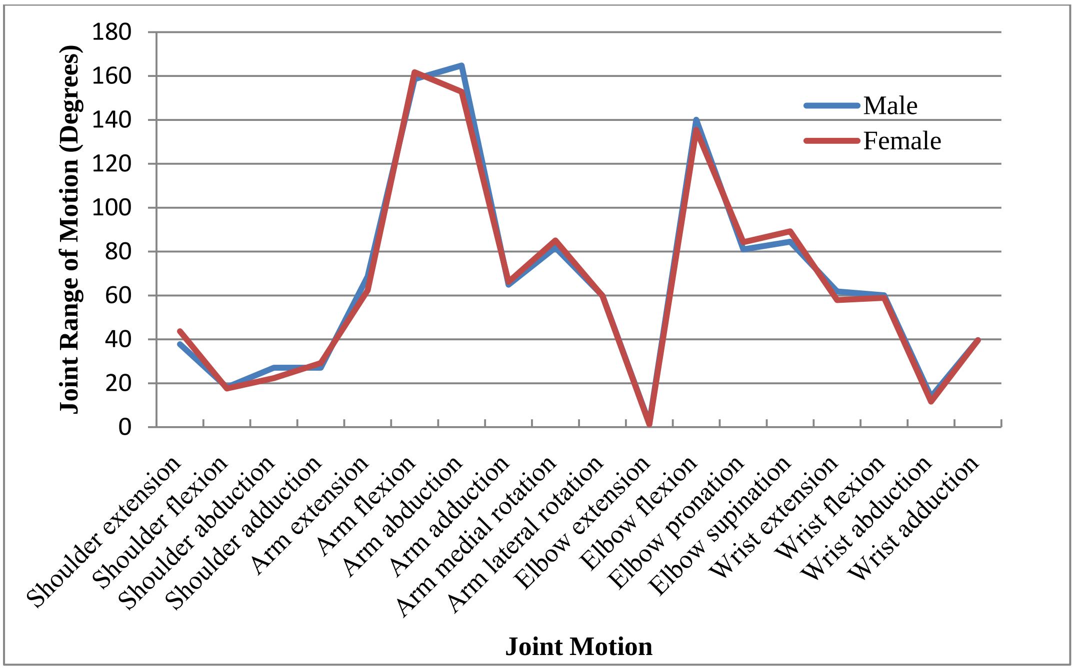


Figure 5.2: Comparison of joint ROM for two gender groups (N=42), (n1=13, n2=29); N, n1 and n2 show total number of subjects, subjects belong to male group and subjects belong to female group respectively

Table 5.5: Effects of gender on joint range of motion, ANOVA results

	Specific Joint	Degree of Freedom	F-Value *	Significance
01	Shoulder Extension	1	2.278	0.140
02	Shoulder Flexion	1	0.309	0.582
03	Shoulder Abduction	1	0.673	0.418
04	Shoulder Adduction	1	0.463	0.500
05	Arm Extension	1	0.963	0.333
06	Arm Flexion	1	0.570	0.455
07	Arm Abduction	1	1.108	0.300
08	Arm Adduction	1	0.010	0.922
09	Arm Medial Rotation	1	1.162	0.288
10	Arm Lateral Rotation	1	0.059	0.810
11	Elbow Extension	1	0.366	0.549
12	Elbow Flexion	1	1.095	0.302
13	Elbow Pronation	1	1.035	0.316
14	Elbow Supination	1	1.762	0.193
15	Wrist Extension	1	0.982	0.328
16	Wrist Flexion	1	0.001	0.973
17	Wrist Abduction	1	1.272	0.267
18	Wrist Adduction	1	0.129	0.721

* Found variation of the group averages

5.4.3. Effect of disability on joint ROM

Mean and standard deviation values of joint ROM values for wheelchair users and arthritis subjects are shown (table 5.3) in comparison with able-bodied subjects. For this analysis, no discrimination was made on the basis of age and gender, so that an overall effect on joint range of motion for people with disability can be analysed. Joint range of motion data for a total of 66 subjects was analysed in this study, from which 8 were wheelchair users, 16 were arthritis patients and 42 were fully able-bodied. Furthermore, among these 66 subjects, 19 were male and 47 were female subjects. It can be seen (table 5.3, figure 5.3) that people with disability (wheelchair users and arthritis patients) have reduced joint mobility as compared to the able-bodied. The ANOVA results (table 5.6) clearly identify that this decrease is significant ($p<0.05$) for arm flexion (30^o and 18%), arm abduction (42^o and 27%) and arm lateral rotation (16^o and 27%), elbow flexion (14^o and 10%), elbow supination (19^o, 22%), wrist extension (11^o, 18%), and wrist flexion (7^o, 12%).

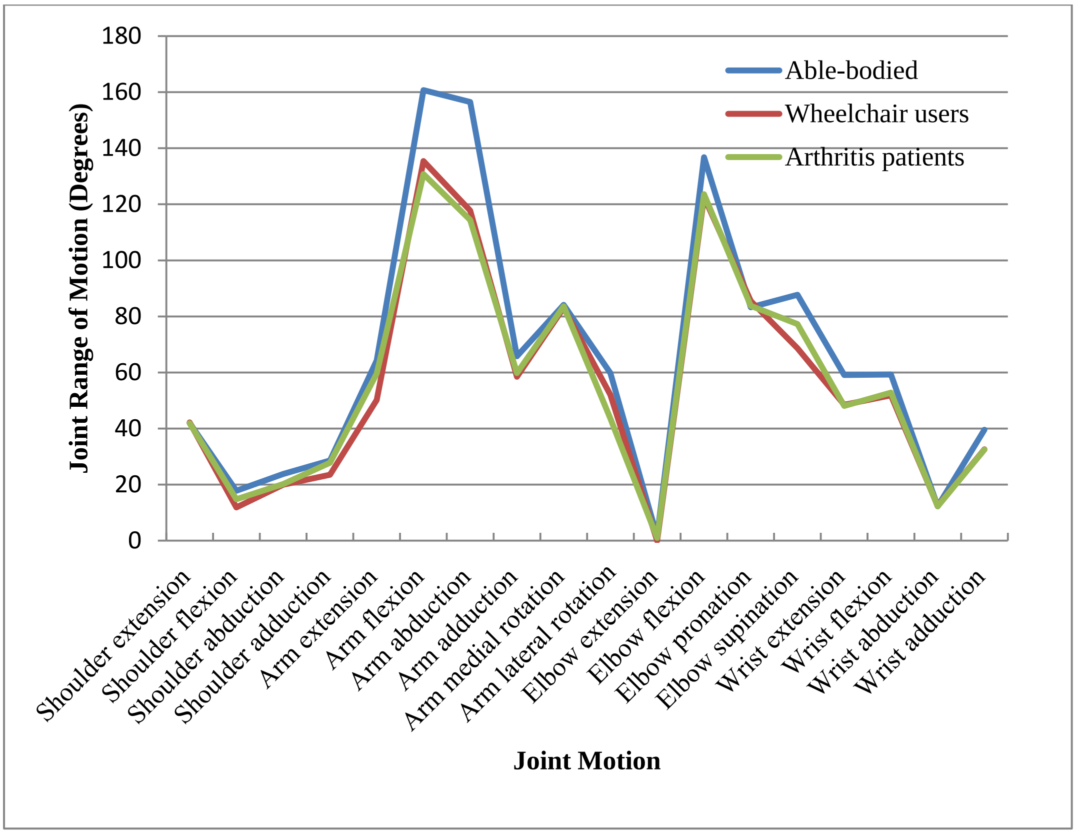


Figure 5.3: Comparison of different joint ROM for different ability groups (N=66), (n1=42, n2=8, n3=16); where N, n1, n2, n3 and n4 show total number of subjects, subjects with able bodied, wheelchair users and arthritis patients respectively

Table 5.6: Effects of disability on joint range of motion, ANOVA results

	Specific Joint	Degree of Freedom	F-Value *	Significance
01	Shoulder Extension	2	0.003	0.997
02	Shoulder Flexion	2	1.872	0.162
03	Shoulder Abduction	2	0.719	0.491
04	Shoulder Adduction	2	0.573	0.567
05	Arm Extension	2	1.106	0.337
06	Arm Flexion	2	5.641	0.006
07	Arm Abduction	2	12.351	0.000
08	Arm Adduction	2	1.001	0.373
09	Arm Medical Rotation	2	0.024	0.976
10	Arm Lateral Rotation	2	5.208	0.008
11	Elbow Extension	2	3.049	0.054
12	Elbow Flexion	2	3.309	0.043
13	Elbow Pronation	2	0.105	0.900
14	Elbow Supination	2	4.649	0.013
15	Wrist Extension	2	3.613	0.033
16	Wrist Flexion	2	3.318	0.043
17	Wrist Abduction	2	0.001	.999
18	Wrist Adduction	2	2.263	0.112

* Found variation of the group averages

It is interesting to note that wheelchair users have higher joint mobility for shoulder extension, arm flexion, arm abduction, arm lateral rotation and elbow pronation than that for arthritis patients. Moreover, shoulder extension and elbow pronation joint range of motion values for wheelchair users are slightly higher than that of able-bodied people. This increase might be because of an excessive and very regular use of the arms and shoulders for operating the wheelchairs.

Measurement of anthropometric and physical characteristics of people with specific disabilities is of vital importance. This information can be used in developing the appropriate designs of products, equipment, tools and services, so that these people might perform their activities safely either in occupational or non-occupational working environments.

Previous studies on the functional capabilities of the population focus on non-disabled adults where data bases from larger sample sizes have been constructed. It is evident that physical characteristics of the people with disabilities are different at the individual as well as the group level (Jarosz, 1996).

5.5. Joint mobility; data variation and inclusive design challenges

It has been seen in the section 5.4 that joint mobility is significantly influenced by age and disability. Just knowing this significance is not enough when designers try to accommodate all these variations into design solutions. This section (5.5) will further highlight the variations at the individual level and their implications for inclusive design. As described in section 4.5 (previous chapter) that simply designing for 5^{th} and 95^{th} percentile excludes a considerable proportion of the population. Section 5.5.1 and 5.5.2 will explain these issues and challenges with reference to the accommodation of older and disabled people.

5.5.1. Age and inclusive design challenges

This section presents individual's joint mobility data, belonging to two age groups. The subjects have been divided into two age groups; 20-60 years age and 60-81years age. The aim was to highlight the challenges faced by the older workers in being accommodated in the working environment because of the reduction in their joint mobility, and whether or not the conventional 5^{th} and 95^{th} percentile values can serve the purpose. The graphical presentations below (figures 5.4 to 5.8) demonstrate these issues for shoulder flexion, arm flexion, arm abduction, wrist extension and wrist flexion. Further discussion is made at the end of the section 5.5.2.

Shoulder flexion

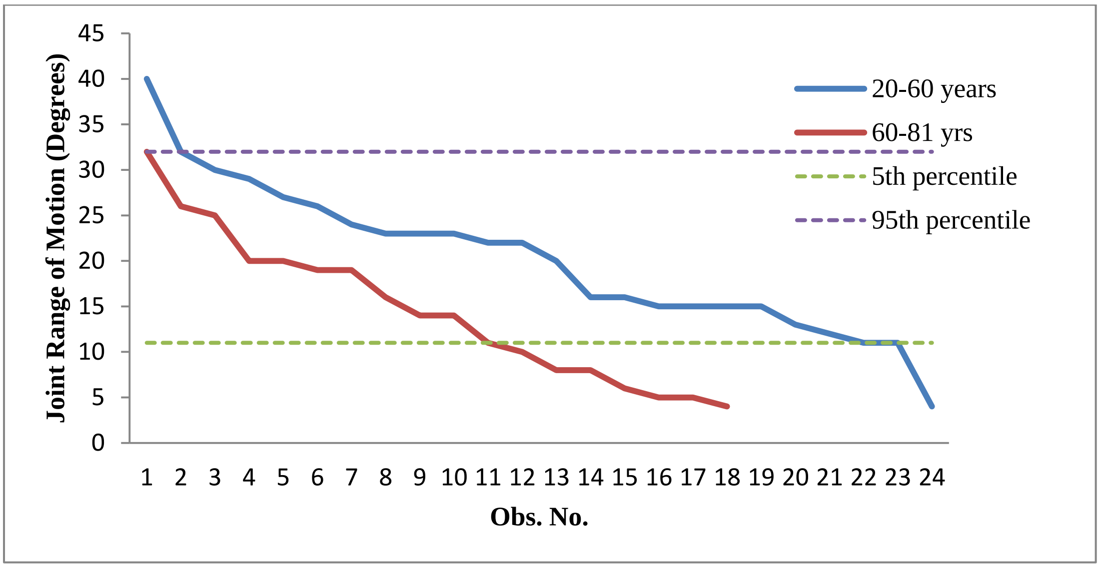


Figure 5.4: JROM variations for shoulder flexion in different age groups and its relevance with 5th and 95th percentile design criteria

Arm flexion

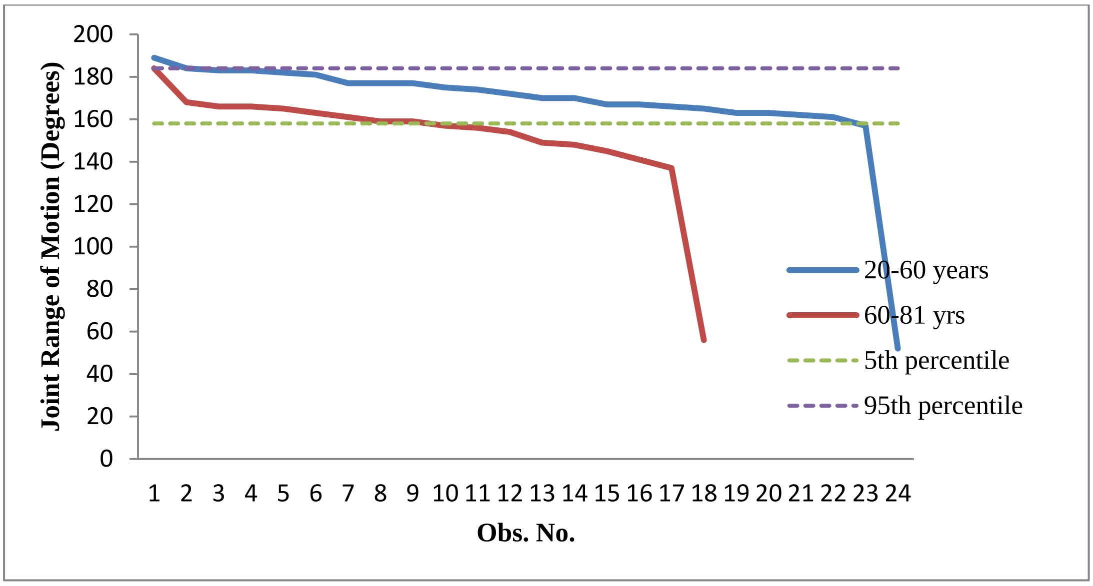


Figure 5.5: JROM variations for arm flexion in different age groups and its relevance with 5th and 95th percentile design criteria

Arm abduction

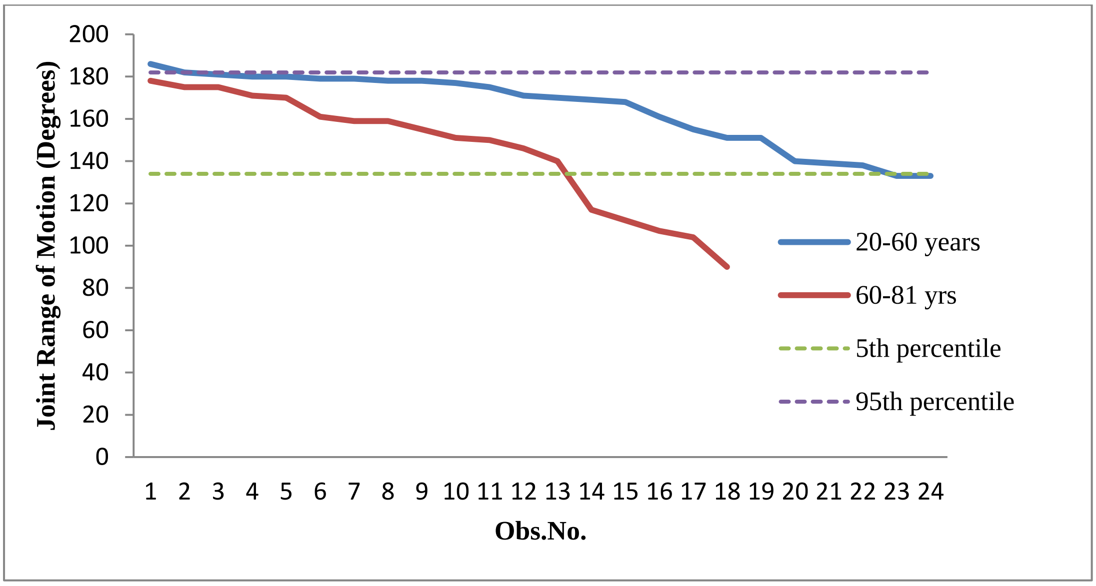


Figure 5.6: JROM variations for arm abduction in different age groups and its relevance with 5th and 95th percentile design criteria

Wrist extension

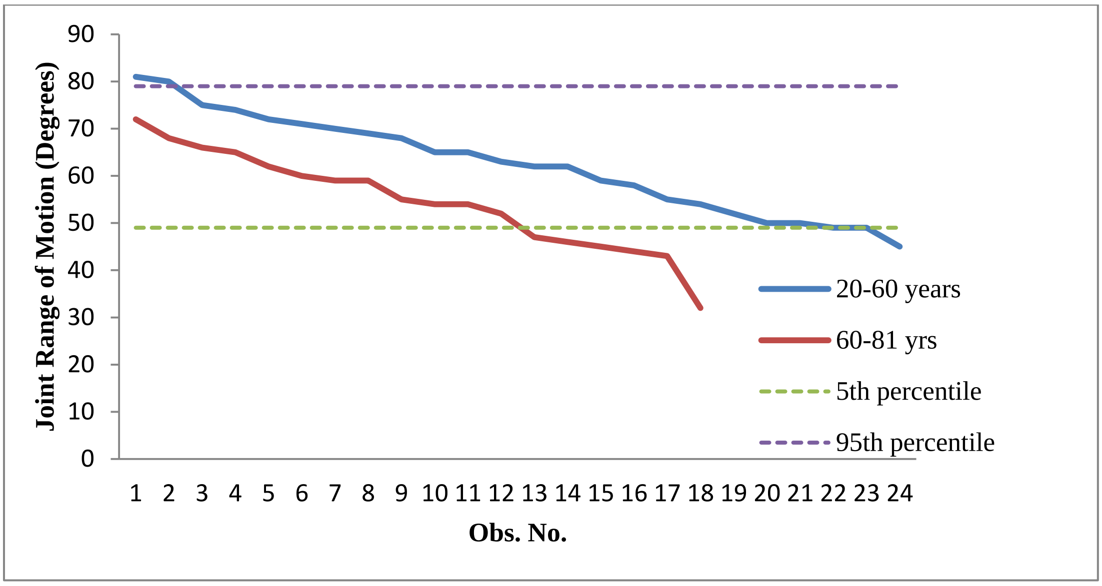


Figure 5.7: JROM variations for wrist extension in different age groups and its relevance with 5th and 95th percentile design criteria

Wrist flexion:

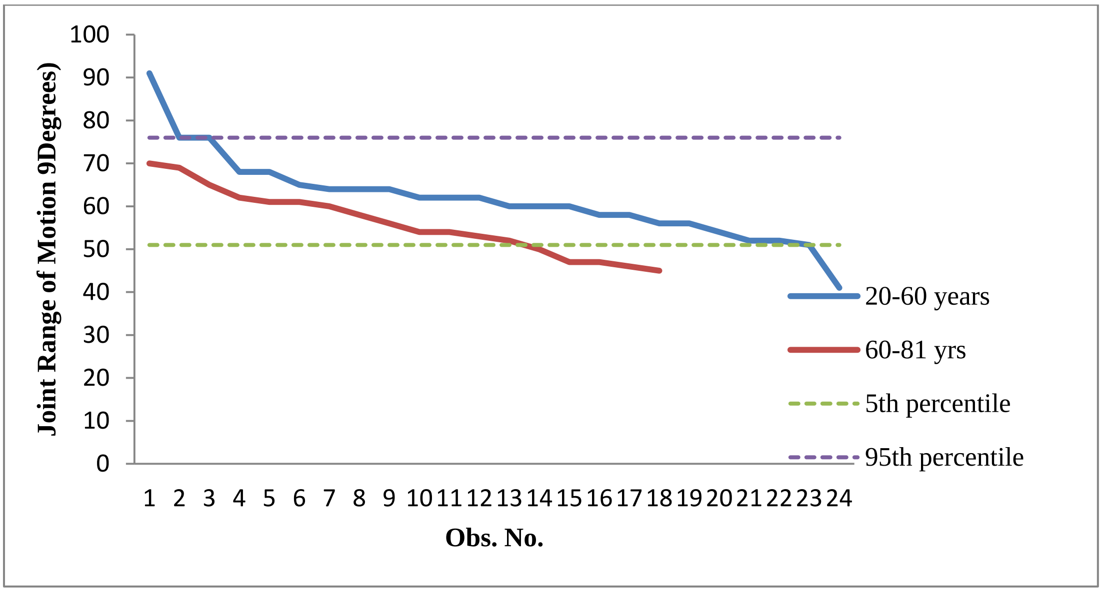


Figure 5.8: JROM variations for wrist flexion in different age groups and its relevance with 5th and 95th percentile design criteria

5.5.2. Disability and inclusive design challenges

It was found that like age, specific conditions such as wheelchair use and arthritis also have a significant effect on joint mobility for certain joints. Sections 5.5.1and 5.5.2 present the variations in joint mobility of a broad range of population, includes able-bodied people, wheelchair users and arthritis patients. Figures 5.9 to 5.14 show these variations (for arm abduction, arm lateral rotation, elbow flexion, elbow supination, wrist extension and wrist adduction respectively) within the group and between groups, and correlation of these individual joint range of motion values with 5th and 95th percentile values calculated for the able-bodied.

Arm abduction

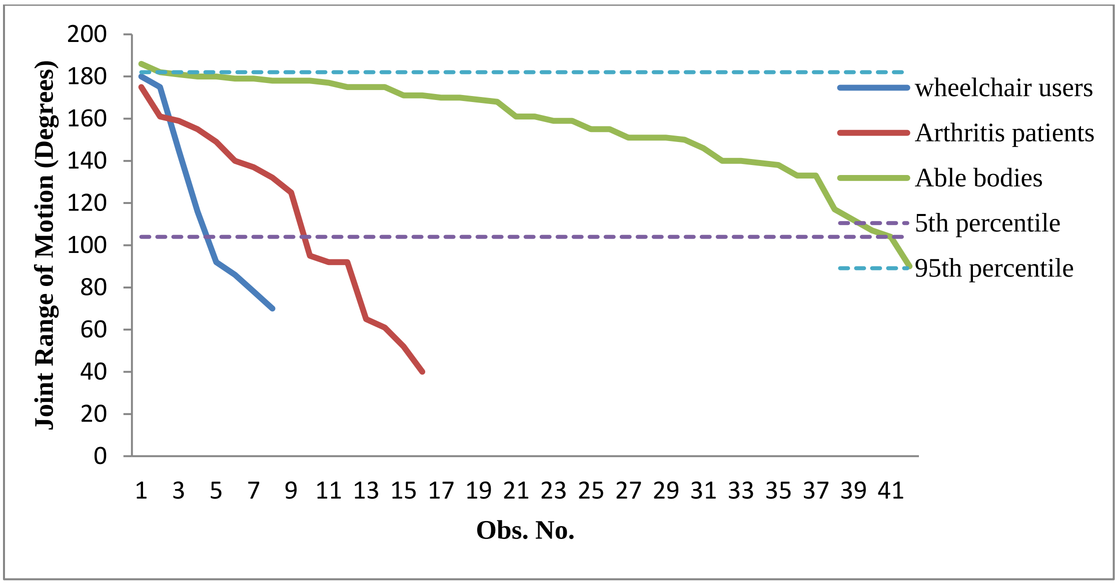


Figure 5.9: JROM variations for arm abduction among the people with different types of disabilities and its relevance with 5th and 95th percentile design criteria

Arm lateral rotation

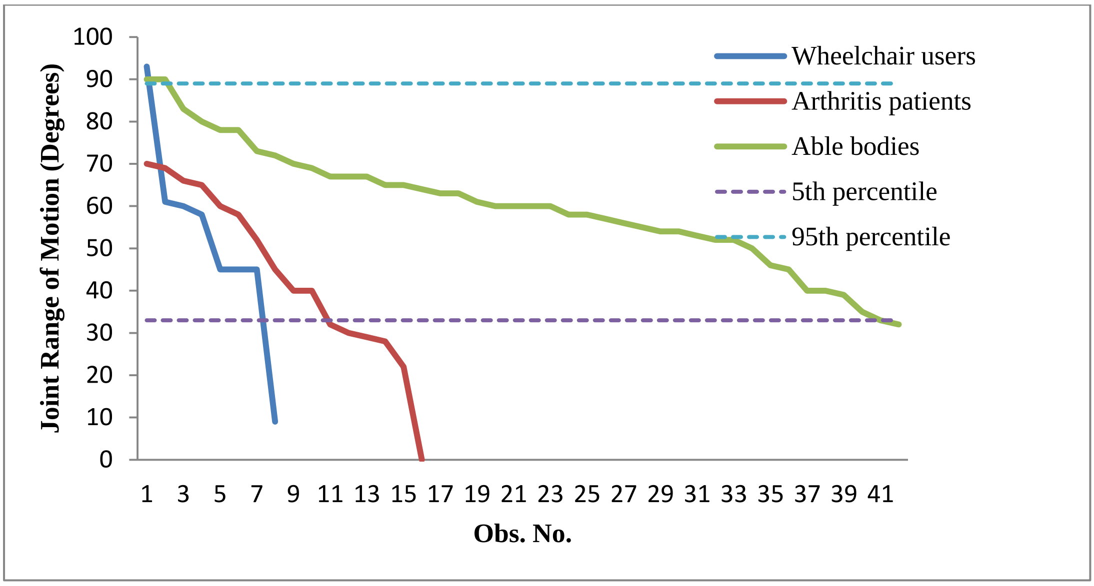


Figure 5.10: JROM variations for arm lateral rotation among the people with different types of disabilities and its relevance with 5th and 95th percentile design criteria

Elbow flexion

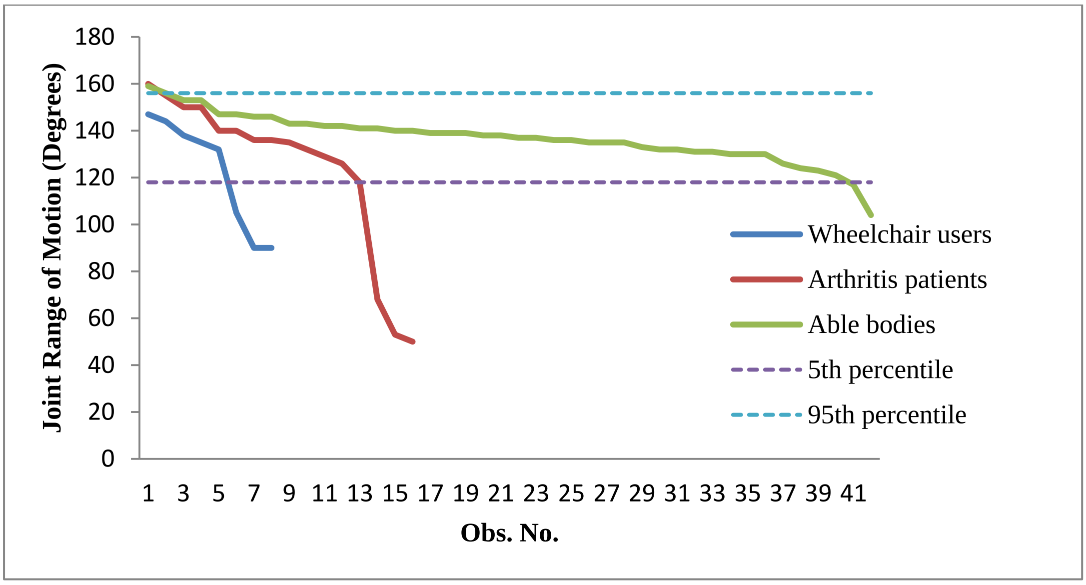


Figure 5.11: JROM variations for elbow flexion among the people with different types of disabilities and its relevance with 5th and 95th percentile design criteria

Elbow supination

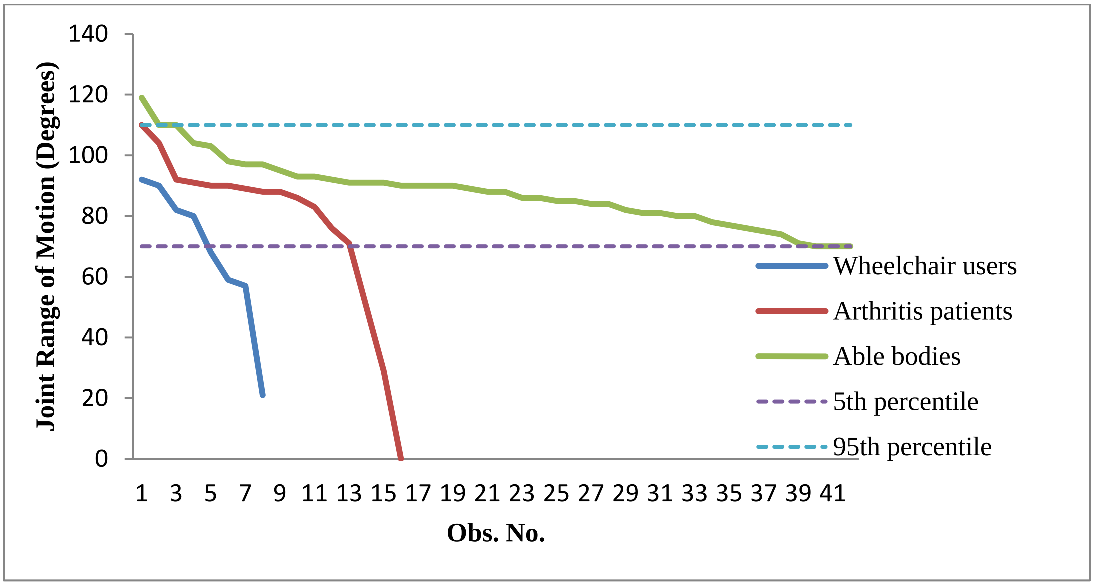


Figure 5.12: JROM variations for elbow supination among the people with different types of disabilities and its relevance with 5th and 95th percentile design criteria

Wrist extension

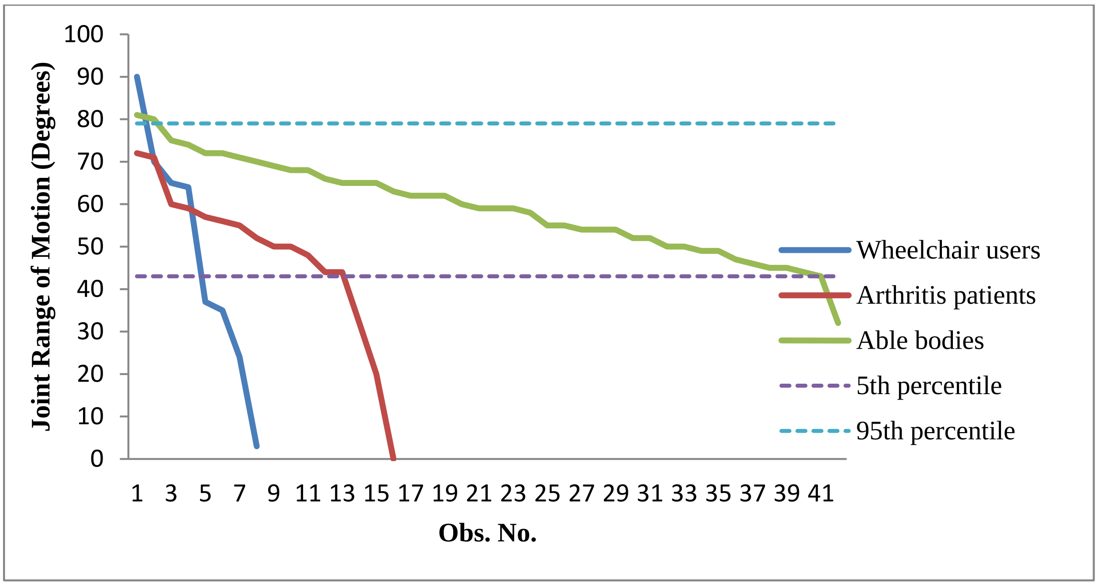


Figure 5.13: JROM variations for wrist extension among the people with different types of disabilities and its relevance with 5th and 95th percentile design criteria

Wrist adduction:

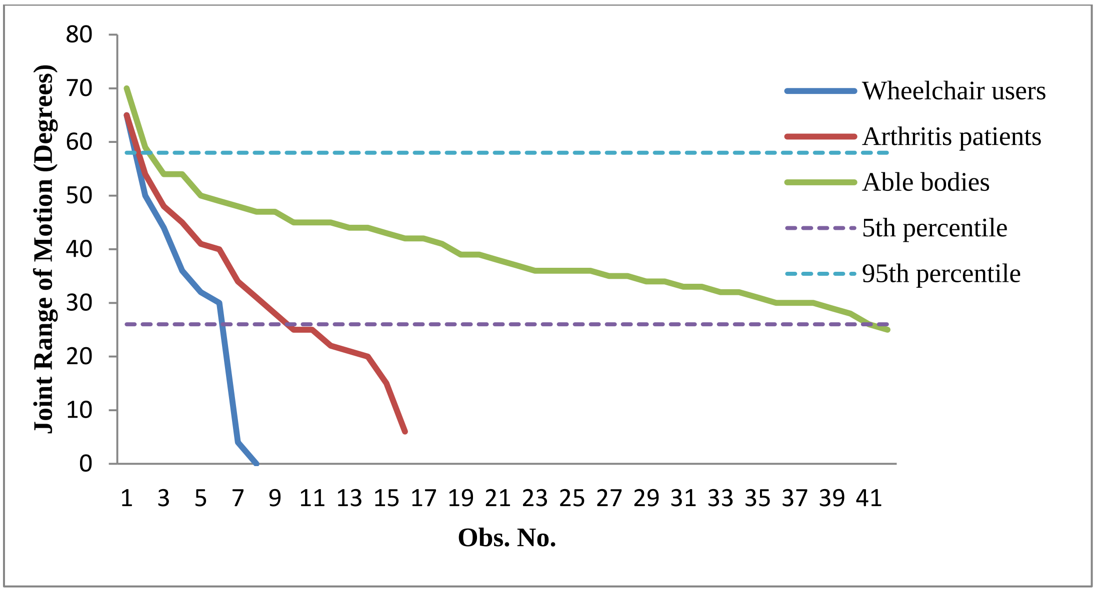


Figure 5.14: JROM variations for wrist adduction among the people with different types of disabilities and its relevance with 5th and 95th percentile design

The 'design for all' or 'inclusive design' philosophy aims to accommodate the design needs of the largest percentage of the population so that 'designed out' scenarios may be minimized. Joint range of motion data influences design decisions made by designers during a design process. Ultimately, these decisions directly affect human work performance; not only in industrial environments but also in the activities of daily living. As far as manufacturing assembly activities are concerned, the majority of the activities require a 'reach' in combination with quick, fast and accurate movements. As highlighted in the previous section, joint mobility is influenced by age and disability, so accommodation of these variations during the design of workplaces or systems becomes significantly important.

Understanding of the factors that influence design decisions, and the quantification of the number of people 'designed out', has always been a challenging part of the inclusive design method. It can be understood by analysing variations within the data that directly or indirectly affect any design decision. It's extremely important to understand and conceptualize these variations before making design recommendations.

This section clarifies these variations in joint range of motion data within a group and in comparison with other groups. Figures 5.4 to 5.14 show joint ROM values (degrees) for individual subjects and their difference from other subjects within the group and in comparison with the subjects of other groups. Moreover, if design criteria are set as the commonly used 5th or 95th percentile, the graphs illustrate the older workers and people with disabilities whom it might be impossible to accommodate. Figures 5.4 to 5.8 show the overall population divided into two groups, one of 20-60 years old and the other of 60-81 years old. The purpose of combining the two age groups used in the previous analysis (20-40 years and 40-60 years) is to analyse and highlight the differences in joint mobility constraints of those people who are likely to be working in an industrial environment (20-60 years) and those who are likely to be retired (60-81 years). Furthermore, the 5th and 95th percentile values were calculated on the basis of joint mobility data of the 20-60 years age group, where the objective was to understand whether or not the design decisions made on the basis of these younger working peoples' joint mobility constraints data are acceptable for older workers (>60 years of age).

Table 5.7: Showing inappropriateness of using 5th percentile value for inclusive design method, accommodating older people

Joint mobility category	Total falling outside of 5th percentile criteria (total population of 42)	Total falling outside of 5th percentile criteria belong to older age group (>60 years of age, 18 people)
Shoulder flexion	8 (19% of total)	7 (39% of older population)
Arm flexion	8 (19%)	7 (39%)
Arm abduction	5 (12%)	5 (28%)
Wrist extension	7 (17%)	6 (33%)
Wrist flexion	5 (12%)	4 (22%)

Table 5.8: Showing inappropriateness of using 5th percentile value for inclusive design method, accommodating people with disabilities like wheelchair users and arthritis patients

Joint mobility category	Total falling outside of 5th percentile criteria (total population of 66)	Total falling outside of 5th percentile criteria belong to disability group (wheelchair users and arthritis patients, 24 in total)
Arm abduction	11 (17% of total population)	10 (42% of the group having people with some disabilities)
Arm lateral rotation	6 (9%)	6 (25%)
Elbow flexion	7 (11%)	6 (25%)
Elbow supination	7 (11%)	7 (29%)
Wrist extension	7 (11%)	6 (25%)
Wrist adduction	10 (15%)	9 (38%)

Table 5.7 clearly indicates how it becomes challenging when designers attempt to include older people in a design process. Designing for the younger population (20-

60 years of age) is relatively easy, as among the 42 there are only 8 persons that might have difficulty in performing any activity that requires a shoulder flexion value more than he/she possesses. However, against the same joint mobility criterion (5^{th} percentile value for 20-60 years of age group), attempts for accommodating older people give many challenges because of lower joint mobility capabilities and some abnormal variations in the data. It is interesting to note that for shoulder flexion 7 out of the total of 18 (table 5.7) people belonging to the older age group (>60 years of age) might be facing difficulty in performing activities and that represents 39% of the older population. More interestingly, for arm abduction all people, whose joint mobility falls outside the 5^{th} percentile criterion, belong to the older population age group. The same trend is followed for arm flexion, wrist extension and wrist flexion, shown in table 5.7.

The same challenge is faced when the 5^{th} percentile criterion for able-bodied people (42 people, 20-81 years of age) is used and it is found difficult to address the design needs of the people with specific disabilities like wheelchair users and arthritis patients. For example, the total number of people unable to match themselves with this 5^{th} percentile criterion are 10 (15% of the total population of 66), and 9 out of these belong to the disability group. This shows that in this situation about 38% of the total population (24 people) belonging to disability group, will not be happy with this, as their joint mobility constraints will restrict them in performing activities that require wrist adduction more than the 5^{th} percentile value for able-bodied people. Table 5.8 clarifies this inclusive design challenge against arm lateral rotation, elbow flexion, elbow supination and wrist extension. It is evident from the data, that at least 25% of the total population belonging to the specific disability groups (wheelchair users and arthritis patients), will not be comfortable in the use of products, services and environments that have been designed against the criterion of 5^{th} percentile joint mobility of able-bodied people (table 5.8)

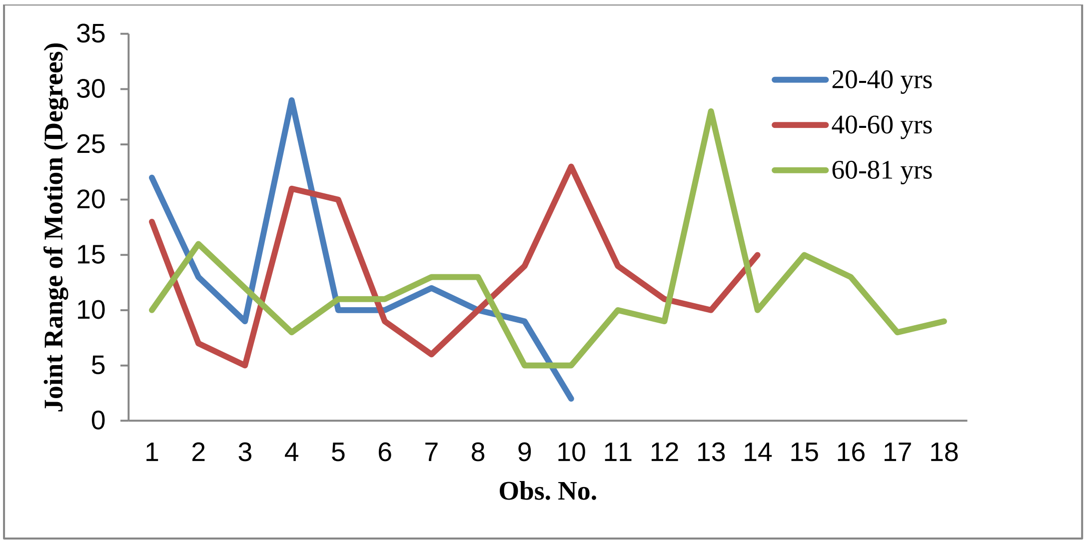


Figure 5.15: Showing the lowest value (Wrist abduction) individual belongs to the younger group (20-40 years)

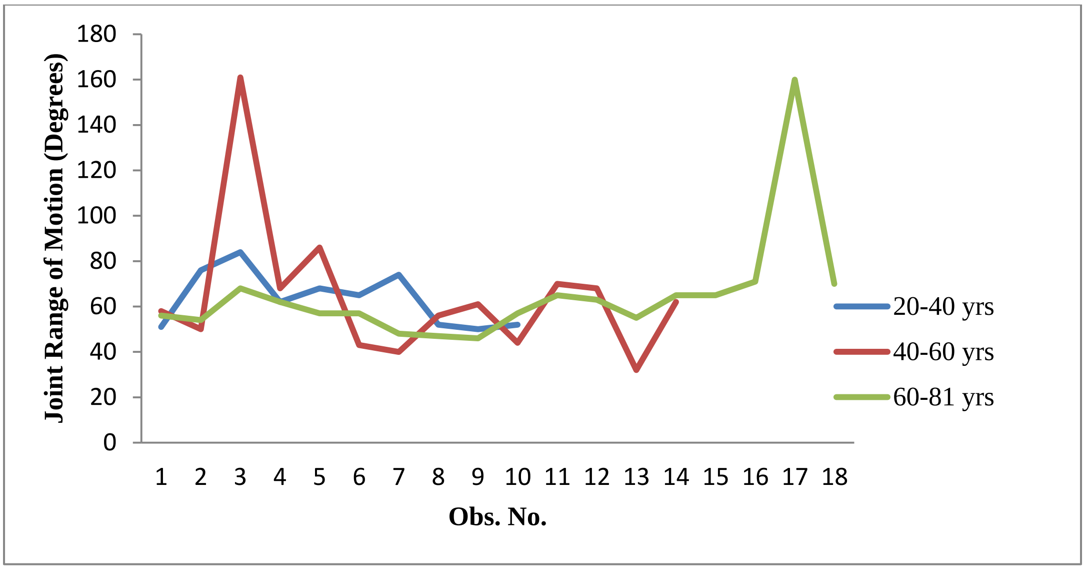


Figure 5.16: Showing two individuals with extra-ordinary joint mobility (arm extension)

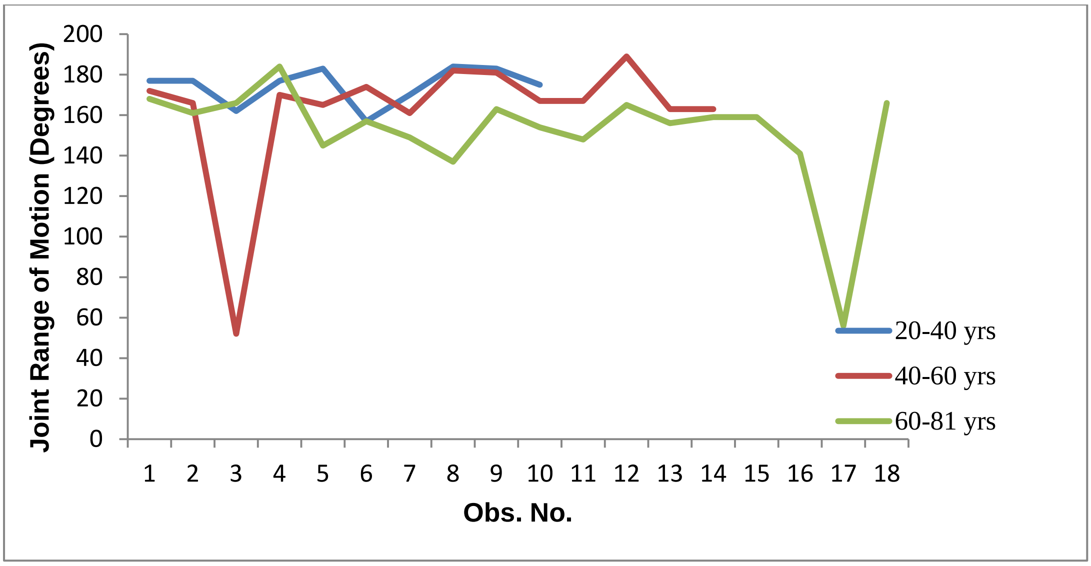


Figure 5.17: Showing effects of individual's very low joint mobility (arm flexion)

It is quite evident from the data that there are a number of subjects which show abnormal trends in their joint mobility. For example, there is an overall decrease in joint range of motion for wrist abduction with age; however, the subject with the lowest value belongs to youngest age group (20-40 years), shown in figure 5.15. Similarly, figure 5.16 shows that there are two subjects in the data with extra-ordinary joint mobility for arm extension and neither belongs to the younger group. Moreover, these differences are so large that these values significantly affect the median values for that group. In the same way, an individual's lower joint mobility capabilities prominently influence overall design decisions, as shown in figure 5.17.

During the design phase, the maximum and minimum values of any decision factor are of prime importance as they provide a criterion that must be fulfilled by the designer. In the light of the above evidence, it can be said that even a very few abnormal values in the data will restrict the designers in reaching design solutions. So, there is always a need to have a deep insight of the data so that these abnormalities and their potential impacts on the design decisions might be understood properly. In a 'design for all' or 'inclusive design' approach, it becomes much more important to understand and address all these issues so that a better decision can be made. In including people with disabilities such as wheelchair users and arthritis patients, it is known that the lower limit of joint mobility for most of the values approaches zero. Zero joint mobility means that if any working activity involves that movement, it will not be feasible for these people. Setting a lower limit of zero joint range of motion closes all options for the designers. Conclusively, a pragmatic design approach is needed to address all these issues so that an inclusive design approach can be rightly understood and promoted.

5.6. Conclusions

This research was conducted to understand and evaluate the difference in joint range of motion for different age groups, genders and people with disabilities like wheelchair users and arthritis patients. In addition, this study also focuses on the understanding of the ‘inclusive design’ method so that the challenges faced by the designers may be addressed. In order to achieve these objectives, the HADRIAN database has been reanalysed where joint mobility data of 66 people belonging to different age groups, genders and the levels of disability has been investigated. It contains total 18 joint ranges of motion values for the upper extremities - the shoulder, arm, elbow and wrist. All these motions are involved not only in most industrial activities but also in activities of daily living. The results reveal that older people and people with disabilities like wheelchair users and arthritis patients face a clear decline in their joint mobility. Age-induced decline for arm abduction, arm medial rotation, arm lateral rotation, wrist flexion and wrist adduction was very significant. Joint mobility of wheelchair users and arthritis patients is considerably lower than fully able-bodied people for arm flexion, arm abduction, arm lateral rotation, elbow flexion, elbow supination, wrist extension and wrist flexion. However, no significant differences have been noted for gender groups, dominant and non-dominant sides of the body.

Furthermore, it was revealed that joint mobility variation within the group and between the groups is quite important in understanding and promoting an inclusive design method. This research provides valuable information about the joint motion capability of a wide range of population that also includes wheelchair users and arthritis patients. These findings can be utilized for the designing of safe and comfortable workplaces, products and services for a wider range of population groups. Moreover, accommodation of an ageing workforce in industrial environments can also be promoted by addressing their design needs proactively, which can ultimately lead to a safe and productive working environment. Lack of information about the physical characteristics and limitations of people with specific disabilities, like wheelchair users and arthritis patients, limits the choice for design solutions. Designers have very limited options for designing products and environments that can be used effectively and safely by these people. Availability of such data becomes very critical and important when thinking about the design of products, services and environments; that are equally good for the able-bodied and those with disabilities. The inclusive design approach aims for the integration of the disabled along with the able-bodied population during the design phase so that a maximum proportion of the population can be accommodated.

Integration of disabled people into working systems is very important so that they can feel themselves an integral part of the society and live their lives independently. However, modern working systems demand a skilful, efficient, hardworking and committed workforce, but working environments are usually designed for the able-bodied. Accommodation of people with some special needs can only be made possible if designers and planners can address the design needs of these people. In this way, they can perform well in a safe and satisfactory way. They will be equally productive as able-bodied workers.

It is known that joint range of motion data is very important because of its use in the design of workstations. As identified above, people with disabilities like wheelchair users and arthritis patients have significantly lower joint mobility as compared to able-bodied people for some specific joints. Any specific activity that involves and requires a specific level of joint mobility can be evaluated at some pre-design phase in terms of whether or not it will be feasible for an individual or a group of people. This joint mobility data can be used for the assessment of already designed workspaces for their suitability for people with some disabilities. In this way, faulty workspaces might be redesigned for these people where they can carry on their professional as well as daily living activities.

This is clear from the above discussion that varying work performing capabilities influence one’s ability to do work. Next chapter will be explaining the effect of individual factors like skill and experience on task performing strategies in terms of the level of risk attached. For that purpose, a case study at a furniture manufacturing industry has been conducted and discussion is made on the results.

Chapter 6

Investigation and Comparison of Ergonomic Risk Assessment for a Diverse Workforce in Manufacturing Industry

6.1. Introduction

This chapter mainly focuses on the investigation and comparison of ergonomics-based risk assessment for a diverse workforce where the level of the individual's work performing skill has been used as a criterion. The objective of this investigation was to understand whether or not human work performing skill influences working strategies, whether or not working strategies are influenced by skill and how much risk is involved with any adopted strategy. Finally, how skill plays its role regarding workplace safety and human well-being was investigated.

Section 6.2 explains the background context of the factors affecting risk at work and also describes the causes and effects of work related musculoskeletal disorders. The next section (6.3) briefly explains the step-by-step method used to achieve the aim of the study. Section 6.4 demonstrates the results in detail – divided into two main categories of differences in object handling strategies and differences in working strategies and their impact regarding the adoption of working postures. On the basis of these results, section 6.5 suggests some general recommendations that might be considered useful for the promotion of more human friendly work practices. Finally, section 6.6 draws some conclusions of the case study.

6.2. Factors affecting risk at work

The rates of injuries at work have reduced substantially over the past decade (H.S.E., 2011). However, still an estimated 603, 000 workers had an accident at work in 2010/11. Moreover, about 200, 000 of these injuries result in more than 3 days absence from work and 150,000 in an absence of more than 7 days (Figure 6.1) and nearly two million working days were lost due to handling injuries and slips and trips. Handling injuries are found to be the most commonly reported kind of accident at work. Estimates highlight that manufacturing industry jobs accounted for about 10% of the British workforce, but 21% of fatalities and 15% of reported injuries to employees in 2010/11. Moreover, 1.9 million lost working days (0.73 days per full-time equivalent worker) due to self-reported work related illness or workplace injuries were estimated for manufacturing industry in 2010/11 (H.S.E., 2011)

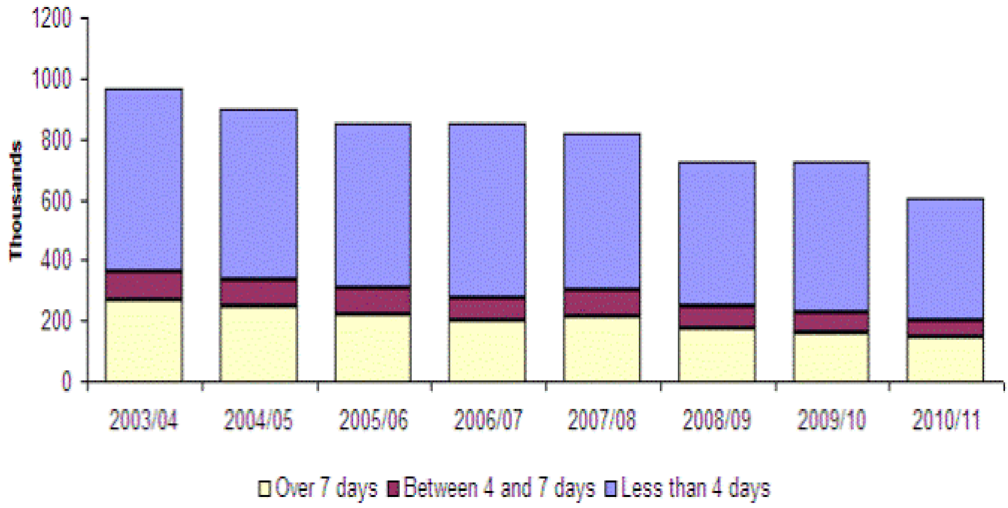


Figure 6.1: Self-reported non-fatal injury amongst people who worked in the last 12 months, by absence duration (HSE, 2011)

Similarly, Bureau of Labor Statistics (B.L.S) in the U.S.A. indicates that nearly 3.1 million non-fatal workplace injuries and illnesses were reported in private industries (for full time workers) during 2010. This result in an incidence rate of 3.5 cases per 100 full-time workers compared with the rate of 3.6 reported in 2009. Statistics also show that this trend of decline in incidence rate has been evident since 2002. However, manufacturing industry is the only private sector that has experienced an increase in the incidence rate of injuries and illness in 2010 (4.4 cases per 100 full-time workers) as compared with the previous year (4.3 cases per 100 full-time workers). It is important to mention that the manufacturing industry sector accounted for over 30% of all private industry occupational cases reported in 2010. The health care and social assistance along with service providing industries contributed 24.2 % of all private industry illness cases and experienced an incidence rate of 30.2 cases per 10,000 full-time workers in 2010 – down from 34.8 cases in 2009. The Health care and social assistance sector shows an incidence rate of injuries and illness of 5.2 cases per 100 full-time workers, against 5.4 cases in 2009. Interestingly, about 820,300 injuries and illness cases were reported among state and local government workers in 2010, with a rate of 5.7 cases per 100 full-time workers; which is significantly higher than that of (3.5 cases per 100 full-time workers) in the private industry sector (B.L.S., 2010). Previously, it was mentioned by the Research Council and Institute of Medicine (2001) that musculoskeletal disorders of lower back and upper extremities are an important and costly health problem, where these disorders account for about 70 million physician office visits in the United States annually. Moreover, nearly 1 million people were affected by work related musculoskeletal disorders and took time away from work for treatment and recovery. Estimates show that an economic burden between $45 and $54 billion (annually) was incurred due to lost wages, compensation costs and lost productivity, during 1999 (Research Council and Institute of Medicine, 2001).

Organizations start to seriously think about the prevention of work-related musculoskeletal disorders (WRMSDs) where it becomes necessary to highlight major risk factors causing these disorders. The risk factors are multifactorial; however, these factors can be classified into three main categories: individual, physical and psychosocial/organizational (Kee and Karwowski, 2007).

Physical demands of work are considered a major reason for work related musculoskeletal disorders (WRMSDs) in different working areas. Many studies have been conducted to find for the causes of these WRMSDs in different types of industries. For example, construction industry workers are exposed to high risk of WRMSDs because of the physical demands of work such as manual material of handling, awkward postures, and use of vibrating tools (Latzaa et al., 2000; Sobeih et al., 2006). Some other studies conclude that in the health care sector, activities like transferring patients, lifting and positioning are the typical activities that involve high physical demands and are linked with injuries to nurses and WRMSDs (Simon et al., 2008; Engels et al., 1996). In the same way, many manufacturing activities still consist of manual activities and are associated with heavy physical workload, harmful working postures and complex and highly repetitive body movements. These working conditions lead to WRMSDs that affect organizations in terms of lower quality, reduced productivity, increases in the cost of wage compensation and medical expenses (Karwowski and Marras, 2003; Chaffin et al., 2006). Another study conducted by Wassell et al. (2000) concludes that load lifting and moving are the main causes of back injuries in transport and retail sector organizations (Wassell et al., 2000). Generally, it is believed that poor working postures, repetitive actions, high peak loads, static load, vibration, stress and work pace are the most common physical factors which are responsible for WRMSDs in industry (Pinzkea and Kopp, 2001; Keyserling et al., 1988; Ryan, 1989; Aarås et al., 1988). The Bureau of Labour

Statistics (2007) concluded that the trunk and upper extremities are mainly linked with high prevalence of WRMSDs, where hands, wrist, shoulder and lower back are mainly exposed to risk during work. It was further noted that lower back pain or injuries are the main cause of absence from work (B.L.S., 2007).

In recent years, researchers have paid more attention to psychosocial factors at work that can account for risk at work and ultimately be converted into WRMSDs. Lacey et al. (2007) investigated the relationship of piecework with musculoskeletal pain and perceived workplace psychosocial factors. It was found that piecework system workers were more likely to feel limb pain and experience an adverse psychosocial working environment. It was further found that the perceptions of little job control, little supervisory support and high physical demands of such work result in poor general health and well-being of workers that can be improved by modifying workplace psychosocial factors like improved work organization and management. Sobeih et al. (2006) reviewed literature where the objective was to investigate a linkage between psychosocial work factors and musculoskeletal disorders among construction industry workers. Eight cross-sectional and two cohort studies were reviewed. It was concluded that WRMSDs among construction workers were associated with psychosocial factors like high job stress, job dissatisfaction, lack of job control and high quantitative job demands. It was further found that many associations were still significant even after an adjustment of some important factors like physical demands of work and demographics. This shows the complexity of the issue as many psychosocial factors are associated with musculoskeletal disorders in many different ways (Sobeih et al., 2006). Similarly, analysis shows that back or neck pain related disability has pronounced association with psychosocial work factors of nursing staff in hospitals, homes and home care (Simon et al., 2008). Other case study investigations add to this growing body of evidence, where nursing staff at Chinese hospitals were observed. Evidence shows that high mental pressure and inadequate work support contribute significantly towards musculoskeletal complaints (Smith et al., 2004). Some other factors like low rewards, lack of social support, lack of autonomy and the perception of an insufficient safety climate are also related with work-related musculoskeletal complaints (Smith et al., 2004, Sobeih et al., 2006, Hofmann and Mark, 2006, Hollman et al., 2001, Stone et al., 2007).

True conceptualization of the meanings of individual factors has always been a challenge as meanings are different to different people. More recently, reports from the National Research Council (NRC) and Institute of Medicine (IOM) have defined the factors thought to affect individual or personal responses to workplace exposure, and thought of as physiological and psychological attributes (NRC/IOM, 2001). Cole and Rivilis (2004) listed a distribution of factors, measured at the individual level and their potential underlying constructs (Table 6.1) (Cole and Rivilis, 2004).

They listed nine individual factor types like demographics, age, work, anthropometry, psychological, lifestyle, and comorbidity, past history and social, that affects the individuals in different ways. For example, social factors like economic conditions (poverty), minority and race, and divorced-widowed can construct lower level of support.

Table 6.1: What do individual factors represent? (Cole and Rivilis, 2004)

Usual naming of factor types	**Individual factor(s)**	**Potential construct(s)**
Demographic	Gender, Different tasks, capacities and reactions to stress, all resulting in different exposures	Differential labour market
Age	Cumulative exposure	Decreased tolerance, Different skills and experience
Work	Work-style	Different biomechanical exposures
Anthropometry	Height and weight	Mismatch between equipment and person, Differential tissue demands
Psychological	Personality	Differential kinematics Differential coping capacity
Lifestyle	Physical activity, hobbies, sports Smoking, drugs	Additional loads or physical exposures, Additional exposures
Comorbidity	Diabetes, pregnancy Distress, depression	Additional internal exposures Altered biochemistry, different pain perception threshold
Past history	Episode of MSK disorder	Lower tolerance
Social	Divorced–widowed, Minority race, Poverty	Lower social support, Discrimination, Complex socio-health contexts

Because of the multifactorial nature of WRMSDs, there has been much discussion to correlate and determine a relationship between indices and the prevalence of work related musculoskeletal disorders with individual's work factors like age, gender, anthropometry, work strategy, hobbies, physical activities outside work etc. It was concluded that individual factors influence a person's response to different risk factors in the workplaces and elsewhere. However, these factors and their underlying constructs may contribute to prevalence of MSDs in a variety of ways (Kerr, 2000, Cole and Rivilis, 2004, Wahlström, 2005).

It is noted that traditional working practices in manufacturing and service industries usually assign tasks with repetitive movements, lesser physical demands and high work pace to women. On the other hand, men are often found to work with extreme physical demands and low levels of repetitiveness. Punnett and Herbert (2000) conducted research to find a relationship between work-related musculoskeletal disorders and gender. They compared MSD ratios for females to male and reported that the gender ratio was close to 1 for back pain; it was 2 or higher for upper extremity disorders and female are more likely to leave work due to work-related MSDs. This difference might be due to non-occupational factors like household work, muscular strength, health care seeking behaviour, and recreational activities etc. (Punnett and Herbert, 2000). In 2004, Treaster and Burr reviewed literature to determine whether or not gender differences affect upper-extremity musculoskeletal disorders. Articles were reviewed from both general and working population perspectives and it was concluded that women had significantly higher chances of upper-extremity musculoskeletal disorders as compared with men. This same trend has been found in studies based on self-reporting and plant/workers compensation records (Treaster and Burr, 2004). Similar kinds of findings have been concluded by Wahlström (2005), where a review of the literature concluded that the same difference in the prevalence of MSDs regarding the use of visual display units (VDU) exists (Wahlström, 2005). In another study conducted on Swedish VDU users, it was noticed that women are more exposed to physical and psychosocial risk conditions at work (Karlqvist et al., 2002). However, in a few studies such as Hooftman et al. (2009), no gender differences regarding the prevalence of musculoskeletal disorders among workers was reported and it is thought that men and women are equally vulnerable to risk factors at work (Hooftman et al., 2009). There are many studies showing the effects of differences in working techniques and their potential impact on risk exposure of workers using VDUs (Visual Display Units) during their work. It has been found that individuals with poor working techniques have to work with a higher level of risk exposure in the forearm, shoulder and wrist (Lindegård et al., 2003; Aarås et al., 1997; Karlqvist et al., 1998). Some other studies also highlight the importance of working techniques with relevance to risk exposure of workers in different working environments (Palmerud et al., 2012; Kilbom and Persson, 1987). Guo et al. (2004) concluded on the basis of a nationwide survey in Taiwan, that gender, age and education level have significant association with MSDs and found that many body parts like the back, neck, shoulders, hands and wrists are commonly affected. Construction and metal industries were among the top ten where MSDs affect multiple body parts.

Like gender, age is also considered a contributing factor to work-related musculoskeletal disorders. A study conducted over 256 workstations on an assembly line for a middle range car manufacturing company, concluded that older workers usually like to work on jobs with low workload. Age and strain are not independent variables and head-neck-shoulder symptoms occur more frequently in older workers as compared with younger ones (Landau et al., 2008). In 2005, Aittomäki et al. addressed the question of interaction between age and workload and found that older public sector personnel like less physically demanding work. The results also suggested that for physically demanding tasks, work-related ailments are more common in women as compared to men (Aittomäki et al., 2005). In spite of the fact that physical work capacity of an individual declines with age, still about 50%, 30% and 15-20% of older workers (aged 45 or more), were exposed to repetitive work, harmful working postures and handling of heavy loads respectively in the 15 European Union member states (Paoli, 1997). Furthermore, the prevalence of musculoskeletal disorders, between the age of 51 and 62, may increase up to 15% and may have more serious implications for workers handling work with high physical demands (Ilmarinen, 2002). Many studies indicate that older workers suffer from more serious but less frequent workplace injuries and illnesses than younger workers and these can be prevented by understanding and anticipating the consequences of reduced physical and cognitive abilities to perform any work. Moreover, promotion of age-friendly workplaces and environments may lead to higher productivity, competitiveness and sustainable business practices (Silverstein, 2008). Welch at al. (2008) investigated the interaction of age with work limitations, musculoskeletal disorders and physical functioning on 1000 construction roofers, between the ages of 40 and 59. Data analysis revealed that old age has an association with medical conditions and reduced physical functioning that is related to musculoskeletal disorders (Welch et al., 2008)

On the other hand, Pransky et al. (2005) found that residual symptoms of injury have a lesser relationship with older workers as compared to younger workers, and workers over 55 years of age are more contented than those in the cohort of under 55 (Pransky et al., 2005). Low back injuries are the most commonly reported injuries among material handlers where effects of age in relevance with these are conflicting. In a cohort study, a total of 2152 reporting low back injuries were investigated and it was concluded that there is no significant evidence about the association of age and low back injuries. Moreover, it was revealed that a higher proportion of workers over the age of 55 lost work time because of their injuries, and workers over 45 had a higher average number of lost workdays per injury (Peek-Asa et al., 2004)

Differences in working techniques also play an important role in exposing workers to risk factors. To highlight the effects of an individual's work techniques and their association with risk factors a study was conducted on 79 highly structured jobs in an engine assembly plant. It was noticed that different workers like to perform their work in significantly different ways, especially when they have an option to adopt a work method of their own choice. Because of these work method variations, significant differences (at 57 out of 79 workstations) in the use of lower body postures were noticed (Keyserling et al., 2010). As discussed earlier, women are more commonly exposed to musculoskeletal disorders. To explore the evidence of difference in work techniques between men and women, a cross-sectional case study was conducted in a metal industry where data was collected for men and women performing the same task within the same industry. Results revealed that women perform their work in different ways as compared with men. For example, they worked more frequently with their hands at above shoulder level than men, and this is considered a risk factor for neck and shoulder disorders (Dahlberg et al., 2004).

Another concept similar to 'work technique' is' work style', which is conceptualized as a multidimensional stress response to work, where physical, physiological, behavioural and cognitive factors play their role in responding to stress. A number of articles have been published on the importance of work style, especially for computer users, where it has been concluded that wrist postures, speed of movements, and applied forces while keying are the variables that are considerably different for different people because of the change in their work style (Feuerstein, 1996; Feuerstein et al., 1997; Haufler et al., 2000)

In the light of the above discussion, it can be concluded that humans are different in their physical, physiological and cognitive abilities and they respond differently to physical, psychosocial and organizational factors regarding their risk exposure during work. Moreover, these changes lead them to perform similar work tasks in entirely different ways. Very little has been suggested about the solution of these issues. It becomes more significant when the global workforce is becoming diversified and consequently these variations will be more prominent in future. This chapter focus on human variability issues with reference to potential variations in working strategy and their impact on risk exposure of workers having different levels of skill and experience and performing similar kind of manufacturing assembly activities. This study will also provide a guideline towards the implementation of an inclusive design strategy that can potentially address these variability issues and be used to promote design solutions that are equally acceptable for a diverse workforce.

6.3. Method

For understanding human variability issues with reference to variations in work performing strategies and the level of risk attached with them, 12 workers with different level of skills have been selected at a furniture manufacturing industry and observed at different work stations. They were divided into three teams (each team consists of 4 workers working on 4 different work stations) on the basis of their level of skill. These teams were identified as specialized workers, multi-skilled workers and semi-skilled workers. Their skill levels were categorized by experts at the organization. Specialized workers were those who were excellent at their specialized jobs and used to performing their job activities at the same workstation. They prefer to perform similar kinds of activities during assembly activities of a variety of sofa models. Conversely, multi-skilled workers belong to that group of workers who are considered flexible in their job rotation; however, they are considered equally productive against similar job activities at different workstations. Semi-skilled workers are rated as significantly less skilled when compared to specialized and multi-skilled workers.

A problem was faced in the video recording of older workers due to legislative issues that do not allow discrimination of older workers. Because of this the human relations department of the collaborating company was unwilling to share data about workers' ages. As an alternative another important type of diversity, that of 'skill', was used differentiate workers' performance, and consequently the focus was on the level of skill rather than age during data collection.

All these workers were video recorded at least five times for a single activity consisting of a variety of manual assembly task elements. For the purpose of understanding basic differences in working strategies, all workers have been recorded against the same model of sofa. Task completion time has not been considered and their task performing strategies were evaluated on the basis of established ergonomic evaluation criterion. For this study, OWAS and REBA methods were used for risk assessment. Recorded videos have been analysed and 764 snap shots were taken for analysis purposes and 706 were finally selected for risk assessment analysis. The method of this study can be divided into six main categories, as shown in figure 6.2.

The OWAS (Ovako Working Posture Analysing System) and REBA (Rapid Entire Body Assessment) are postural analysis systems which are used to identify and highlight the sensitivity and level of MSDs attached with any adopted posture during work. These collect information about postures of different body parts like back, arms, legs, neck and load handled and provide an estimate of the level of risk of MSDs attached and suggests actions against them. These action categories simply provide the information about risk level and what is the necessity of corrective actions from not necessary to necessary now.

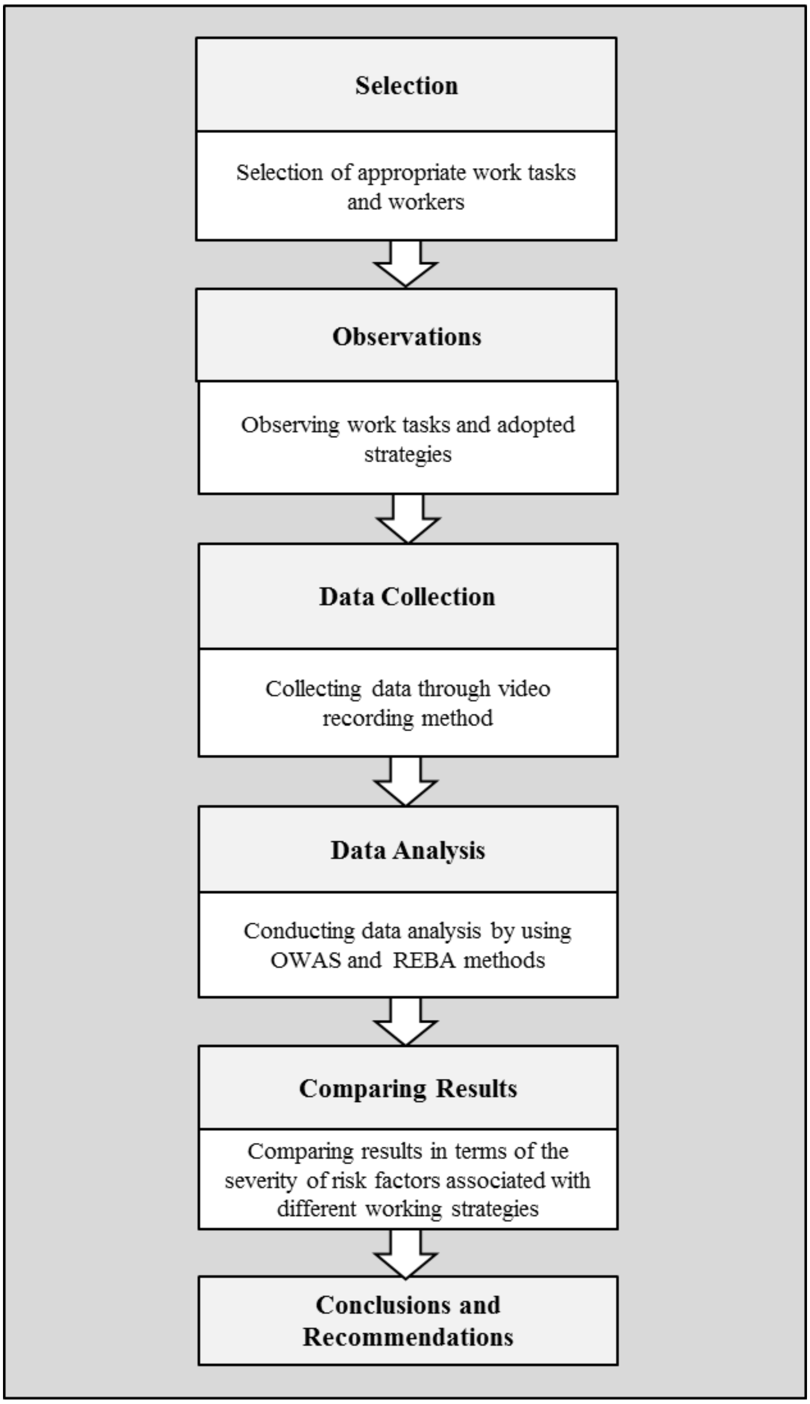


Figure 6.2: Flow diagram: Method of study for an 'Inclusive Design' approach to workplace design, based on differences in task performing strategies

6.3.1. Selection of appropriate work tasks and workers

Selection of appropriate work tasks and workers is significantly important as the objective of the study was to address human variability issues, work technique variations and their potential impact on work performance in terms of productivity, quality and human well-being. Selection of an inappropriate task may lead to some unrealistic findings and finally end up with no benefits. In this study, selection of the workers was made on the basis of their level of skill and experience, so that an understanding of working strategy variations affected by the level of skill and experience could be captured. Moreover, appropriate selection of work tasks is equally important, so that variations in task elements might be addressed properly. Tasks with low levels of difficulty may not show the variations that are being sought. Inappropriate selection of work tasks may lead to a useless exercise that contributes nothing in terms of suggesting solutions for a diverse workforce,. For this study, four work stations were selected where furniture manufacturing assembly tasks of a reasonable level of complexity were performed.

6.3.2. Observations

It is extremely valuable to observe workers and their working strategies in a pilot study where it can be observed whether or not the proposed method of data collection will be useful and experimental needs are met before starting data collection. At this stage, workers are observed and recorded in the actual working environment for a short time, so that the needs of the experimental setup can be investigated and modified accordingly. In this study, observers held group discussions and interviews with workers concerning difficulties and problems with their current working practices, possible causes of their injuries and illnesses, and their suggestions for improvements. These group discussions and interviews helped in developing a friendly and participatory working environment. During this phase, a prototype study was conducted where a few workers were recorded for a short period of time. These video recordings were critically analysed before the start of actual data collection.

6.3.3. Data collection

Data collection consists of video recording selected workers for a variety of tasks at different work stations. Workers were selected on the basis of their levels of skill, where the criteria for their selection was as under:

Specialized workers: Those who are well trained for specialized (selected) tasks, with a company skill rating of at least 100

Multi-skilled workers: Those who are trained to work on different workstations with similar activities, and with rating of at least 100

Semi-skilled workers: A category of workers who are not well trained for selected jobs and have ratings less than 100

For this purpose, 12 workers with different level of skills (4 in each category) were recorded on 4 work stations. Each worker was recorded at least 3-4 times against the same task elements. An appropriate distance between the recording device (camera) and worker/workstation was maintained so that the recorded videos could show working postures and process sequences in a clear way. Keeping in view the complexity of task and variations in work performing methods, a few activities were recorded from different angles.

6.3.4. Data analysis

This step contained an in-depth analysis of all data collected in the form of videos and snap shots of workers performing their job activities in the actual working environment. Recorded videos were watched and snap shots of different working postures showing the difference in working strategies of workers were taken for making a comparison of variations in their work method for similar kinds of work. Selected postures were analysed to access the level of risk involved in any adopted strategy. Risk exposure was estimated through OWAS and REBA methods, where codes are generated on the basis of work postures on back, arms, legs, neck and load being carried. As mentioned earlier, this study aimed to compare postural loading of a set of workers having different levels of skill and adopting different working strategies. The purpose of using these two techniques was only to verify the conclusions from both techniques, that help in answering the question whether or not differences in working strategies influenced by the level of skill affect work risk exposure. A detailed description of these methods is given below:

6.3.4.1. OWAS method

The OWAS method (Ovako Working Posture Analysing System) was firstly developed by a Finnish Steel Company. It collects information about worker postures of the back, arms, legs and load handled (force applied). OWAS classifies postures of the back into four categories, arms into three, legs into seven and three for force applied or weight handled. Different combinations of these four categories provide an opportunity to estimate the degree of their impact on the musculoskeletal system. It has 252 (4 x 3 x 7 x 3) postures and load combinations, where each posture is identified by a four digit code (Karhu et al., 1977; Karhu et al., 1981). For example, code 2351 shows 2 for back posture, 3 for arm posture, 5 for leg and 1 for load being handled. The observer has to identify this four digit code by defining four digits showing each posture category (for back, arm, leg and load) adopted by the worker during the work. A video image of each task element was used for defining these codes. Table 6.2 shows the description of position against the OWAS code, whereas, table 6.3 demonstrates different posture combinations with respect to the action categories. First two columns on the left show posture codes for back and arms; whereas, two rows on the top shows combinations for legs and load handled. A four digit code constructed after a combination of back, arms, legs and load handled categories, gives us a number in the table that describes the action needed against a posture. As mentioned above, if any posture combination identifies high risk for musculoskeletal system, it will belong to a higher action category, which states the urgency of a corrective action. These four action categories and their relationship with urgency for corrective action are described in table 6.4

Table 6.2: OWAS postures code definition (Karhu et al., 1977; Karhu et al., 1981; Karwowski and Marras, 2003)

Body parts	OWAS code	Description of position
Back	**1**	Back straight
	2	Back bent
	3	Back twisted
	4	Back bent and twisted
Arm	**1**	Both arms below shoulder level
	2	One arm at or above shoulder level
	3	Both arms at or above shoulder level
Leg	**1**	Sitting
	2	Standing on both straight legs
	3	Standing on one straight leg
	4	Standing or squatting on both feet, knees bent
	5	Standing or squatting on one foot, knee bent
	6	Kneeling on one or both knees
	7	Walking or moving
Load handle	**1**	Load < 10kg
	2	10 < Load < 20kg
	3	Load > 20kg

Table 6.3: Action category for each individual OWAS classified posture combination

Back	Arms	1			2			3			4			5			6			7			Legs
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	Load
1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	
	2	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	1	1	1	1	1	1	
	3	1	1	1	1	1	1	1	1	1	2	2	3	2	2	3	1	1	1	1	1	2	
2	1	2	2	3	2	2	3	2	2	3	3	3	3	3	3	3	2	2	2	2	3	3	
	2	2	2	3	2	2	3	2	3	3	3	4	4	3	4	4	3	3	4	2	3	4	
	3	3	3	4	2	2	3	3	3	3	3	4	4	4	4	4	4	4	4	2	3	4	
3	1	1	1	1	1	1	1	1	1	2	3	3	3	4	4	4	1	1	1	1	1	1	
	2	2	2	3	1	1	1	1	1	2	4	4	4	4	4	4	3	3	3	1	1	1	
	3	2	2	3	1	1	1	2	3	3	4	4	4	4	4	4	4	4	4	1	1	1	
4	1	2	3	3	2	2	3	2	2	3	4	4	4	4	4	4	4	4	4	2	3	4	
	2	3	3	4	2	3	4	3	3	4	4	4	4	4	4	4	4	4	4	2	3	4	
	3	4	4	4	2	3	4	3	3	4	4	4	4	4	4	4	4	4	4	2	3	4	

Number 1 to 4 in the box show the OWAS Action Category

Table 6.4: The OWAS action categories for prevention (Karhu et al., 1977; Karhu et al., 1981; Karwowski and Marras, 2003)

Action Category	Explanation
1	Normal and natural posture with no harmful effect on the musculoskeletal system - No action required
2	Posture with some harmful effect on the musculoskeletal system – Corrective actions required in the near future
3	Postures have a harmful effect on the musculoskeletal system – Corrective actions should be done as soon as possible
4	The load caused by these postures has a very harmful effect on the musculoskeletal system – Corrective actions for improvement required immediately

The OWAS method is used to assess the area of discomfort by analysing postures during work. Research shows the usefulness of this postural assessment technique in several occupational settings, including automotive, construction, agriculture, hammering tasks, nursing and poultry industry. OWAS analyses are able to detect the level of discomfort and risk involved in any working strategy and suggest recommendations for improvement and corrective measures on work redesign, work environment, equipment used at work and correct working postures, to minimize WRMSDs (Karhu et al., 1977; Mattila et al., 1993; Engels et al., 1994; Scott and Lambe, 1996; Karwowski and Marras, 2003; Nevala, 1995).

6.3.4.2. REBA method

Like OWAS, the REBA (Rapid Entire Body Assessment) is also a postural analysis system that is used to identify the sensitivity of musculoskeletal risk involved in working postures. Postural risk assessment in REBA is also based on a postural classification scheme including scores for upper arms, lower arms, wrist, trunk, neck and legs. The method also accommodates the extent of external forces/loads applied, muscular activity caused by static, dynamic, rapidly changing or unstable postures and the coupling effect. Tables (6.5 - 6.10) below show the type of movement with position of a particular body part and score based on the level of risk involved in that task. Table A (6.11) shows a combination score obtained by looking at scores gained by trunk, neck and legs and table 6.12 shows scores for load/force applied, whereas Table B (6.13) identifies a new score attained by the combination codes of upper arm, lower arm and wrist and table 6.14 describes different types of couplings like good, fair, poor and unacceptable. Similarly, table C (6.15) provides a final score that is calculated by adjusting the scores A and B into table C and table 6.16 presents activity scores based on the type of the movements of body parts, task repetitiveness and sudden changes in the postures. Moreover, score adjustments due to load, coupling and effects on muscular activity due to static, dynamic or changing postures are made after calculating scores from table A, B and C accordingly. Unlike OWAS, REBA provides five action levels that show the level of corrective action based on the level of severity of any adopted working posture (table 6.17) (Hignett and McAtamney, 2000). Janowitz et al (2006) developed and validated a revised REBA schema for assessing physical demands of heterogeneous jobs in hospitals. It was further highlighted that the REBA provides a mechanism for recording postures of virtually all parts of the body, excluding the position of foot and ankle that are considered key components associated with hospital settings, in particular tasks commonly associated with computer use and other office tasks (Janowitz et al., 2006). Initially, researchers found a 62-85% agreement on scoring various postural conditions by using REBA, except for the upper arm category (Hignett and McAtamney, 2000).

Table 6.5: Group A, positions and scores for trunk

Movement	**Score**	**Change score**
Upright	1	+1 if twisting or side flexed
$0^0 – 20^0$ flexion **$0^0 – 20^0$ extension**	2	
$20^0 – 60^0$ flexion **> 20^0 extension**	3	
> 60^0 flexion	4	

Table 6.6: Group A, positions and scores for neck

Movement	**Score**	**Change score**
0^0 – 20^0 flexion	1	+1 if twisting or side flexed
> 20^0 flexion or extension	2	

Table 6.7: Group A, positions and scores for legs

Position	**Score**	**Change score**
Bilateral weight bearing, walking or sitting	1	+1 if knee(s) between 30^0 and 60^0 flexion
Unilateral weight bearing, feather weight bearing or an unstable posture	2	+2 if knee(s) are >60^0 flexion (not for sitting)

Table 6.8: Group B, positions and scores for upper arms, lower arms and wrist

Position	**Score**	**Change score**
20^0 extension to **20^0 flexion**	1	+1 if arm is: ➢ Abducted ➢ Rotated
>20^0 extension **20^0-450 flexion**	2	
45^0 – 90^0 flexion	3	+1 if shoulder is raised
>90^0 flexion	4	-1 if leaning, supporting weight of arm or if posture is gravity assisted

Table 6.9: Group B, positions and scores for lower arms

Movement	**Score**
60^0-100^0 flexion	1
< 60^0 flexion or **> 100^0 flexion**	2

Table 6.10: Group B, positions and scores for wrist

Movement	**Score**	**Change score**
0^0 – 15^0 flexion/extension	1	+1 if wrist is deviated or twisted
>15^0 flexion/extension	2	

Table 6.11: Table A (scores after combining trunk, neck and legs scores)

Trunk		Neck											
		1				2				3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
1		1	2	3	4	1	2	3	4	3	3	5	6
2		2	3	4	5	3	4	5	6	4	5	6	7
3		2	4	5	6	4	5	6	7	5	6	7	8
4		3	5	6	7	5	6	7	8	6	7	8	9
5		4	6	7	8	6	7	8	9	7	8	9	9

Table 6.12: Load/Force scores

Load/Force			
0	1	2	1
<5kg	5-10kg	>10kg	Shock or rapid build-up of force

Table 6.13: Table B showing scores after combining lower arm, upper arm and wrist scores

		Lower arm					
Upper arm		1			2		
	Wrist	1	2	3	1	2	3
1		1	2	2	1	2	3
2		1	2	3	2	3	4
3		3	4	5	4	5	5
4		4	5	5	5	6	7
5		6	7	8	7	8	8
6		7	8	8	8	9	9

Table 6.14: Coupling

0	1	2	3
Good	Fair	Poor	Unacceptable
Well-fitting handle and a mid-range, power grip	Hand hold acceptable but not ideal or coupling is acceptable via another part of the body	Hand hold not acceptable although possible	Awkward, unsafe grip, no handles. Coupling is unacceptable using other parts of the body

Table 6.15: Table C, combining score A and Score B

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

Table 6.16: Activity scores

+1 1 or more body parts are static, e.g. held for longer than 1 min

+1 Repeated small range actions, e.g. repeated more than 4 times per min (not including walking)

+1 Action causes rapid large range changes in postures or an unstable base

Table 6.17: REBA action levels

Action level	REBA score	Risk level	Action (including further assessment)
0	1	Negligible	None necessary
1	2-3	Low	May be necessary
2	4-7	Medium	Necessary
3	8-10	High	Necessary soon
4	11-15	Very high	Necessary now

6.3.5. Identification of the awkward working postures and results comparison

The results from the above exercise identify the level of risk involved with any adopted posture and the final action categories of OWAS and REBA provide guidelines about which body segment is being discomforted. Both methods have been used to provide greater detail about the level of risk involved with any adopted strategy. The level of action category in both methods gives guidelines to the observer as to whether or not any adopted working strategy is harmful and if it is harmful, what level of urgency it demands. Action categories 3 and 4 identify high levels of risk and demand action as soon as possible and immediate corrective actions respectively. In particular, this study provides information about the influence of the level of skill involved in musculoskeletal disorders based on the difference in working strategies. It is also possible to analyse whether the results of both methods are showing the same or different relationships between the levels of skill, adopted working strategy and musculoskeletal disorders. Furthermore, it identifies which body part is exposed to risk more frequently and what level of risk is involved.

6.3.6. Recommendations for an optimal working strategy

As mentioned earlier, this study includes a variety of workers where individual's working strategies for the same task element are captured and then an ergonomics risk assessment is carried out. After identifying awkward working postures, the observer can easily conclude from the results which method is more appropriate and friendly. Furthermore, the least harmful working method is taken as a recommended working strategy, which is selected from the actual adopted working strategies. However, this selected method can further be improved by taking into account fundamental ergonomics principles that will ultimately lead to an optimal working strategy. Corrective actions can be a change in working posture, working procedure, process sequence, load handling strategy, smart movements of body parts used etc.

6.4. Results and Discussion

The overall analysis is divided into two categories:

- *Object handling strategies*
- *Postural assessment*

6.4.1. Object handling strategies

A significant variation in object handling strategies has been found during the analysis. Recorded videos have been analysed for the assessment of how object handling methods vary with the change in working skills and experience. It was noticed that semi-skilled workers faced maximum difficulties in manual handling of the objects and the working method was found to have a high level of risk. As subjects were recorded for at least 3-4 times for each cycle of their work, findings are based on the most commonly used working procedures. It was found that the main difference in object handling was the orientation and fixing the object on the workstation. For example, at workstation 1, with the same task element, a specialized worker moved or rotated the object (sofa) only twice during one cycle, whereas, the multi-skilled did it 6 times and semi-skilled 11 times. An immense amount of total time was wasted in managing this activity again and again by a semi-skilled worker. Furthermore, the sofa was a heavy product, its physical handling demands considerable effort and adoption of some awkward postures. Postural assessment results will be discussed in the next section of this chapter. Table 6.18 shows the frequency with which specialized, multi-skilled and semi-skilled workers moved the object during one complete cycle on different workstations. It is important to mention that work activities were different at different workstations but the same at each workstation. For example, the same task was accomplished by workers of different skills at workstation 1; however, it was different as compared with other workstations. It is evident from the table that variations in the levels of skill greatly affect object handling strategies of manufacturing assembly workers. These changes increase non-value added time that leads to a significant increase in overall cycle time. It's obvious that on continuous production lines workers have to maintain the flow of the line. This increase in cycle time can adversely affect work performance as more energy and pace is needed to meet these requirements. These work conditions will lead to injuries, illnesses, feelings of tiredness at the individual level and the organization has to compromise on work productivity and product quality.

Table 6.18: Comparing object handling strategies, the number shows how many times a sofa was rotated from its previous position

	Workstation 1	**Workstation 2**	**Workstation 3**	**Workstation 4**
Specialized workers	2	2	3	2
Multi-skilled workers	6	2	4	3
Semi-skilled workers	11	5	2	5

As an example, a few frames from the original videos are shown in figures 6.3. 6.4 and 6.5; these show differences in object handling strategies adopted by different workers on the same workstation (workstation 1) for the same activity. Specialized workers changed the position of the sofa only twice; firstly, when it was received from the previous workstation so as to set its position vertical at some appropriate distance from the body, and finally at the completion of the work. Subsequent frames show the difficulties faced by multi-skilled and semi-skilled workers. It can be noted that change in the position of the object (sofa) requires a strenuous physical effort with an exposure to risky postures. The semi-skilled worker has moved and rotated sofa 11 times putting in a lot of physical effort, as shown in the frames below (table 6.18 and figure 6.5).

From the above results, it can be concluded that skill has a significant role in the planning and performing of any manufacturing assembly task. Highly skilled workers, as specialized in this case, are more productive and safe because of their better planning and work performing skills (Figure 6.3). So, training and experience make workers more productive and safe as they do their work with better planning. Table 6.18 also shows that specialized workers are equally good for the other three workstations as well. However, at workstation 3, the semi-skilled worker was even better in work planning than a specialized worker. It is suggested that less skilled workers should not be under-estimated all the time, as they might be equally good or even better at carrying out some tasks. Their working strategies should be analysed carefully during selection of an optimal working strategy. From the above discussion, it can be concluded that more skilled workers are better at object handling. However, there is a chance that individual differences can make a less skilled worker even better than a specialized and fully skilled worker and this might be due to different attitudes towards work.

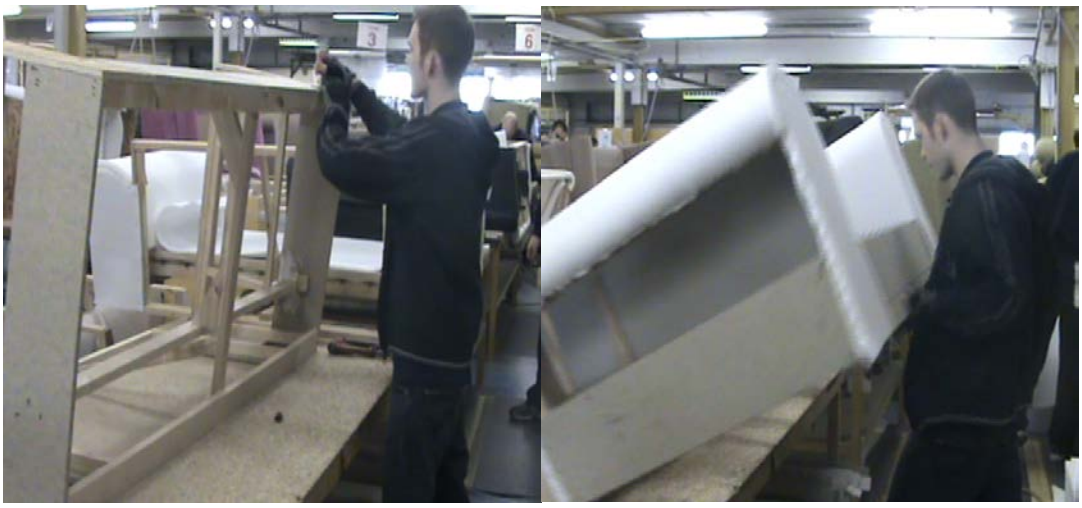


Figure 6.3: Specialized worker’s object handling strategies

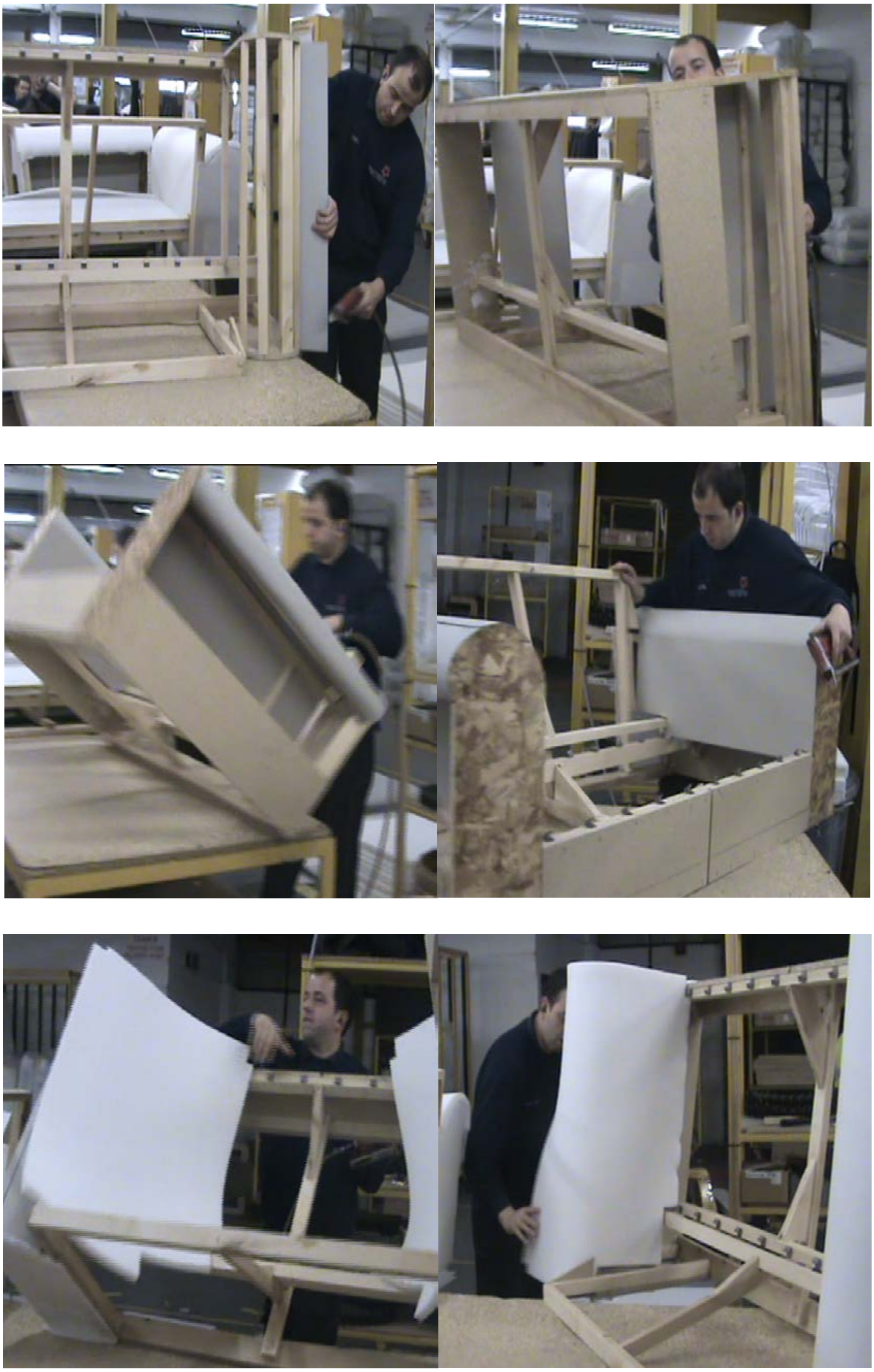


Figure 6.4: Multi-skilled worker’s object handling strategies

Figure 6.5: Semi-skilled worker’s object handling strategies

6.4.2. Postural assessment

6.4.2.1. OWAS results

OWAS postural assessment shows that specialized workers adopt safer work strategies as compared with multi-skilled and semi-skilled workers. However, there is an exception at workstation 3 where a semii-skilled worker performed exceptionally well. Results can be summarised as:

- Overall analysis shows that about 33% of the total postures need some quick corrective actions (as they belong to action categories 3 and 4), that indicates that this is not a very safe place to work (Figure 6.7, table 6.22).
- The percentage of the postures belonging to action category 1 and 2 is the highest for specialized workers (Figure 6.6, 6.8, 6.9, 6.10 and table 6.22). These action categories are considered relatively safe. Higher valid percentages indicate that specialized workers are better in their working strategies as compared to multi-skilled and semi-skilled workers.
- For action categories 3 and 4 specialized workers show a smaller percentage of poor postures and this indicates again that they are working with safe and healthy working postures (Figure 6.6, 6.8, 6.9, 6.10 and table 6.22).
- Surprisingly, the semi-skilled worker at workstation 3 is exceptionally good in terms of his exposure to risk (Figure 6.11, 6.12 and table 6.29)
- Overall analysis shows that the following posture codes have high impacts on the results, especially in action categories 3 and 4 (table 6.19, 6.20, 6.21, figure 6.7):
    - Back posture code 4 (commonly found in 67.3% of postures falling under action categories 3 and 4)
    - Arms posture code 2 (found in 27.4% of postures relate to action category 3 and 4)
    - Legs position codes 3 and 4 (represent 22.1% and 41.2% of postures in action category 3 and 4)

- Load carrying code 3 (common in 34.1% of postures in action category 3 and 4)

- The results indicate that back position (code 4), legs position (code 4) and load carrying during work (code 3) are the prominent causes for risk at work. These codes are described as under:

    - Back - bent and twist
    - Legs - standing or squatting on both feet with knees bent
    - Arms - one arm at or above shoulder level
    - Load - load > 20kg

Table 6.19: Accessing prevalence of postures that are more harmful and major causes of risk exposure through OWAS method

Posture Category	**Description**	**Representing percentage of postures against action category 3 & 4**
Back posture code 4	bent and twist	67.3
Arms posture code 2	one arm at or above shoulder level	27.4
Legs position codes 3 and 4	standing or squatting on both feet with knees bent	63.3
Load carrying code 3	load > 20kg	34.1

- The above findings clearly highlight the causes of risks involved with the work. Simultaneous bending and twisting movements with knees bent are found to be prominent causes of work related ailments. Moreover, handling tools or objects and performing work where at least one arm is at or above shoulder level is also a prominent cause of risk.

- As mentioned in the previous section, manual object handling is a cause of musculoskeletal disorders and this problem is more evident with semi-skilled workers.

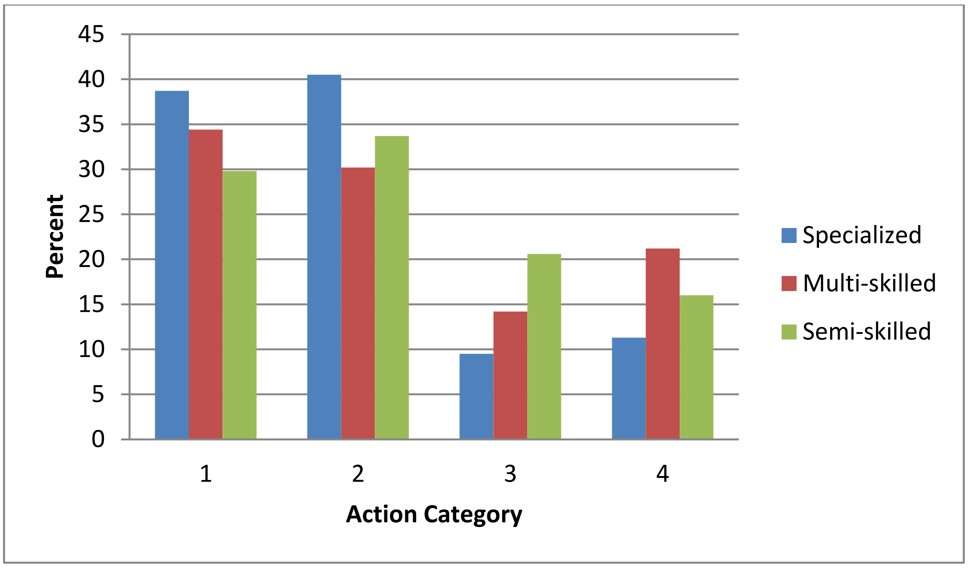


Figure 6.6: OWAS: overall workplace risk assessment results for workers of different skills

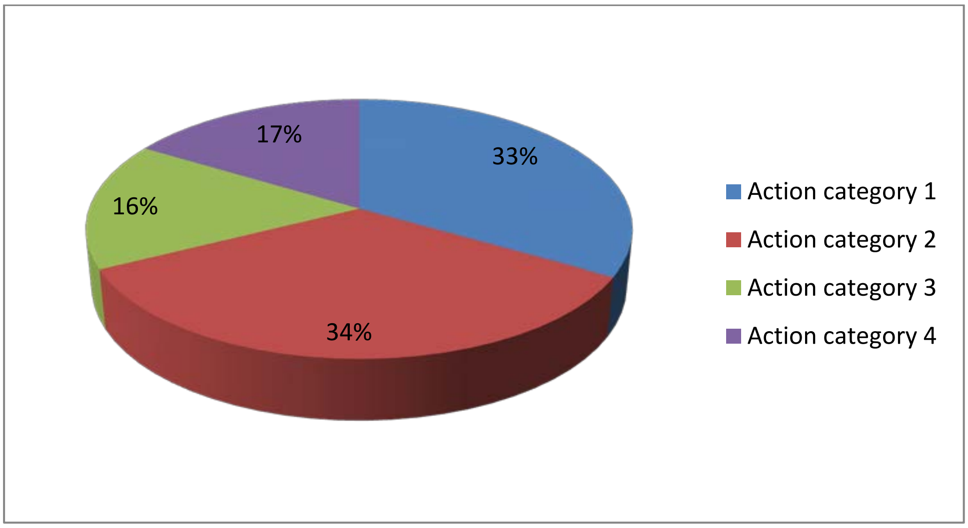


Figure 6.7: OWAS: overall workplace risk assessment results

Note: As mentioned previously that action categories 1, 2, 3, 4 show the level of necessity for corrective actions. Action category 1 shows that no corrective action is required; whereas, action category 4 requires corrective actions immediately.

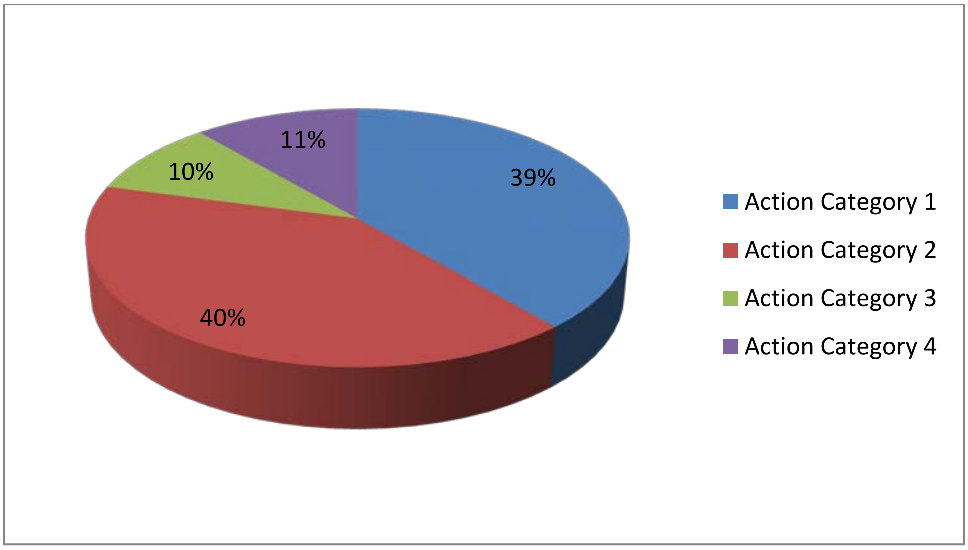


Figure 6.8: OWAS: overall workplace risk assessment results for specialized workers

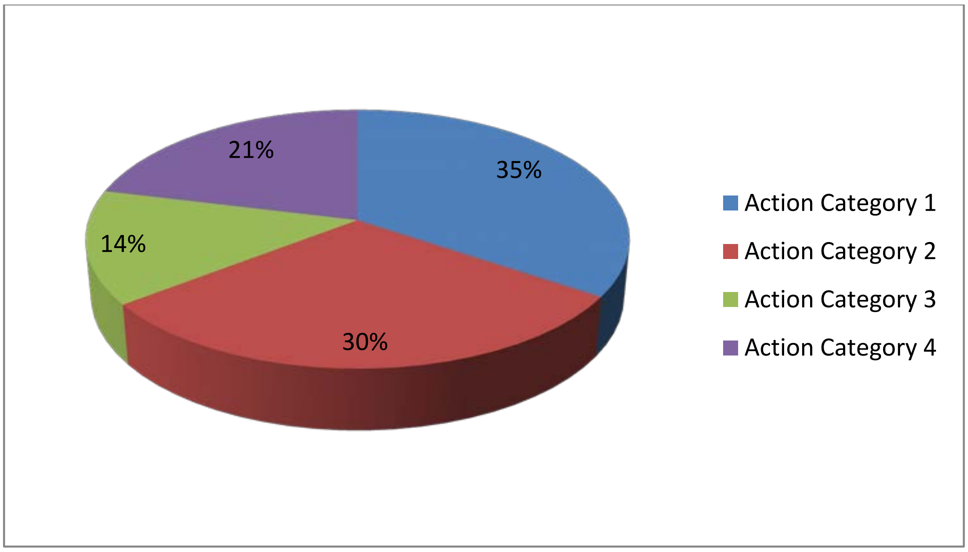


Figure 6.9: OWAS: overall workplace risk assessment results for multi-skilled workers

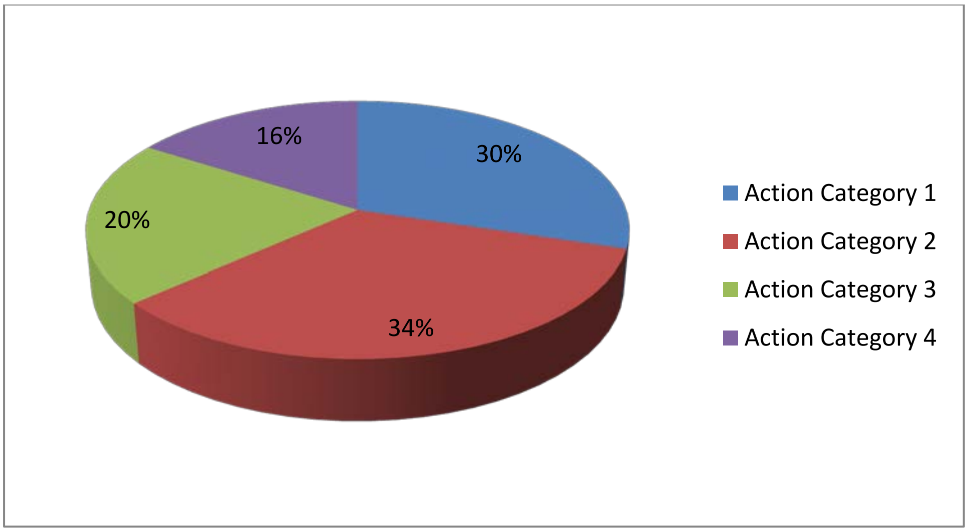


Figure 6.10: OWAS: overall workplace risk assessment results for semi-skilled workers

6.4.2.2. OWAS Skill and workstation based risk assessment analysis

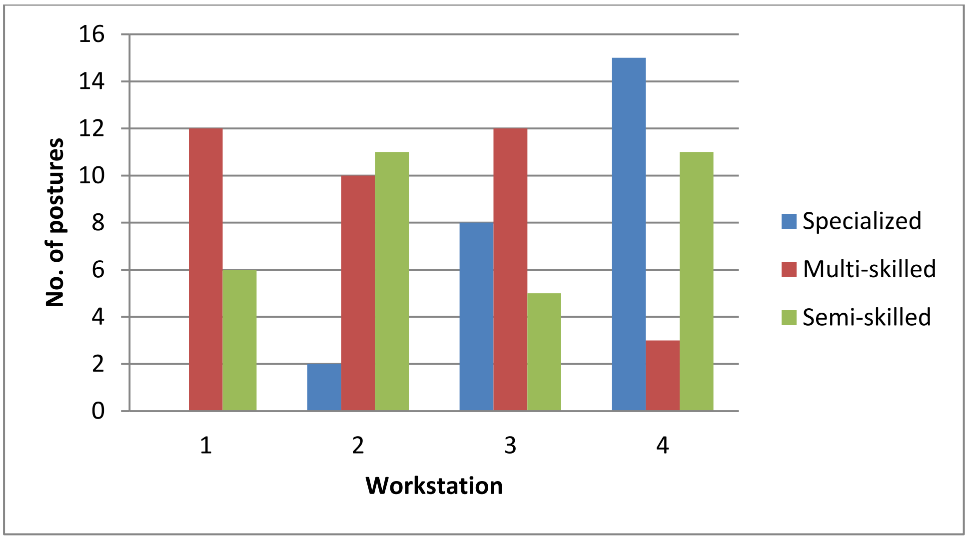


Figure 6.11: OWAS: skill and workstation based risk assessment results (action category 4)

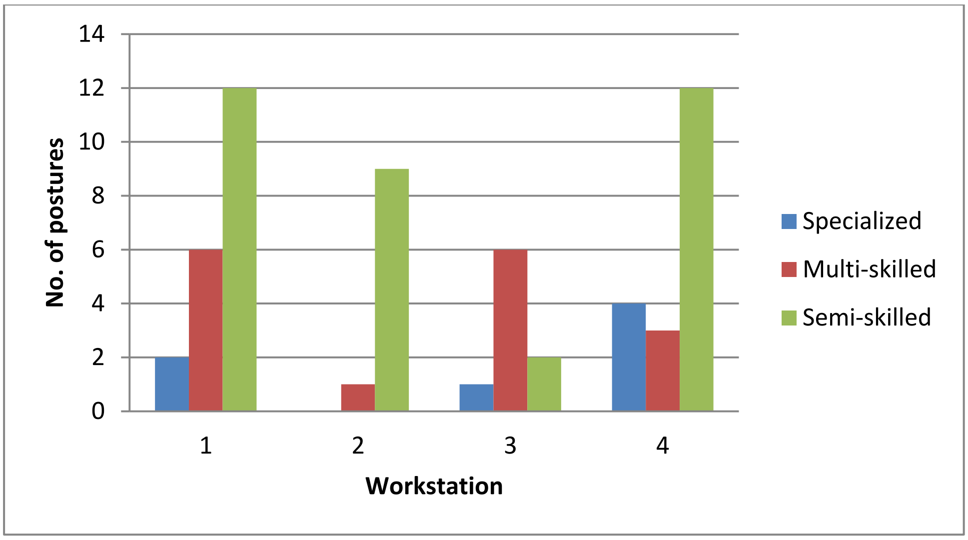


Figure 6.12: OWAS: skill and workstation based risk assessment results (action category 3)

Table 6.20: OWAS: showing prevalence of different body part positions

OWAS overall analysis			Valid Percentage			
Body part	**Code**	**Frequency**	**overall**	**specialized**	**multi-skilled**	**semiskilled**
Back	1	177	23.1	26.2	26.9	22.3
	2	151	19.7	21.4	20.8	20.8
	3	79	10.3	13.1	12.3	9.1
	4	299	39.1	39.3	40.1	43.4
Arm	1	401	56.8	56	53.3	59.5
	2	182	25.8	28.6	25.5	24.5
	3	123	17.4	15.5	21.2	16
Legs	1	2	0.3	0	0.5	0.3
	2	443	62.7	74.4	59.9	58.6
	3	106	15	11.9	9.9	19.9
	4	97	13.7	6	20.8	13.2
	5	42	5.9	2.4	8	6.4
	6	5	0.7	2.4	0	0.3
	7	11	1.6	3	0.9	1.2
Load	1	563	79.7	80.4	84	76.7
	2	1	0.1	0	0	0.3
	3	142	20.1	19.6	16	23

Table 6.21: OWAS: showing prevalence of different body part positions for action categories 3 and 4

Category 3 & 4			Valid Percentage			
Body part	**Code**	**Frequency**	**overall**	**specialized**	**multi-skilled**	**semiskilled**
Back	1	0	0	0	0	0
	2	64	28.3	17.6	32.9	28.6
	3	10	4.4	.0	9.6	2.5
	4	152	67.3	82.4	57.5	68.9
Arm	1	139	61.5	58.8	63.0	61.3
	2	62	27.4	32.4	24.7	27.7
	3	25	11.1	8.8	12.3	10.9
Legs	1	0	0	0	0	0
	2	34	15.0	14.7	9.6	18.5
	3	50	22.1	26.5	11.0	27.7
	4	93	41.2	29.4	54.8	36.1
	5	40	17.7	11.8	23.3	16.0
	6	5	2.2	11.8	.0	.8
	7	4	1.8	5.9	1.4	.8
Load	1	149	65.9	70.6	75.3	58.8
	2	0	0	0	0	0
	3	77	34.1	29.4	24.7	41.2

Table 6.22: OWAS: showing results for different action categories by level of skill

OWAS		Valid percentage			
Action Category	**Frequency**	**Overall**	**Specialized**	**Multi-skilled**	**semiskilled**
1	235	33.3	38.7	34.4	29.8
2	242	34.3	40.5	30.2	33.7
3	113	16	9.5	14.2	20.6
4	116	16.4	11.3	21.2	16

6.4.2.3. REBA results

REBA results also highlight similar relationships between level of skill and risk exposure as found by the OWAS method. Like OWAS, action categories 3 and 4 are considered harmful and need quick action for improvement. The results can be summarised as:

- REBA analysis indicates that the workplace is not a safe place to work, as about 50% of the postures require quick corrective action (in action categories 3 and 4), as shown in Figure 6.14, table 6.29).
- Semi-skilled workers are more commonly exposed to risk during their work. However, a semi-skilled worker at workstation 3 was exceptionally good as he was less exposed as compared to other workers of the same skill (semi-skilled) at different workstations and different level of skills on the same workstation (Figure 6.13, 6.15, 6.16, 6.17, 6.18, 6.19 and table 6.26).
- For action category 3, multi-skilled and semi-skilled workers are found to be unsafe as compared with specialized workers, except for workstation 3 (Figure 6.19 and table 6.29).
- Similarly, for action category 4 (figure 6.18 and table 6.26), semi-skilled workers are more likely to adopt risky postures during their work, except

workstation 3. Moreover, specialized and multi-skilled workers are at a similar level of risk to exposure involved with their working strategies

- Figure 6.13 clearly shows that for low risk action categories (0,1,2), the percentage of postures falling in these action categories is higher for specialized workers as compared to multi-skilled and semi-skilled workers.

- On the other hand, multi-skilled and semi-skilled workers were found with more unsafe working methods/postures for action categories 3 and 4; where the multi-skilled worker at workstation 3 was an exception. However, this trend is very significant for action category 3 and no clear indication is found against action category 4 (figures 6.13, 6.15, 6.16, 6.17, 6.18, 6.19 and table 6.24).

Assessing prevalence of postures that are more harmful and major causes of risk exposure (Tables 6.23, 6.24, and 6.27)

- For trunk postures, codes 3 and 4 covers overall 63.5% of postures falling in the action category of 3 and 4, where a number of trunk position combinations including different values of flexion/extension and side flexed or twist movements can be a cause of this high risk. It is noted that usually side flexed and twisted trunk positions significantly affect the level of risk involved in any working posture.

- Similarly, neck position codes 2 and 3 account for more than 90% of overall postures belonging to action category 3 and 4 where $>20^0$ flexion/extension and side flexed movement are prominent causes of risk.

- Unilateral/bilateral weight bearing with knee flexion covers about 30% of the postures belonging to action category 3 and 4. It shows that there might be a problem with the object (sofa) or workstation height that demands an adoption of such leg postures where the task cannot be completed without knee flexion.

- Like OWAS, high load carrying also has a significant role.

- Codes 4 and 5 cover overall about 74.5% of upper arm postures where a high level of arm flexion with abduction, rotation or raised shoulder position are the most commonly used upper arm movements. Similar to leg position, upper arm positions also highlight the same issue of inappropriate height adjustability of object (sofa) or workstation. Moreover, lower arm position code 2 also emphasizes the same issue.

- Wrist positions showing high flexion with deviation and twist movements, accentuate the need of training aiming to teach workers about safe holding of tools and objects.

Table 6.23: Assessing prevalence of postures that are more harmful and major causes of risk exposure through REBA method

Posture category	Description	Representing percentage of postures against action category 3 &4
Trunk position Code 3 and 4	Different combinations include 0^0-20^0, 20^0-60^0, >60^0 flexion/extension and side flexed or twist	63.5
Neck position code 2 and 3	Three possible combinations of 0^0-20^0 flexion/extension, >20^0 flexion/extension and side flexed movement	93.6
Legs position code 3	Unilateral/bilateral weight bearing with knees flexion	30.4
L/F carrying code 2	>10kg	21.7
Upper arm position code 4 and 5	Different combinations include >90^0 flexion, 45^0-90^0 flexion with abduction, rotation or raised shoulder position	74.5
Lower arm position code 2	<60^0 flexion or >100^0 flexion	66.7
Wrist position code 3	>15^0 flexion/extension with deviation and twist	81.1

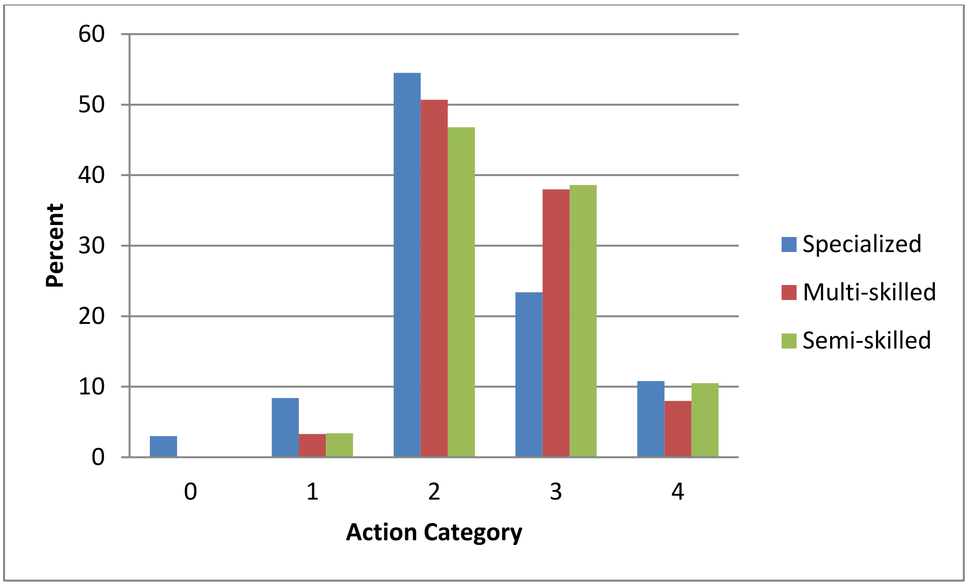


Figure 6.13: OWAS: overall workplace risk assessment results for workers of different skills

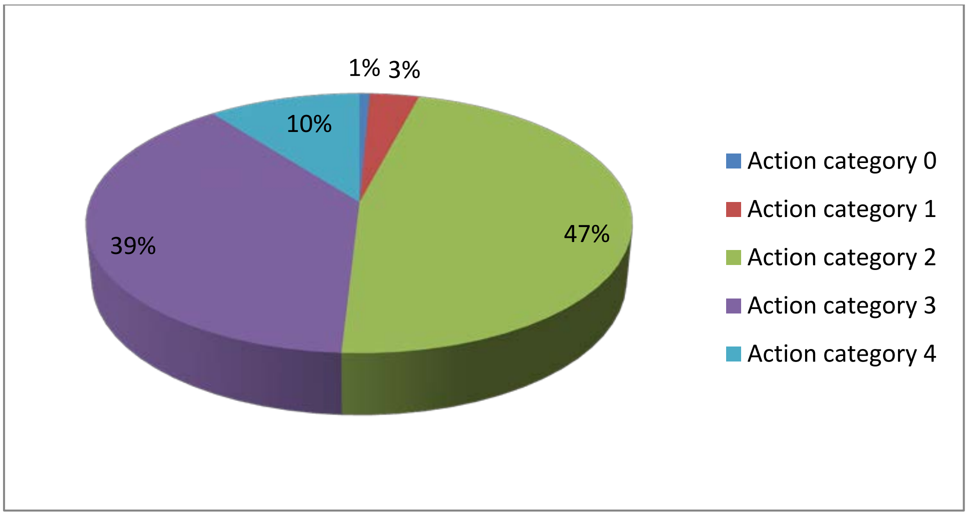


Figure 6.14: REBA: overall workplace risk assessment results

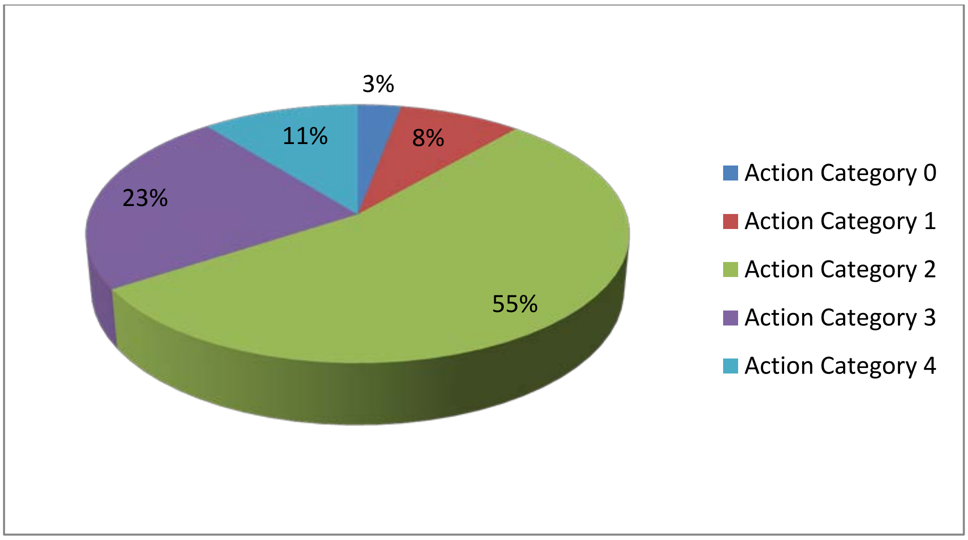


Figure 6.15: REBA: overall workplace risk assessment results for specialized workers

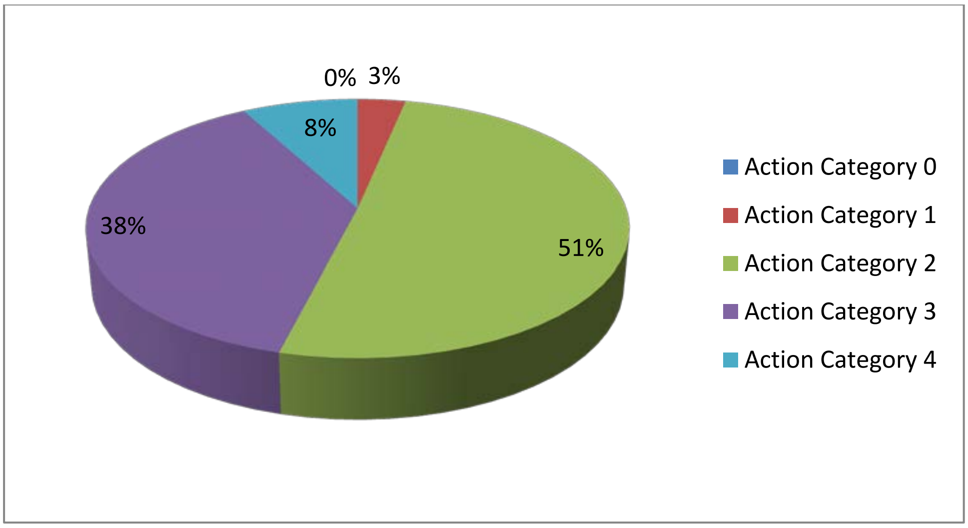


Figure 6.16: REBA: overall workplace risk assessment results for multi-skilled workers

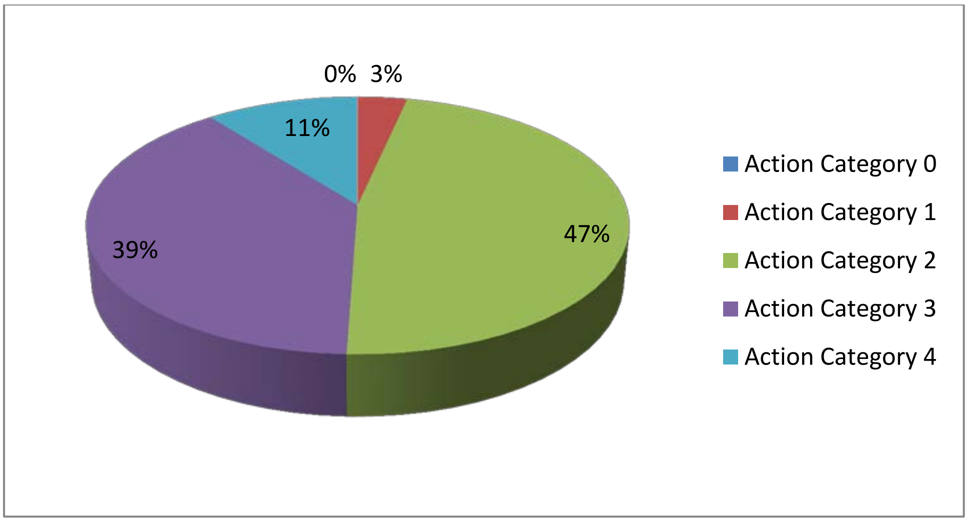


Figure 6.17: REBA: overall workplace risk assessment results for semi-skilled workers

6.4.2.4. REBA Skill and workstation based risk assessment analysis

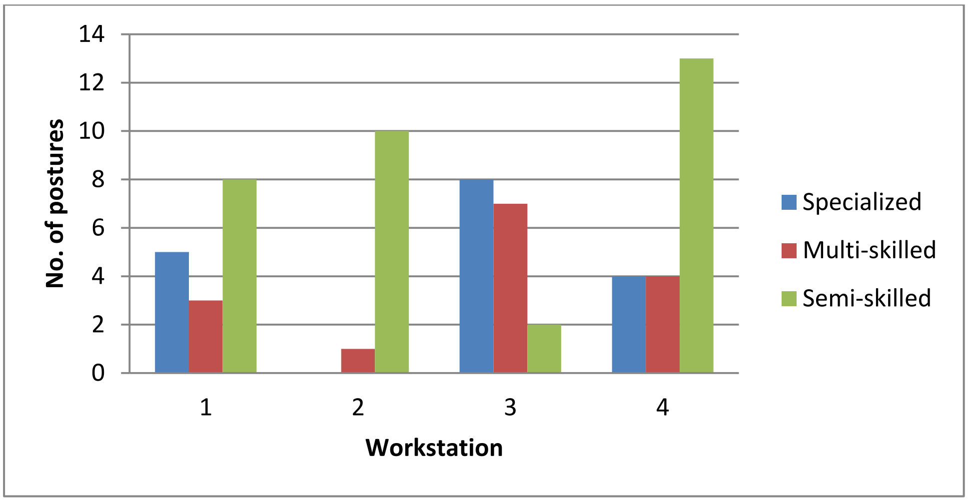


Figure 6.18: REBA: skill and workstation based risk assessment results (action category 4)

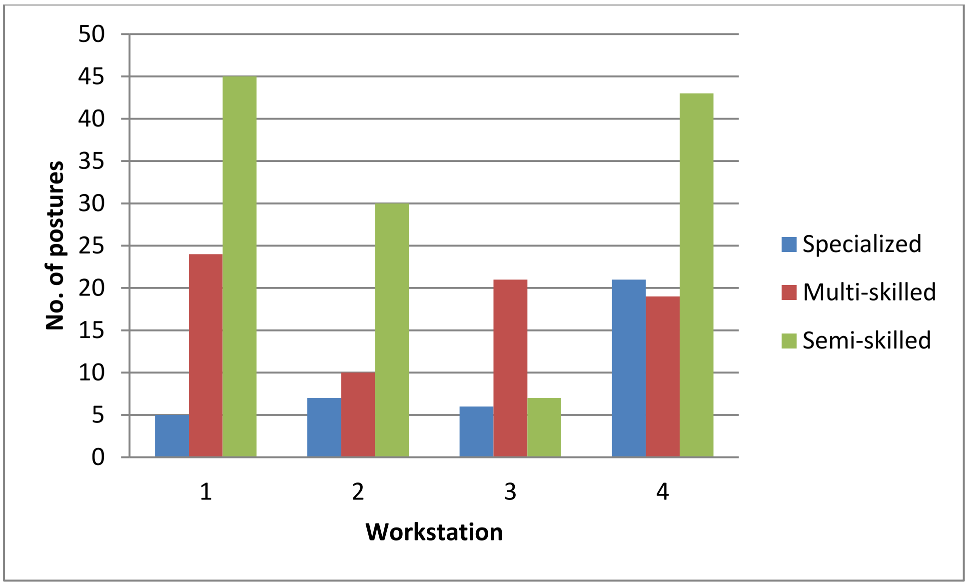


Figure 6.19: REBA: skill and workstation based risk assessment results (action category 3)

Table 6.24: REBA: showing prevalence of different body part positions

REBA overall analysis			Valid Percentage			
Body part	**Code**	**Frequency**	**overall**	**specialized**	**multi-skilled**	**semiskilled**
Trunk	1	86	12.2	22.8	12.7	6.5
	2	230	32.6	30.5	35.7	31.7
	3	213	30.2	22.8	27.7	35.7
	4	120	17.0	14.4	19.2	16.9
	5	56	7.9	9.6	4.7	9.2
neck	1	133	18.9	24.6	23.5	12.9
	2	327	46.4	48.5	45.5	45.8
	3	245	34.8	26.9	31.0	41.2
Legs	1	339	48.1	64.7	54.0	35.7
	2	230	32.6	20.4	22.5	45.5
	3	119	16.9	12.0	22.5	15.7
	4	17	2.4	3.0	.9	3.1
L/F	0	559	79.3	84.4	82.6	74.5
	1	0	0	0	0	0
	2	146	20.7	15.6	17.4	25.5
Upper Arm	1	62	8.8	19.8	4.2	6.2
	2	91	12.9	16.2	11.7	12.0
	3	161	22.8	21.0	24.9	22.5
	4	280	39.7	25.1	41.3	46.2
	5	111	15.7	18.0	17.8	13.2
Lower Arm	1	357	50.6	52.1	53.5	48.0
	2	347	49.2	47.9	46.0	52.0

	3	1	.1	.0	.5	.0
Wrist	1	64	9.1	19.2	7.5	4.9
	2	91	12.9	12.0	9.0	16.0
	3	549	78.0	68.9	83.5	79.1

Table 6.25: REBA: showing prevalence of different body part positions (for action categories 3 and 4)

Category 3 & 4			**Valid Percentage**			
Body part	**Code**	**Frequency**	**overall**	**specialized**	**multi-skilled**	**semiskilled**
Trunk	1	2	0.6	0	0	1
	2	70	20.3	19.6	24.5	18.3
	3	120	34.8	26.8	33.7	37.7
	4	99	28.7	26.8	32.7	27.2
	5	54	15.7	26.8	9.2	15.7
neck	1	22	6.4	1.8	2	9.9
	2	147	42.6	50	45.9	38.7
	3	176	51	48.2	52	51.3
Legs	1	72	20.9	30.4	25.5	15.7
	2	151	43.8	28.6	32.7	53.9
	3	105	30.4	32.1	39.8	25.1
	4	17	4.9	8.9	2	5.2
L/F	0	270	78.3	92.9	83.7	71.2
	1	0	0	0	0	0
	2	75	21.7	7.1	16.3	28.8

Upper Arm	1	5	1.4	1.8	1	1.6
	2	25	7.2	8.9	8.2	6.3
	3	58	16.8	10.7	17.3	18.3
	4	170	49.3	33.9	46.9	55
	5	87	25.2	44.6	26.5	18.8
Lower Arm	1	114	33	35.7	35.7	30.9
	2	230	66.7	64.3	63.3	69.1
	3	1	0.3	0	1	0
Wrist	1	16	4.7	10.7	3.1	3.7
	2	49	14.2	8.9	8.2	18.8
	3	279	81.1	80.4	88.7	77.5

Table 6.26: REBA: showing results for different action categories by level of skill

REBA		**Valid percentage**			
Action Category	**Frequency**	**Overall**	**Specialized**	**Multi-skilled**	**semiskilled**
0	5	0.7	3	0	0
1	24	3.4	8.4	3.3	3.4
2	330	46.8	54.5	50.7	46.8
3	272	38.6	23.4	38	38.6
4	74	10.5	10.8	8	10.5

Table 6.27: REBA: assessing prevalence of overall body part positions and their contribution to risk

Body part	Code	Frequency	Overall percentage
Trunk	1	2	0.6
	2	70	20.3
	3	120	34.8
	4	99	28.7
	5	54	15.7
neck	1	22	6.4
	2	147	42.6
	3	176	51
Legs	1	72	20.9
	2	151	43.8
	3	105	30.4
	4	17	4.9
L/F	0	270	78.3
	1	0	0
	2	75	21.7
Upper Arm	1	5	1.4
	2	25	7.2
	3	58	16.8
	4	170	49.3
	5	87	25.2
Lower Arm	1	114	33
	2	230	66.7

	3	1	0.3
Wrist	1	16	4.7
	2	49	14.2
	3	279	81.1

6.4.3. Comparing OWAS and REBA results

As mentioned earlier, REBA categorizes action levels into 5 categories starting from 0, whereas OWAS categorizes into 4 starting from 1. For comparison purposes, REBA action categories 0 and 1 are combined as they are very similar in presenting the level of severity attached with them. It can be concluded from figure 6.20 that OWAS underestimates risk level associated with working postures as it found 33.3% of working postures belong to action category 1 which is high as compared with REBA, which is only about 4.1% (figure 6.20 and table 6.28). On the other hand, for action categories 2 and 3, it highlights significantly lesser postures for these action levels and the trend is more prominent for action level 3 where it shows only 16% (113) postures as compared with 38.6% (272). Another study conducted by Kee and Karwowski (2007), compared three observational techniques OWAS, REBA and RULA, and reported similar findings when results between OWAS and REBA are compared with each other (Kee and Karwowski, 2007).

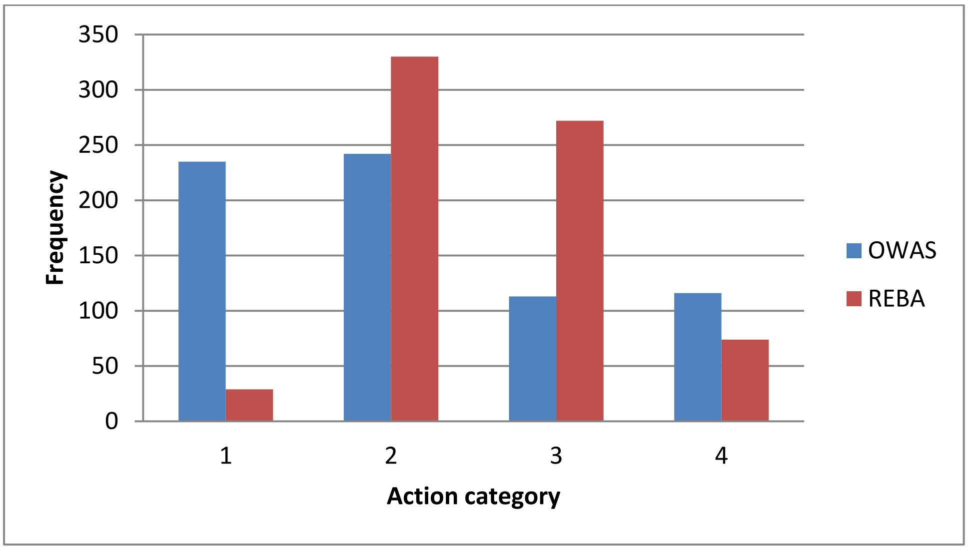


Figure 6.20: Comparison of OWAS and REBA postural analysis results

Table 6.28: Comparing OWAS and REBA results for different action categories

Action Category	REBA		OWAS	
Action Category	**Frequency**	**valid percent**	**Frequency**	**valid percent**
0	5	0.7	Not valid	Not valid
1	24	3.4	235	33.3
2	330	46.8	242	34.3
3	272	38.6	113	16
4	74	10.5	116	16.4

The objective of using both observational risk assessment techniques was only to verify the relationship between individual factors under observation (skill, experience) and risk exposure associated with different working strategies. It was revealed that both techniques demonstrate a similar kind of relationship between individual factors like skill and experience and level of risk involved with workers work accomplishing strategies. For this purpose, all 4 workstations have been analysed separately to provide a deeper insight. Table 6.29 shows the number of postures recommended for action categories 3 and 4 for each workstation and workers with different level of skills, by both OWAS and REBA work assessment analysis. It is very clear that semi-skilled workers are more vulnerable to risk factors associated with their work as compared with specialized and multi-skilled workers and this trend is highly visible in action level 3 results for both OWAS and REBA (table 6.29). An interesting fact draws attention to workstation 3, where a semi-skilled worker is shown relatively safe in working and highlighted by both OWAS and REBA methods.

Furthermore, table 6.22 and table 6.26 also feature similar results, leading to the conclusion that skill and training play an important role in prevention of hazardous working conditions

Table 6.29: Comparing OWAS and REBA results, number of postures for action categories 4 and 3 (based on skill and workstation)

Action Category 4 (Risk level is very high, action is necessary now)									
REBA	**Workstation**				**OWAS**	**Workstation**			
	1	**2**	**3**	**4**		**1**	**2**	**3**	**4**
Specialized	5	0	8	4	***Specialized***	0	2	8	15
Multi-skilled	3	1	7	4	***Multi-skilled***	12	10	12	3
Semi-skilled	8	10	2	13	***Semi-skilled***	6	11	5	11
Action Category 3 (Risk level is high, action is necessary soon)									
REBA	**Workstation**				**OWAS**				
	1	**2**	**3**	**4**		**1**	**2**	**3**	**4**
Specialized	5	7	6	21	***Specialized***	2	0	1	4
Multi-skilled	24	10	21	19	***Multi-skilled***	6	1	6	3
Semi-skilled	45	30	7	43	***Semi-skilled***	12	9	2	12

The above discussion reveals that working strategies are greatly influenced by individual factors like skill, experience and training. Skilled workers have been found relatively safe at their work as compared to multi-skilled and semi-skilled workers under similar working conditions. Individual differences affect object handling strategies, assembly process planning and working postures adopted by workers that finally put them in safe or unsafe working conditions. These differences considerably influence value added time, productivity and human well-being at work.

6.5. Recommendations

From the above discussion, the following recommendations are made for the improvement of working strategies in manufacturing industries:

- Avoid complex back/trunk movements that contain both bending and twisting movements simultaneously.

- Use appropriate tools and object handling aids to handle and lift objects during the work; especially as in this case the weight of the object was greater than 40kg. Manual handling of such a heavy object is harmful for worker's health and well being

- Standardize work practices in such a way that height of the object and workstation are appropriate. Findings show that raising arms at or above shoulder level and bending knees are prominent causes for risk during the work. For example, the workstation should be designed with an appropriate height and object orientation so that the worker's arm does not move above shoulder level. Similarly, bending of knees can also be avoided by controlling these design variables.

- Select optimal working strategies and train the workforce accordingly. These human variability issues should be considered at some earlier design stage so that optimal working strategies can be implemented where people can survive with their existing differences.

- Differences in working strategies should be taken as an opportunity as it provides a large pool of working methods where designers have a choice for selection.

This case study also validates the list of issues faced during any manual work, and suggested solutions as recommended by the Centre of Disease Control and Prevention at the National Institute for Occupational Health and Safety (NIOSH), where similar kinds of guidelines have been outlined to prevent work-related musculoskeletal disorders often involving strains and sprains to the lower back, shoulders and upper limbs during manual material handling (NIOSH, 2007)

6.6. Conclusion

Different workers adopt different working strategies and these differences significantly affect the level of risk. In this study workers of varying skill were analysed and it was found that workers with high levels of skill are better in adoption of relatively safe and productive working strategies. So, it can be concluded that training and experience reduce the chances of musculoskeletal disorders because of the fact that well trained workers adopt easy and safe working methods. These findings reveal that human variability issues are directly linked with individual and organizational work performance, so these issues must be highlighted and solved during any work standardization process. Selection of optimized working procedures and then training the workforce accordingly is a key to success where workers with their existing differences can perform in an equally productive way. Moreover, it was also found that load handling is the key area that causes wastage of time and is a major cause of risk for less skilled workers. Non-value added time can be significantly decreased by avoiding unnecessary movements of objects, which lead to awkward body postures. This evidence provides an opportunity to understand the human variability issues regarding working patterns and their effects on work performance. It also throws light on how varying levels of skill and experience are linked to work safety and productivity. Understanding and anticipating human differences and their relationships with workplace safety and human well-being, is considered as a potential way to address future workforce challenges.

Conclusively, it can be said that individual factors like skill and experience has a significant effect on workplace safety and work productivity. As mentioned in section 3.2, the final step is to use human capabilities and task performing strategies data to validate the inclusive design method (proposed in this research) with the help of appropriate design tool. Chapter 7 will be explaining and verifying how human modelling based inclusive design strategy can be used for this purpose.

Chapter 7

Inclusive Design for Manufacturing Assembly Workers, A Case Study at a Furniture Manufacturing Company

7.1. Introduction

This chapter validates the concept of using a digital human modelling inclusive design strategy for manufacturing workplace and environment design. Assembly working strategies that have been captured (and discussed in chapter 6) are used for the assessment of the suitability of working methods in relation to human variability issues and an inclusive design strategy. The objective of this experimentation was to validate the successful use of the HADRIAN inclusive design strategy for manufacturing assembly activities. This investigation is mainly focused on human variability issues especially the decrease in joint mobility with age, and its impact on the acceptability of any working method for a broad range of workers with varying physical capabilities, joint mobility in this case.

Section 7.2 briefly highlights the need for the research aim set for this case study. Section 7.3 explores and concludes the effective use of digital human modelling or computer-aided ergonomic tools for manufacturing workplace risk assessment. A step-by-step explanation of the research method adopted for this case study is provided in sections 7.4 and 7.5. Concept validation and discussion of the results is made in section 7.6 and section 7.7. Further to the previous discussion, section 7.8 describes the task evaluation process in detail. Section 7.9 and section 7.10 discuss the strengths and limitations and conclusions of this case study respectively.

7.2. Background

As mentioned earlier, the global workforce is becoming more diverse and the proportion of older workers is significantly increasing in most parts of the world. . Keeping in view the dramatic demographic changes, all stakeholders like governments, organizations, welfare agencies and planners are seriously thinking about how to effectively utilize this segment of population. To meet future challenges the UK government launched a strategy called ‘Building a society for all ages: a choice for older people’. It was emphasized that these demographic changes should be taken as an opportunity rather than a threat where there is a chance to build a society where people are not judged by their age but by their capabilities and needs. Moreover, this requires a shift in attitudes and expectations across the whole society and negative stereotypes about older workers should be avoided so that every person of every age can contribute to a sustainable economy (HM Government, 2009).

Working environment consists of a number of things which workers are to interact with during their work. Products in the working environment might be referred to as tools, devices and equipment; whereas, workstation might be referred as the place especially designed for a particular work. This can consist of tables, benches, chairs and different products like tools, devices and equipment attached with that work station. However, what should be the focus of a design engineer mainly depends on the type and level of interaction between human and other parts of the system whether that is a product or workstation.

Productive utilization of older people, especially in working environments, is not a simple challenge to meet. Design exclusion of older adults is caused by a number of reasons including social, cultural, economic, lack of knowledge and experience and highly complex instructions and designs (Benyon et al., 2005). Specifically, older adults found problems in using products because the capability demand was greater than the capability of the user. This mismatch between demand and capability is usually because of a significant reduction in physical, physiological and cognitive capabilities of older people. In order to prevent such design exclusions designers have to understand and accommodate the design needs of older people with these reduced functional capabilities (Keates and Clarkson, 2004). So, a complete understanding of the reduction in the capabilities of older workers and the provision of highly relevant data can help designers in preventing design exclusion for older workers. There are some datasets available that describe human capabilities in general and older workers' capabilities in particular but may be found to be of limited practical use because of the way data is presented. Gyi et al. (2000) conducted a survey with 50 design professionals to establish the current situation concerning the availability and utilization of the available data in relation to the needs of older and disabled people. It was found that the available data is rarely in sufficient detail to enable professionals to make informed design decisions. Furthermore, existing data tools are not easy to access and designers rarely evaluate designs at early design stage and do not try to include the design needs of older and disabled people, unless specifically requested. Goodman et al. (2006) carried out a survey to investigate the level of awareness, perceptions and barriers for promoting an inclusive design strategy in different industries. A conclusion was that a lack of awareness and lack of availability of appropriate inclusive design tools are the main reasons for this situation. It was further noted that companies which have not adopted inclusive design methods often feel that inclusive design has limited commercial value.

It is evident from this discussion that lack of sufficient data on human capabilities and unavailability of proper inclusive design tools are the main reasons resisting the promotion of an inclusive design strategy. Next section will be discussing how human modelling systems uses human capabilities data to improve system's work performance and how these tools facilitate designers to make early design assessments that can be used to improve any working system especially manufacturing working environment.

7.3. Digital human modelling and manufacturing work assessment

Manufacturing industry around the globe is facing enormous market pressures for the optimization of their working systems so that organizations can achieve and sustain higher levels of productivity and quality. Moreover, they also have to maintain worker's well-being and health because of new legislation passed in most industrial countries (Zink, 2005). Designing workplaces according to ergonomic principles gives benefits in terms of better working environments with improved worker's health and well-being. Hendrick (2003) investigated the economic impact of ergonomic interventions and concluded that 'good ergonomics is good economics' and most ergonomics projects can be justified in terms of economic benefits (Hendrick, 2003). Similarly, Eklund (1995) attempted to explain a relationship between ergonomic work conditions and quality of work and revealed that quality deficiencies were three times greater for work tasks with ergonomics problems as compared with other tasks. Discomfort, organizational factors and time pressure were found to be the main causes of quality problems (Eklund, 1995). Moreover, it was reported that ergonomics improvements in assembly can considerably reduce worker's discomfort and improve productivity (Vink et al., 2006).

As discussed previously, the average age of employees is increasing due to demographic changes that increase the risk of musculoskeletal disorders, especially when workers are to perform physically demanding job activities. To accommodate older workers in workplaces, it is considered extremely important to investigate design solutions at some earlier design stage. Moreover, earlier product and process design evaluations are equally important for keeping design costs at reasonable levels, as redesign costs increase the final cost of the product. This highlights the importance of proactive ergonomic design assessment at some early design stage. Computer-aided simulations tools, such as digital human modelling tools (DHMs) are effective in facilitating proactive ergonomic design investigations. However, it's very important to assure that DHM simulation results are delivering valuable outcomes in terms of workplace improvements. Fritzsche (2010) carried out a study for investigating a relationship between DHM simulation results and real life assessment, and reached the conclusion that the correlation is fairly high. Furthermore, it was also found that certain workloads, such as static postures and extra strains might be detected more reliably in DHM simulations as compared with real-life assessments. However, estimation of action forces is difficult to estimate through DHM simulations as their direct observation is rather difficult (Fritzsche, 2010, Demirel and Duffy, 2007). In spite of the many limitations of DHM tools, it has been concluded that early design investigations based on digital human modelling can substantially reduce overall product development costs including design, engineering and ergonomics evaluation costs. In part this is because these tools enable the development and testing and assessment of a virtual product prototype without any real contact with users and operators. Similarly, designers can check different options before going for actual production and so expansive product design and development costs can be reduced significantly. Recently, a concept of participatory ergonomics in collaboration with the use of DHM tools has been found extremely useful. It was further concluded that product or workplace design visualizations using DHM can improve design by facilitating a cooperation between designers, engineers, managers and workers where requirements for all stakeholders can be effectively addressed at some early design stage (Sundin et al., 2004, Chaffin, 2005).

Today, there are many digital human modelling systems commercially available in the market such as SAMMIE, SAFEWORK, JACK, RAMSIS etc. and their effective use in product, process and workplace design has been reported in many studies. In spite of all these efforts, there is very little evidence of these tools being used in the promotion of an inclusive design strategy that aims for the accommodation of a broader range of the population's design needs. It is already mentioned that as an exception, a digital human modelling based tool HADRAIN was developed.. HADRIAN provides ergonomics data in a highly visual form and integrates this data with an 'inclusive design' or 'design for all' philosophy through a computer-based design tool SAMMIE. Data was collected for 100 individuals having a broad range of human capabilities with special attention to older and disabled people. A database provides data about their age, capabilities like joint range of motion, body shape, anthropometry, experiences and preferences with a range of daily activities including domestic and transport related tasks. HADRIAN is also equipped with a CAD-based task analysis system where accessibility issues are reported at the level of individual subjects. Virtual individuals with their task performing capabilities are used to carry out any task analysis and results show why an individual is excluded and how these issues and problems can be eliminated. Previously, it has been successfully used for daily living activities like kitchen activities, use of ATM by wheelchair users, and transport related activities. However, this CAD-based human modelling inclusive design strategy has not been used for industrial activities (Marshall et al., 2010).

This chapter mainly focuses on the use of a digital human modelling based inclusive design strategy for industrial activities like manufacturing assembly activities where most of the work is done manually and ergonomics issues include demands for physically effort, repetitiveness, quick and fast movements with high level of productivity and quality. For the validation of this concept, older workers' capabilities (joint mobility) data is used to assess assembly related tasks.

7.4. Method

The digital human modelling SAMMIE system has been used for the concept validation of using a human modelling based inclusive design strategy in a manufacturing assembly environment. Data captured at a furniture manufacturing industry (discussed in detail in chapter 6) is again used for human modelling based risk assessment of any adopted working strategy. As mentioned in the earlier chapter 6, manufacturing assembly workers at the furniture manufacturing company were recorded to capture a variety of working strategies, methods and procedures. Some of the data has been used here to validate the concept of human modelling based inclusive design method. Selected snap-shots of a variety of workers performing similar tasks were used for the purpose of analysis. The SAMMIE human modelling tool has been used to generate a CAD model of the working environment that includes the sofas that are being assembled, tools used during the assembly operations and other relevant objects. Selected postures recorded in the factory have been replicated by human models in SAMMIE. SAMMIE has the capability of developing a customized human by defining different anthropometric and capabilities data like joint mobility constraints. Previously, it has been concluded that joint mobility decreases with age depending on specific joint and type of motion carried out. Actual joint mobility data of 31 workers belonging to an age group of greater than 40 years has been used to assess suitability of working postures or strategies for these older workers. Postures adopted in the real assembly working environment have been replicated by 31 older workers where their joint mobility constraints data has been used as a criterion for the acceptability of postures.

7.5. Method Explanation

This section describes the steps followed for the validation of a digital human modelling based inclusive design strategy. Figure 7.1 shows the sequence of different steps followed during this study. A description of these steps follows:

7.5.1. Capturing capabilities data for inclusive design

As mentioned earlier, thinking about inclusive design implementation starts from the availability of relevant data that can be used within the design investigation process. As far as accommodation of older workers into working environments is concerned, it is extremely important to understand the decline in human capabilities with age. Capabilities data provides information about the challenges that a worker might face because of a mismatch between capabilities and job demands. A major proportion of manufacturing assembly activities comprise of quick and repetitive movements of different body parts, especially the upper extremities. In this respect, completion of different task elements during work is mainly dependent on joint mobility. Capturing joint mobility constraints will provide an opportunity to assess suitability of any task element for older workers. It is evident from the body of literature that joint mobility decreases with age and similar findings have been concluded at chapter 5. For analysis purpose, 31 older worker's joint range of motion data was used during this investigation. It provided the following upper extremity joint constraints:

- Arm flexion
- Arm extension
- Arm abduction
- Arm adduction
- Arm medial rotation
- Arm lateral rotation
- Shoulder flexion
- Shoulder extension
- Shoulder abduction
- Shoulder adduction
- Elbow flexion
- Elbow extension
- Elbow pronation
- Elbow supination
- Wrist flexion
- Wrist extension
- Wrist abduction
- Wrist adduction

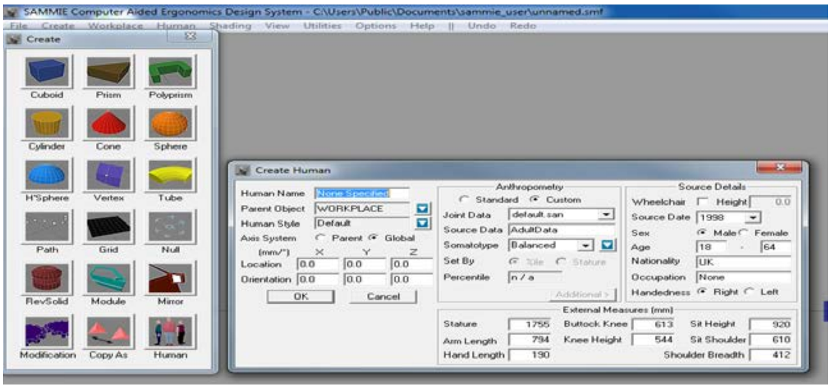
All these joint mobility constraint values show angular deviation of any specific joint with reference to its neutral position. Having greater joint mobility simply means a person with more flexibility in movements and better chances of performing any assembly task.

7.5.2. Translating capabilities data into a usable format

Previously published literature draws attention to the importance of translation and presentation of design data (capabilities data) in an appropriate way where designers can easily understand and effectively utilize it during the design process. If the design team is not properly trained and unable to understand the design data it is interpreting, use of the data could lead towards unrealistic and awkward design solutions (Gyi et al., 2000; Marshall et al., 2010). In this research, efforts have been made to present joint mobility data in a simple format and its graphical presentation make it easily understandable so that less experienced designers can effectively use it.

7.5.3. Using capabilities data in a design tool

In addition to the unavailability of sufficient data necessary to enable professionals to make more informed and realistic design decisions, existing design tools are not in a format or language that designers find easy to use (Gyi et al., 2000). Furthermore, it was highlighted that the majority of designers use computer-aided design tools that assist them during the design process. Keeping in view all these issues, a suggested way forward is to integrate capabilities data with existing design tools (figure 4.4) so that ergonomists and designers can utilize it. For this purpose, joint mobility data is integrated with an existing computer-based design tool SAMMIE (Sammie-Cad, 2012). SAMMIE allows the creation of a human model where designers use capabilities data from available databases and percentile values are usually used as a reference. Figure 7.1 shows how SAMMIE allows a customized human definition where the user can define anthropometry, sex, age, nationality, occupation, and many external measurements like stature, arm length, hand length, buttock knee, knee height, sitting height etc. By defining joint constraints data for appropriate individuals, older people in this case, it is possible to validate any design scenario in terms of its acceptability or feasibility for older workers. Measured joint constraints like flexion, abduction and rotation are used to generate data files for individuals with their varying capabilities and used for task analysis. The content of these files is illustrated in figure 7.1.



Originally from: Barter, Emmanuel, and Truett; as reported in Dempster, with additions from Boeing etc. Further additions and refinements made by Case, Freer, and Marshall (2001).(I4) 19 12

	Flexion				Abduction				Rotation			
	Maximal		Comfort		Maximal		Comfort		Maximal		Comfort	
	max	min	max	min	max	min	max	min	max	min	max	min
Pelvis	180	-180	180	-180	180	-180	180	-180	180	-180	180	-180
Lumbar-Spine	50	-20	40	-1	30	-30	20	-20	25	-25	20	-20
Thorax	20	-10	15	-10	10	-10	5	-5	10	-10	8	-8
Left-Shoulder	35	-0	35	-0	50	-35	50	-35	30	-3	10	-1
Left-Upper-Arm	90	-45	90	-45	70	-30	70	-30	45	-45	45	-45
Left-Elbow	90	-0	90	-0	2	-2	1	-1	80	-90	80	-90
Left-Wrist	40	-70	40	-70	15	-50	15	-50	2	-2	1	-1
Right-Shoulder	35	-0	35	-0	50	-35	50	-35	30	-3	10	-1
Right-Upper-Arm	90	-45	90	-45	70	-30	70	-30	45	-45	45	-45
Right-Elbow	90	-0	90	-0	2	-2	1	-1	80	-90	80	-90
Right-Wrist	40	-70	40	-70	15	-50	15	-50	2	-2	1	-1
Left-Hip	102	-50	45	-45	75	-31	45	-30	35	-70	25	-60
Left-Knee	125	-1	50	-1	2	-2	1	-1	43	-36	35	-30
Left-Ankle	40	-38	35	-20	23	-24	15	-15	7	-7	5	-5
Right-Hip	102	-50	45	-45	75	-31	45	-30	35	-70	25	-60
Right-Knee	125	-1	50	-1	2	-2	1	-1	43	-36	35	-30
Right-Ankle	40	-38	35	-20	23	-24	15	-15	7	-7	5	-5
Neck	60	-65	50	-40	40	-40	40	-40	80	-80	55	-55
Head	20	-30	10	-20	2	-2	1	-1	2	-2	1	-1

Alternative

	Swing				Sweep				Rotation			
	Maximal		Comfort		Maximal		Comfort		Maximal		Comfort	
	max	min	max	min	max	min	max	min	max	min	max	min
Left-Upper-Arm	90	0	90	0	190	-80	135	-30	25	-130	10	-100
Right-Upper-Arm	90	0	90	0	190	-80	135	-30	25	-130	10	-100
Left-Hip	102	0	45	0	270	-90	210	-50	35	-70	25	-60
Right-Hip	102	0	45	0	270	-90	210	-50	35	-70	25	-60

Figure 7.1: Using joint range of motion data for defining human capabilities in SAMMIE

7.5.4. Getting feedback on design inclusiveness

After defining human capabilities within a design analysis tool (SAMMIE in this case), designers can recall a number of humans in a virtual environment. CAD modelling provides an opportunity to develop models for working environments where designers can generate models for products, workstations, tools etc. being used during any work performing activity. Now, by following conventional digital human modelling procedures of ergonomic risk assessment, designers can experiment with a diverse population and assess acceptability against any design scenario. The results found will provide feedback about how much risk is involved with this activity and whether an individual defined in the database is able to perform the task or not. In this case study, joint mobility data with other anthropometric values has been used at the back end, so feedback about reach, access and acceptability of specific postures will define inclusiveness of any working method. As far as this case study is concerned, a pool of working strategies captured in the furniture manufacturing industry will be analysed and their feasibility for older people will be considered.

7.5.5. Conclusions and recommendations

Finally, conclusions will be reached about the inclusiveness of any working procedure, posture or strategy for a diverse workforce; older workers in this case. As mentioned in the previous chapter, video recordings have been made for a variety of workers based on their work experience and level of skill, so a comparison about the level of acceptability of any work strategy will inform the designers about the inclusiveness of any scenario. Furthermore, designers can easily understand possible reasons for design exclusion and how this issue can be addressed so that older workers might be accommodated in working environments. Promotion of optimal working strategies will increase design inclusiveness. All these steps are shown in figure 7. and figure 7.3.

Figure 7.2 is a general flow diagram about the promotion of an inclusive design strategy within an industrial environment and shows that design inclusiveness starts with highlighting and capturing potential capabilities differences among the humans and then using that data for design assessment. Any mismatch between job demands and workers capabilities will make that work task unacceptable for that individual.

Moreover, figure 7.3 shows a flow diagram of digital human modelling based inclusive design method for task assessment where joint mobility data of older workers is used in computer-based tool SAMMIE for task assessment of manufacturing assembly activities.

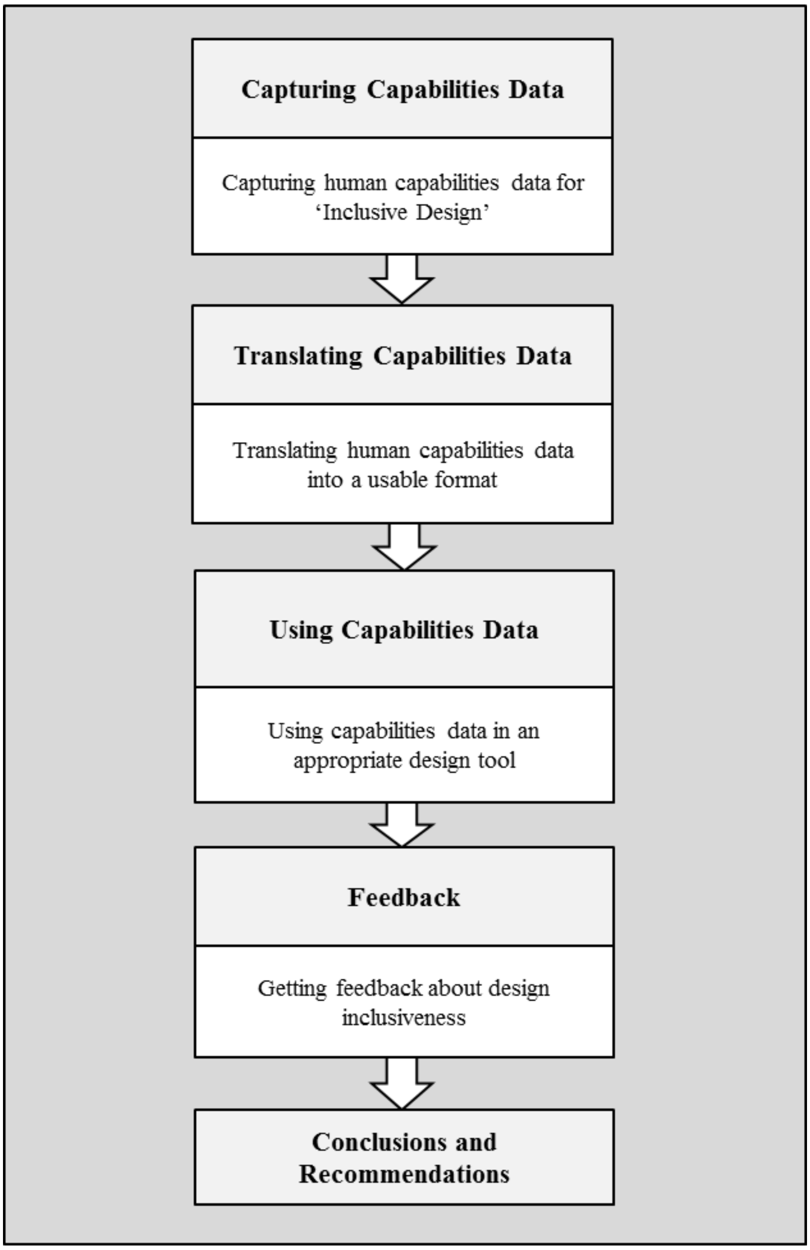


Figure 7.2: Inclusive design method flow diagram

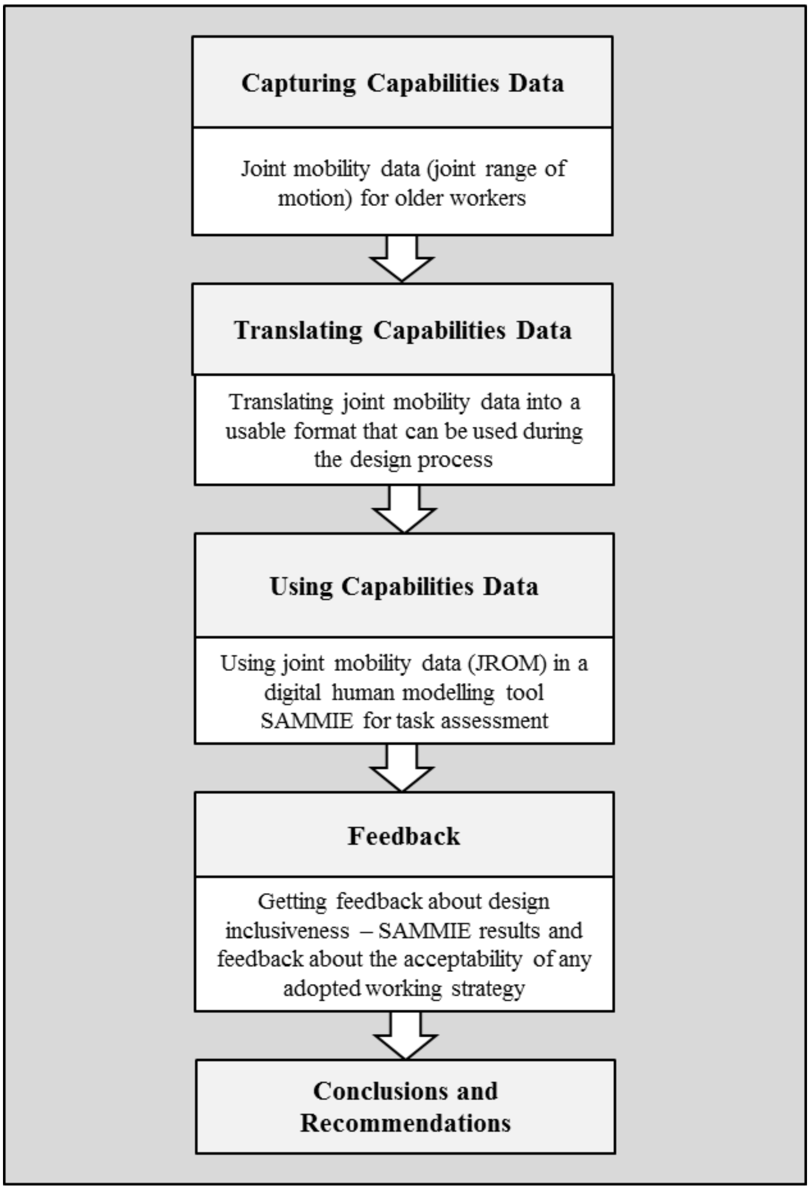


Figure 7.3: Digital Human Modelling (DHM) based inclusive design method flow diagram, for task assessment

7.6. Validation case study at a furniture manufacturing industry

Previously, it has been concluded in chapter 5 that different workers perform their activities in different ways and this has a significant impact on their work performance and level of risk exposure where level of skill and experience play their role. Experienced and highly skilled workers are found to be more productive in terms of productivity and workplace safety. It has been suggested that differences in working strategies and patterns offer a diverse pool of working methods and this diversity provides more design solutions. These possible solutions can be used for getting optimal working methods that are equally acceptable for older workers. However, validation of their acceptability can be made through a digital human modelling based computer-aided tool where individual's joint mobility data is used for highlighting a mismatch between job demands and older workers' capabilities.

7.7. Results and discussion

Figure 7.4 shows three workers carrying on the same assembly operation on a workstation. It is very clear that they are performing their task in entirely different ways. Differences in their working methods are significant in terms of tool handling, tool orientation, object or product orientation and body posture. It can be said that orientation of the object (sofa) and holding of a tool (drill) account for significant differences in adopted postures. The most difficult posture is adopted by worker 3 (method 3), where the position of the upper-arm, lower-arm, neck and orientation of the hand might be the assessment criterion for the acceptability of this method's inclusiveness. It is also clear that the position of the upper-arm and lower-arm of worker 3 is the most awkward and differentiating feature and has a direct relationship with joint mobility of the workers. It seems that a variation in joint constraints of upper-arm and lower-arm for older people can make this method unsuitable for them.

Digital human modelling tools are capable of predicting risk involved during work, with an acceptable level of reliability. Use of the computer-based digital human modelling tool SAMMIE can provide information about the acceptability of these working strategies regarding their inclusiveness for older workers. For this purpose, computer-aided modelling of the workplace has been carried out where virtual humans can be placed and design assessments can be carried out. During this experimentation, all 31 workers (older) are evaluated performing each working method. In this way, 93 (31x3) scenarios have been created and attempts are made to replicate actual working postures of older workers. The differences in joint mobility capabilities, means it is unlikely that all older workers can adopt all these working postures. For the purpose of analysis, lower-arm and upper-arm positions of these actual working postures have been replicated in SAMMIE. Assessment of a fully capable SAMMIE human model was first made to check whether or not a fully capable person can perform this particular activity in this way, and what level of joint mobility requirements are involved in any adopted posture. The joint constraints of a fully capable SAMMIE human model set the criteria for comparison of these (actual working postures with joint constraints of fully capable SAMMIE human model) and older workers (with limited and varying levels of joint mobility).

It was concluded in chapter 5 that complex body movements that contain both simultaneous bend and twist have a high level of risk at work and these must be avoided. Clearly, worker 3 (method3) is adopting a complex and relatively difficult trunk/back posture, where the main cause of this awkward posture is the orientation of the object (sofa). It can be seen that the orientation of the sofa for worker 1 and 2 is different, and this determines the view and height of the object (position of the working object with reference to face, shoulders etc.). Difficulty in viewing the working object and inappropriate height led worker 3 to adopt an unfriendly working posture where the neck is bent, the trunk/back is bent and twisted and one elbow is above shoulder level. In comparison with worker 3, worker 2 is performing better in terms of level of risk, but worker 1 seems very relaxed and comfortable during his work. Moreover, working strategies of worker 1 and 2 are different in tool holding and object holding, where positions of the shoulder are different. All these aspects can be seen in Figure 7.4.

The above discussion revels that, differences in these work organization issues lead to entirely different working strategies where adopted postures demand different joint mobility capabilities. For example, the positions of the upper-arm and lower-arm are found to be different for these three working methods. For finding the exact joint mobility requirements necessary for a successful replication of these postures, the SAMMIE computer aided modelling system has been used. This process starts with capturing actual dimensions of the objects used during any working process. In this case, these objects are the sofa, work table and drill gun. After developing a computer-aided model of the work environment, a virtual human is placed at an appropriate place and the actual posture is replicated with a human model, where joint mobility requirements can be found. The SAMMIE human model is composed of 19 limbs where movements of these limbs are controlled through joint mobility constraint data. Figure 7.5 shows all these limbs (L) and joint mobility constraints data for any selected limb against any selected posture (R). For this case study, actual working postures of assembly activity for three different methods have been replicated by a SAMMIE human model, where joint mobility requirements have been noted (figure 7.4). It is very clear from the snap shots that upper-arm and lower-arm movements are significantly different for these methods and are considered important for an inclusiveness of these working strategies.

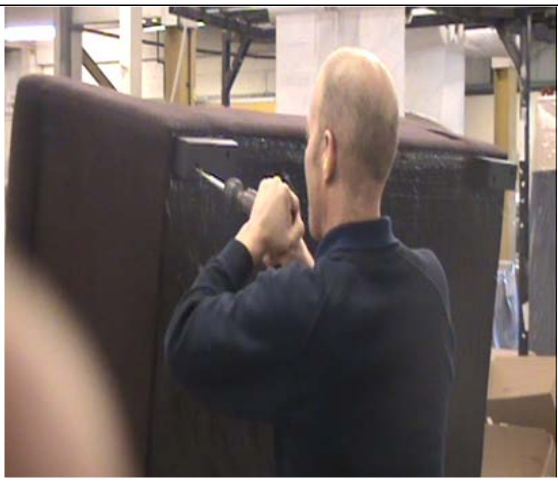
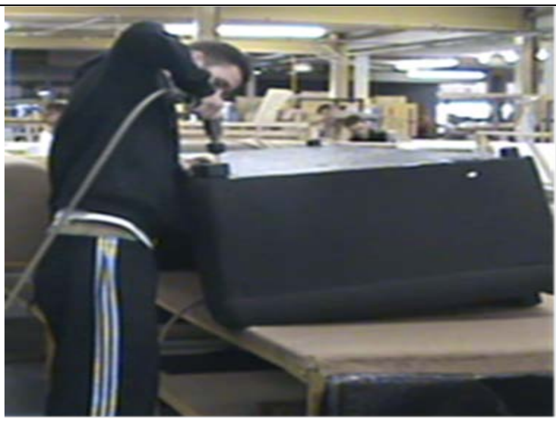
Worker	Description	
Worker 1 **(Method 1)**	Tool is held by two hands Both arms are below shoulder level No bend or twist in trunk Neck is straight Object is at appropriate height	
Worker 2 **(Method 2)**	Tool is held by one hand (other hand is used to grip the object) Both arms are nearly at shoulder level Trunk has little bent or twist Neck is twisted Object is at appropriate height	
Worker 3 **(Method 3)**	Tool is held by one hand (other hand is used to grip the object) One arm is above shoulder level Trunk is bent and twisted Neck is bent and twisted Object is at lower height	

Figure 7.4: Three workers performing same task with different methods

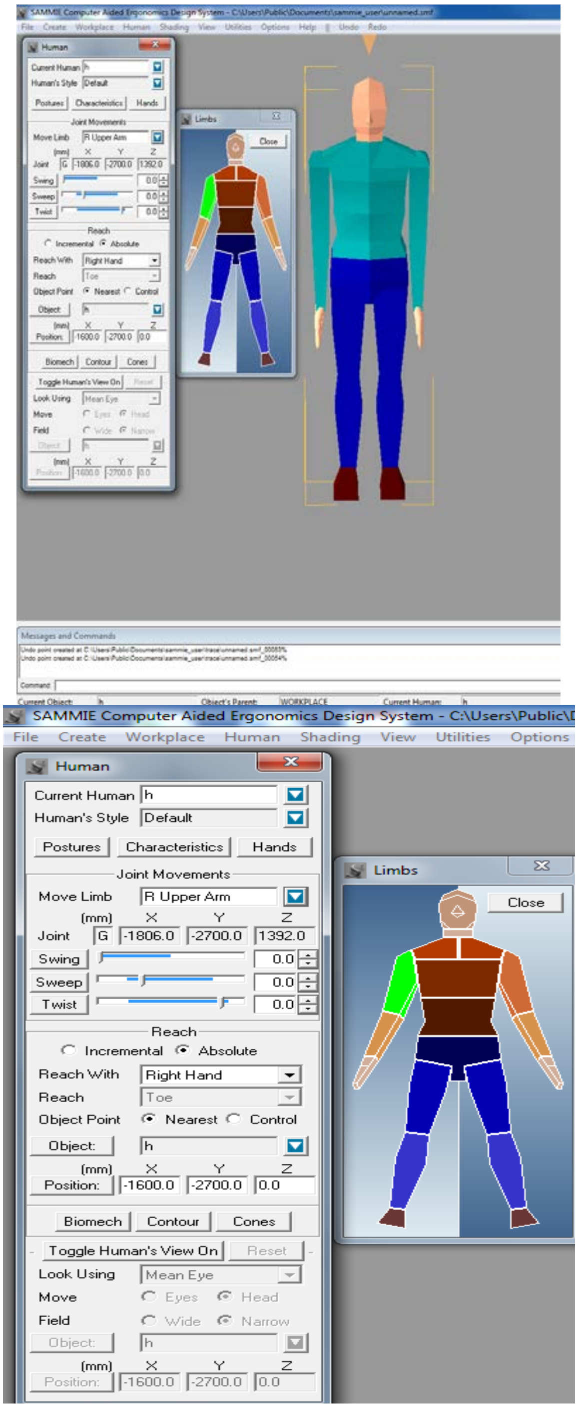
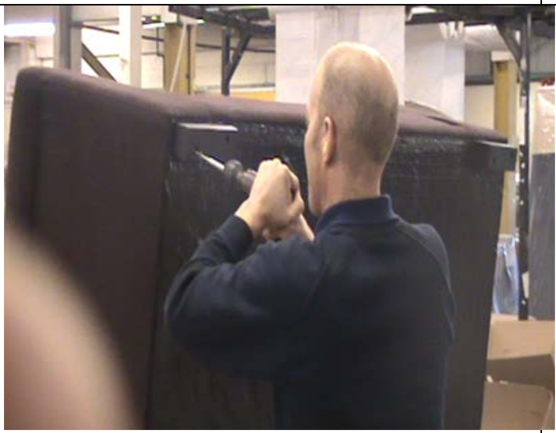


Figure 7.5: SAMMIE human model, showing 19 limbs (L) and joint constraints data (R)

Figure 7.6 illustrates that working method 3 imposes the highest level of joint mobility requirements, where the lower arm bend (R) demands a 141^0 extension which is high as compared with the other two methods, where it is 129^0 and 136^0 respectively. Similarly, right upper-arm swing value (113^0) is also significantly higher than that of method 1 and 2 (47^0 and 92^0 respectively). So, these pre-defined joint mobility requirements can be used as criteria to investigate the acceptability of any method for a broad range of the population. The HADRIAN database consists of joint mobility data for about 100 people, of which about 31 people belong to an age group of greater than 40 years without any functional disability that can reduce joint mobility. The joint mobility data of these 31 older and fully capable people has been utilized to assess the acceptability of any working strategy for older workers at the individual level. As mentioned earlier in this chapter, SAMMIE has the capability of managing capability data for individuals, where a designer has to provide a manual input about all these parameters that defines any human’s work performing capability.

During experimentation, 90 working postures have been analysed where every older worker (virtual human with actual joint constraints of an older worker of HADRIAN database) has been given a trial against three different working methods shown above. Figure 7.7, 7.8 and 7.9 show the examples of posture replication by SAMMIE (middle) and an older worker (right) against working method 1, 2 and 3 respectively. Joint mobility requirements needed by a fully capable human (SAMMIE) for the approximate replication of an adopted posture, set a criterion for the acceptability of a method for any individual and older workers in general. The aim was to investigate whether or not the digital human modelling system SAMMIE can be used to investigate inclusiveness of any adopted working strategy.

Worker	Actual working posture	SAMMIE-MAN (Fully capable human) joint mobility requirements		
Worker 1 (Method 1)		Upper Arm(R)	swing	47
			sweep	18
			twist	25
		Lower Arm (R)	Bend	129
			Cock	0
			Twist	25
		Upper Arm(L)	swing	67
			sweep	-9
			twist	-28
		Lower Arm (L)	Bend	115
			Cock	0
			Twist	-25
Worker 2 (Method 2)		Upper Arm(R)	swing	92
			sweep	62
			twist	8
		Lower Arm (R)	Bend	136
			Cock	1
			Twist	2
		Upper Arm(L)	swing	87
			sweep	44
			twist	-8
		Lower Arm (L)	Bend	92
			Cock	1
			Twist	-23

Worker 3 (Method 3)		Upper Arm(R)	swing	113
			sweep	95
			twist	20 red
		Lower Arm (R)	Bend	141
			Cock	0
			Twist	72
		Upper Arm(L)	swing	34
			sweep	-26
			twist	-8
		Lower Arm (L)	Bend	126
			Cock	-1
			Twist	-35

Figure 7.6: Joint mobility requirements for an assembly activity, performed in three different ways, captured by replicating actual working posture in SAMMIE-CAD

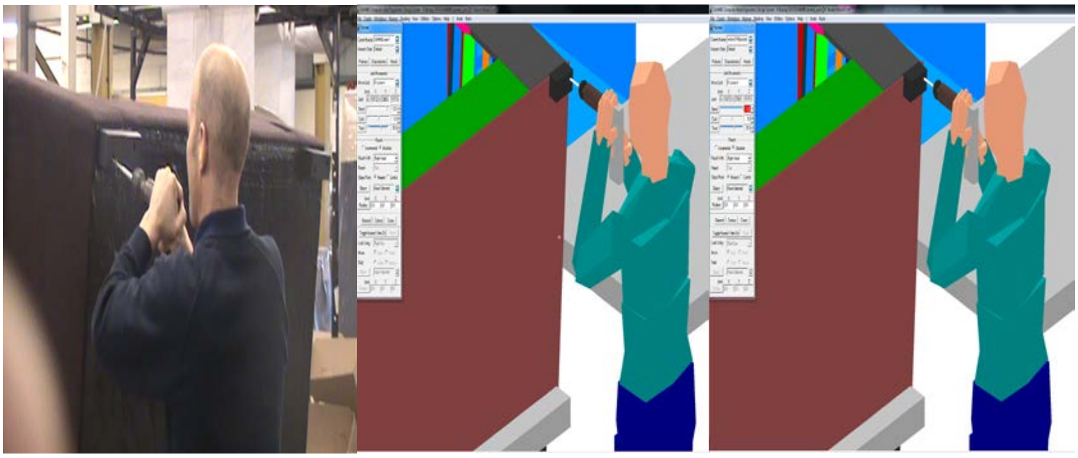


Figure 7.7: Using SAMMIE human modelling system to assess task inclusiveness for method 1

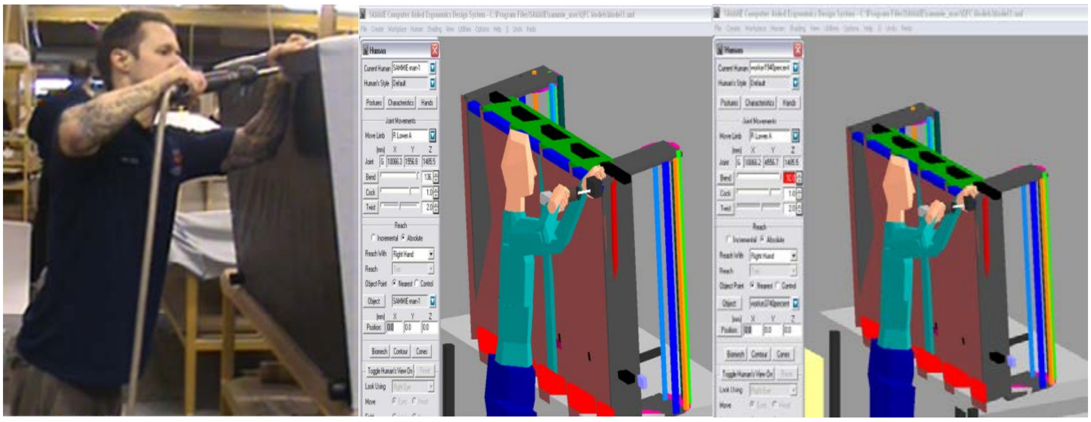


Figure 7.8: Using SAMMIE human modelling system to assess task inclusiveness for method 2

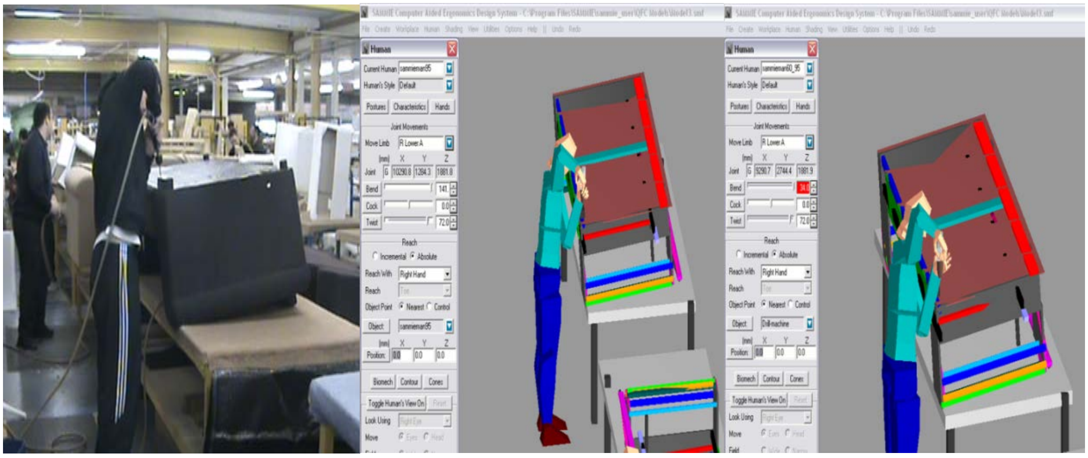


Figure 7.9: Using SAMMIE human modelling system to assess task inclusiveness for method 3

7.8. A deep insight

This section is a detailed description of the design evaluation process through the SAMMIE human modelling system. Figures 7.10, 7.11 and 7.12 show the same worker (Number 19 in the HADRIAN database) with his own joint mobility constraints. For comparison purposes, he has been shown to perform the same activity in three different ways, shown previously. Here the aim is to assess whether or not he is capable of performing these activities based on his limited joint mobility as he is 73 years old. It has already been discussed that method 1 and 2 impose relatively less joint mobility requirements as compared with method 3. Here, figure 7.11 clearly indicates that worker 19 can easily accomplish this assembly task by adopting method 1. However, the same worker is unable to successfully complete the same assembly task element through methods 2 and 3. Red colours in figure 7.11 and 7.12 indicate unacceptability of these two methods for this worker. In this way, it can be concluded that a person with limited joint mobility can easily perform this assembly task by adopting work method 1. Unlike method 1, the other two methods demand high joint mobility requirements and make them unacceptable for the same worker.

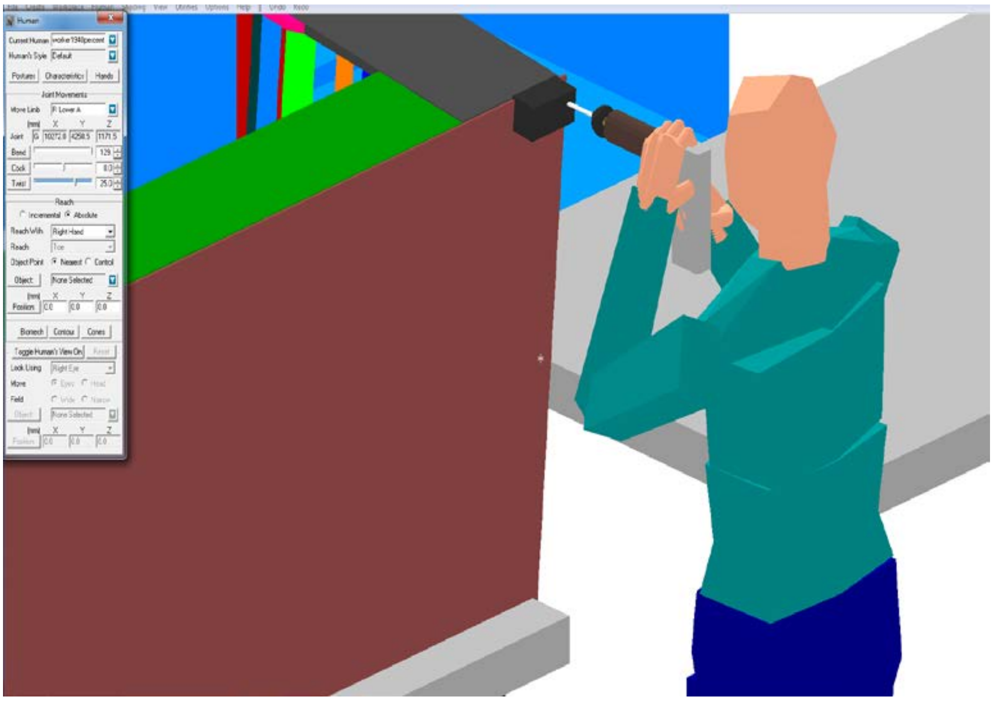


Figure 7.10: HADRIAN database worker19, SAMMIE result shows design inclusion for work performing method 1

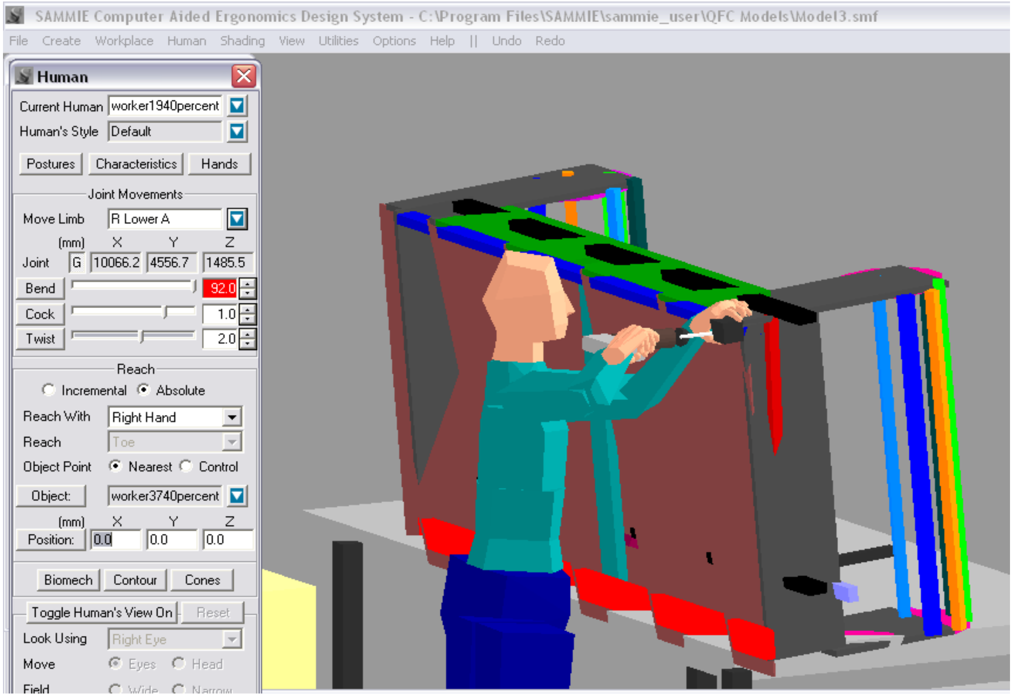


Figure 7.11: HADRIAN database worker19, SAMMIE result shows design exclusion for work performing method 2

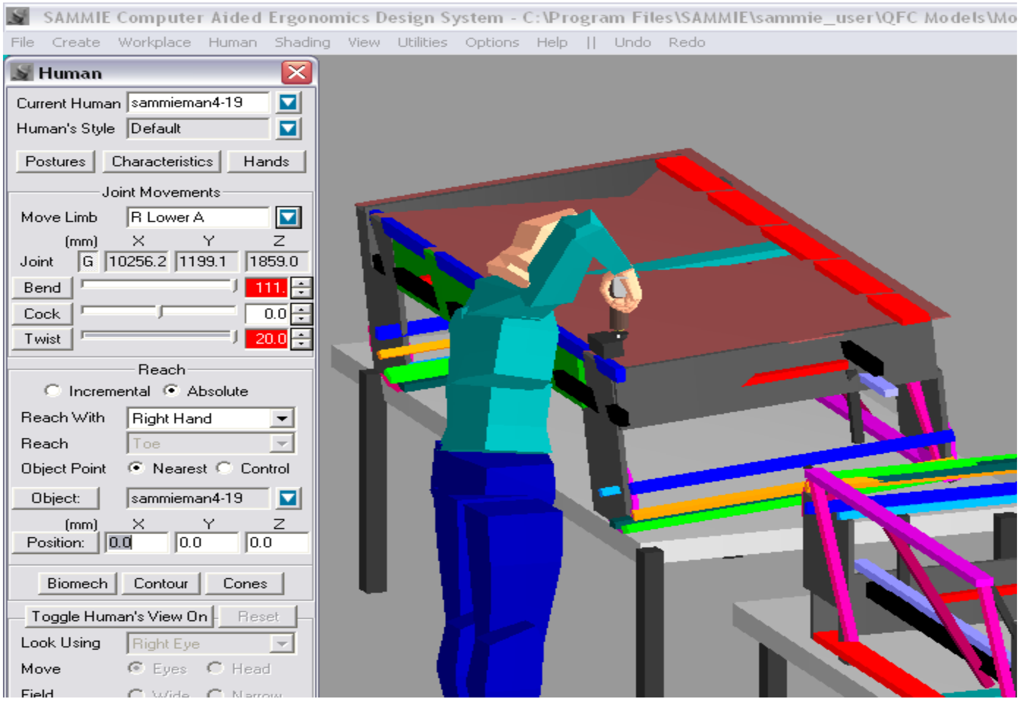


Figure 7.12: HADRIAN database worker19, SAMMIE result shows design exclusion for work performing method 3

As described above, the database has been used to define 31 older workers (>40 years of age) with individual joint constraints and then given a trial against these three working methods for the same assembly activity. The results indicate that work method 1 is acceptable for 84% of the older workers, which is the highest proportion as compared with 48% and 19% for methods 2 and 3 respectively. Table 7.1 summrizes the results and shows that only 5 out of 31 older workers were found to be excluded for method 1, whereas 16 and 25 for method 2 and 3 respectively.

Table 7.1 : Comparing design exclusion results for different work methods

Total number of workers	**31**	
Design exclusion of method 1	**5**	**16%**
Design exclusion of method 2	**16**	**52%**
Design exclusion of method 3	**25**	**81%**

The above results indicate the usefulness of the human modelling based inclusive design method where designers, ergonomists, engineers, managers and planners can promote such work practices that are equally acceptable for a broad range of the population, for example, older people in this example. The results clearly indicate that method 1 is the optimal solution in terms of its accepability for older workers, based on joint mobility criteria. As all these assessments are actually based on the captured working strategies adopted by different workers, so the pool of avaible solutions can be increased by capturing more workers.

7.9. Strengths and limitations

This case study has shown a great potential for using the digital human modelling technique for the promotion of an inclusive design approach in industrial applications. In the future, workforce diversity will increase and people with different backgrounds, cultures, sizes, shapes, age and expereinces will be sharing the same workplaces. The inclusive design method provides an opportunity to address all these issues proactively so that safe, healthy and productive workplaces might be assured. In future, organizations will have to think more seriously about these human variability issues, so that they can retain their skilled and experienced workforce, which will be a key driving force for achieving organizational sustainability. This study provides an idea about how the proposed inclusive design method can work for the benefit of individuals and organizations, in terms of workplace safety, productivity and human well-being. It also highlights the importance of the availability of more realistic human capabilities data (physical, physiological and cognitive) and use of that in an appropriate design tool.

On the other hand, validation of the proposed method has been carried out only for furniture manufacturing assembly activities. There is a need to validate the method against more industrial applications where its usefulness can be assessed against a variety of applications. Moreover, this case study has only used the physical capabilities context of human working capabilities, but the concept should also be validated for some more complex dimensions of human capability such as physiological, psychological and cognitive abilities. Similarly, older workers' capability data is not limited to joint mobility; there are many other functional capabilities that decline with age, so other avaiable data should also be used to promote healthy and safe working of the ageing workforce. Initially, the proposed method has been validated through SAMMIE, where older worker's joint mobility data has been used manually. Previously, the HADRIAN automated task evaluation method (based on SAMMIE human modelling) has been used for some simpler applications like kitchen based activities, use of ATM machines, and transport related activities. There is a need to enhance the automated task evaluation capability of HADRIAN from simple activities to some complex industrial activities like manual assembly operations.

7.10. Conclusion

A digital human modelling based inclusive design approach is considered useful for addressing work-related issues of a diverse workforce, especially older workers. Like joint mobility data, other functional capabilities data can be collected and used for assessing whether or not working conditions, environments and strategies are suitable for a broad range of the population. This proactive design approach benefits individuals and organizations by securing safe working conditions where people, with their existing differences, can perform at their best. In this way, global workforce challenges of diversity and ageing can be addressed by promoting such design practices. However, still there is a need to capture more data about the human differences and effectively utilize that in appropriate tools, so that more realistic work strategies can be implemented.

Chapter 8

Conclusions and Recommendations for Future Work

8.1. Introduction

It has been stated several times in this thesis that the aim of the research is to "support the 'inclusive design' process by the provision of relevant data and new application methodologies". The research has presented a new three step approach to achieve this aim and to meet the objectives set in chapter 1. This chapter contains an overview of the conducted research in relation to how these objectives have been met, discusses the conclusions from the research and how they contribute to knowledge. The limitations of the research are discussed together with possible directions for continuing the research in future.

8.2. Meeting the objectives

The research objectives are detailed in section 1.2. This section consists of a brief discussion of how each has been met.

Objective 1: *To explore current global workforce challenges and their relationship with individual and organizational work performance.*

A review of the current literature, discussed in chapter 2, highlights the important global workforce challenges as the increase in workforce diversity and the increase in the proportion of older workers in future organizations. These challenges are directly linked with human variability issues that significantly contribute to individual and organizational work performance. For example, the effects of age and the relationship with work performance have been discussed in the reviewed literature. Furthermore, individual factors like skill and experience and their impact on task performing strategies have been discussed in chapter 6 where it is found that the level of skill plays a contributing role in the selection of task performing strategies. Selection of more productive, safe and healthy working strategies positively contributes in achieving an optimal individual and organizational work performance, by adopting risk free, less time consuming and less physically demanding working procedures.

Objective 2: *To identify the research gap in the literature relating to the promotion of the inclusive design method for addressing global workforce challenges, especially a safe and healthy accommodation and retention of older workers.*

In relation to objective 1, the reviewed literature (chapter 2) also confirms that the inclusive design method is extremely useful for addressing global workforce challenges by accommodating the design needs of a diverse workforce, especially older workers, during the design process. It is quite evident from the literature that the ‘inclusive design’ method has been effectively used to address similar kinds of issues; however, there is still a need to explore the viability of this approach for achieving an inclusive work environment by addressing human variability issues at an early design stage. There is a gap about the use of ergonomic based human modelling method for addressing the needs of older workers at workplaces. Furthermore, it is also found that that the implementation of inclusive design method is still needed relevant data that can support the design process.

This work has addressed the gap by providing data about working capabilities and task performing strategies of different workers, and this has a direct relevance for the effective use of the ‘inclusive design approach’ for workplace design. This research has further contributed by successfully using a human modelling based strategy to highlight and address the design needs of older workers in manufacturing workplaces.

Objective 3: *To understand human variability issues in terms of work performance capabilities and strategies, and their implications for ‘inclusive design’ in general and for older workers in particular.*

This objective of understanding human variability issues in terms of work performance capability has been achieved by analysing the Disability Follow-up Survey (DFS) data and the HADRIAN database (discussed in chapters 4 and 5). Furthermore, a comprehensive statistical analysis (chapter 5) to properly understand the effects of age, gender and disability further highlights the significance and impact of these variability issues and their relevance within the inclusive design process. Moreover, the HADRIAN database contains human capability data for a broad range of the population where a comparison between the joint mobility data of older and younger workers further facilitates the understanding of human variability issues and their significance in addressing the design needs of older workers.

Objective 4: *To investigate how experience and level of skill affect work performance strategy, in terms of productivity and risk exposure.*

Chapter 6 explores the effects of factors such as experience and skill on work performance. Videos recorded at a furniture manufacturing company provide comprehensive data for analysis purposes. Investigations have been based on fundamental ergonomic principles, and two ergonomic assessment methods, OWAS and REBA, have been used to assess the level of risk involved with any adopted strategy. Moreover, differences in object (sofa in this case) handling strategies have also been considered separately. Furthermore, analysis of the data reveals the contribution of particular kinds of body movements or postures that significantly affect human well-being at work. Data analysis has been carried out by two different methods (OWAS and REBA), so that a deep insight can be taken into account, and the results have been validated for each method.

Objective 5: *To validate the usefulness of HADRIAN proactive digital human modelling approach for the implementation of an inclusive design strategy for addressing the design needs of older workers.*

A digital human modelling based inclusive design strategy has been used to validate the concept of using human capability data along with the captured task performing strategies and behaviours for the assessment of the level of acceptability of any adopted strategy for older workers. For this purpose, a case study has been presented in chapter 7 to validate the research method presented in chapter 3. The conclusion is that this three step approach is effective in addressing the design needs of a diverse workforce, especially older workers. So, utilizing human capability data (joint mobility data, chapter 5) and task performing strategies (chapter 6) in a digital human modelling, can proactively address the design needs of older workers in manufacturing workplaces.

Objective 6: *To develop a design methodology for the promotion of an 'Inclusive Work Environment'; where people with their existing differences can coexist productively.*

The research method (described in chapter 3) is a novel three step guideline methodology that has been used to promote such working environments that are equally acceptable for the majority of workers, in spite of their existing differences.

Step 3 of the research method (presented in chapter 7) indicates how this approach can be used to promote a safe, productive and healthy working environment.

8.3. Conclusions and Contribution to Knowledge

This thesis has drawn a number of conclusions that can be considered as knowledge contributions from the research. These include:

- Highlighting the fact that workforce diversity is increasing where the proportion of older workers is rapidly increasing, and that these issues bring many challenges for organizations.
- Managers, engineers, ergonomists and designers are aware of the fact of an ageing population; however, very little is known about the accommodation and retention of older workers at workplaces by providing them an inclusive work environment.
- The ‘virtual user trial’ approach using a limited number of individuals is at least as relevant as using statistical representations of populations with in DHM as conventionally used.
- Because of similarity in the severity scores used in the HADRIAN database and the Disability Follow-up Survey (DFS), it might be said that any design recommendation made by the HADRIAN task analysis system is likely to represent its acceptance for millions of the UK population – based on particular functional capability defined in both of the datasets.
- Age and disability play significant roles in determining the joint mobility of an individual that often directly defines the capability to perform tasks like manual assembly. Moreover, the decrease in joint mobility caused due by age and disability (wheelchair users and arthritis patients) depends on the joint and type of the motion used. However, gender does not play any significant role as the joint mobility of men and women are approximately the same. Furthermore, these human capability variations become challenging when designers wish to include all in the design process. The conventionally use of 5^{th} and 95^{th} percentile values of the ‘normal’ population are not a true presentation of the whole population, especially older workers.

- Skill and experience play a vital role in the selection of working strategies. Skilful workers are more likely to adopt safe, easy and productive working strategies, based on the analysis of object handling strategies and body postures for manual assembly tasks (captured at a furniture manufacturing company). It can be concluded that training and experience reduce the chances of musculoskeletal disorders, injuries, slips, falls, back pain etc. that directly affect individual and organizational work performance. Selection of optimized working strategies and procedures, followed by training the workforce accordingly, can be a successful way to accommodate all by minimizing the impact of differences caused by age, skill, experience and background.
- Ergonomic risk assessment methods like OWAS and REBA can be used to access and promote such working strategies that are more inclusive and acceptable.
- A digital human modelling based inclusive design strategy can proactively address the design needs of older workers by identifying mismatches between human capabilities and task requirements. In this way, the proposed inclusive design strategy can be used for assessing whether or not working conditions, strategies and behaviours are suitable for a broad range of the population.
- Finally, the proposed three step approach has been found highly useful for developing a realistic understanding of human variability issues and their relevance to work performance, along with promoting inclusive working strategies that are equally acceptable for the majority of workers.

8.4. Scope and Limitations

It is highly important to have a review of the methods employed during the entire research, so that the strengths and limitations of the method can be highlighted and discussed. As mentioned in chapter 3 (section 3.2) this research suggests a three step design framework that promotes the utilization of inclusive design strategy for addressing the design needs of a diverse workforce. These three steps are capturing human working capabilities, capturing task performing strategies and finally verifying design inclusiveness by using appropriate tools and methods.

The focus of this research was mainly to suggest and validate the inclusive design strategy to address the design need of workers at workplaces with a special interest in achieving an inclusive work environment where older workers can carry on their work safely in a manufacturing assembly environment. Validation of the proposed method was carried but by capturing, analysing and utilizing human capabilities and working strategies data for recommending such working procedures that are equally safe, productive and acceptable for older workers.

This research has focused on the physical capabilities of humans, and more particularly on joint mobility data for a sample population that represents older and younger, able-bodied and disabled, and male and female populations. It cannot be said that the capability data is a true reflection of the whole population; however, it represents most segments of society. As said, the most dominant issue in this research was to meet the design needs of the older population; so, it contains a significant and realistic representation of the older population. Conclusions made in the previous section clearly highlight that these findings can be used by designers and ergonomists in the main design process to conceptualize such design procedures and methods that can address design challenges in the light of these. These findings can be used for the designing of products, processes, and environments, so that these can be made more usable, assessable and acceptable.

The method proposed in this research has been validated only against one case; that is furniture manufacturing assembly environment. There is a need to validate the method for other industrial applications. However, the validation of the research framework will require many other requirements to be met that actually define the potential limitations of this research. For example, the first step is to capture highly relevant capability data which is the direct need of the task. In this research, the focus was on manual assembly activities; therefore, joint mobility data has been captured and analysed as it has a direct relevance with fast, quick, accurate and simultaneous movements of the upper extremities, considered necessary for such activities. Similarly, task performing strategies data (chapter 6) have also been captured in a manufacturing assembly environment of a furniture company. So, the scope and limitations of this research can be discussed at three different levels. Firstly, human capabilities; secondly, task performing strategies; and lastly the

HADRIAN task assessment strategy. The following paragraphs discuss these in detail.

There are many other dimensions of human capability like physiological, psychological and cognitive. which are directly used in the successful accomplishment of any task. This research has reported a good understanding of human variability issues caused due to the differences in working capabilities and their significance for the promotion of inclusive design method. However, it has focused on a single dimension of the physical working capabilities of human, which is joint mobility (joint range of motion), and this defines a limitation of this study. However, the impact of different factors like age, gender, skill, experience, background etc. on working capabilities of human can be captured, analysed and used in the design process.

As concluded in chapter 6, skill and experience play an important role in determining the type of working strategy and posture adopted by the worker. In this research, the strategies and postures of workers with different levels of skill and experience have been captured for similar kinds of manual assembly tasks. The analysis was made on the basis of assessing the level of risk exposure associated with an adopted strategy, and differences in the object handling strategies. A complete understanding of how skill and experience affect human behaviours in terms of the selection of working strategies provides an opportunity to set guidelines and procedures that can be used to train workers, for achieving a working environment that is more inclusive, safe and productive. As an example, this research (chapter 6) concludes that the object handling strategies during manual assembly work are influenced by the level of skill possessed by the worker. Orientation of the object (sofa in the case study presented in chapter 6) on the working table is the key element that influences the selection of working postures. At the same time, the sequence of the operations, which is also directly linked with object orientation, affects task completion time which is associated with individual and organizational productivity. Moreover, some other very useful conclusions have been made in that manual material handling (lifting a weight greater than 40kg), complex movements that contain simultaneous bend and twist movements of back/trunk, raising the arms at or above shoulder level and bending of the knees are the prominent causes of musculoskeletal disorders and injuries. This useful information can be used to standardise working procedures and train workers accordingly so that the optimal output can be achieved and maintained. Similarly, recorded videos can also be used to design more safe and secure workstations where workers with differences in age, skill, experience and background can perform equally well.

In this research data (for step 2) was only collected at a furniture manufacturing company, where video recordings were carried out over four workstations and 12 workers of varying levels of skill, performing manual assembly activities. There is a further need to validate the results concluded by this research in other types of industrial environments and focusing on finding a relationship between other factors such as age, task complexity, background and culture with task performance.

As concluded in the literature review (chapter 2), the digital human modelling based methodology is effective in proactively addressing design related issues in product, process and environment design. Moreover, the HADRIAN human modelling based inclusive design strategy has been used for some relatively simple applications including transport-related and kitchen-based activities etc. where the main objective was to understand and address design related issues faced by older and disabled people in performing their activities of daily living. This research has extended the scope of the HADRIAN inclusive design strategy from simple activities to industrially-based activities and shown that the use of this method is equally useful for industrially-based applications. However, this research is focused on manual assembly activities; it can be said that this approach can be further validated for other applications. In this research, the initial validation of the concept has been carried out by using joint mobility data of older workers for assessing the level of acceptability of any working strategy for older workers, by using HADRIAN human modelling system. Only joint mobility data has been used for replicating the adopted postures for determining whether or not an individual is capable of performing the task element in a particular way, as captured through the video recording. Unlike previous validations of the HADRIAN method, this research has just focused on the validation of the three step approach where only the effects of joint mobility have been considered during the task assessment procedure. The HADRIAN human modelling strategy is based on a multivariate task analysis system that provides the opportunity to divide an overall task into task elements so that an automated task evaluation can be carried out by using human capability data along with working behaviours. In this research, only one task element has been validated by using only one type of human capability data (joint mobility) against some specific tasks. However, the validation case study presented in chapter 7 meets the requirements of the research, as the objective was to validate the effective use of a human modelling based inclusive design method for addressing the design needs of older workers – by using capabilities data to validate the inclusiveness of working strategies, methods or procedures. The case study (presented in chapter 7) clearly indicates how this strategy can help designers in the development of an inclusive work environment that is equally acceptable for all – by promoting such working methods that are realistically more friendly, safe, productive and acceptable.

More precisely, it can be said that the approach used in this research is useful in achieving more sustainable and optimal design solutions that can provide an ‘inclusive work environment’, where more diverse workforces can be accommodated and utilized affectively. For example, chapter 5 concludes that age adversely affects the joint mobility that is directly linked with human work performance capability. Data captured at the furniture manufacturing company (chapter 6) indicates that along with some other factors, upper-arm and lower arm movements (arm at or above shoulder level) are among the major causes of musculoskeletal disorders and injuries (based on the ergonomic assessment made by using OWAS and REBA methods). Joint mobility decreases with age that can potentially affect work performance of older workers. Working strategies and methods that need higher level of mobility should be avoided for older workers. Designers have to implement all this by using appropriate methods, tools or techniques. Finally, the human modelling based inclusive design method used in this research (chapter 7) validates the concept and generates highly valuable information for designers, engineers and ergonomists.

8.5. Recommendations for Future work

There are many directions for the extension of this research:

- Validation of the research method for other industrial applications;
- As discussed, it is extremely important to capture and analyse human capability data and conceptualize human variability issues and their

relationship with many other factors like age, skill, background, gender etc. Eventually the data must be converted into a useable format so that designers can use it during the design process. It would be interesting to understand the effects of age and disability on other capabilities like cognitive, physiological, psychological etc. and how these effects and variations can be addressed and minimized and how they influence inclusive design decisions;

- Additional development of HADRIAN could be made possible by integrating more functional capabilities and working behaviours data so that the method can be used for a wider range of applications. For example, the HADRIAN task analysis system could be enriched by capturing and integrating highly relevant data about fundamental task performing strategies for reach, grasp, move, position and release activities carried out during manual assembly activities. Similarly, inclusion of a wide variety of tasks and working behaviours would facilitate the use of this method for many different types of activities;
- Including other factors like fatigue, external work environment, task complexity etc. and their relationship with age, skill, background and disability would be highly relevant to inclusive design. In this research, only skill and experience have been considered for finding a relationship between these factors and the level of risk involved with the adopted working strategies. Moreover, other criteria like product quality, work productivity and effective time utilization could also be used to further enhance the understanding of human variations and their impact on overall individual and organizational work performance;
- There is a good potential for carrying out research into understanding the differences in working behaviours caused due to age and how older workers make adjustments to fulfil task demands, in spite of a decline in their functional capabilities. These findings could be used to design products, processes and environments that are more accessible and inclusive; and finally lead to achieving a sustainable and inclusive working environment where workers feel themselves comfortable and productive.

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