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Joint mobility and inclusive design challenges

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A B S T R A C T

The aim of this research study was to understand and evaluate the effect of different factors including age, gender, disabilities and medical conditions on joint mobility. Joint mobility data from a group of 66 people from a previously existing database has been re-analysed. Twenty four participants had disabilities and 42 participants were considered to be 'able bodied' with no recognised disability. For each individual, 18 joint range of motion values were measured and an ANOVA test was employed to demonstrate the influence of the selected factors on joint range of motion. Post Hoc (Tukey) tests were also performed to gain deeper insight into significance levels and correlations between the factors. The results clearly indicate that joint ROM significantly decreases ($p < 0.05$) with increasing age for arm abduction, arm medial and lateral rotation, wrist flexion and wrist adduction. Moreover, people with disabilities (wheelchair users and arthritis sufferers) showed a considerable decrease in joint mobility for arm flexion, arm abduction, arm lateral rotation, elbow flexion, elbow supination, wrist extension and wrist flexion. The results also highlight that designing products, equipment, services or workplaces against 5th and 95th percentile criteria is unable to provide appropriate and necessary support for achieving the objective of design inclusiveness. Rather designers should have a deep insight of the data variations at a predesign phase so that more appropriate and informed design decisions can be made that are more likely to be acceptable for a broad range of the population.

1. Introduction

It is very important to design products, workspaces and equipment to accommodate the widest range of the population. Joint range of motion (ROM) is one of the factors which directly influence the performance of workers. Like the general population, the worker population has different anthropometry, capabilities and preferences which directly or indirectly affect work ability. There are many factors that influence joint range of motion. The aim of this study was to determine how age, gender, and some specific conditions like arthritis and the use of wheelchairs affect ROM. The importance of these variations and challenges for designers, engineers and ergonomists has also been highlighted in terms of their relevance to inclusive design.

2. Importance of joint range of motion in 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 specialized design". Subsequently, the inclusive design term was also related to providing quality of life and independent living for the ageing population (Waller and Clarkson, 2009). So, the 'design for all', 'inclusive design' or 'universal design' philosophy aims to accommodate the design needs of the largest percentage of the population so that 'designed out' scenarios may be minimized. The challenge for design inclusivity is that it is difficult 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). Despite the need to consider the broadest range of the population in the design process, designers experience

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difficulties in doing so as the implementation of inclusive design is challenging due to the lack of relevant data and appropriate tools that can help in designing products, processes and environments (Gyi et al., 2000). Digital human modelling (DHM) can be a useful tool as it provides a computer model of the human alongside the computer model of a product, but to be useful DHM systems need appropriate data including that on joint range of motion.

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 workspace 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 (1966)).

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 caused high discomfort levels for simple repetitive exertions. It was further concluded that the combination of flexion and ulnar movements caused more discomfort as compared to other simpler and easier motions. Digital human modelling systems generally try to minimise this problem of discomfort increasing as the maximum joint extension is approached by algorithmic methods. Typically a combination is used of a proposal by Barnes (1963) that the least significant (most distal) body links be moved first, and the idea that links tend to arrange themselves so that joint angles are kept within a normal or 'comfort' range of movement. Precisely what these comfort ranges might be has been the subject of considerable research (Schmidt et al., 2014 provide a very comprehensive review for the particular application of automotive seating). However, in the study reported here the focus is on people likely to have reduced mobility and for whom inclusion within designs is likely to be reliant on use of the full range of motion rather than a comfort range.

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 old. Chung and Wang (2009) also conducted a study on a Taiwanese population of 1134 workers and measured 28 joint ranges of motion values and evaluated the effects of age and gender on joint ROM. It was concluded that joint ROM decreased with increased age; especially in the wrist joint and the cervical spine. Furthermore, female workers had greater joint ROM values than males for the upper extremities, lower extremities and cervical spine joints. The same kinds of conclusions were reached by Chaparro et al. (2000), in comparing wrist joint ROM values among different age groups and genders. The results suggested that females had greater wrist joint mobility; however, an older person (age 90) had only 60% joint ROM when compared to 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 found that there was a decline in shoulder range of motion with age except for internal rotation which increased with age. As far as the effect of gender is concerned, it was again found that female subjects had 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.

The effects of other factors like ethnicity, occupation, race and daily activities 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 ROM values for Swedish and Icelandic people. No differences were found for shoulder joints but Swedish women had significantly greater joint mobility for the hip (five out of eight groups) and wrist (six out of eight groups) as compared to Icelandic women. Roach and Miles (1991) compared age-gender-race groups and found that the 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 also influence joint ROM. Wolf et al. (1979) found that people who spent most of their time sitting and doing little exercise, had a 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 cases the lower extremity joint ranges of motion values have been studied and no significant difference has been found between sides of the body (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 was 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 ROM 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 a number of factors that influence joint ROM. Joint mobility is an important factor that influences the work performance in working environments where there is likely to be a variety of people with different ethnic backgrounds, races, age, gender and capabilities. There is a need for designers and ergonomists to understand these differences at pre-design phases of product and workplace design, so that the maximum number of people can be accommodated. Although many studies have been conducted to discover differences in joint mobility capabilities, no effort has been made in highlighting the implications of these differences and variations for inclusive design. This article mainly focuses on the differences in joint ROM values for a broad range of the population and their potential impact on the implementation of an inclusive design strategy. The following sections briefly describe the methodology adopted for capturing joint mobility data and analysing the data from an inclusive design perspective.

3. Data capture methodology

Digital human modelling tools have been used as a means to perform task evaluation at early stages of the design process. However, the promotion of inclusive design practices has been a challenge because of the provision of accurate and relevant data on potential users and effective ways of utilising the available data during concept generation and product development. HADRIAN (Human Anthropometric Data Requirements Investigation and

Analysis) is a tool developed at Loughborough University, which works in conjunction with the long-standing digital human modelling tool SAMMIE. HADRIAN provides the means for achieving optimized design scenarios through virtual task evaluations where human capabilities data of a broad range of the population (100 people) along with task performing strategies are used for design assessment. It provides an opportunity to evaluate the acceptability of proposed designs of products or services for each individual in the database based upon the criteria set by the designer. The tool has the capability to identify individuals that have been designed out and why, so that designers can modify the design to accommodate a large proportion of the population. Early research work was concerned with Activities of Daily Living and was part of the Extending QUAlity Life programme (Case et al., 2001; Porter et al., 2004). The focus was on the domestic environment and laboratory studies were used to capture task behaviour so that it could be modelled in the digital modelling system (Fig. 1).

Subsequent work extended the scope to transport issues as part of the AUNT-SUE (Accessibility and User Needs in Transport —Sustainable User Environments) programme. Fig. 2 illustrates a case study undertaken with the London Docklands Light Railway. (Summerskill et al., 2010; Marshall et al., 2010).

More recently the issue of an ageing population has become an important concern in the industrial environment. Legislation in the UK has removed the retirement age and so it can be expected that there will be increasing number of older workers who are likely to have reduced capability in some physical aspects. A substantial case study was undertaken in a furniture manufacturing company to gain some understanding of the impact of potentially reduced mobility on manual assembly tasks (Case et al., 2011). Fig. 3 illustrates the simulation of working postures that are potentially difficult or impossible for older or disabled workers. Task performing strategies of different workers in a furniture manufacturing company have been captured through video-taping. To determine the exact joint mobility requirements necessary for a successful replication of these postures, the SAMMIE computer aided modelling system was used. After developing a computer-aided model of the work environment, a virtual human was placed appropriately and the actual posture replicated with a human model, to establish the joint mobility requirements. It is clear that the working method shown in Fig. 3 imposes high joint mobility requirements, where the right lower arm bend demands a 141^0 extension and right upper-arm adduction of 113°. The SAMMIE computer aided modelling environment helps in pre-defining the joint mobility requirements that can be used as criteria to investigate the acceptability of any task on the basis of joint mobility constraints. For example, a worker from the HADRIAN database (number 19) who is 73 years old with specific joint mobility constraints defined in the database was used in trying to replicate the strategy (working posture) so that its acceptability could be assessed with given joint constraints. Violations of joint constraints and unacceptability of this working method for this particular person were highlighted (in red on the menu of Fig. 3(b)) as the method imposes unobtainable joint mobility requirements in comparison with the capability possessed by the individual. In this way, the joint constraint data were used to evaluate the acceptability of working strategies.

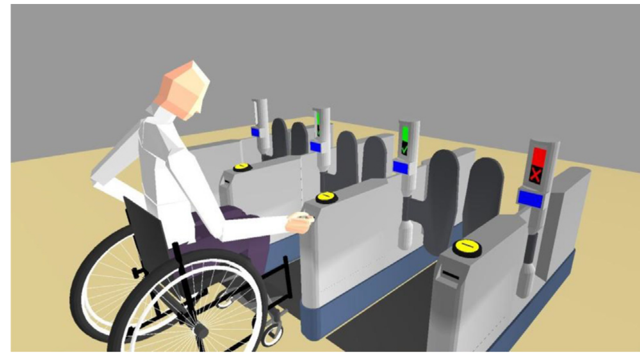


Fig. 2. Simulation of transport accessibility: Docklands Light Railway (Summerskill et al., 2010; Marshall et al., 2010).

The research reported here focuses on analysing joint ROM data of the individuals captured during the HADRIAN development process and was particularly aimed at the research on older workers. The objective was to understand the effects of age, gender, and some types of disabilities on joint ROM. Analysis of the database provided evidence of relationships between the factors and joint mobility, and showed how variations in this capability can be accommodated during an inclusive design process.

A total of just over 100 people participated in the original study; however, only 66 subjects have been selected for this analysis. The remainder has been excluded from the analysis on the basis of being older than 80 years, or having severe disabilities. This was because, along with the main focus of how different factors affect joint ROM, another consideration was to understand how older workers can be accommodated in working environments. For

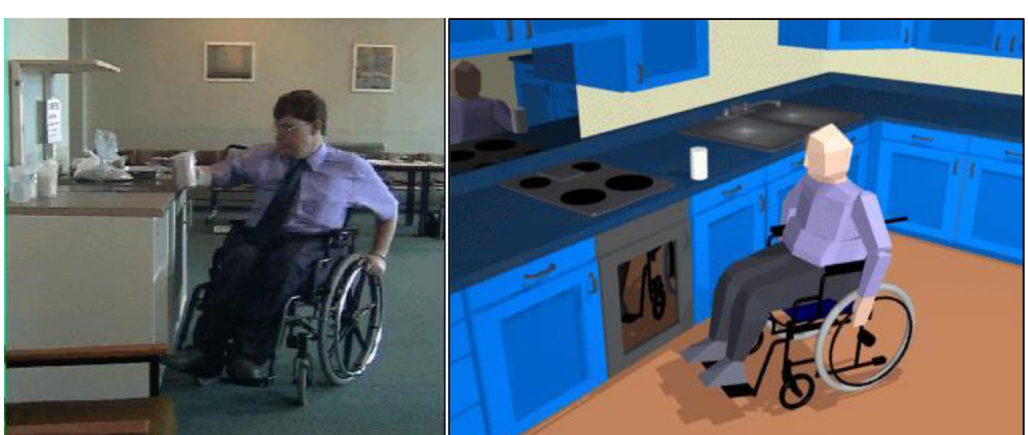
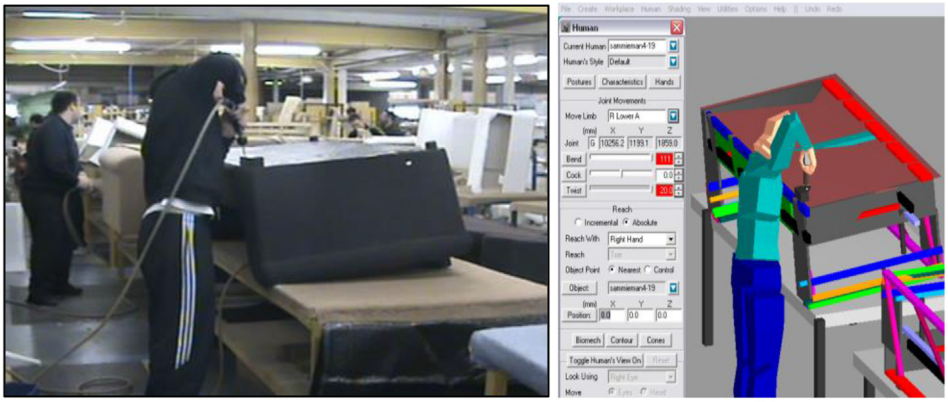


Fig. 1. Collecting task behaviour knowledge in the laboratory and simulating it in the HADRIAN digital human modelling tool. (Case et al., 2001; Porter et al., 2004).



(a) (b)

Fig. 3. Evaluation of the working postures of older workers in furniture manufacture (a) in the factory, (b) computer simulation (Case et al., 2011).

comparison purposes, the sample was divided into two main categories of able-bodied subjects and people with disabilities. Furthermore, the 42 able-bodied subjects were divided into three age groups, i.e. 20–40, 41–60, and 61–80 years to compare joint mobility capabilities between different age groups, where these age groups consisted of 10, 13 and 19 subjects respectively (Table 1).

Joint ROM data was collected using a goniometer (Summerskill et al., 2010; Sims et al., 2012). The trials required ethical approval from Loughborough University before they could proceed and the total length of experimental time for each subject was kept to a maximum of 1 h, in order to reduce the risk of fatigue and the risk of exacerbation of any conditions amongst the older and disabled participants. Participants were asked after each section of the trials if they felt fit to continue, and were reminded regularly that if they wished to stop they were free to do so.

Maximal comfortable joint ranges were measured for upper arm movements using a goniometer (shoulder flexion/extension and abduction/adduction; upper arm flexion/extension, abduction/adduction and medial/lateral rotation; elbow flexion/extension and pronation/supination; and wrist flexion/extension and abduction/adduction). Joint ranges were captured using the basic protocol outlined in Older Adultdata (Smith et al., 2000). Participants were asked to adopt the appropriate posture and move the relevant limb/joint to their comfort limit (Table 2). The joint angle was then recorded. Each measure was repeated three times with a brief rest between each, with the mean joint ROM recorded for each joint. Participants were carefully briefed that it was important that they only adopt a comfortable posture in each instance. It was stressed that participants should not go beyond what they would consider normal during activities of daily living.

Descriptive statistics were computed for each joint range of motion value and means and standard deviation values for different groups (age, gender, and disability) were calculated (Tables 3–5). An ANOVA test was employed to demonstrate the influence of age, gender and a specific disability on joint ROM. Post Hoc (Tukey) 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.

4. Results and discussion

4.1. General considerations

The data presented was originally collected with an emphasis on older subjects with disabilities and these aspects are considered in subsequent sections. However it is worth considering how the studied population compares with more broadly defined populations. Body mass index (BMI) is useful for general comparison of populations. The sample of people with disabilities, (24 subjects), were categorized into wheelchair users (8 subjects) and arthritis sufferers (16 subjects). The 'stature' of wheelchair users was only measured in the sitting position and as a consequence it was only possible to determine BMI for the remaining 58 subjects. A mean BMI of 28.2 with a standard deviation of 6.0 was found which is comparable with the BMI of 27.4 with a standard deviation of 4.0 reported in a large study of British subjects (Martin et al., 2013). Also, the Health and Social Care Information Centre (2014) reported that in 2012 approximately 25% of the UK population were categorised as obese (BMI > 30). This compares to 28% of the applicable HADRIAN sample and so it can be concluded that the HADRIAN population is representative of the general population in this respect.

In considering the distribution of measured joint ranges of motion Table 6 provides a comparison in terms of standard deviations from the mean.

The mean values are discussed in the next section. The standard deviations compare well for the younger age groups (e.g. comparing the 20–40 year olds of this study with the 25–34 year

Table 1
Subject groups.

Able-bodied (n = 42)						Subjects with disabilities (n = 24)			
Aged 20–40 (n = 10)		Aged 41–60 (n = 13)		Aged 61–80 (n = 19)		Wheelchair users		Arthritis sufferers	
Male	**Female**	**Male**	**Female**	**Male**	**Female**	4	4	4	13
4	7	4	9	4	14				

Table 2
Joint constraint measurement methods.

Joint	Angles	Method
Shoulder	Extension/flexion	Range of motion on the coronal plane either side of horizontal. The person sits erect with shoulders relaxed and the arm by the side and fingers pointed. For extension the shoulder is raised, for flexion the shoulder is lowered. Measured at the midpoint of the palpable junction between the proximal end of the clavicle and the sternum at the upper border (jugular notch) of the sternum.
Shoulder	Abduction/ adduction	Range of motion on the horizontal plane either side of the coronal plane. The person sits erect with shoulders relaxed and the arm by the side and fingers pointed. For abduction the shoulder is moved backward, for adduction the shoulder is moved forward. Measured as the deviation of the midline of the shoulder.
Shoulder	Positive/negative rotation	Range of motion on the sagittal plane either side of vertical.
Upper arm (Glenohumeral)	Extension/flexion	Range of motion in the sagittal plane either side of vertical. The person stands erect with the arm by the side and fingers pointed. For flexion the arm is moved forward, for extension the arm is moved backward. Measured at the mid region of the palpable bony mass of the head and tuberosities of the humerus.
Upper arm (Glenohumeral)	Abduction/ adduction	Range of motion in the coronal plane either side of vertical. The person stands erect with the arm by the side and fingers pointed. For abduction the arm is moved away from the body, for adduction the arm is moved across the body. Measured at the mid region of the palpable bony mass of the head and tuberosities of the humerus.
Upper arm (Glenohumeral)	Medial/lateral rotation	Range of motion in the horizontal plane either side of sagittal plane. The person stands with the upper arm by the side, elbow flexed to 90° parallel to the sagittal plane of the body. For lateral rotation the arm is rotated away from the body, for medial rotation the arm is rotated into the body.
Elbow	Flexion/extension	Range of motion in the sagittal plane either side of horizontal. The upper arm is supported with the lower arm and hand horizontal, palm up. For flexion the lower arm is bent upward, for extension the lower arm is bent downward.
Elbow	Pronation/ Supination	Range of motion in the coronal plane either side of vertical. The forearm and hand are supported with the hand in a thumb-up neutral position. For supination the hand is rotated outward, for pronation the hand is rotated inward.
Wrist	Extension/flexion	Range of motion in the sagittal plane either side of horizontal. The forearm is supported with the hand horizontal, palm down. For extension the hand is bent upward, for flexion the hand is bent downward.
Wrist	Abduction/ adduction	Range of motion in the horizontal plane either side of the midline of the forearm. The forearm is supported with the hand horizontal, palm down. For abduction the hand is moved inward, for adduction the hand is moved outward.

olds of Stubbs et al. (1993)). This is to be expected as generally the younger subjects of our study did not suffer disabilities. Similarly many of the standard deviations compare well between this study's 61–80 year olds and Reese and Bandy's (2010) 60–84 year olds. However there were large differences in arm extension, flexion and abduction, reflecting the greater extent of disability in our older group.

4.2. Effects of age on joint range of motion

Tables 3–5 show the mean and standard deviation values of joint ROM angles for the shoulder, arm, elbow and wrist for different age, gender and disability groups, along with ANOVA results, which clearly identify that there were many joint ROM values which appeared to be affected by age and disability; however, there was no evidence of significant influence of gender for any joint ROM values.

For analysing the effects of age on joint ROM, the able-bodied subjects (42) were divided into three subgroups. (20–40 years, 41–60 years and 61–80 years). 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 approaching or past a typical retirement age (61–80 years).

Table 3 and Fig. 4 show that there was a decrease in joint ROM with age for most of the joints; however, its significance depended upon the type of motion and the joint itself. Joint ROM values varied

Table 3
The means and standard deviations of joint ROM for different age groups and effects of age, ANOVA results.

Joint motion	20–40 years (n = 10) ROM degrees (std dev)		41–60 years (n = 13) ROM degrees (std dev)		61–80 years (n = 19) ROM degrees (std dev)		Degrees of freedom	F-value[a]	Significance
Shoulder extension	40.0	(14.4)	39.4	(11.5)	44.8	(10.5)	2	1.0	0.4
Shoulder flexion	22.7	(11.0)	17.7	(4.7)	15.2	(8.4)	2	1.1	0.3
Shoulder abduction	28.7	(13.7)	23.6	(11.3)	21.3	(11.2)	2	0.6	0.5
Shoulder adduction	27.3	(11.5)	30.2	(12.7)	28.1	(10.6)	2	0.2	0.8
Arm extension	63.4	(12.1)	64.4	(32.5)	64.6	(24.2)	2	0.3	0.8
Arm flexion	174.5	(9.0)	162.2	(34.1)	152.5	(25.8)	2	2.1	0.1
Arm abduction	171.2	(15.1)	158.8	(18.3)	147.2	(27.9)	2	2.1	0.1
Arm adduction	64.2	(15.7)	62.6	(17.4)	68.9	(13.8)	2	0.2	0.8
Arm medial rotation	90.0	(0.0)	75.0	(18.2)	87.2	(5.0)	2	8.6	0.0
Arm lateral rotation	70.7	(11.9)	52.4	(10.4)	59.2	(14.5)	2	4.2	0.0
Elbow extension	1.9	(1.4)	2.1	(2.4)	0.8	(1.2)	2	2.4	0.1
Elbow flexion	145.1	(7.8)	135.8	(9.1)	133.2	(10.4)	2	4.4	0.0
Elbow pronation	83.9	(11.7)	82.8	(13.3)	83.4	(11.7)	2	0.1	0.9
Elbow supination	93.0	(12.5)	83.2	(9.8)	88.0	(10.5)	2	2.3	0.1
Wrist extension	64.8	(10.2)	59.2	(9.2)	56.0	(11.8)	2	2.3	0.1
Wrist flexion	67.0	(9.8)	58.3	(8.6)	55.9	(7.5)	2	4.9	0.0
Wrist abduction	12.6	(7.6)	12.9	(5.9)	11.6	(5.0)	2	0.2	0.8
Wrist adduction	49.9	(9.4)	34.9	(5.9)	37.4	(7.3)	2	11.2	0.0

[a] Variation of the group averages.

Table 4
The mean and standard deviations of joint ROM for two gender groups and effects of gender, ANOVA results.

Joint motion	Male (n = 13) ROM degrees (std dev)		Female (n = 29) ROM degrees (std dev)		Degrees of freedom	F-value[a]	Significance
Shoulder extension	37.8	(12.7)	43.7	(11.1)	1	2.278	0.1
Shoulder flexion	18.2	(8.1)	17.6	(8.8)	1	0.309	0.6
Shoulder abduction	27.1	(11.7)	22.3	(11.9)	1	0.673	0.4
Shoulder adduction	27.1	(12.8)	29.2	(10.7)	1	0.463	0.5
Arm extension	68.7	(29.6)	62.3	(22.2)	1	0.963	0.3
Arm flexion	158.6	(34.5)	161.7	(23.5)	1	0.570	0.4
Arm abduction	164.8	(13.7)	152.8	(26.9)	1	1.108	0.3
Arm adduction	64.9	(16.4)	66.2	(15.1)	1	0.010	0.9
Arm medial rotation	81.8	(16.3)	85.1	(9.9)	1	1.162	0.3
Arm lateral rotation	59.9	(13.2)	59.8	(14.9)	1	0.059	0.8
Elbow extension	1.8	(2.2)	1.3	(1.5)	1	0.366	0.6
Elbow flexion	140.1	(9.2)	135.4	(10.7)	1	1.095	0.3
Elbow pronation	81.0	(12.5)	84.3	(11.7)	1	1.035	0.3
Elbow supination	84.5	(11.4)	89.2	(11)	1	1.762	0.2
Wrist extension	61.8	(12.2)	57.9	(10.4)	1	0.982	0.3
Wrist flexion	60.1	(8.4)	58.9	(9.9)	1	0.001	1.0
Wrist abduction	13.8	(7.1)	11.6	(5.2)	1	1.272	0.3
Wrist adduction	39.7	(8.4)	39.6	(9.9)	1	0.129	0.7

[a] Variation of the group averages.

Table 5
The mean and standard deviations for joint ROM for people with different abilities and effects of disability, ANOVA results.

Joint motion	Able-bodied (n = 42) ROM degrees (std dev)		Wheelchair users (n = 8) ROM degrees (std dev)		Arthritis patients (n = 16) ROM degrees (std dev)		Degree of freedom	F-value[a]	Significance
Shoulder extension	42.0	(11.8)	42.2	(8.6)	41.9	(11.9)	2	0.003	1.0
Shoulder flexion	17.8	(8.5)	11.9	(10.5)	14.8	(8.3)	2	1.872	0.2
Shoulder abduction	23.8	(11.9)	20.0	(12.3)	20.2	(11.8)	2	0.719	0.5
Shoulder adduction	28.6	(11.3)	23.5	(19.9)	27.8	(10.0)	2	0.573	0.5
Arm extension	64.3	(24.5)	50.2	(20.7)	59.6	(28.3)	2	1.106	0.3
Arm flexion	160.7	(27.0)	135.4	(42.8)	130.8	(42.2)	2	5.641	0.0
Arm abduction	156.5	(24.2)	117.8	(43.8)	114.4	(43.5)	2	12.351	0.0
Arm adduction	65.8	(15.3)	58.5	(15.9)	59.8	(24.4)	2	1.001	0.4
Arm medial rotation	84.1	(12.1)	83.1	(15.6)	83.6	(10.1)	2	0.024	1.0
Arm lateral rotation	59.8	(14.2)	52.0	(23.5)	43.6	(21.3)	2	5.208	0.0
Elbow extension	1.5	(1.8)	0.0	(0.0)	1.0	(1.5)	2	3.049	0.0
Elbow flexion	136.8	(10.4)	122.6	(23.8)	123.6	(34.9)	2	3.309	0.0
Elbow pronation	83.3	(11.9)	85.5	(14.8)	83.8	(12.5)	2	0.105	1.0
Elbow supination	87.7	(11.2)	68.6	(23.3)	77.3	(28.4)	2	4.649	0.0
Wrist extension	59.1	(11.0)	48.5	(28.5)	48.1	(18.2)	2	3.613	0.0
Wrist flexion	59.3	(9.3)	51.9	(13.8)	52.8	(10.9)	2	3.318	0.0
Wrist abduction	12.3	(5.9)	12.4	(5.9)	12.3	(8.1)	2	0.001	1.0
Wrist adduction	39.6	(9.4)	32.6	(22)	32.5	(15.5)	2	2.263	0.0

[a] Variation of the group averages.

Table 6
The mean and standard deviations for joint ROM of different age groups from this study (Hussain et al.) and Stubbs et al. (1993) and Reese and Bandy (2010).

Joint Motion	Hussain et al. 20–40 years		Stubbs et al. (1993) 25–34 years		Hussain et al. 41–60 years		Stubbs et al. (1993) 45–54 years		Hussain et al. 61–80 Years		Reese and Bandy (2010) 60–84 years	
	ROM	Std dev	ROM	Std dev	ROM	Std dev	ROM	Std dev	ROM	Std dev	ROM	Std dev
Arm extension	63.4	(12.1)	66.3	(14.0)	64.4	(32.5)	61.9	(15.4)	64.6	(24.2)	44.0	(12.0)
Arm flexion	174.5	(9.0)	179.6	(11.0)	162.2	(34.1)	172.4	(7.5)	152.5	(25.8)	165.0	(10.0)
Arm abduction	171.2	(15.1)			158.8	(18.3)			147.2	(27.9)	165.0	(19.0)
Arm medial rotation	90.0	(0.0)	103.4	(16.4)	75.0	(18.2)	93.3	(16.1)	87.2	(5.0)	63.0	(15.0)
Arm lateral rotation	70.7	(11.9)	70.8	(22.3)	52.4	(10.4)	53.3	(16.9)	59.2	(14.5)	81.0	(15.0)
Elbow extension	1.9	(1.4)			2.1	(2.4)			0.8	(1.2)	4.0	(4.0)
Elbow flexion	145.1	(7.8)	147.3	(3.7)	135.8	(9.1)	148.4	(2.9)	133.2	(10.4)	144.0	(10.0)
Elbow pronation	83.9	(11.7)	86.2	(7.2)	82.8	(13.3)	86.3	(6.6)	83.4	(11.7)	71.0	(11.0)
Elbow supination	93.0	(12.5)	101.1	(9.2)	83.2	(9.8)	104.5	(7.3)	88.0	(10.5)	74.0	(11.0)
Wrist extension	64.8	(10.2)	76.5	(12.6)	59.2	(9.2)	73.5	(12.0)	56.0	(11.8)	63.0	(8.0)
Wrist flexion	67.0	(9.8)	70.2	(8.1)	58.3	(8.6)	69.0	(8.8)	55.9	(7.5)	64.0	(10.0)
Wrist abduction	12.6	(7.6)	24.5	(9.3)	12.9	(5.9)	19.4	(8.1)	11.6	(5.0)	19.0	(6.0)
Wrist adduction	49.9	(9.4)	51.1	(8.6)	34.9	(5.9)	44.3	(4.8)	37.4	(7.3)	26.0	(7.0)

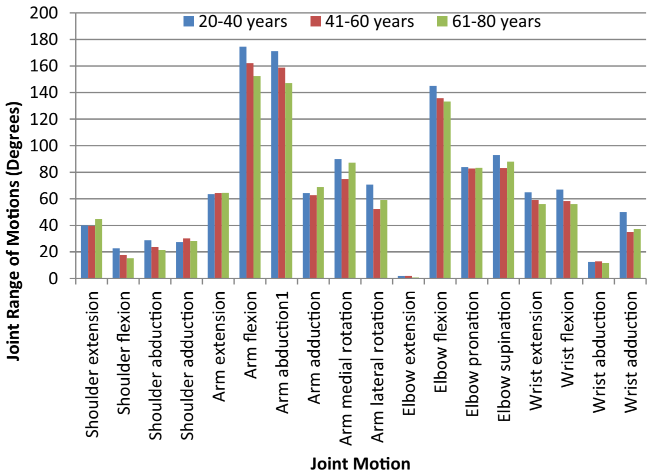


Fig. 4. Comparison of mean joint ROM for different age groups (n = 42), (n1 = 10, 20–40 years), (n2 = 13, 41–60 years), (n3 = 19, 61–80 years).

among different age groups, and these differences were 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 41–60 years, were found to be approximately 14.9° (30%) in wrist adduction, 18.3° (26%) in arm lateral rotation, 15° (17%) in arm medial rotation, 8.7° (13%) in wrist flexion, 13° (7.6%) in arm abduction and 10° (6.9%) in elbow flexion (Table 3).

There were some joint ROM values, such as arm flexion, elbow flexion, elbow supination and wrist extension for which the differences were not statistically significant (Table 3). The effect of age on joint ROM was also reported by different researchers in previous studies. As mentioned previously Chung and Wang (2009) concluded that age reduces joint mobility in Taiwanese workers, and they identified that the largest reduction in joint ROM was in the wrist joint. This decrease was 16.6° (26%) and 10.9° (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 41–60 years) were 59° (std. dev. = 9.2°) and 58° (std. dev. = 8.6°) respectively, which is very similar to the 62° (std. dev. = 11.9° and 57° (std. dev. = 10.1°) 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° per five years for male subjects between 45 and 60 years old (Allander et al., 1974).

It is interesting to note that the oldest age group (61–80 years) had higher joint ROM for shoulder extension, arm adduction, arm medial rotation, arm lateral rotation, elbow supination, and wrist adduction when compared to the 41–60 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 the 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 this must be considered seriously during the pre-design phase of any product, service or workplace design.

4.3. *Effect of gender on joint range of motion*

Table 4 shows a comparison between male and female joint range of motion mean values for able-bodied subjects. There was no clear pattern of increase or decrease of joint mobility found between the two gender groups, and this is also quite clear from Fig. 5. However, the capability of joint mobility is different for both genders, and depended upon the joint and the type of motion. In this study, ANOVA tests were also performed to evaluate the significance of this difference in the joint range of motion values but no statistically significant differences were noted for any of the joint motions (Table 4). A total of 7 out of 18 joint values showed that females had greater joint mobility than male subjects, the greatest percentage increase being 16% (5.9°) for shoulder extension. Moreover, increases in joint ROM for females as compared to males were approximately 8% (2.1°) for shoulder adduction, 2% (3.1°) for arm flexion, 2% (1.3°) for arm adduction, 4% (3.3°) for arm medial rotation, 4% (3.3°) for elbow pronation and 6% (4.7°) for elbow supination. On the other hand, 9 out of 18 values showed that males had higher joint mobility as compared to females. Among these, elbow extension showed the greatest percentage difference of 24% (0.5°) between males and females. Furthermore, shoulder flexion at 3.7% (0.6°), shoulder abduction at 17.6% (4.8°), arm extension at 9.3% (6.4°), arm abduction at 7.3% (12.0°), elbow flexion at 3.3% (4.7°), wrist extension at 6.3% (3.9°), wrist flexion at 1.9% (1.2°) and wrist abduction at 16.6% (2.2°) showed the same pattern of decrease in joint ROM for females. Joint range of motion for arm lateral rotation and wrist adduction were approximately the same for both genders. However, it is worth noting that statistically there was no significant difference in joint mobility between male and female subjects.

4.4. *Effect of disability on joint range of motion*

Mean and standard deviation values of joint ROM values for wheelchair users and arthritis sufferers are shown (Table 5) 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 could be analysed. Joint range of motion data for a total of 66 subjects was analysed in this respect, of which 8 were wheelchair users, 16 were arthritis sufferers 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, Fig. 6) that people with disabilities had reduced joint mobility as compared to the able-bodied. The ANOVA results (Table 5) clearly identify that this decrease was significant ($p < 0.05$) for arm flexion (30°, 18%), arm abduction (42°, 27%) and arm lateral rotation (16°, 27%), elbow flexion (14°, 10%), elbow supination (19°, 22%), wrist extension (11°, 18%), and wrist flexion (7°, 12%).

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

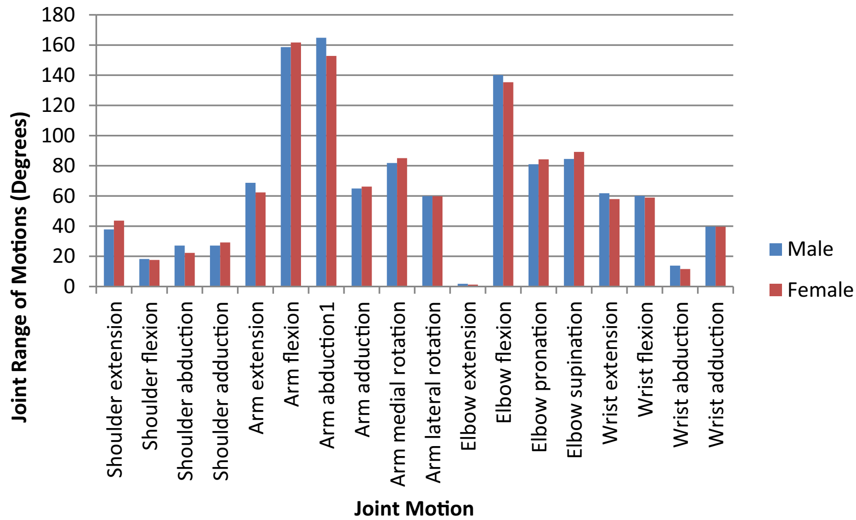


Fig. 5. Comparison of mean joint ROM for two gender groups (n = 42), (n1 = 13, male), (n2 = 29, female).

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 the physical characteristics of the people with disabilities are different at the individual as well as the group level (Jarosz, 1996).

5. Joint mobility; data variations and inclusive design challenges

It has been seen in section 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 further highlights the variations at the individual level and their implications for inclusive design. Usually, data is presented in percentile values (e.g. 5th, 50th and 95th percentile). This type of presentation of anthropometric data presentation seems quite simple and straightforward; however, it raises a number of issues when such data are used as design criteria. Fifth percentile simply means that 5% of the population will have a lower value than the given value (5th percentile value). So, designing for 5th and 95th percentile values will potentially exclude 10% of a population. Moreover, most design problems are multivariate in nature, but percentiles are univariate. It becomes more significant when designers and ergonomists try to accommodate older people and those with disabilities as they have more prominent variations in design data as compared with able-bodied and younger populations. Sections 5.1 and 5.2 explain the issues and challenges faced due to the effects of age and disability on joint mobility that ultimately cause variations in the data.

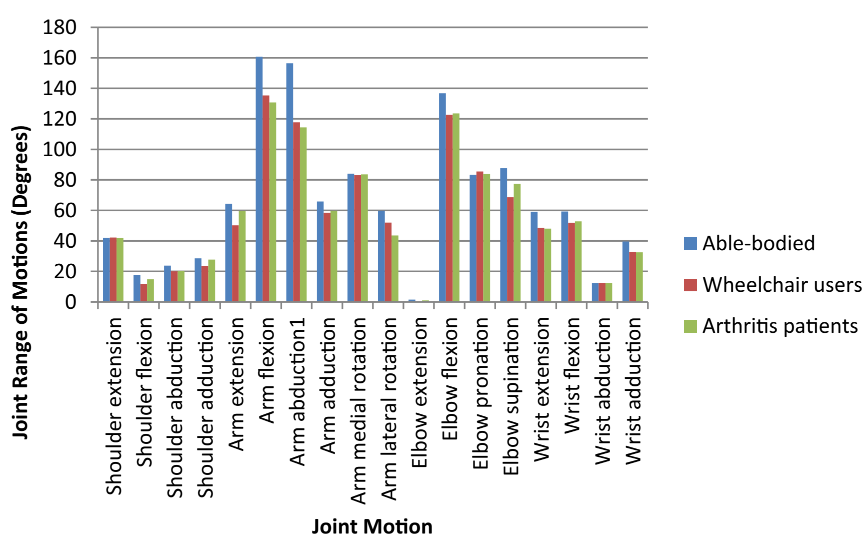


Fig. 6. Comparison of mean joint ROM for different ability groups (n = 66), (n1 = 42, able-bodied), (n2 = 8, wheelchair users), (n3 = 16, arthritis sufferers).

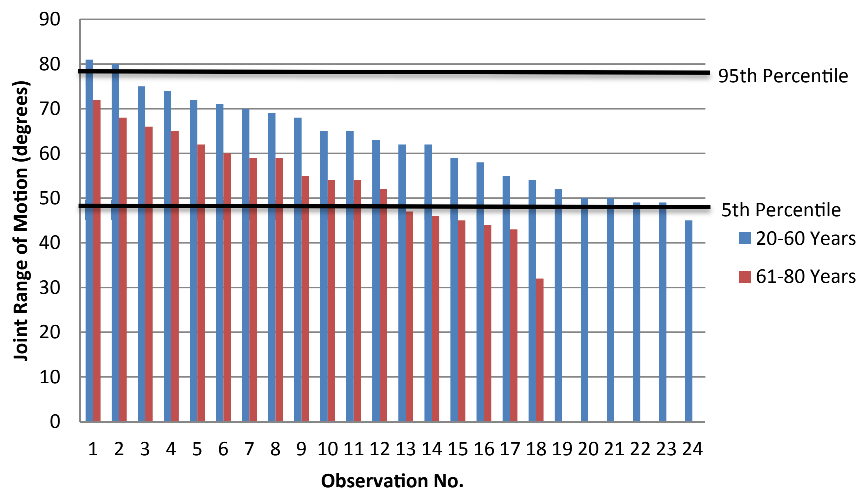


Fig. 7. JROM variations of wrist extension for different age groups and its relevance to 5th and 95th percentile design criteria.

5.1. Age and inclusive design challenges

This section presents joint ROM data of individuals belonging to two age groups. The subjects were divided into two age groups; 20–60 years and 61–80 years. The aim was to highlight the challenges faced by older workers in being accommodated in the working environment because of the reduction in their joint mobility, and to determine whether or not the conventional 5th and 95th percentile values can address the design needs of older workers. The graphical presentations below (Figs. 7 and 8) demonstrate these issues for wrist extension and wrist flexion. The values have been shown in decreasing order to highlight the extent to which the 5th and 95th percentile boundaries are exceeded. Further discussion is provided in the section 5.3.

5.2. Disability and inclusive design challenges

It was found that like age, specific conditions such as wheelchair use and arthritis also had a significant effect on joint mobility for certain joints. This section 5.2 presents the variations in joint mobility of a broad range of the population, including able-bodied people, wheelchair users and arthritis sufferers. Figs. 9 and 10 show these variations (for arm abduction and elbow flexion 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.

5.3. Explanation

Joint range of motion data can be used by designers and ergonomists during a design process where it can influence design decisions. Ultimately, these decisions directly affect human work performance; not only in industrial environments but also in the Activities of Daily Living (ADL). ADLs include all the activities that define an individual's ability to maintain independence and have high importance in the context of inclusive design. Joint mobility

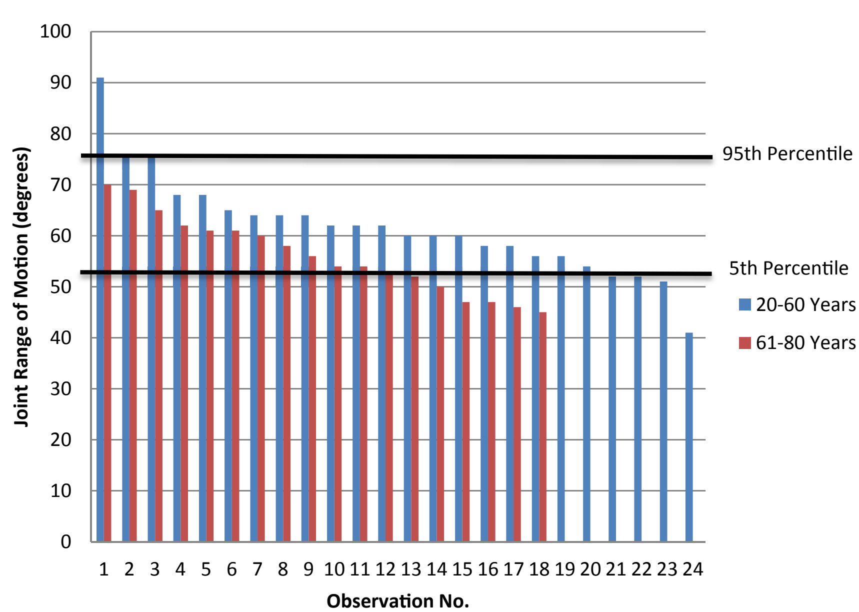


Fig. 8. JROM variations of wrist flexion for different age groups and its relevance to 5th and 95th percentile design criteria.

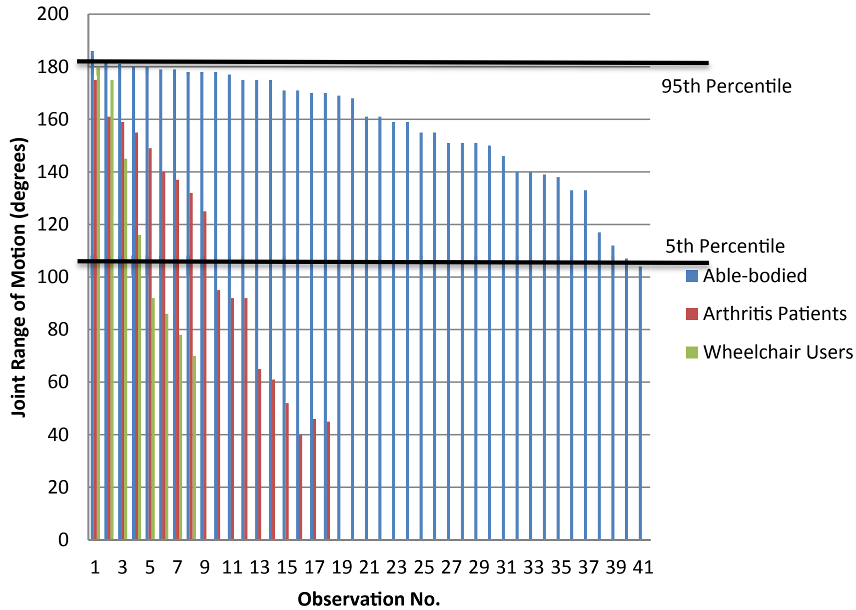


Fig. 9. JROM variations of arm abduction for people with different types of ability and its relevance to 5th and 95th percentile design criteria.

has direct relevance with activities that require a 'reach' from one point to the other and flexibility is needed to move different body parts for the adoption of appropriate postures. These activities include tasks like picking up a cup of tea and placing it on a table, picking items from a shelf, inserting an ATM card into a machine and opening doors etc. Similarly, the majority of manufacturing assembly activities also require a 'reach' in combination with quick, fast and accurate movements where the relevance of an appropriate design becomes more significant. 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 is 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. Figs. 7 to 10 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, these graphs illustrate that the commonly used design criteria of 5th and 95th percentile values based on joint range of motion data of able bodied people, cannot serve the purpose of including people with certain disabilities.

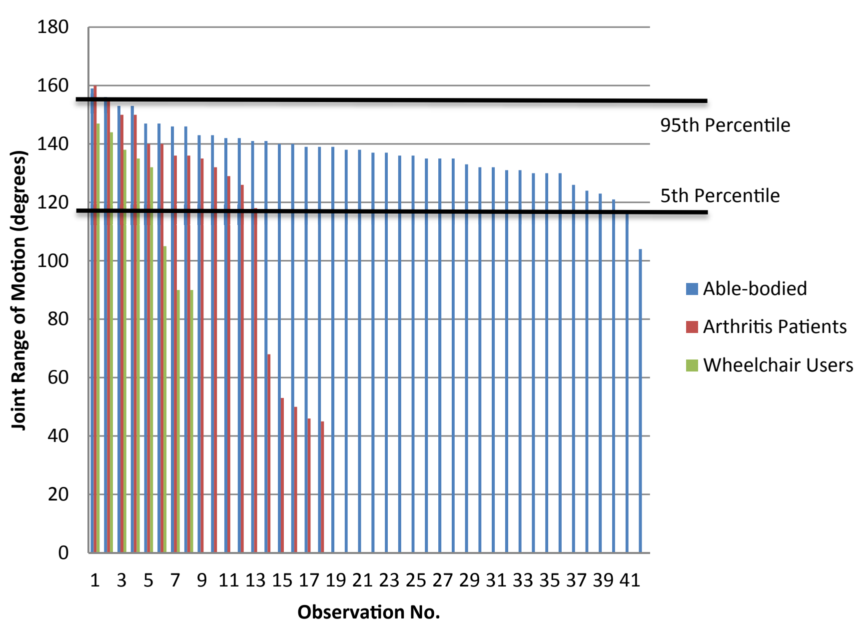


Fig. 10. JROM variations of elbow flexion for people with different types of ability and relevance to 5th and 95th percentile design criteria.

Figs. 7 and 8 show the overall population divided into two groups, one of 20–60 years old and the other of 61–80 years old. The purpose of combining the two age groups used in the previous analysis (20–40 years and 41–60 years) was 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 more likely to be retired or approaching retirement (61–80 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 were acceptable for older workers (>60 years of age).

Tables 6 and 8 show the challenges of accommodating older and disabled people in a commonly used design process. Table 8 indicates that designing for an able-bodied population of 20–80 years of age did not work well for older people as joint mobility of older people was generally affected by age, and this decrease is quite significant for some specific joint ROM values. It highlights that setting a design criterion of 5th percentile value (joint ROM values of the 20–80 years age group) did not fulfil the design needs of older people (>60 years of age). As an example, for shoulder flexion, only 19% of the total population (42 people, 20–80 years of age) were excluded from the design when the able-bodied (20–80 years of age) joint ROM 5th percentile value was used as a design criterion. However, if the same criterion was used to assess the level of acceptability of this criterion for older people, 7 out of 18 people (39% of the older population) were excluded from the design. Interestingly, for arm abduction all people, whose joint mobility falls outside the 5th percentile criterion, belonged to the older population age group. The same trend was followed for arm flexion, wrist extension and wrist flexion, shown in Table 7.

The same challenge is faced when 5th percentile joint ROM value (joint ROM data of 66 people including people from all age groups and people with disabilities) is used as a criterion and attempting to address the design needs of people with disabilities. Table 8 shows that for arm abduction value only 17% of total population (66 people, including people from all age groups and people with some disabilities) were excluded, where 10 out of 11 (42% of the population with disabilities that contains arthritis sufferers and wheelchair users) people belonged to the disability group. It is quite clear that for elbow supination, 7 people were excluded from the total population of 66, and all of these belonged to the disability group (arthritis patients and wheelchair users). The same trend was shown for arm lateral rotation, elbow flexion, wrist extension and wrist abduction. The above discussion clarifies the challenge of accommodating the design needs of people with disabilities by using a conventional design process of using 5th percentile values. In the light of the above discussion, it is important to further explore the issue to gain greater knowledge of how data variations at the individual level influence design decisions.

It was evident from the data that there were a number of subjects which showed abnormal trends in joint mobility and that these variations were so large as to significantly affect the median values for that group. An individual's lower joint mobility capabilities prominently influenced overall design decisions, as shown in Fig. 11 there were two individuals that had significantly lower joint mobility than the others.

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 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 like wheelchair users and arthritis sufferers, 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.

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. In addition, this study also focused on the understanding of the 'inclusive design' method so that the challenges faced by the designers might be addressed. In order to

Table 7
Accommodation of older people (20–80 years old) using a 5th percentile criterion.

Joint mobility category	Total excluded from total population of 42 able bodied people from all age groups	Total excluded from the population of 18 people >60 years of age
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 8
Accommodation of able-bodied and disabled people using a 5th percentile criterion.

Joint mobility category	Total excluded from total population of 66 able bodied people and people with disabilities	Total excluded from population of 24 people with disabilities
Arm abduction	11 (17% of total population)	10 (42% of the group having people with 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%)

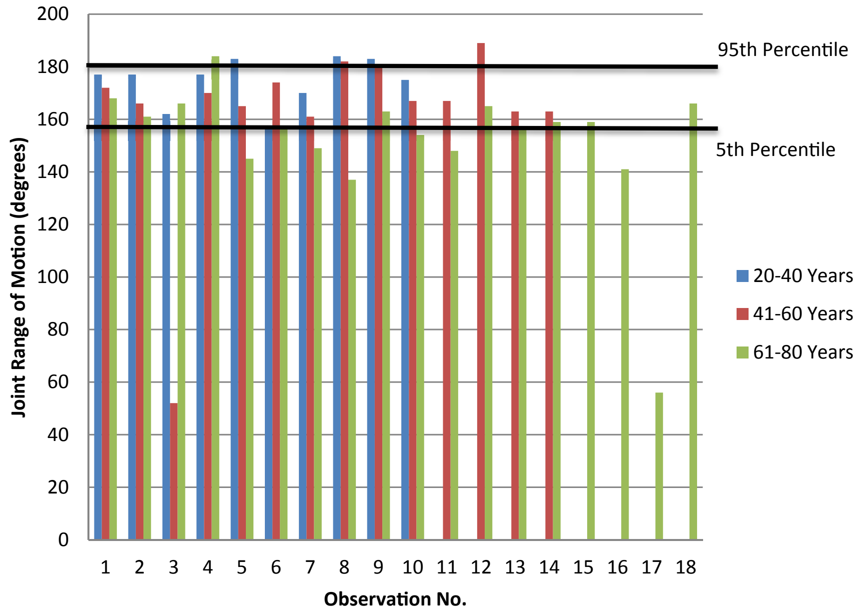


Fig. 11. JROM variations of arm flexion for different age groups and relevance to 5th and 95th percentile design criteria.

achieve these objectives, the HADRIAN database was re-analysed and the joint mobility data of 66 people belonging to different age groups, genders and the levels of disability was investigated. The database contains a total of 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 revealed that older people, wheelchair users and people with arthritis complaints faced 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 sufferers was 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 were noted for gender groups.

Furthermore, it was revealed that joint mobility variation within the group and between the groups was 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 sufferers. 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 sufferers, 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 at the integration of those with disabilities along with the able-bodied population during the design phase so that a maximum proportion of the population can be accommodated.

Integration of older and 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 so that they can perform well in a safe and satisfactory way like 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 like wheelchair users and arthritis sufferers have significantly lower joint mobility as compared to able-bodied people for some specific joints. A conclusion can be drawn that in general designers should not design to the maximum range of joint motion. 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 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.

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