THE ERGONOMICS AND DESIGN OF AN INCLUSIVE BEST-FIT SOLUTION TO WORKBENCHES

A Thesis submitted for the degree of Doctor of Philosophy

By

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Abstract

In a time when the developed world, is trying to reduce the human and economic costs of musculo-skeletal disorders (MSDs), any contribution to such an endeavour would be welcome. These economic costs are estimated to be in the tens of billions of Euro in the EU countries and similarly in the USA, the cost in human pain has not been measured. It may surprise many that in spite of all the advancements in science and technology, that two generations of people, who are very significantly taller than the people of a century ago, are still working in industry and in education at benches, which have not changed, either in height or design in centuries. Some, like wheelchair users do not have the opportunity to work at a bench at all.

At the outset this research project, had the primary objective of determining an ergonomic best-fit, for a broad range of users of workbenches. These included the young school going population (12-13 year olds), the senior students (16 plus years old), adults, and a cohort of surrogate wheelchair users. The research also endeavoured to determine if adolescents, who were of the same stature as adults, had the same workbench ergonomics requirements. The secondary objective, which was completely dependant on the first, was to design a bench, which would suit the ergonomic requirements of this diverse group.

The research has identified the best-fit workbench heights for the total cohort, while recognising the individual differences in relation to bench height ergonomics, for each of the sub-groups tested.

The findings of the research have shown, that using surrogate wheelchair users to determine ergonomic data for this type of activity is fully justified. In combining the raw data for a similar number of *wheelchair users*, a best-fit bench height has been *confirmed at 100 mm above knee height*. There are no significant differences between the ergonomic requirements for males and females at workbenches. Body part discomfort has been reduced significantly, for the wheelchair users, at the identified height and endurance has been extended. Importantly the career options for wheelchair users have been extended, empowering them to make broader career choices.

The outcomes of the research relating to three groups making up the able-bodied cohort have shown that an ergonomic best-fit is possible, which suits the needs of this diverse group. A height of 150 mm under elbow height has been identified as best-fit, and this reduces the discomfort considerably while extending endurance. Robust working heights have been identified, but the female working heights at workbenches, are not as robust as for the males.

For all groups it has been shown that *bench height has a significant effect* on body part discomfort and endurance, and while there were differences in efficiency, which were not quite significant, it is suggested that working in an ergonomically compromising position must, in the long term, in addition to increasing the risk of MSDs, likely also influence productivity, and quality of work.

An *inclusive test-workbench has been designed* and built which satisfies the ergonomic needs of the diverse user group described above.

Table of Contents

List of Figures

List of Tables

Nomenclature

ADA	Americans with Disabilities Act
ANOVA	Analysis of variance
ABPD	Aggregate Body Part Discomfort
BP	Body Part
BPD	Body Part Discomfort
BS	British Standard
DDA	Disability Discrimination Act
FOS	Factor of Safety
ID	Inclusive Design
ILO	International Labour Organisation
KH	Knee Height
MRMT	Minnesota Rate of Manipulation Test
NRB	National Rehabilitation Board
OWAS	Ovaka Working-posture Analysis System
QDI	Quadratic Discomfort Indicator
QEI	Quadratic Endurance Indicator
REBA	Rapid Entire Body Assessment
RSI	Repetitive Strain Injury
RULA	Rapid Upper Limb Assessment
SD	Standard Deviation
SWU	Surrogate Wheelchair User
UD	Universal Design
VAS	Visual Analogue Scale
WBPD	Work-related Body Part Discomfort
WMSD	Work-related Musculo-Skeletal Disorders
WSR	Wilcoxon Signed Ranks (test)
WUs	Wheelchair Users

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1 INTRODUCTION

As humans learned that it is easier and more comfortable to work in an upright position than it is when stooped, surfaces to work on, such as workbenches were developed. While the solutions appear wide and varied, the basic requirement remains the same - comfort and stability. This is particularly true of craftspeople who shape and form wood, metal and other materials at workbenches. Yet, for all the technological advances in tooling and equipment, standard workbenches have remained unchanged for centuries, perhaps even for millennia. Yes, some hobby driven changes, such as the Black and Decker 'Workmate' have met a real need for the amateur, the hobbyist and the travelling or on-site craftsperson. However in engineering workshops and classrooms in Europe and elsewhere the workbenches in use now, differ very little if at all from those of one, two or more hundred years ago.
During the course of this research, on entering a newly fitted woodwork classroom in an Irish secondary school, there were 24 student places at bright, new and beautiful pine workbenches. The benches they had replaced were in the adjacent store awaiting dispatch. The difference between the old and new - none! They were exactly the same in every way - height, width, length and complete design in every detail. The old benches were seventy-one years old. If we stood the pupils or the adults of seventy years ago beside those of today *their* design details would not have changed but the stature of people today would be much greater. Were wheelchair users considered as possible students at these benches? No! The year 2002 was set aside as The European Year of the Disabled, yet all these benches were wheelchair user inaccessible.

1.1 The scope and objectives of the research

This research project addresses issues relating to universal design of workbenches, which will meet the needs of the 5th and 95th percentiles (and hopefully beyond), whether able-bodied or wheelchair users. The stature-range of the able-bodied subjects measured for this research was 543 millimetres (21.4 inches). This research addresses a number of issues relating to bench design with the objective of accommodating individual differences and extremes in stature as well as wheelchair users, reducing discomfort, (which may lead to Repetitive Strain Injury (RSI) or Musculo-Skeletal Disorders (MSDs)), and increasing endurance time and efficiency.

This thesis has addressed the following research questions:

- How can people with a broad range of statures be accommodated at a workbench?
- Can a best-fit bench height be established for a range of the most common engineering and woodwork exercises?
- Can surrogates be used to establish ergonomic data for wheelchair users?
- Can Body Part Discomfort (BPD) for workbench users be reduced?
- Can work endurance be estimated and extended?
- Are there gender differences for bench requirements, whether wheelchair users or able-bodied?
- Does a teenager whose stature corresponds to that of an adult have the same bench ergonomics requirement?
- Does a bench design philosophy emerge from the research?
- From the data gathered and analysed can a bench be designed which is an ergonomic best-fit-for-all solution?

This research has established that the vast majority of workbench users are working in significantly uncomfortable work positions, which can be addressed by the application of universal/inclusive design criteria and design-ergonomics-best-fit.

1.2 How the thesis is structured

Chapter 2 begins with a short history of benches and through the literature review discusses a number of relevant areas. These include the effects of RSIs and MSDs, in the context of human injury and cost in time and money, Universal Design/ user centred design approach in the context of able-bodied and wheelchair user ergonomics and the relationship between design ergonomics and work. The literature search did not reveal any ergonomic data relating to workbench activities for youths (12 to 18 years old). This research therefore, should contribute to knowledge relating to workbench design and ergonomics for this age group.

In Chapter 3, a strategy for accommodating Wheelchair Users (WUs) is discussed. This is in the context of recent research into wheelchair user accessibility in engineering workshops (O'Herlihy and Gaughran 2002). The design of the experiment method is discussed. One problem identified was that of workbench access and a small cohort (eleven) of WUs were tested for workbench access. However the difficulty of finding sufficient 'ambulant' WUs, prompted the question, is the use of Surrogate Wheelchair Users (SWUs) appropriate for establishing workbench ergonomic data? According to Goldsmith (2000) this is satisfactory, but this relates to sedentary work only. The previous WU data has been analysed and compared with the SWUs, The combined cohort has been analysed in the context of best-fit working heights and gender comparisons for BPD, endurance, subjective work-height evaluations and efficiency.

Chapter 4 discusses the methodology for the design of experiments relating to the three subgroups of the able-bodied test subjects. The demographics of the test subjects, is discussed and the test bank and evaluation methods are selected based on previous ergonomic data collection design methods. The design of the test-rig results from a pilot pre-test analysis of a cross section of potential users. The timing, location, and makeup of the subgroups is also discussed.

Chapter 5 discusses the statistical analyses of the able-bodied cohort including evaluation and analysis of the raw data. A comparative analysis of the anthropometric data is made, as well as identifying subgroups and the test data required for parametric and nonparametric evaluation. The discussion of findings is initially divided into three subgroups and discussed in four sections as follows:

- Adult subjects are discussed and analysed with male and female test subjects. The data is analysed for significance in four main elements; endurance, subjective height evaluation, efficiency and BPD. Male and female comparative analyses are made;

- Senior second level students, 16 plus years old, with male and female test subjects. The data is analysed for significance in four main elements; endurance, subjective height evaluation, efficiency and BPD. Male and female comparative analyses are made;

- Junior second level students, 12 to 13 years old, with male and female test subjects. The data is analysed for significance in four main elements; endurance, subjective height evaluation, efficiency and BPD. Male and female comparative analyses are made.

- The final part of Chapter 5 makes an analysis of the total cohort and discusses similarities and differences between the subgroups, including gender, the WUs/SWUs and overall implications.

Chapter 6 presents a synthesis the findings in the context of formulating design criteria for workbenches, and applying these to the design of an ergonomic best-fit test/prototype bench which applies the principles of UD to an inclusive solution, for bench users who may be seated, standing, male, female, younger or older and short or tall.

The final Chapter (7) consists of the main findings and arguments in the thesis and the conclusions, which may be drawn from these. Future work in this and cognate areas is also addressed.

1.3 Contribution to knowledge

A Universal Design approach to workbenches has been followed through the application of design ergonomics in establishing:

1.3.1 Wheelchair users

- The appropriateness of using surrogate wheelchair users to establish design data for wheelchair users;
- a best-fit height for male and female wheelchair users has been devised;
- criteria for an inclusive workbench, which can broaden the career prospects of wheelchair users and reduce the possibilities of RSIs/MSDs for the whole bench using population.

1.3.2 Second level school students

- Best-fit ergonomic data for young male and female students at workbenches in practical classrooms has been established. These include improved comfort and endurance;
- it has been shown that benches currently in use in schools (as well as in general use) do not meet the ergonomic needs of the workbench using population;
- a height of 150mm below elbow height has emerged as an ergonomic best-fit for younger bench users.

1.3.3 Adults

- Robust working heights have been established as evidenced in the new data, which cater for a range of bench processing activities;
- a height of 150mm below elbow height has emerged as an ergonomic best-fit for adult male and female bench users;
- the significance of the overall height rating when compared to individual subjective height ratings, show that general bench height has a more important role in a subject's satisfaction ratings.

1.3.4 Gender issues

- The best-fit height for females is less robust than for males;

- while female adults had significantly greater aggregate BPD scores their endurance scores were better than for the males;

1.3.5 Inclusive bench design

- A more inclusive workbench/test-rig has been designed and constructed to meet the needs of a very broad population of users, including wheelchair users.

2 LITERATURE REVIEW

2.1 Workbenches – a short history

The ground or the knee, were likely to have been the first workbenches and the hand the original vice. What people refer to as the 'modern bench', dates back three or four centuries. However work holding devices and surfaces date from pre-history and have developed according to human need and ingenuity. The recognition of working in a comfortable and work-accessible position, where each craftsperson was their own 'ergonomist' meant that as far as was possible, each worked at a best-fit for themselves and the job on hand. The variety of activities illustrated in the print by Davier (The Egyptian Carpenters), in The Workbench Book, Landis, 1998, show how each task was considered in the context of comfort and convenience. This print is from the original stucco-work detail in the tomb of Nebanon and Ipuki, and dates from about 1475 B.C.E. The use of adze, saws and a 'vice' is depicted on 'benches' of various height and design, as shown in Figure 2-1

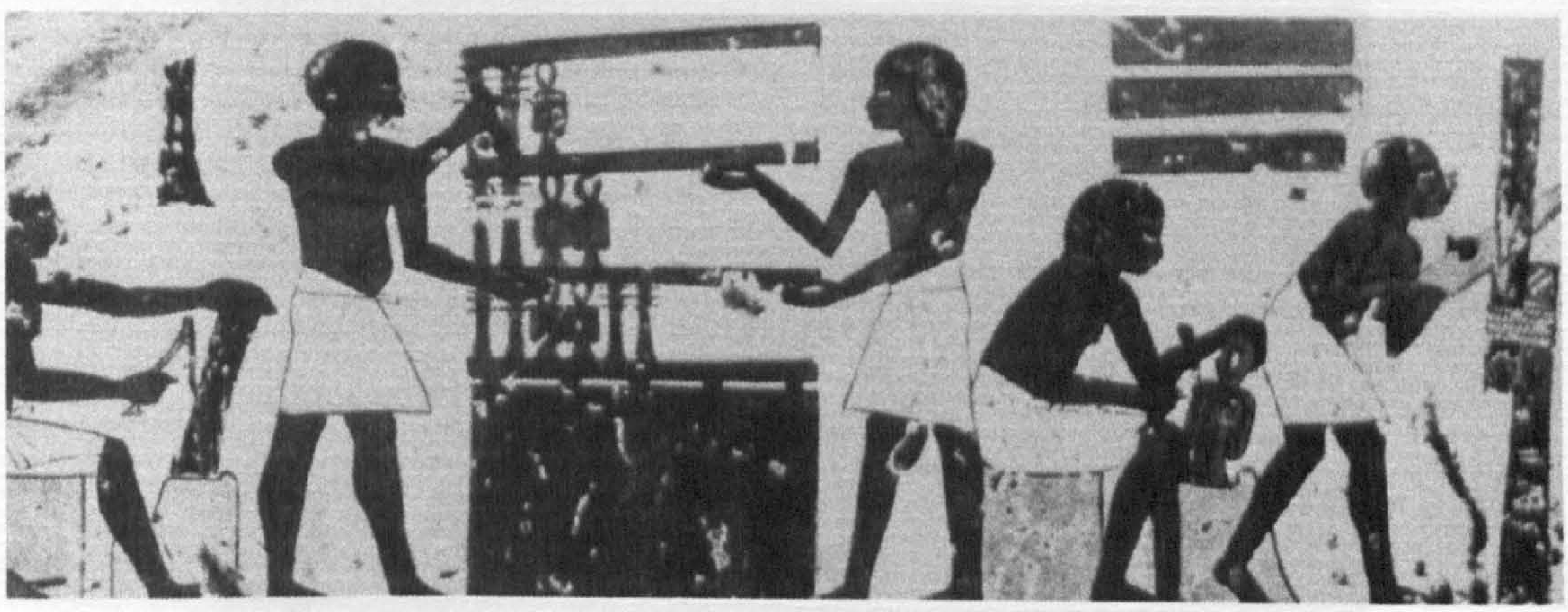


Figure 2-1 The Egyptian carpenters

Solomon, the ancient King of Israel (10th century B.C.E.), and overseer of the great temple built to house the Ark of the Covenant his people had with Jehovah, said in admiration of the craftsmen of the work: 'Have you beheld a man skilful in his craft, he will stand before kings and not before common men' (Proverbs 22:29). The description of the work in the temple at 1st Kings Ch. 6,7, and 8, would indicate that the craftsmen must have had benches or work-surfaces, other than the ground, in order to produce such very fine craftwork.

In 1934, a stout oak plank, with four angled mortises for splayed legs was found in Saalburg in Germany. It dated from 250 B.C.E. and in the centre at one end had another mortise, which was likely for a bench-stop. Relief carvings of Roman craftsmen from that and later eras show them either seated at a low bench or standing at taller benches, depending on the nature of the work. Through medieval times, right up to the 1400s, benches in Germany had changed little from the early Roman version of the workbench. However a hundred years later, as depicted in the drawing of Nuremburg engineer Loffelholz, the bench has become much more sophisticated, with movable benchdogs, and side and end vices, as seen in Figure 2-2 below.

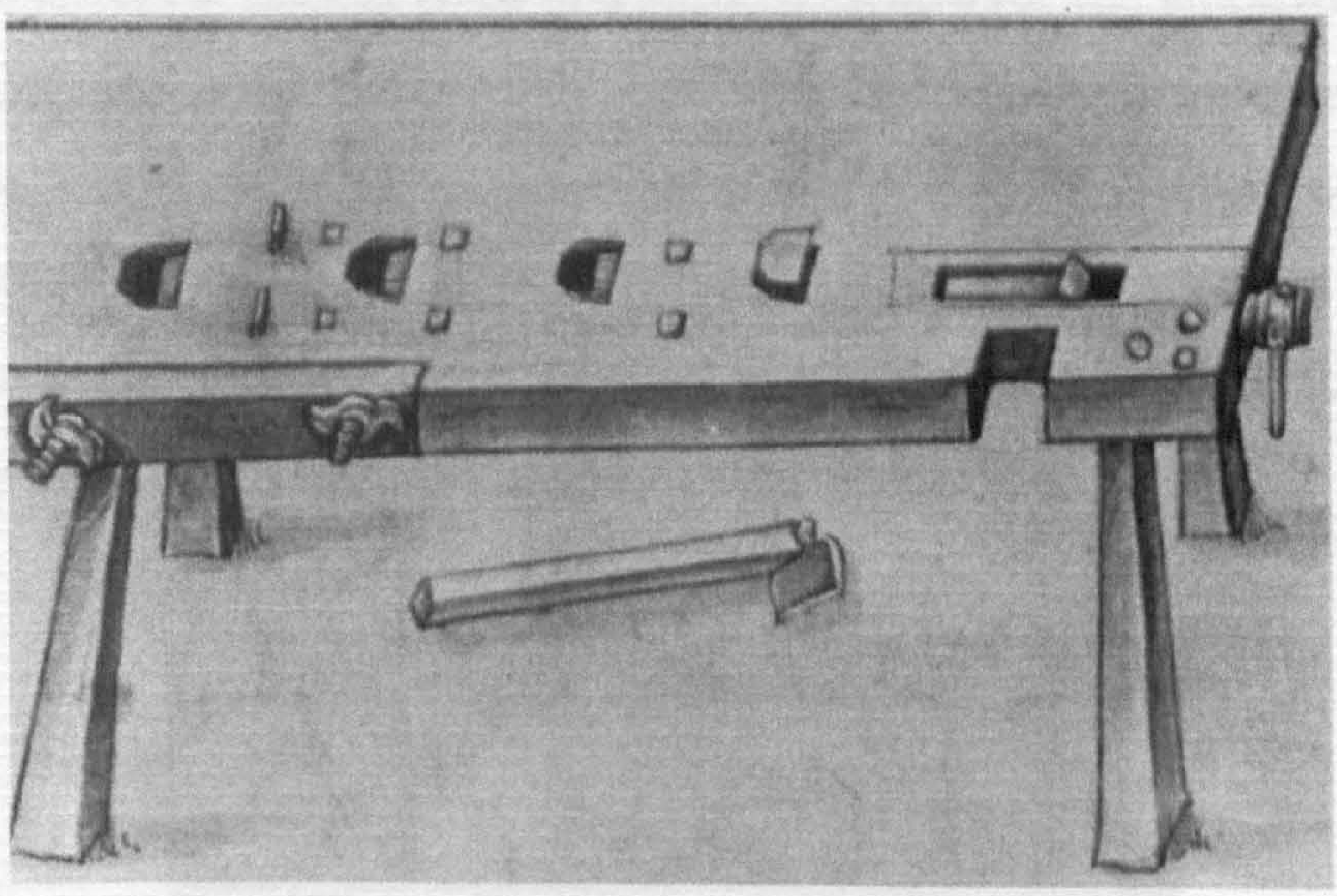


Figure 2-2 Löffelholz bench drawing 1505 (Greber, 1956)

By the late 17th and into the 18th centuries, the now 'traditional' cabinetmakers and joiners benches were well established in Europe. Benches in North America were reflecting the design of the English benches of the time. The

1816 painting by Foster (Figure 2-3), of an English woodworking shop, show what the workbench of the day looked like, (Nicholson in Landis 1998).

Figure 2-3 1816 woodwork shop in England

The bench height appears low, when judged against the hand-tools. The benches do however appear to be of a suitable height for the woodworkers of the day (note the man planing on the mid-left), but from anthropometric observation and clothing in museums from that period, the stature was much lower. So the benches were likely fairly well ergonomically suited to the workers. In the illustration of the Swedish workshop in around 1900, the benches appear taller but so do the craftsmen, Figure 2-4.

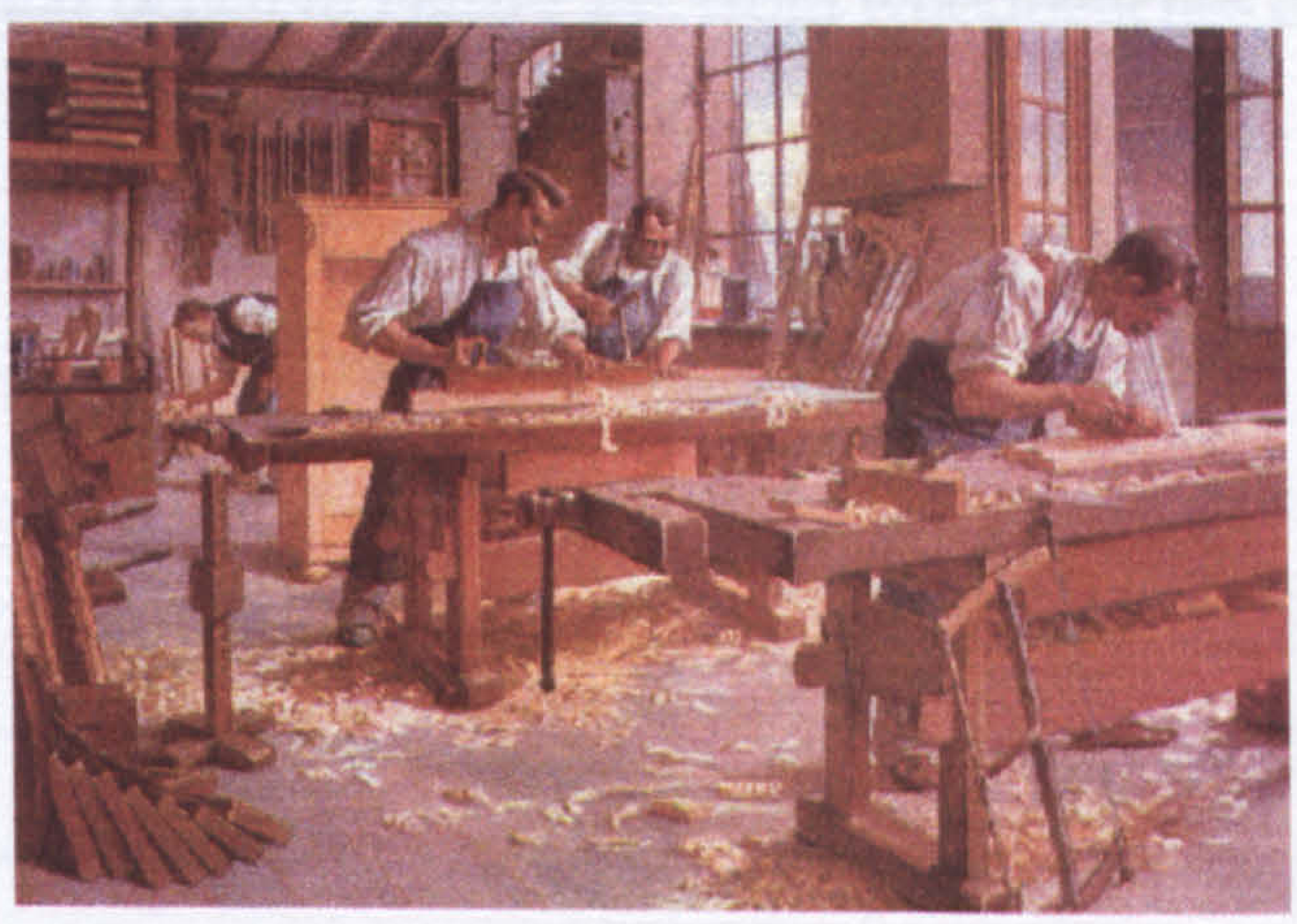


Figure 2-4 A Swedish workshop c. 1900 (National Library of Sweden)

Recently I worked on an almost identical bench, which was made in Holland and these are still the standard benches in that part of Europe. The workbench over the past few hundred years has changed little. If one were to buy a 'modern' workbench from the suppliers of today, such as the one in Figure 2.5, which is advertised on an U.S.A. website (www.growinglifestyle.com), it is the traditional bench, reproduced century after century. Ergonomists say that the average increase in stature of adult humans is about a millimetre per year. Recent anthropometric measurements, of under 18s, associated with this research, when compared with Pheasant's (1970) data, indicate growth well in excess of that. This appears to have accelerated in the last 15 to 20 years.

Figure 2-5 A 'modern' high quality workbench.

Apart from considering the ergonomic suitability for users of different stature, the inaccessibility for a wheelchair user is obvious because of the lower rails and tool storage cabinets, see to that. The same may be said of the less elaborate but similar bench in Figure 2-6, from woodbenches.com

Figure 2-6 A beech workbench

As mentioned in Chapter 1, the Introduction, the scene has not changed in schools, with the benches of seventy years ago being identical to those of today. While some endeavours have been made to modernise benches in schools where woodcraft, engineering and technology are taught, the basic ergonomics of the benches has not improved and in some instances could be said to have got worse. For example, height has not changed, while young people have increased in stature and the assigned/available work area has decreased. One such bench is seen in Figure 2.7 below.

Figure 2-7 Modern four-place bench with 'drop-on' engineering vice.

What has not changed about these benches is the 'standard height', i.e. 800 millimetres. The bench height in several second level schools surveyed was normally 800mm, with the exception of one engineering classroom where the bench height was 770mm. All were wheelchair inaccessible and were much too low for all but the smallest students.

However not all craftspeople settle for the standard workbench and some see the need to design their own. The carver in the picture in Figure 2-8, has adapted the hydraulic lift column from a dentist's chair to suit his needs. The adjustability of the column allows it to be used in either a sitting or standing position.

Figure 2-8 A purpose made adjustable bench. (Landis 1998)

Some benches are entirely different to those normally used in the western world. The Japanese beam bench is one such example. The craft techniques practiced at these benches are different, as are the methods of work holding which dates back centuries. Figures 2-9 and 2-10 are examples of these (Landis 1998).

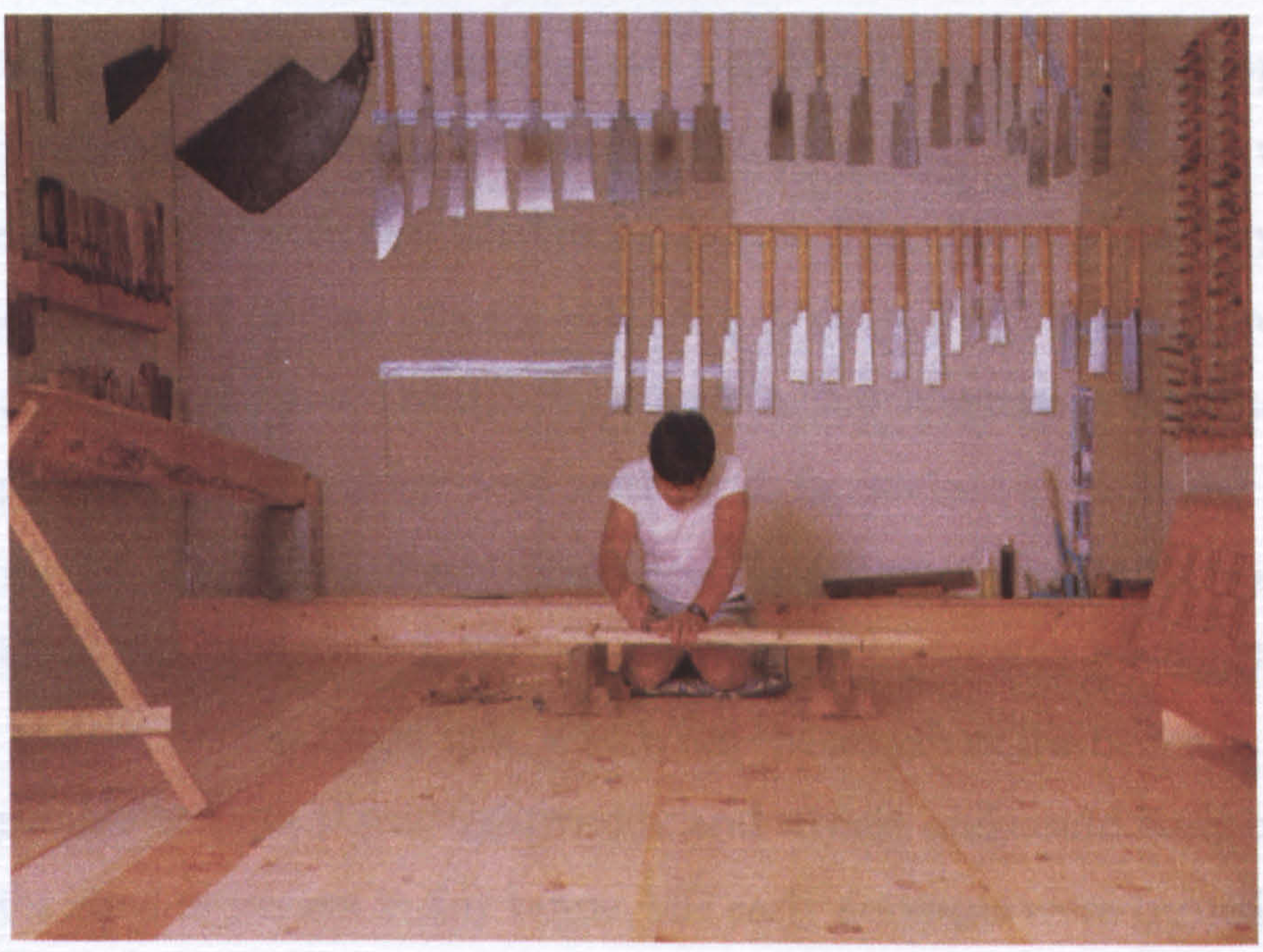


Figure 2-9 Traditional Japanese workshop

It is only in the context of the total workshop with its tooling and other fixtures that the beam bench makes any sense. It would be completely out of context in the western workshop. The Westerner is confounded by the lack of vices and fixtures. Tradition dictates that stops and the craft-workers body substitute. Sitting on the work when mortising stabilises the work. Small and large trestles are used as required, whether sitting, kneeling or standing and the feet become the clamping or work holding devices Figure 2-10.

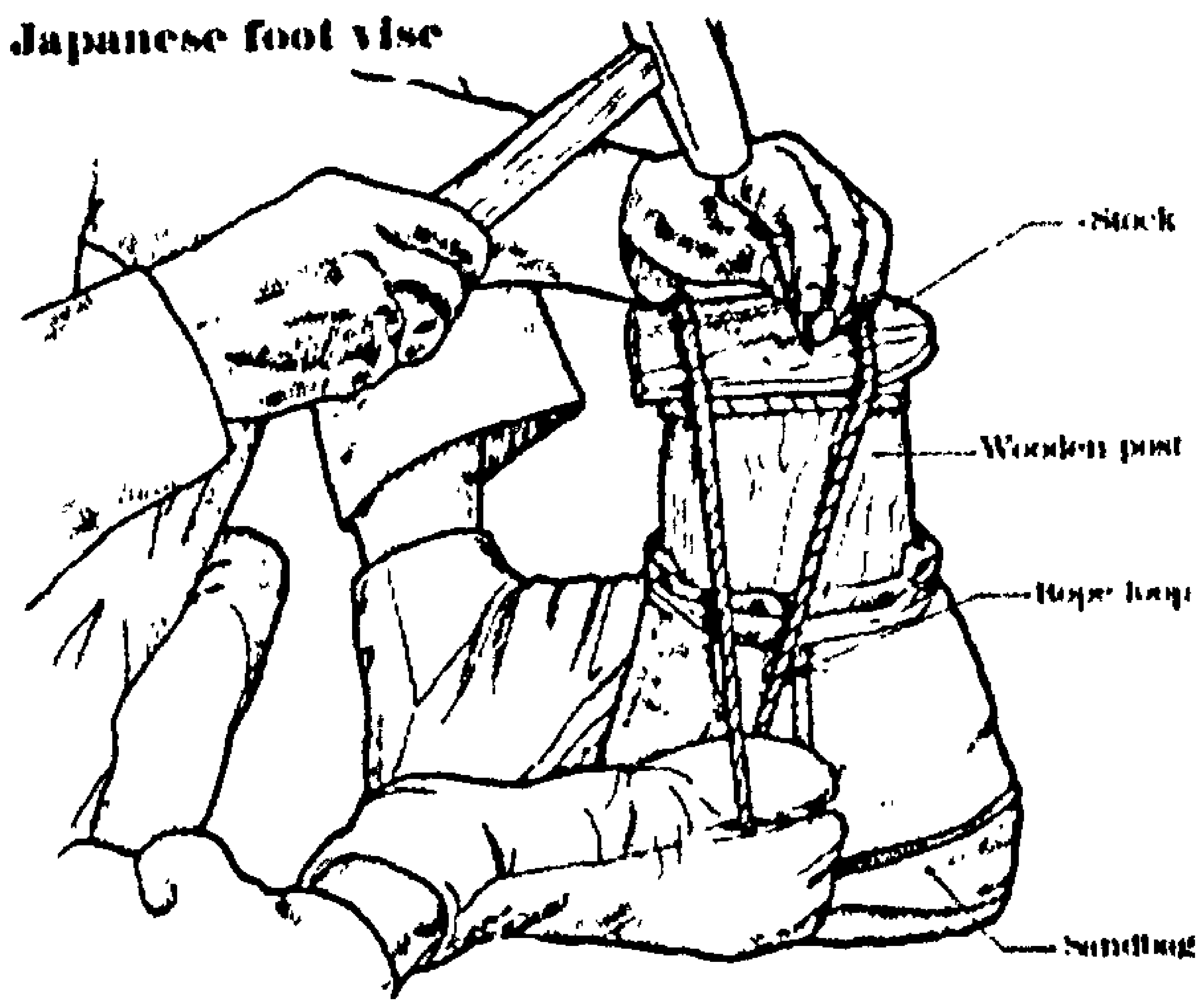


Figure 2-10 Japanese foot clamp/vice

Whenever the craftsperson worked on site and away from the workshop they normally carried work trestles or 'horses'. These not only were used to work on and stand on but were also used as toolboxes. The idea of portability and convenience as well as easy storage led South African, Ron Hickman on the path to designing the now famous Black and Decker Workmate. After several prototype attempts, the earlier ones were rigid, he devised a crude and heavy folding model. The early attempts had a standard Record vice and a heavy double beam top. Undeterred, Hickman continued to develop the bench until it had a built-in flexible angle vice, which ran the length of the bench, it had two adjustable heights, it was lightweight and strong, and could hang on the wall of the shed or garage in any home. His early attempts were turned down, first by Black and Decker, for the do-it-yourself (DIY) market and later by the Stanley Tool Company. In 1969, Stanley tools commented in a letter to Hickman that the sales potential for the product: *'could be measured in dozens* *rather than in hundreds'*. He had been turned down by Record, Spear and Jackson, Marples and others. He could have taken a once off payment of £50,000 from Black and Decker U.K., when he first approached them in 1967, but would later settle for 3% royalties. The first frames were die cast aluminium and when Black and Decker began production of the Mark II, they became Britain's largest consumer of aluminium castings, with the exception of the motorcar industry. It would be several years before the U.S.A. market managers would 'risk' taking on the Workmate, (Landis 1998).

In 1974 in Kildare in Ireland, a purpose built plant went into operation, output would be half-a-million per year. In Spring 1976 over one million Workmates had been sold and by 1986 the figure reached twenty million. Figure 2-11 below, shows the aluminium cast Black and Decker Workmate Mark II and one of it's modern counterparts, (Mollerup, 2001).

Many developments on the Workmate have taken place since the Mark II, like a pressed steel frame and tilting and vertical clamping models. However this was always intended as a DIY tool. As can be seen from the illustration, it is capable of much but is not ergonomically friendly. In the context of Universal Design (U.D.), it would not suit the needs of many. If the user is tall they would have to stoop quite a lot to reach the top. The height extended is 810mm and at the lower 'sawhorse' level is approximately 600mm high.

Some of the well-known benches designers like the Shaker models in the U.S.A., the French, Roubo bench or the much liked Scandinavian benches all have one thing in common; they have not been designed with the variations of stature of the user in mind. And while some of these are so ornate as to be centuries old works of art, they are generally ergonomically uncomfortable.

Figure 2-11 The B and D Mark II and today's B and D Workmate 225

In recent years designers and ergonomists have been working on 'workstation' design. This normally concerns the standing or sitting position of workers in manufacturing plants or at computer stations, Das and Sengupta, 1996; Sengupta and Das, 1997; Frazer, 2002; Lee and Haselgrave, 1999. Workbench design for the use of woodworkers, metalworkers and others is seldom, if ever, researched. There is nothing to be found on the design of workbenches for young school students in practical classes.

A Universal Design (U.D.) approach is needed, to devise a solution to the problem of a more fully inclusive bench. The next section addressed U.D. approaches and the principles, which should impact on such a solution.

2.2 Work-related musculoskeletal disorders (WMSDs)

2.2.1 Introduction

Musculoskeletal disorders (MSDs) are one of the most common work-related ailments affecting millions of European workers, incurring costs of billions of euro to the EU economy. The main group is back pain/injuries and work related upper limb disorders commonly known as repetitious strain syndrome (RSS or RSI - Repetitive Strain Injury). Unless effective steps are taken, the workforce suffering will increase and the cost to the economy will continue to rise, (EASHW 2000). In the USA the situation is similar. In Washington State alone, from 1992 to 2000 there were 380,485 compensations paid for MSDs relating to the neck, back and upper extremities. The result, in addition to the pain and discomfort, was $2.9 billion in costs, (Washington State Department of Labor & Industries, 2001). In 1999, according to the Bureau of Labor Statistics in the USA, nearly 1 million people each year report taking time away from work to treat and recover from musculoskeletal pain or loss of function due to overexertion or repetitive motion either in the low back or upper extremities. Although there is a risk of long-term disability with both types of disorder, the majority of individuals return to work within 31 days. Estimated workers' compensation costs associated with these lost workdays range from $13 to $20 billion annually. However, in order to determine the total economic burden, indirect costs related to such factors as lost wages, lost productivity, and lost tax revenues must be added to the cost of compensation claims, leading to estimates as high as $45 to $54 billion annually for musculoskeletal disorders reported as work-related (Marras, 2000).

In Canada, the reports on MSDs and RDSs paint the same picture. The Canadian Centre for Occupational Health and Safety (CCOSH) reports: "When job design ignores the basic need of the human body (and individual workers), work can cause discomfort in the short term and eventually lead to severe and chronic health problems", (CCOSH, 1998).

On August 3rd 2001 in a letter responding to the Occupational Health and Safety Administration (OHSA), of the USA, concerning regulatory approaches to address 'ergonomic hazards' the Independent Lubricant Manufacturing Association (ILMA) said that the OSHA had failed to identify what were 'significant risks' and stated that scientific knowledge had yet to identify a 'close - response relationship' between risk factors and biophysical effect, e.g. force repetition and awkward postures' (Metallo, 2001).

Using a term like 'ergonomic hazards' is like using the term 'safety hazards'. Design ergonomics are used to identify and reduce hazards, and these workplace hazards abound. In using the term 'awkward postures', Metallo identified a key area, which contributes to MSD and RSI. Awkward postures contribute greatly to MSD (Marras, 1995; Dul and Weerdmister, 2001; Kroemer and Grandjean, 1997; Kee and Karwowski, 2001; Keyserling, 1988; Moore, 1991; Ryan 1989).

In considering the extent of MSDs, it is worth noting that in the United States alone, in 1992, The American Academy of Orthopaedic Surgeons reported that in 1988; '..the number of musculoskeletal impairments reached 30 million' and say that; 'MSDs are responsible for the greatest number of physician office visits in the U.S.' (Marras and Lavanderet et al., 1993). Praemer et al., 1972, studied the breakdown of MSDs, and found that back or spine impairments were responsible for over half of all MSDs (51.7%). Next came the lower extremity or hip (37.3%), and this was followed by the shoulders (11.0%), (Praemer et al., 1992). While some MSDs may be unrelated to mechanical factors, however many of the MSDs result from mechanical damage to the musculoskeletal system and a significant proportion of these relate to lower back disorders, (Marras et al., 1993, 1995).

According to Bernard, (1997), muscle strain is probably the most common type of pain, whether it is work or non-work related. The research shows that there are a number of major risk factors associated with low back injuries, these are:

- Heavy physical work;
- lifting and forceful movements;
- bending and twisting (awkward movements);
- whole body vibration; and
- static work postures.

When some of these factors occur at the same time, then the greater the injury risk. By reducing the load or force and maintaining, where possible, neutral body positions, the risk is minimised. The diagram below (Figure 2-12), shows the body in the neutral position as identified in relation to the anatomical planes, the Coronal, Sagittal and Axial planes. Moving the back, neck, shoulders etc. out of these planes, places the body parts in non-neutral positions. There are however, tolerances associated with neutral posture, which are unlikely to cause any significant discomfort. The further flexion (e.g. bending forward) or extension (bending/stretching backward) occurs, the greater the stress on the body parts and the likelihood of injury, if there is over exertion or the motion is regularly repeated (RSI), (Chaffin, 1987; Rowe 1981; Sanders and McCormick, 1993).

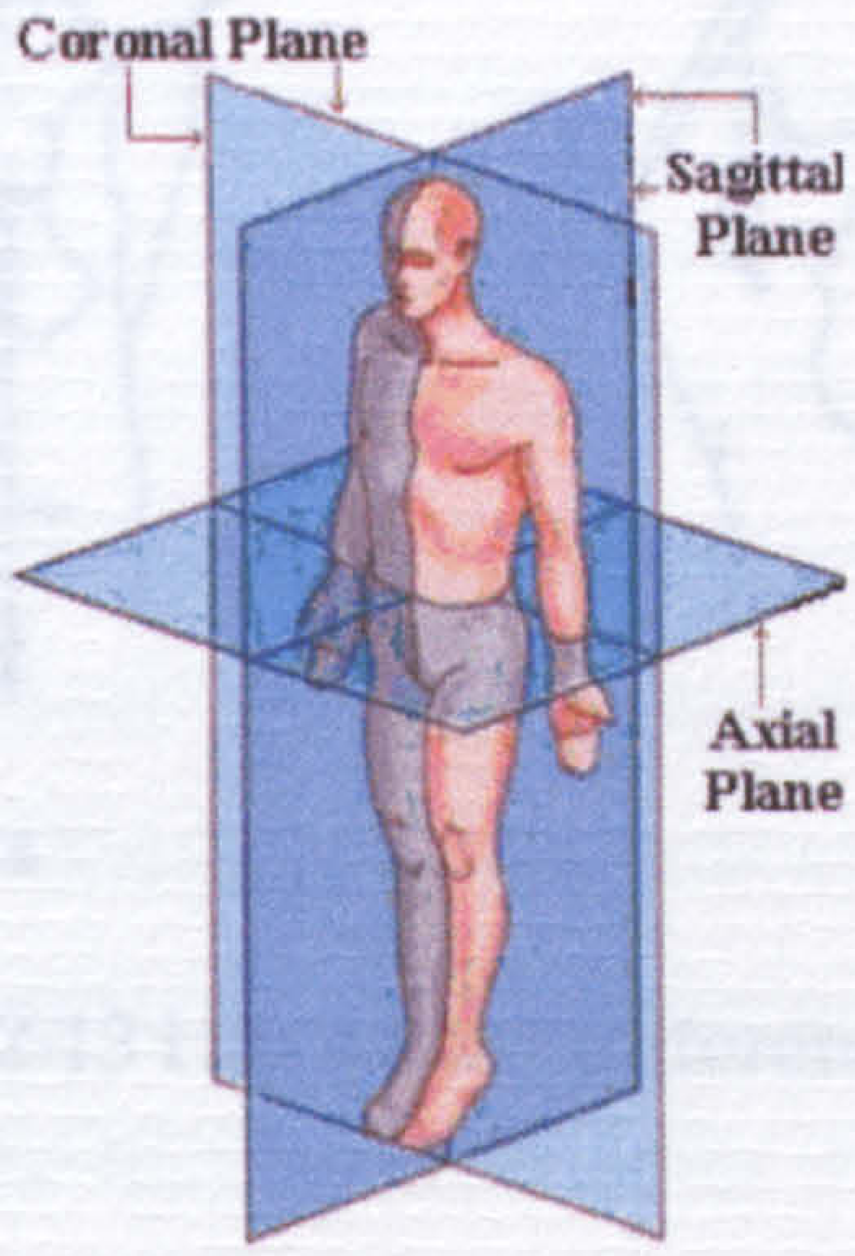


Figure 2-12 The Anatomical Planes

Apart from the general planar description of posture, there are also gender differences in skeletal and muscular structure, which can cause greater stresses in the female anatomy than that of the male. For example the location of the hip sockets in the male are directly below the lumbar vertebrae in males but in the female are located significantly further forward. According to Tichauer, Miller, et al, (1973), this can produce a force couple such that lifting stress in the back muscle in women, for the same object can be as much as 15% greater than for men (see Figure 2-13). This difference alone is sufficient to conclude that gender comparisons should be made when measuring discomfort levels for the same task. In considering gender differences for assembly tasks, O'Sullivan and Gallwey, (2002), concluded that in relation to elbow flexion that females reflected a higher propensity to injury. However the males registered the opposite for the shoulder flexion. It would seem then, that gender comparisons are a necessary part of the data gathering and analysis associated with the design of work or work equipment such as the workbench.

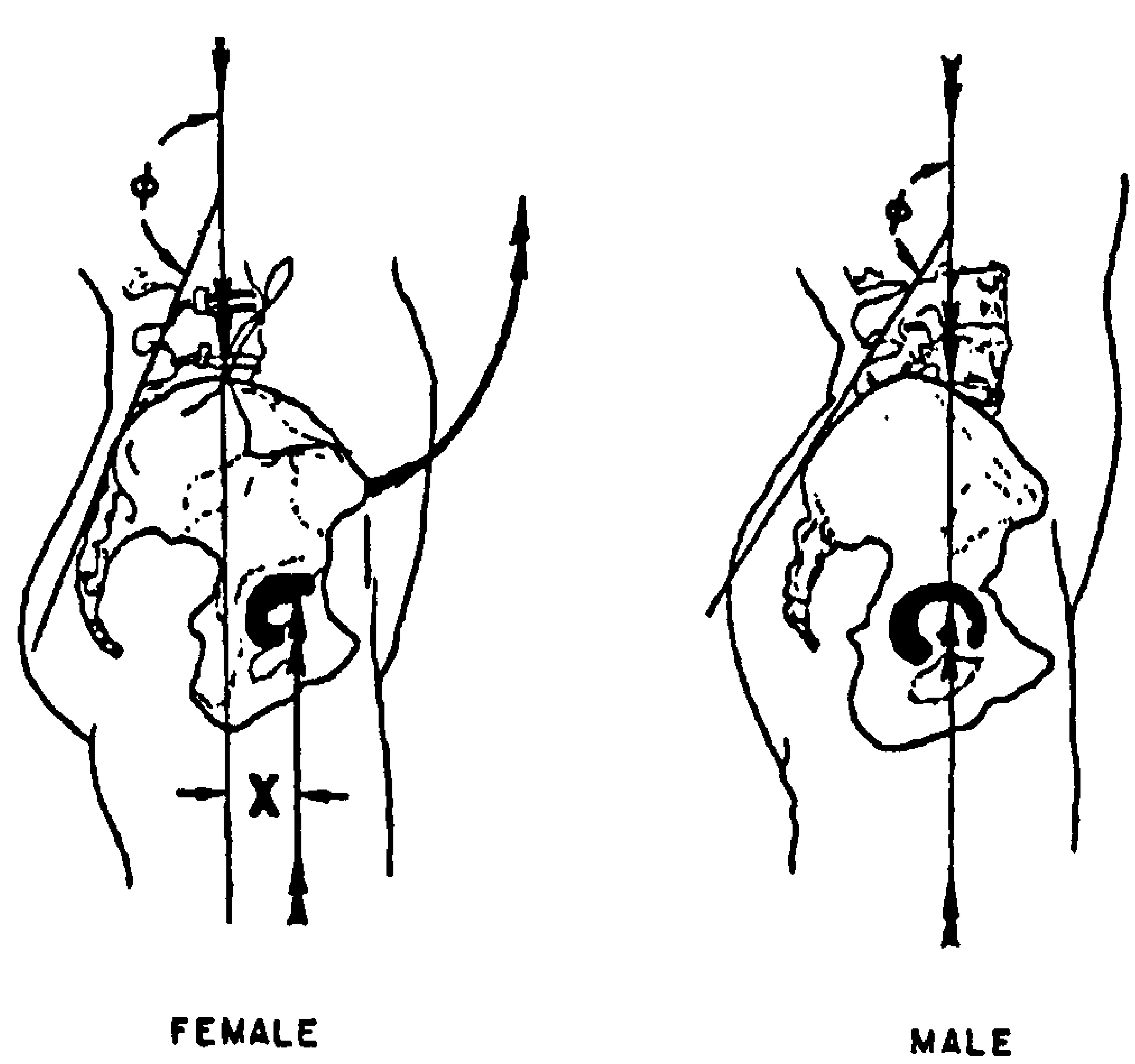


Figure 2-13 Hip socket differences

2.2.2 Determination of discomfort and other RSI causes

Psychophysical measures have been developed and applied to a broad range of work situations, (Corlett and Bishop, 1976; Borg, 1982; Gamberale 1985; Moore and Garg, 1995). The primary objective of such measures is usually to determine causes and locations of discomfort. Corlett and Bishop (1976) developed a body discomfort map for use in pin-pointing and scoring discomfort. They also discuss the direct relationship between awkward working postures and pain. Kee and Karwowski (2001) state that various authors (nine in all) have identified that awkward, extreme and repetitive body postures have been associated with musculoskeletal disorders in industry. They suggest changing the job design rather than the operator so as to improve work conditions and ergonomic fit.

Biomechanical, physiological, epidemiological and psychophysical are the four classified measures of musculoskeletal strain. The biomechanical approach is used to test for strength, endurance time and effects of joint angles. Physiological studies are used to identity individual limitations in central capabilities such as the pulmonary, circulatory or the metabolic functions. Epidemiology is the branch of medical science, which deals with the incidence, distribution and disease control in any population. Epidemiology developed as an approach to the study of epidemics and holds that causation is essentially a conjunction of a 'host' (the victim of the epidemic) an 'agent' (which transmits the disease) and an 'environment' within which the 'host' and 'agent' interact (Tichauer, 1978; Wilson and Corlett, 1995).
The psychophysical approach involves the use of subjective measures to determine discomfort and strain. The underlying premise of the psychophysical approach is that people integrate and combine both biomechanical and physiological stresses in their subjective evaluation of perceived stress (Sanders and McCormick, 1992). People in work situations, have the ability to perceive the strain generated in the body by the given work

task and to make absolute and relative judgments about this perceived effort. According to Kroemer et al., 2001, an individual can evaluate and make a judgment on the relationships between a physical stimulus and its perceived sensation. In 1982, Borg developed formal techniques to rate the perceived exertion with different kinds of efforts. In his opinion, a perceived exertion is prime indicator of physical strain. A variety of information, including signals from the peripheral working muscles and joints, from the central cardiovascular and respiratory functions and from the central nervous system are compiled together to form a perceived exertion. Borg's rate of perceived exertion is widely used in ergonomics, physical and sports medicine as well as sports science.

It was Corlett and Bishop (1976,1978), who led the way in establishing psychophysical tests as a valid measurement system. In 1998 they undertook tests on spot welders using their body part discomfort (BPD) map, developed in 1976. Using the map they were able to assess whole body discomfort, as well as discomfort in various parts of the body. Many researchers have adopted this technique and some have modified it to suit their work test situation. Dimov et al., (2000) using a combination of two physical tests used the body segment instrument, a modification of Corlett and Bishop's scale and the Borg physical scale to determine how carpenters subjectively record the exertion level of body discomfort associated with daily tasks. They identified the mid to lower back, the knees and the neck were the highest areas of discomfort and using Borg's exertion score for the subjects were able to categorise the level of physical exertion for the work. When discussing working postures, Delleman, (1999) explains how he used a modified version of these previous body-mapping systems to address industrial task studies in a number of situations. He used forty parts on the body map and a ten point discomfort scale, Corlett and Bishop had initially used twelve zones and a seven point discomfort scale, and Straker, (1999) used thirteen parts or zones and used a visual analogue scale.

Genaidy and Karwowski (1993) adopted Corlett and Bishops ratings for perceived exertion in the study of the effect of neutral posture deviations on perceived joint discomfort ratings in sitting and standing postures. They identify that at that time the effect of each type of postural deviation on the discomfort perceived by the human body is not well known. Their results revealed several distinct classes of joint deviations from neutral postures, which need to be assigned different weights of postural stress and propose these weightings.

Cameron (1996) has devised a method to assess Work-related Body Part Discomfort (WBPD). Cameron's study discussed how WBPD has been defined, assessed and used and she suggested modifications to the body map and scale of discomfort approach of Corlett and others. She devised a tool for assessing WBPD using three variables, severity, frequency and duration. These are converted into scales where severity goes from 'no discomfort' to 'intolerable'; frequency from 'never' to 'always'; and duration from 'I do not have any discomfort' to 'it doesn't go away'. Cameron claimed that the combination of these elements provides a more accurate prediction of discomfort than previous methods that have been devised.

Marley and Kumar (1994), applied a subjective assessment tool to fourteen different job categories. The assessment procedure took place after an 'ergonomics awareness' seminar for all participants. This was based on a subjective self- assessment using a BodyMap pictograph and a ten-point scale of comfort/discomfort, coupled with a four level frequency scale. They modified Corlett and Bishop's body map zones from twelve to twenty five (including the eyes). They also considered Sauter et al., (1991) and Saldana et al. (1994), both of whom applied 18 body part zones. They used scales, which were a combination analogue and verbal 'anchors'. They concluded that the system could be successfully used as a proactive assessment tool, for regular ergonomic audits.

Using the Visual Analogue Scale (VAS) provides an additional tool for psychophysical scaling. The VAS is usually designed as a 100mm line with descriptors at each end. VAS can be reliably used for children over five. One of the main advantages of VAS is that results can be analysed by quantitative statistical techniques. They have been widely and successfully used in literature including studies on optimum operating table heights for laparoscopic surgery (Berquer et al., 2002), reducing back pain in nurses (Alexander et al., 2001), comparing methods of moving wheelchairs short distances in the health care sector (Woolfrey and Kirby, 1998). Straker, (1999), discusses a range of body discomfort tools and suggests that: *discomfort is a valuable variable for ergonomists to use to assess physical match between workers and their work'.*

2.2.3 The discomfort phenomenon

Some authors consider pain and discomfort to be synonymous. However, Corlett and Bishop (1976); Straker, (1999) and Bates et al., (1989) would refute this. With Bates et al., it was found that when they used pain and discomfort interchangeably, there was a great deal of confusion on the part of the working test group. Their research showed that discomfort intensity tended to increase before pain did. This suggested that discomfort is more sensitive at lower noxious (harmful to well-being) levels of stimuli, than pain is. Some ergonomists suggest that comfort is a separate entity, which is more or less the absence of discomfort. In illustrating the difference between pain and discomfort Branton (1969), points out that the absence of pain does not necessitate the presence of pleasure.

Straker (1999), suggests that with the variety in ethnic and cultural backgrounds, that assessment tools should minimise the number of terms used so as to ensure consistency of use across cultural groups. This makes a good case for the use of analogue scales with minimal descriptive nouns. Kee, (2001) used subjective perceived discomfort scores in the development of an analytical method for generating a three-dimensional isocomfort workspace. He used a mix of numerical and verbal categories.

Measurement of intensity of discomfort has been attempted by the subject of the study to rate the intensity on a scale. This is commonly known as a subjective scale. These may be grouped into four types: graphical rating scales, visual analogue scales, numeric rating scales and verbal rating scales. These may be used separately or in combination with biomechanical or physiological data. As discomfort is thought to arise from mechanical loads around the joints, then Straker says, that these loads may be estimated using position data and biomechanical modelling. Brussenna, Corlett and Pheasant, (1982), have demonstrated a good correlation between joint load and discomfort rating. Branton, (1969), suggests that increased number of postural changes is an indication of an increase in discomfort intensity.

Figure 2-14 below, illustrates the four types of rating scales. Commonly the scale will have five to seven categories.

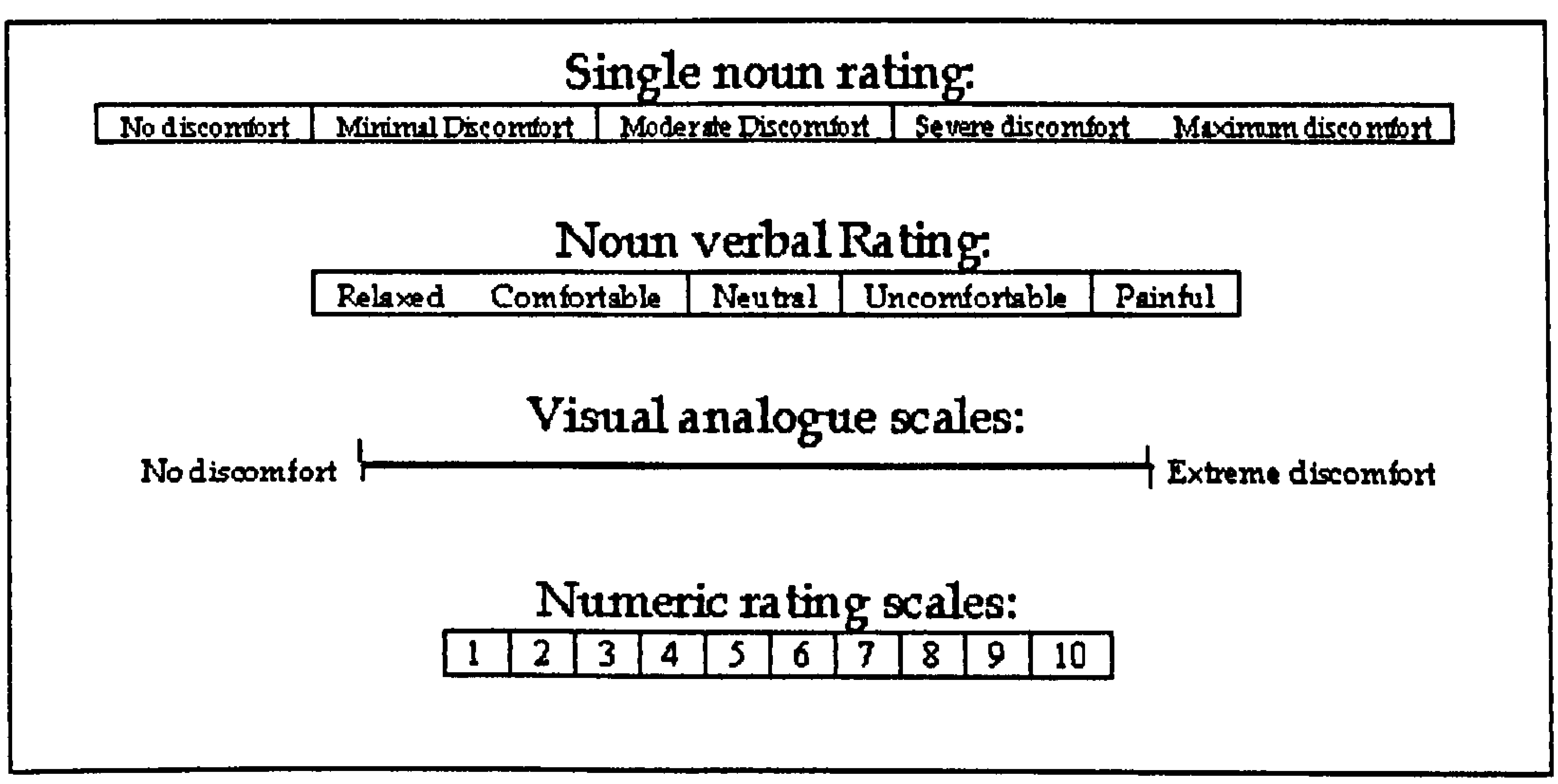


Figure 2-14 Comfort/discomfort rating scales

Sometimes a combination of visual analogue, and numeric or verbal rating scales are used. However there is a tendency to cluster results around the labels along the line. The reliability of discomfort as an assessment tool is prime, and was successfully tested and shown to be valid by Van der Grinten in 1991. According to Straker, several decades of practical experience by ergonomists in research of pain, have resulted in relatively easy to use, valid and sensitive discomfort assessment tools.

Based on the work of Corlett; Branton; Shackel et al., (1969); Drury (1987) and others, the following basic elements relating to discomfort measurement may be derived:

- discomfort measurement is a useful tool in the assessment of physical matches and mismatches;
- consistent use of the sole noun 'discomfort' assists in the validity of the assessment;
- discomfort is a subjective experience and can therefore only be measured by a subject report;
- intensity, location and temporal pattern are important elements of discomfort;
- a visual analogue scale, appears to be most widely used.

The question which has occupied the minds and time of biomechanics and ergonomics experts is; 'what constitutes risk of RSI, MSD etc. (there are a whole range of descriptions which relate to these), and how can the risk be minimised. The next section looks at methods of identifying risk and so presents a basis for taking remedial action.

2.2.4 MSD/RSI risk indicators and ergonomic intervention

The systematic study of the ill effects of poorly designed work situations is not new. About three hundred years ago Ramazzini wrote: *"Manifold is the harvest of diseases reaped by craftsmen...as the cause I assign certain violent and irregular motions and unnatural postures, by which the natural structure of the living machine is so impaired, that serious diseases gradually develop"*. (in Tichauer, E.R., 1978). This was around the year 1700, when unfortunately there was no system of intervention to improve the ergonomic lot of the worker. Neither was there any systematic approach to study the anatomy of function of the living body. The labour force was considered expendable and occupational disease or injury was normally rewarded by dismissal.

It was not until the end of World War I, when because of the immense loss of life in many countries, that any interest was paid to embarking on any intensive study of the effects of working conditions on human work performance and well being (Amar, 1917 in Tichauer, E.R., 1978). During that time, a number of specialties consolidated into the broader discipline, which was dedicated to the study of humans at work: *ergonomics*. The Second World War would push the study of work and working conditions further. So that today the study of ergonomics is a blend of many contributing sciences which together deal with the study of the effects of work and working environments on the worker. Ergonomics as a discipline aims to assist the individual members of the workforce maintain production levels which is economically acceptable to the employer, while maintaining a good standard of psychological and emotional well-being.

The science of ergonomics or what is known as 'human factors, is little more than fifty years old and there are a number of definitions of the term. However a simple definition, which succinctly describes ergonomics is given by Stephen Pheasant (1991): *'Ergonomics is the scientific study of human work'*

Joint angles are frequently used as indicators of best posture and possible discomfort. The description, 'Joint Angle Isocomfort' (JAI), is used by Kee and Karwowski, (2001), and is defined as; 'a boundary indicating joint deviation from the neutral posture, within which the perceived comfort for different body joints is expected to be the same'. The Ergonomics Department at the University of Surrey, in 1999, produced a guidelines paper entitled; 'A Quick Exposure Check (QEC) for work related musculoskeletal risks'. In this they categorised three degrees of back movement. The first was 'almost neutral', the second 'flexed or twisted', and the third 'excessively flexed or twisted' (Figure 2-15). The flexion, extension, and twisting angles for three ranges were; zero to twenty degrees, twenty to sixty degrees and greater than sixty degrees, respectively. These posture categories were then used in conjunction with a questionnaire, related to the task and body part positions. A total score was then recorded to give an overall risk factor.

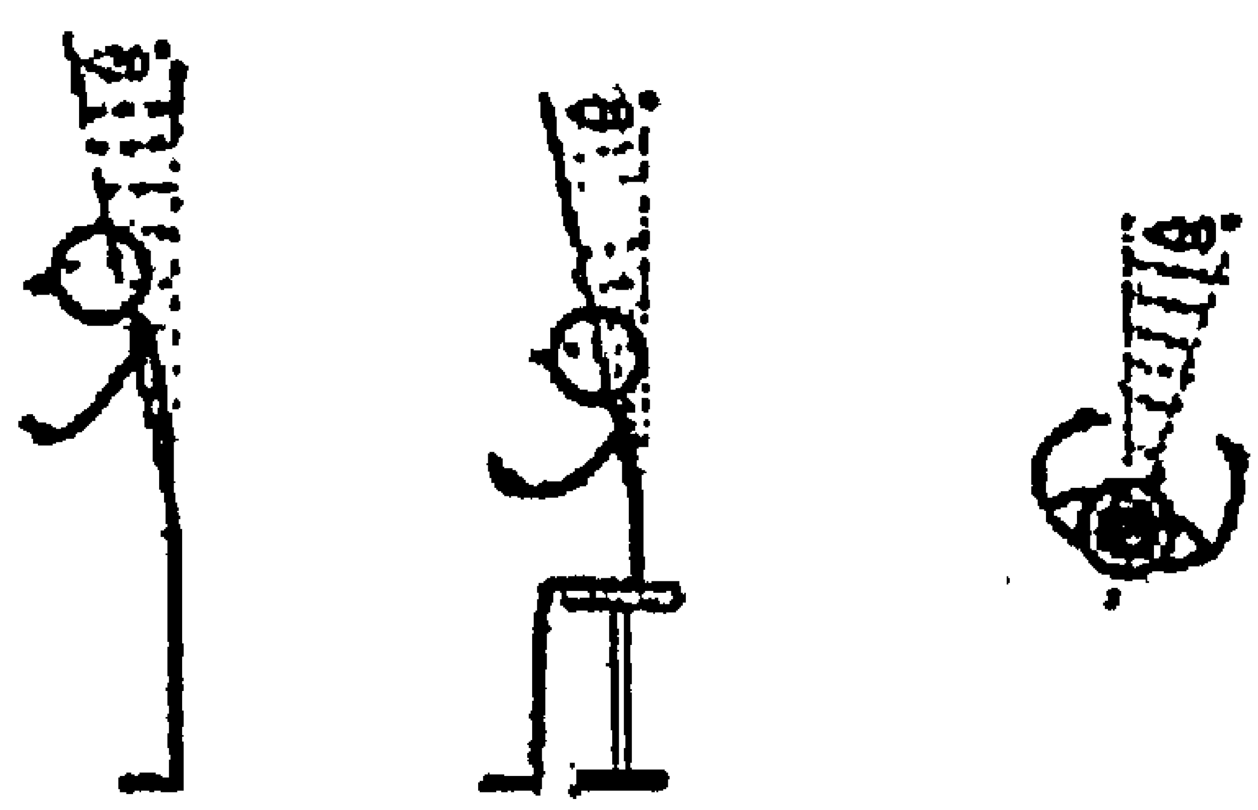


Figure 2-15a 'Almost Neutral' i.e. Less than 20°

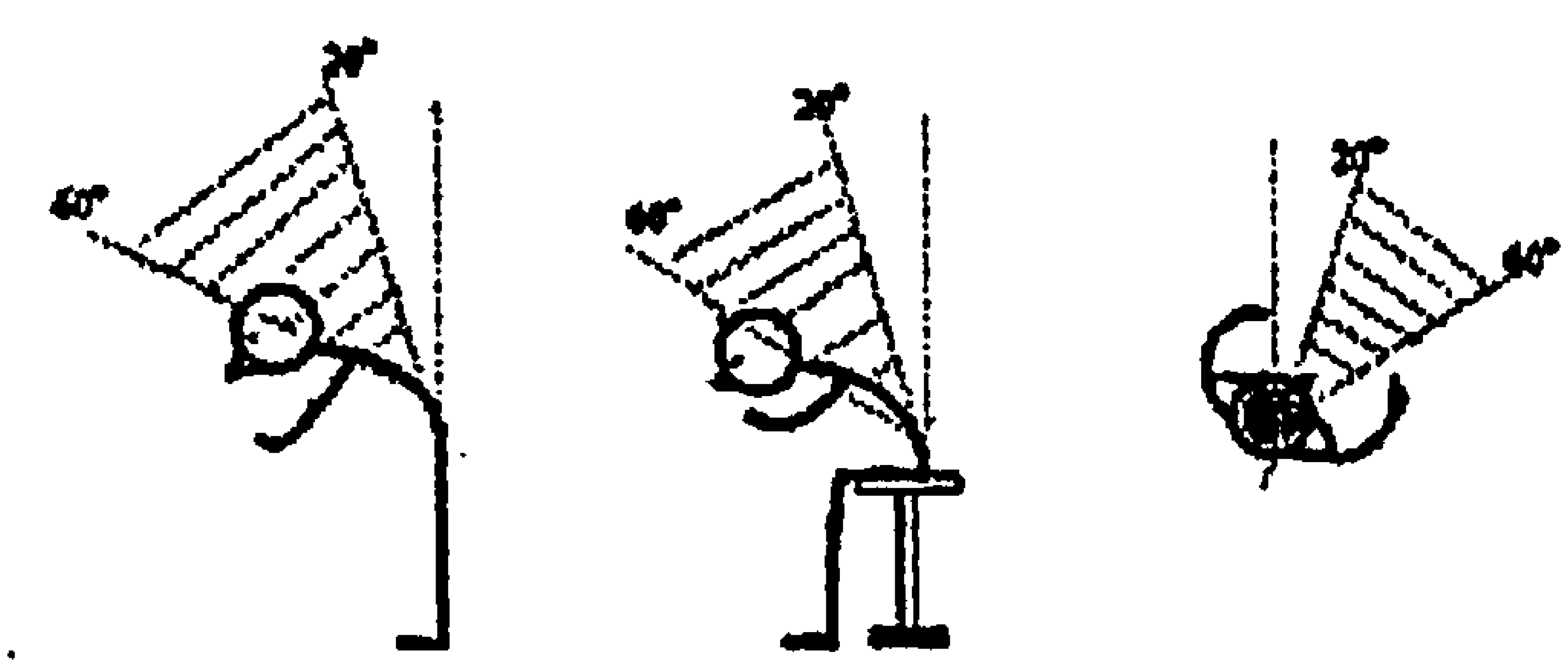


Figure 15 b 'Flexed or Twisted' i.e. 20° to 60°

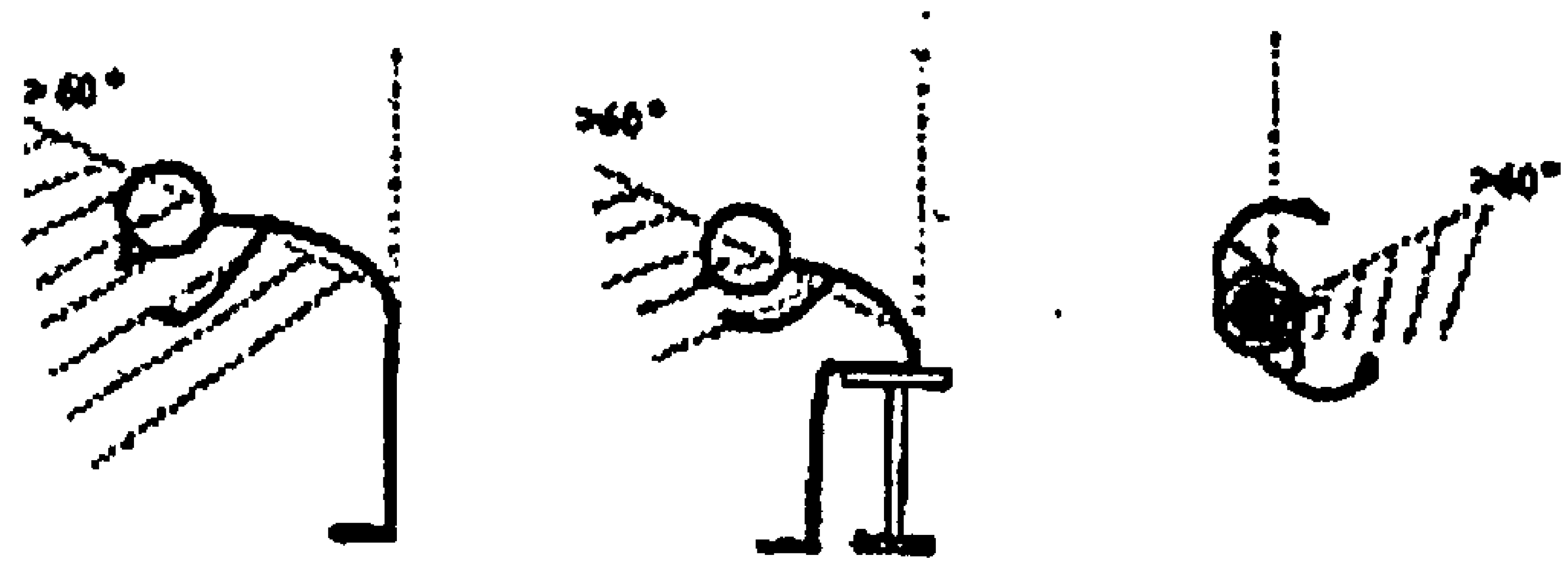


Figure 15c 'Excessively Flexed or Twisted' i.e. Greater than 60°

Similar type ranges of movement were applied to the neck and wrist as well as other body parts. It may be taken that the first posture-category produces the least discomfort and the last the greatest amount of discomfort. Therefore if discomfort scales were applied in all three of the above we would expect the last to have the highest body part discomfort (BPD) score. Li and Buckle, (1999), report that back flexion angles of less than 20° do not appear to contribute to RSIs/MSDs, even over extended periods of exposure.

It would also be reasonable to expect similar ranges in relation to duration for any of the above postures. Delleman, (1999), used a scale of duration to elicit a perceived estimate of duration from the test subjects (sewing machine operators), who had worked at a particular height for five minutes. The estimated endurance was on a five-point scale: 1 = >8 hours, 2 = 6 - 8 hours, 3 = 4 - 6 hours, 4 = 2 - 4 and 5 = <2 hours. He then used the estimated time as a dependant variable. He used a numeric scale to get a subjective judgment on the desk-work height, ranging from 1 (too low) to 5 (too high). The incremental heights, related to the workers sitting heights and was set at 50 mm intervals in line with Dul et al., (1988). The validity of self-reporting for duration was tested by Mortimar et al., (1999), and proved successful.

There is a vast amount of evidence, which tells us that ergonomic intervention works. Whatever the motivation for this intervention, increased productivity, reduced work related RSI, or simply to know – there is usually a benefit to the worker when work design ergonomics are applied. This is borne out by the graph from Westgaard and Aaras, (1985), which shows the result of ergonomic intervention in an electronics company in Norway. The graph results from records of lost days due to MSDs, between 1967 and 1982 (Figure 2-16).

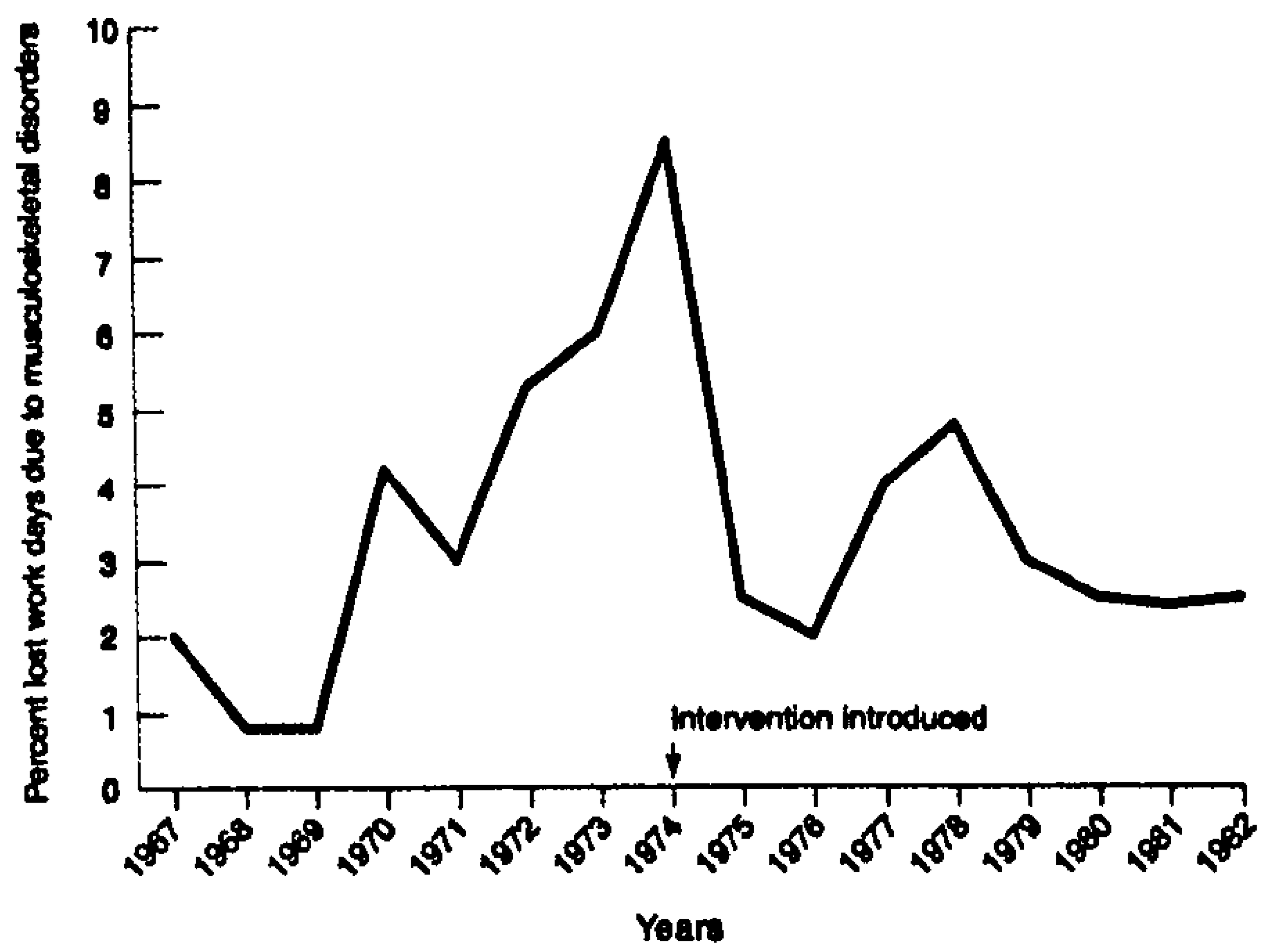


Figure 2-16 Ergonomic intervention in Norway

Mekhora, et al., (2000) was able to show that ergonomic intervention not only worked to reduce RSI in computer users, but that significant improvements could be achieved with little expense. They suggest that workstations should be restructured to suit individual needs.

Kroemer , (1993) points to the myth of 'one healthy upright posture, good for everybody anytime', and says that it must be abolished. He suggests that 'free posturing' be adopted, where operatives may sit or stand, make workstation adjustments and allow for user preferences. These adjustabilities should be applied to seats, desks, footrests, and VDU screens. Das and Sengupta, (1996) suggest an evaluation of a mock-up workstation designed by employing live subjects will significantly enhance the operator-workstation fit.

Speaking of the relationship between ergonomics and quality in assembly work Eklund, (1995) shows that there is a direct relationship between improved quality and ergonomic intervention. He also shows that improving work quality and work conditions should happen simultaneously. His study was to evaluate whether there was a relationship between ergonomic work conditions and quality in a car assembly line. He found that quality deficiencies were three times more common where there was ergonomic problems.

Ergonomic intervention, was also undertaken by Mirka, et al., (2003) on framing carpenters in the home building industry in the U.S.A. Even though dealing with 'seasoned' professionals with years of on-site experience, several of the interventions had positive effects, particularly on shoulder loading. However while the interventions had quite a positive effect overall, the subjective assessment by the workers, showed that they were not too happy when intervention slowed down specific operations. They included self-reporting assessment tools from a study by Phattacharya, (http://oz.uc.edu/~phattat) who tested body part discomfort, in evaluating carpentry tasks on-site.

The conclusion reached is that ergonomic intervention does work to improve work conditions and worker comfort and that a variety of evaluation tools may be usefully employed to collect data including subjective scoring systems by the subjects.

2.3 Workstation design and ergonomics

An important piece of equipment, which requires much ergonomics intervention is the 'workstation' traditionally known as the 'workbench'. The workbench has been an integral part of the equipment in engineering shops, carpentry and joinery and cabinet making shops for centuries and even millennia. Yet it is the piece of equipment, which changes least. Evaluating a large number of benches for this project revealed that the height range for workbenches varied only 60mm (with one exception), from 800 mm to 860 mm, however the users height range was up to 500 mm (20 inches). The prime objective of this research was to examine workbench design ergonomics in the context of Universal Design i.e. to make the design of the workbench as inclusive as possible. This means including the 5th and the 95th percentile or perhaps as Dreyfuss (1993) suggests 'the 1st and 99th percentile'.

Workstation design has been receiving quite a lot of attention during the last decade or so. Websites are available in abundance to advise on choosing the best solution for one's needs. Some ergonomic advise is also available. Joy Ebben (www.iacindustries.com) advises that height flexibility is an important characteristic. She also distinguishes between working height and the work surface and that adjusting to elbow height by seat height or desk height adjustments. Dellman and Dul (2002) in evaluating workstation design for sewing machine operators, suggests a work height of 50 to 150 mm above elbow height and a table slope of 10°. They found that these positions for this type of activity reduced BPD and particularly reduced neck flexion. They used an evaluation model based on Corlett and Bishop, (1976) and include estimated endurance time, BPD aggregate scores and subjective height evaluation.

Stuart Smellie, (2003) examined the limitations of standard workstations for their user population and found that in addition to work heights, that armrests and seat depth had the capacity to cause health problems. He points out that at any workstation there are three points of fixed contact, the floor the seat and the work surface and says that at least two of these variables should exist to meet the needs of the whole user population. Lim and Hoffmann, (1995) showed that improved workplace design reduced occupational health risks to the operator from back injury problems and increased productivity, through more economic use of hand movements. Mekhora, et al., found that ergonomic interventions for computer users, reduced neck tension and there were significant improvements in comfort resulting from the intervention. The study also supported the use of simple materials, which workers can use to improve their own workstations according to ergonomic guidelines.

Wilson and Corlett, (1985) edited a collection of research papers on the ergonomics of working postures. The contributions included study of assembly lines, press shop operations in light engineering facilities, methods of evaluation of body postures and evaluation of the work of seated machine operators. In all cases either significant improvements were brought about by the intervention, or new ergonomic guidelines were established.

Chris McIntire writing in OSN-Canada (www.oshcanada.com), Canada's Health and Safety Magazine, says that we don't buy shoes which are 'average shoe size', so why are workers expected to work comfortably and efficiently at workstations which do not fit their body dimensions? Fixed height work tables force workers to alter their posture to suit the height rather than visa versa. Short people are forced to stretch upwards while the taller workers must stoop excessively. McIntire recommends height adjustability as a solution to worker discomfort, where workers can, where possible, alternate stranding and sitting work positions. This will result in healthier workers and improved productivity.

The Union of Communication Workers of America (UCWA), (www.cwa30248.addt.com), have provided a guidelines booklet on 'Working in a Standing Position'. It informs workers on why working while standing can cause health problems if ergonomic guidelines are not followed. They too recommend that tables and workbenches should be adjustable, particularly to match the worker's body size, and to suit the particular task. They point out that adjustability ensures that the work is carried out in well-balanced body positions. They recommend changing working positions frequently, avoiding extreme bending, stretching or twisting and that after absence that the worker should be allowed time to return to the regular work-pace. Their general guidelines for work heights are: precision work 50 cm above elbow, light work 5 to 10 cm below elbow height and for heavy work demanding downward forces 200 to 400 mm below elbow height.

Stations which accommodate sit-stand variations such as those in Figure 2-17 are recommended.

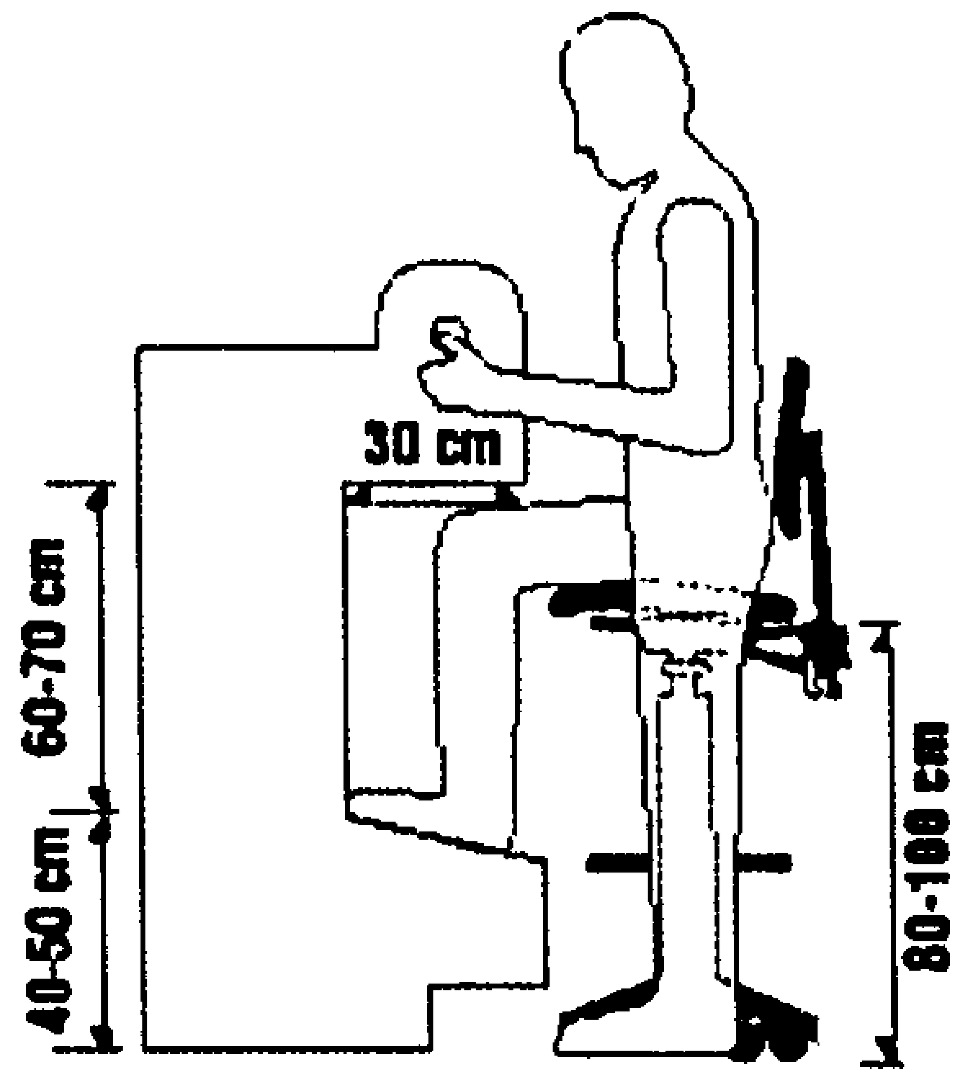


Figure 2-17 A sit-stand workstation

The standing work heights in Figure 2-18 below are those recommended by the Canadian Centre for Occupational Health and Safety (CCOHS). It is interesting to note that these differ upwards from the heights for standing working males recommended by Kroemer and Grandjean, (2000).

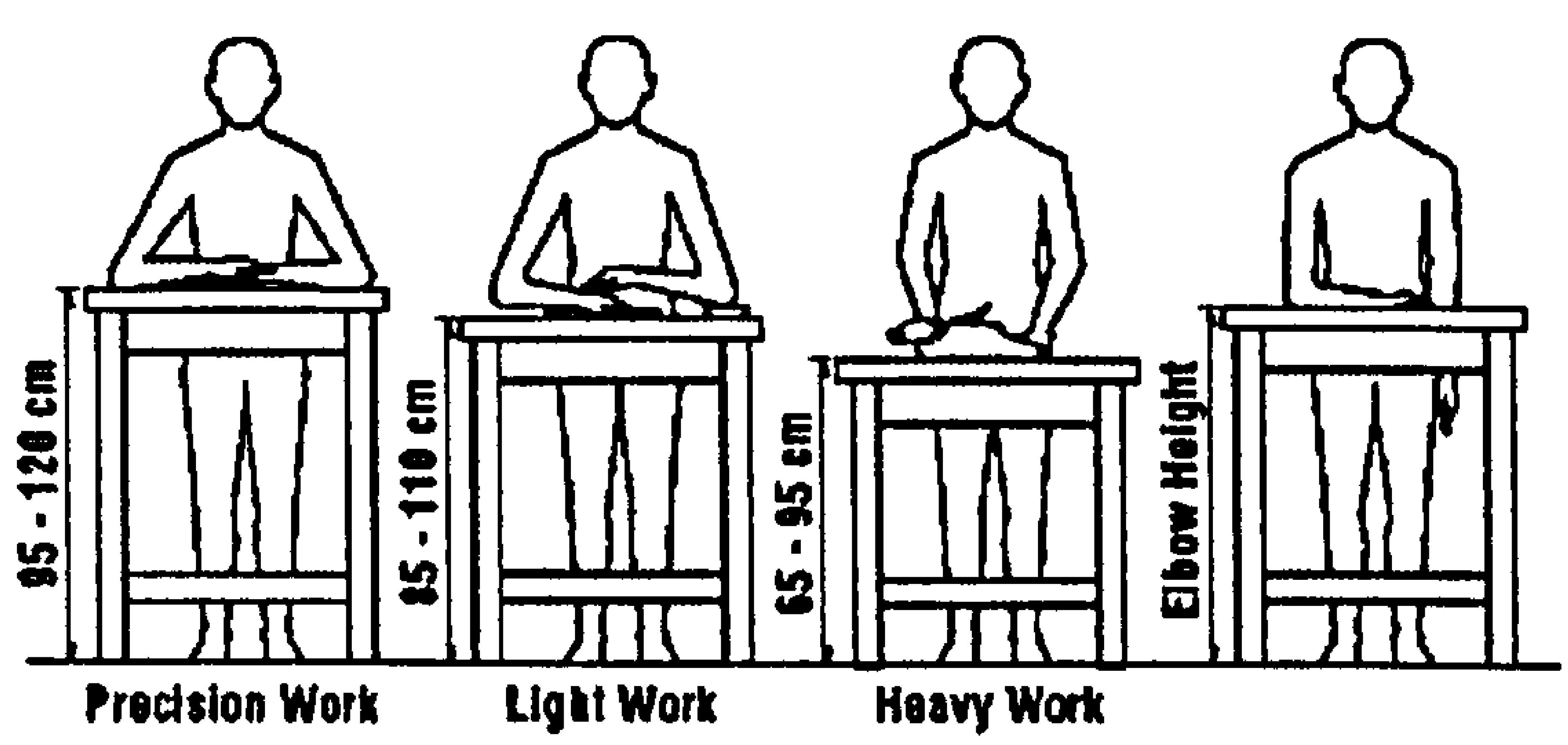


Figure 2-18 CCOHS recommended work heights

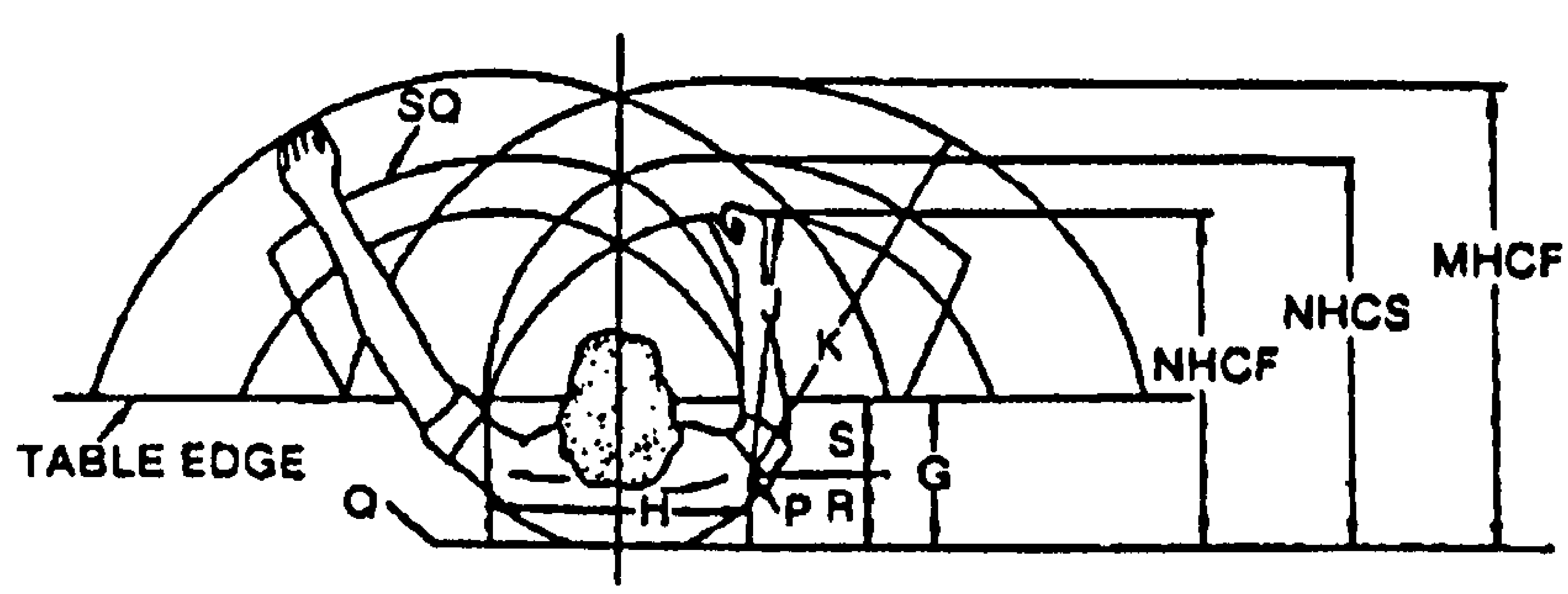
2.3.1 Anthropometry

The anthropometric data gathered for able-bodied people especially in work situations, is well documented. Stephen Pheasant (1998) in his book 'Bodyspace', not only gives the body dimensions but also the application of anthropometric data in a number of work situations. He died prematurely in 1996, but left a comprehensive body of anthropometric and ergonomic knowledge. He defined ergonomics as, *'The science of fitting the job to the worker and the product to the user'*. In his book 'Bodyspace', he lists five criteria for the successful matching of the worker with the job:

- functional efficiency;
- ease of use;
- comfort;
- health and safety and
- quality of working life.

All these criteria appear to be a common sense approach to ergonomic design and yet sometimes, not one but all of these are missing from workstations.

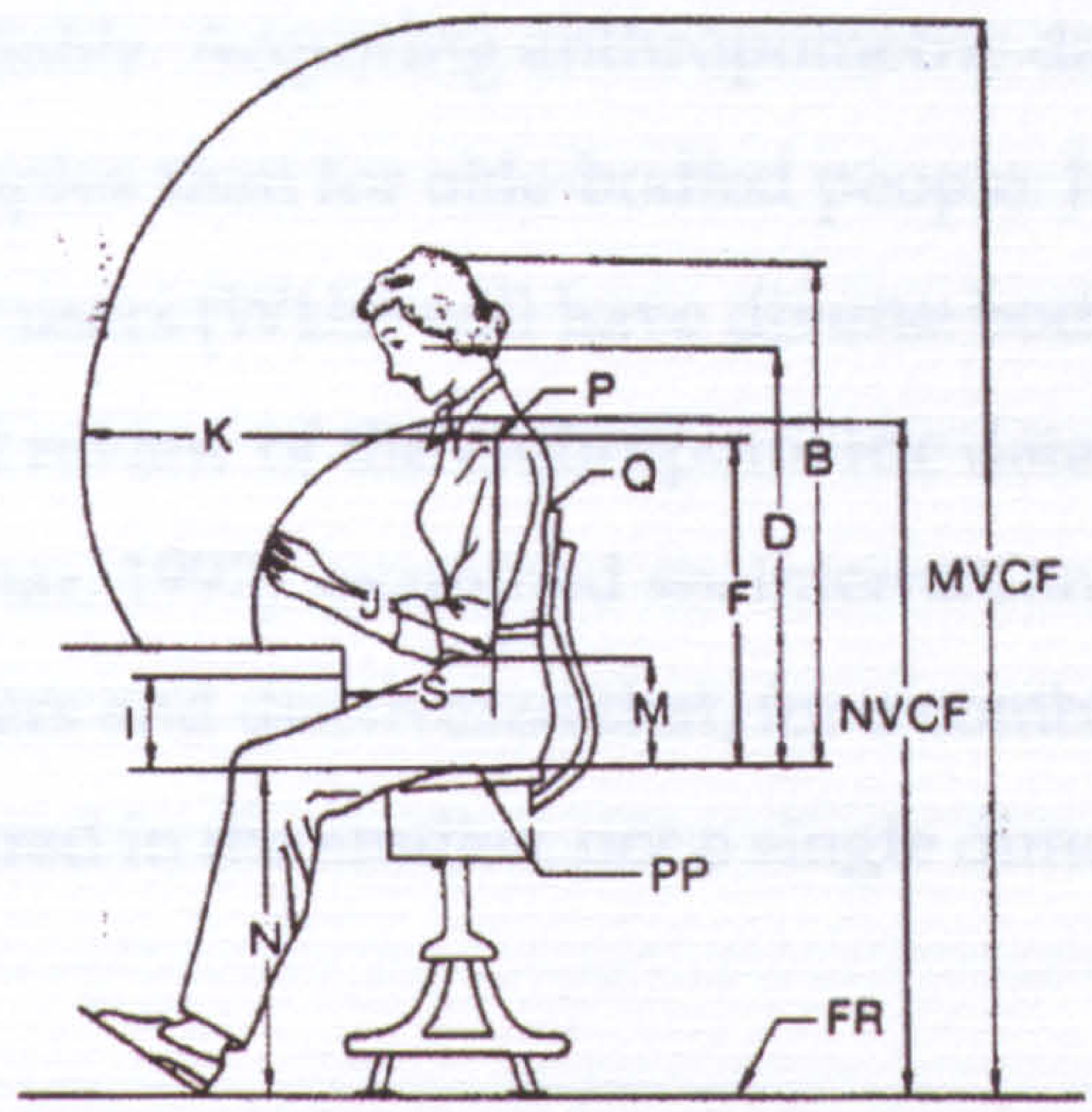
Das and Grady, (1983) also made significant contributions to engineering anthropometric applications in workplace design. They provide anthropometric data which is readily accessible to the workplace designer. These include data for standing, sitting, reaching, and work surface areas derived from practical test sites. They recommend a sit-stand working position rather than a sit only position. The diagram in Figure 2-19 below shows normal and maximum clearance guidelines, in the horizontal plane for seated, standing, or sit-stand working positions for males and females.



Normal and maximum working areas and clearances in the horinzontal plane for a seated (also for standing and sit-stand) male or female operator.

Figure 2-19 Horizontal work area clearance (Das and Grady 1983)

Figure 2-20 shows the vertical plane clearance references for a seated male or female operator.



Normal and maximum working areas and clearances in the vertical plane for a seated (male or female) operator.

Figure 2-20 Vertical work area clearance (Das and Grady 1983)

Proper workstation design is intended to minimise situations such as those illustrated below in Figure 2-21, (www.ergoweb.com).

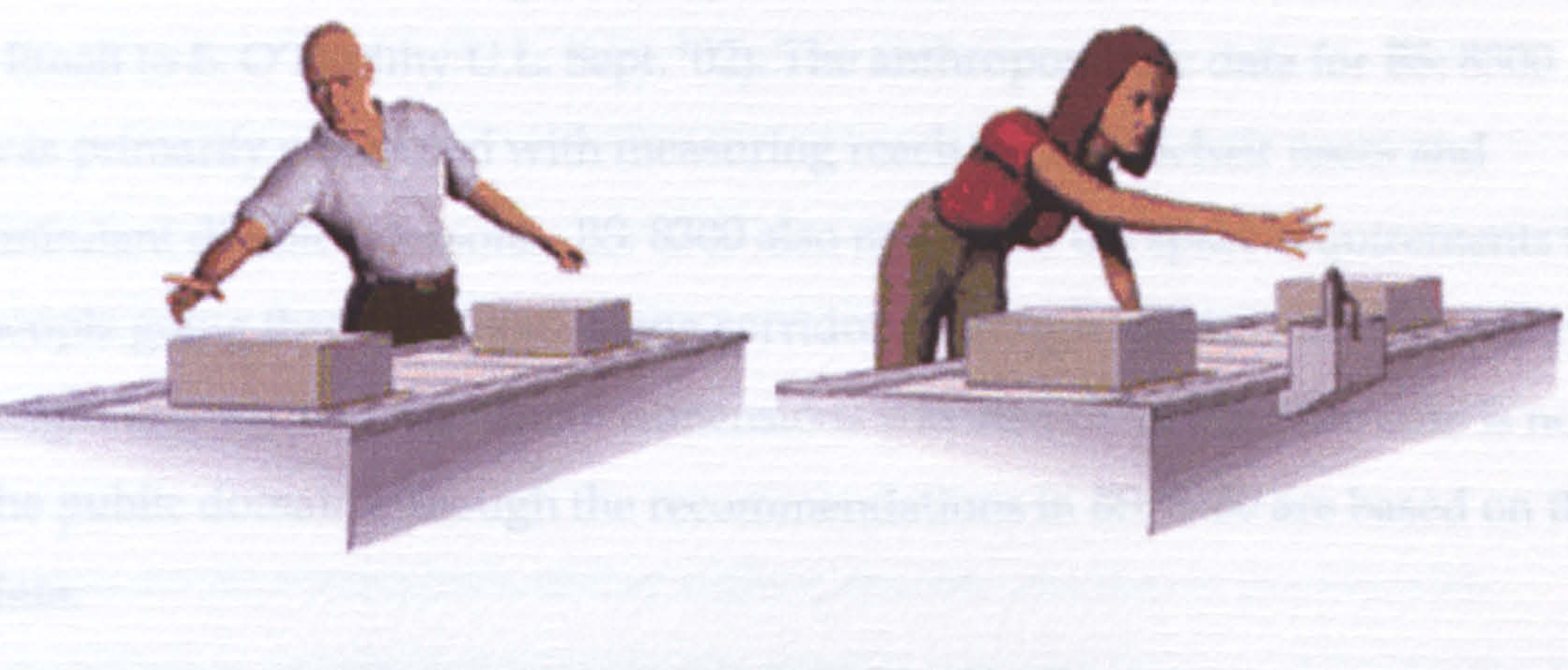


Figure 2-21 Ergonomically compromising work postures

2.3.2 Wheelchair user anthropometrics

Anthropometric data for non-able bodied workers, such as wheelchair users is not so readily available. Acquiring anthropometric data for wheelchair users is perhaps more complex than for able-bodied people. Just as with ambulant people wheelchair users (WUs) will have diverse body dimensions. In a recently published review of the anthropometric data of people with disabilities Goswami, (in Kumar, 1997), examined six international studies of people with lower limb disorders and discovered that, for a combined total of 58 body size descriptors measured in the studies, not a single dimension was found in common.

For collecting anthropometric data, body land-marking and measurement procedures are critical. Goswami also found in his research that none of the studies tried to standardise the technique for measuring or body land-marking people with disabilities (Bradtmiller and Annis, 1997). Robert Feeney and associates undertook anthropometric studies for BS: 8300 and stated that *"...they don't think you will find much in the literature on these topics regarding validated data and measuring methods for collecting anthropometric data"*. (R. Feeney - Email to E. O'Herlihy U.L. Sept. '02). The anthropometric data for BS: 8300 was primarily concerned with measuring reach for wheelchair users and ambulant disabled persons. BS: 8300 also measured the space requirements for people going through doors, along corridors, through lobbies etc. Data on eye height and various wheelchair dimensions was also collected. The data is not in the public domain although the recommendations in BS: 8300 are based on this data.

Nowak 1996 researched the role of anthropometry in the design of work and life environments of the disabled population. The research was broken into two sections. First, of the application of anthropometry for the needs of ergonomics was studied by investigating workspace design. All the Polish data obtained by Nowak (1989), on a group of young people (15-18 years) with motor dysfunction of the lower extremities was used in conjunction with work by Das and Grady (1983). This data was used to determine maximum transverse reach and maximum sagittal reach in workspace design. The results were used for ergonomic analysis at school and for design of school workshops, laboratories and rehabilitation centres in Poland.

In 1996, Jarosz undertook similar research to Nowak (1996). Jarosz took eighteen anthropometric dimensions from 170 wheelchair users. Using this data, Jarosz then determined the maximum transverse reach and the maximum sagittal reach for wheelchair users and compared them with able-bodied users. Jarosz found that the workspace required by people with disabilities would be smaller than that required by their able-bodied counterparts, as their reach range was less.

Das and Kozey, (1999) undertook research to determine reliable and accurate structural anthropometric data measurements for male and female wheelchair mobile users. They wished to enlarge and update the information concerning wheelchair mobile adults for the design of industrial workstations. Their research identifies previous anthropometric studies undertaken for wheelchair users, although there is not a great deal of such data available. Their research shows that even when workstations are ergonomically designed for seated workers, these do not meet the requirements of wheelchair-using workers.

A concern for researchers, is that anthropometric studies on people with disabilities is naturally limited by the sample size available or is limited by the specific conditions of their disability. As a result, there is no major database of anthropometric information for the wheelchair using population, such as there is for the able-bodied population, Case et al. (2001); Marshall et al. (2002).

As industrial environments are often seen as dangerous for wheelchair users, little attempt has been made to integrate them into the workforce, (O'Herlihy and Gaughran, 2002[1]). They found that managers of engineering workshops were generally uncomfortable with the idea of wheelchair users in such an environment. As part of a study on engineering workshop and classroom accessibility, they undertook a study using twelve 'ambulant' (able to propel themselves without the aid of mechanical assistance) wheelchair users to determine a best-fit work height, using a range of dexterity tests, (O'Herlihy and Gaughran, 2002[2]).

Similar to the problem in gathering wheelchair anthropometric data, was the problem of finding suitable subjects. As part of this research a similar number of surrogate wheel chair users underwent the same test-bank. While Goldsmith, (1984) suggests that it is appropriate to use able-bodied people sitting in wheelchairs to establish ergonomic data, this has not been tested for non-sedentary activities. The use of surrogates in this study will allow a comparative analysis of the two test groups, a larger test cohort when combined, and gender comparisons on a number of issues.

Other than the foregoing studies of WUs for best-fit working heights has in the main related to office and reception desks and such like. Figure 2-22 from BS 8300:2001, shows the prime dimensions relating to a reception desk. Any research, which extends the ergonomic database for WUs, especially at workbenches, will serve as a prompt to employers and WUs alike, as to new employment and career opportunities and improved integration and self-esteem.

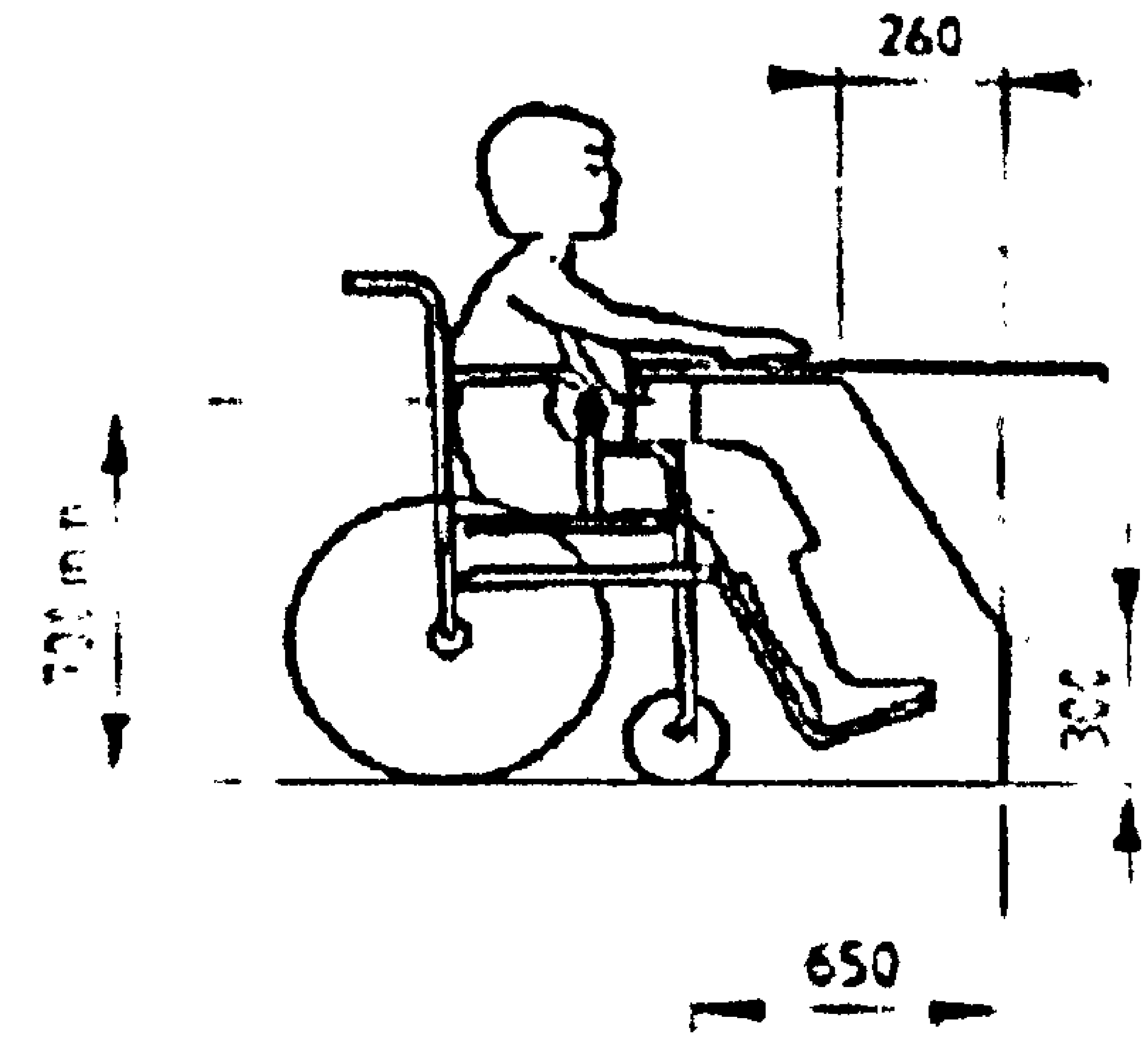


Figure 2-22 Reception desk recommendations from BS 8300:2001

The element of this research associated with WUs, will contribute to the anthropometric and ergonomic data in the context of workbench activities.

2.3.3 Workstation design and ergonomics for wheelchair users

While there is a broad range of publications on workstation design, these are generally concerned with able-bodied workers. Only in recent years has any research taken place relating to WUs in work environments, Nowak (1996); Das and Kozey (1999) and Jarosz (1994). Their research concentrates on reach ranges relating to workstation layout. Hansen et al., (1992) designed a computer workstation for disabled people. Other than O'Herlihy and Gaughran, (2002) there is no evidence of any published works relating to WUs at workbenches in engineering environments.

The whole area of research relating to the integrating of WUs into engineering environments is only in its infancy. It therefore follows that if people do not see it as appropriate to have WU in engineering and other practical workshop situations, it is unlikely that consideration would be given to workbench design to accommodate them. O'Herlihy (2003) established guidelines for the integration of WUs into such environments and as part of that considered workbench accessibility and ergonomics. O'Herlihy's raw data for the WUs at workbenches will combine with the data from surrogate wheelchair users (SWUs), established for this research. The combined data will show that 'the whole is greater than the sum of its parts'.

While there were no WU guidelines for workbenches, there are, however guidelines on how this accessibility can be achieved (ADAAG, 1997; Bar and Galluzzo, 1999; Goldsmith, 2001; BS, 2001). Troy et al., (1997) undertook research on working postures for WUs in office environments, and though they carried out an intensive search of the literature, they only uncovered two published papers on the area they were working on.

Standards for leg space, knee clearance, widths, counter heights, reach ranges have all been established and will need to be accommodated in any inclusive bench design to accommodate WUs.

The Americans with Disabilities Act Accessibility Guide, (ADAAG), provide guidelines for WUs at counters and tables, including

- knee space at least 685mm high, 760mm wide and 485mm deep;
- table heights should be 710mm to 865mm;

The BS 8300:2001 recommends a knee height clearance of 700 mm minimum. It is obvious that there is much work yet to be done in the area of WU ergonomics.

2.3.4 Anthropometry and ergonomics for school children

Anthropometric data for young people is well established, Pheasant (1998); BSI PP7301 and others. However stature for teenagers especially, varies a great deal and is also a variable from decade to decade. Therefore the fact that the group under consideration for part of this research are 12 to 17 year olds, means that appropriate ergonomic data needed to be established as the testing proceeded. A factor in including a cohort in this category in the research is the gains in stature, not just over the past fifty years, but also over the past ten years.

Ergonomic data for teenagers is not as accessible as anthropometric data, especially in work environments, which is what practical classrooms, such as for engineering and technology, may be categorised as. In a study to improve the ergonomics of school furniture design, in Iran, Mououdi and Choobineh (1997) found that there were significant differences between boys and girls for most measurements with the exception of stature and sitting height. They were testing 6 to 11 year olds. Storr-Paulsen (1995) made a comparative analysis of school furniture for ergonomic fit for 7 to 11 year olds. She made recommendations for seating, which would significantly reduce back discomfort. She observed that this was only one of the factors needing ergonomic attention in a multi-factorial of the back health of children. The study used subjective perception of comfort as an assessment tool. The children preferred a tiltable table-top and a height that was 150 mm above the usual designs.

Harrington et al., (1995) examined the effects of workstation design on the sitting postures of young children (mean age 4.7 years). They found that the use of the ergonomic workstations reduced neck flexion and could assist in maintaining a more efficient anatomical alignment of young children when sitting and writing. Their research reports that there was an incidence of 22.8% of elementary school children who complained of backache and 33.3% of the secondary school population. It appears therefore that as children grow older the problem of MSD increases. They claim that the negative effects of poorly designed school furniture, is a significant contributing factor. Ergonomic intervention at this early stage could make a significant contribution to reducing the incidents of lower back pain in future generations.

In Brazil, Paschoarelli and Silova, (1997) undertook a study of ergonomics relating to pre-school furniture. Through the application of existing ergonomics they designed a new pre-school 'workstation', which they claimed improved the quality of life of the children concerned.

Concerning advertisement for a meeting with the theme, 'Back pain in school children', at the University of Surrey, July 2003, the question was asked; why such a meeting? The organisers pointed out that 36% of 11 to 14 year olds suffer ongoing back pain and that children who reported low back pain in school were more likely to suffer low back pain in adulthood (www.eihms.surrey.ac.uk/robens). This means that the workforce of tomorrow is likely damaged, already experiencing MSDs, even before starting the acknowledged rigours of their adult working life. Their academic progress is also likely to be hampered by the distraction of pain.

Mandal, (1997) found that with some small modifications in desk design that significant comfort improvements could be achieved. He makes a very serious observation, pointing out that the ISO standard for the height of school furniture has *decreased* 20 cm, during the last 50 years, while during the same period pupils have *increased* in height by 10 cm! He claims that the ISO standards are based on old anthropometric data and that students are performing in an unnatural erect sitting position. He shows that by raising the desktop by 20 cm and tilting it to 15°, the back flexion can be reduced by a very significant 32°, See Figure 2-23 below, where 'A' is the ISO standard and C is the recommended ergonomic improvement.

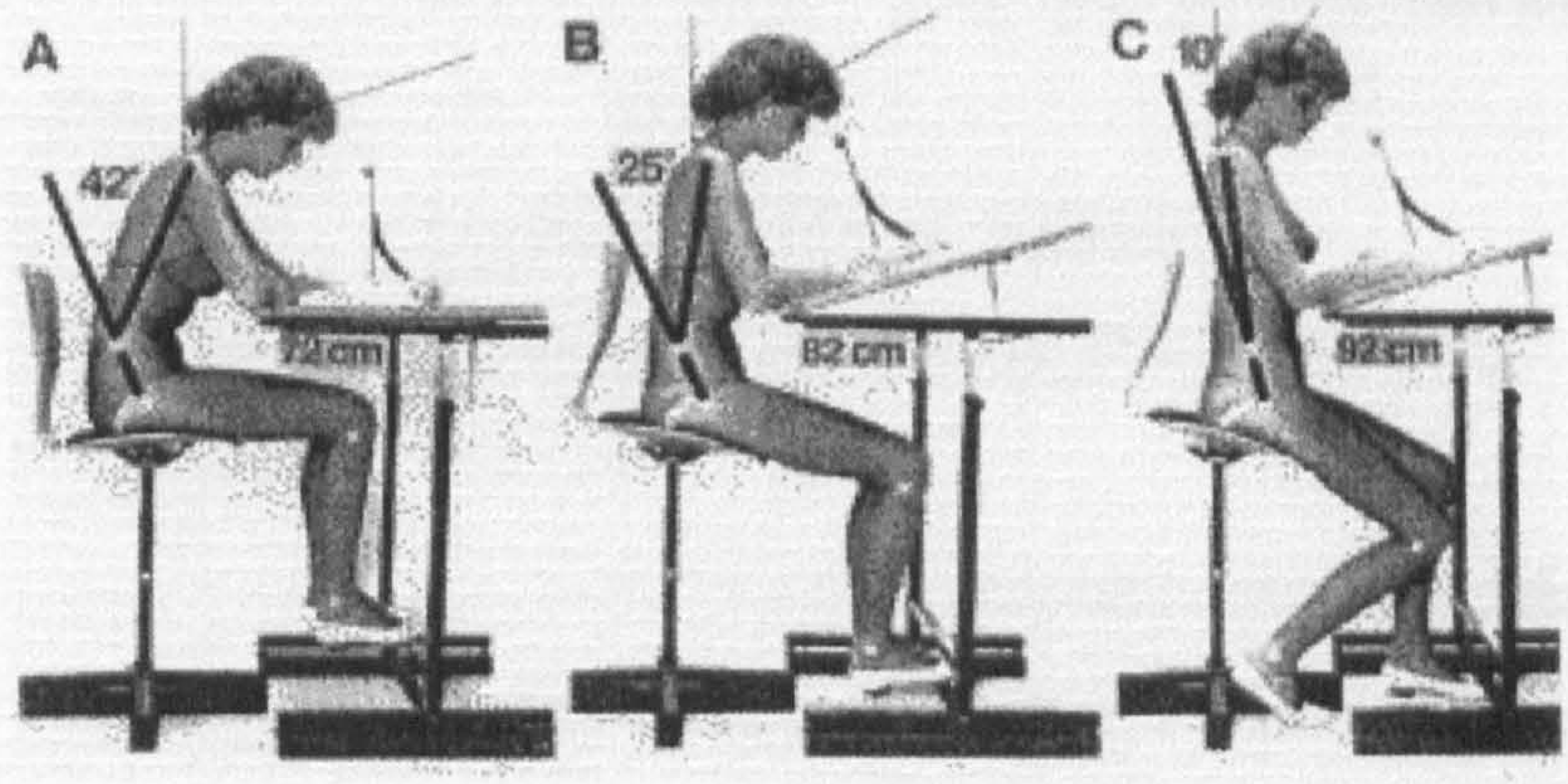


Figure 2-23 Egonomic improvements on Scandinavian school desks

Similar studies have been undertaken in several countries, Lin and Kang, (1997) in Taiwan; Da Silva 1990 in Brazil; Frazer, (2002) in Canada. However the literature search has failed to produce any evidence of ergonomic intervention on workbenches in practical classrooms. And similar to Mandal's findings on school desks, investigations for this research project reveal that workbench heights in Irish schools have not changed in two generations, while the user population has grown in similar proportions to those in Scandinavia.

2.4 Universal/inclusive design.

During the early 1990s and into the new millennium there has been renewed effort to accommodate people with disabilities in all areas of life and living. Inclusiveness need not be a word that is frequently used if it was practiced naturally. Many countries have enacted laws to ensure that people who have disabilities of various ranges, are catered for in public as well as private buildings, in transport, in shops and restaurants and in educational establishments. Among the legislation recently enacted and published to protect the rights of the disabled is:

1990, The American Disabilities Act (ADA);

1991, The American with Disabilities Act Accessibility Guidelines (ADAAG);

1995, The Disability Discrimination Act (DDA), in the U.K.;

1997, The Revised Building Regulations - to include people with disabilities, in The Republic of Ireland;
2000, The Equal Status Act in the Republic of Ireland;
2001, The Disabilities Bill in Ireland and BS 8300:2001 in the U.K.

Other Acts and Regulations, which are more specific and some relating to education have also been published recently. Often in the context of Universal Design (UD), we see publications which refer to 'an aging population' or the so-called 'grey pound', or the 'grey market', (Marshall, 2002; Steinfeld, 1994; Case et al., 2001; Brady and Young 2001).

Brady and Young say that 'inclusive design' and 'design for all' methodologies embrace the challenge of designing mainstream products to include disabled and elderly users. If this is taken as a paradigm then we miss the point of UD and inclusivity. Steinfeld, (1994) suggests that an important implication of UD is that it has mass appeal. He also points out that for UD to be accepted it must have a high standard of aesthetics. Where there is an 'assistive technology' solution required, to have acceptance it must it must not have a medical appearance, as this is not liked by the users. This principle should also apply to universal design solutions. Being inclusive implies including as much of a user population as is possible, wherever the starting point. This may be starting with the young, the tall, the short, the heavy, the male or female, the wheelchair user, the experienced or inexperienced and so on. The approach therefore must be, *to make a design, system, or building accessible to as broad a population as is practicable.*

Some say that this can end in a less than excellent solution by arriving at a compromise design or that a type of 'design schizophrenia' can occur, where the issues ate clouded and confused (Bar-Pereg, 2001).
So how is UD to be defined? The ISDA website, (www.isda.org) puts it succinctly; *'Universal Design means design for people of all ages and abilities'.*

However this is an ideal that can never in an imperfect world, be achieved. The aim must be to see UD in the context of inclusivity. *Inclusive design* may therefore be defines as: *'designing so as to include as broad a user population as is practicable'*. The centre for UD at the University of North Carolina has established seven UD principles. These are:

- Equitable use;
- flexibility in use;
- simple, intuitive use;
- perceptible information;
- tolerance for error;
- low physical effort; and
- size and space for approach and use.

Applying these general principles to any design approach is bound to make the result a better-for-all design. There are situations where design has to be tailored to the client group or individual and where UD principled are minimal, e.g. a racing car or a tower crane.

In 1998 the Engineering Design Centre at the University of Cambridge, the Helen Hamlyn Centre at the royal College of Art, the Central Saint Martins College of the London Institute and the Design Centre U.K. came together to begin a programme of research focused on Inclusive Design. The aim of this collaboration was/is to provide reliable data and information for designers that will lead to products, which enable independence at home or at work for the whole population (Clarkson et al., 2000). The three objectives, which underpin this aim are:

- To give those who commission a design a framework within which they can recognise and understand the benefits of an inclusive design approach;
- to give guidance to those who manage design on how to implement such an approach; and

- to provide designers with the necessary tools, information and appropriate process models to deliver inclusive design.

The group have devised an inclusive design cube, which fills outward from the able-bodied to fill towards the opposite corner as inclusion in a number of areas increases.

Among the major publications on Universal design are: the Universal Design Handbook, Wolfgang and Ostroff, (2002), which covers a broad range of interests, including the built environment, products, multimedia and transportation. The ADAAG guidelines are included on CD for down loading into design drawing. Selwyn Goldsmith is to be seen as one of the pioneers of UD. His book, 'Universal Design', was published in the year 2000, but he had been publishing on inclusive design for nearly four decades before that. For example his book, 'Designing for the Disabled' was first published in 1963.

Goldsmith described UD in these terms. *'Broadly UD means that the products which designers design are universally accommodating, that they cater conveniently for all their users'*, (Goldsmith, 2000). Goldsmith says that for the gathering of anthropometric data that it is justifiable to use surrogates. As this has not been tested in the context of practical manipulative activities, it has been undertaken in the context of workbench design in establishing best-fit height ergonomics. The design of experiments and the analysis of the data is discussed in Chapter 3 of this Thesis.

The universal design approach for the workbench will blend three diverse subject groups, such that the result will be an inclusive design solution. Figure 2-24 below describes diagrammatically the data blend.

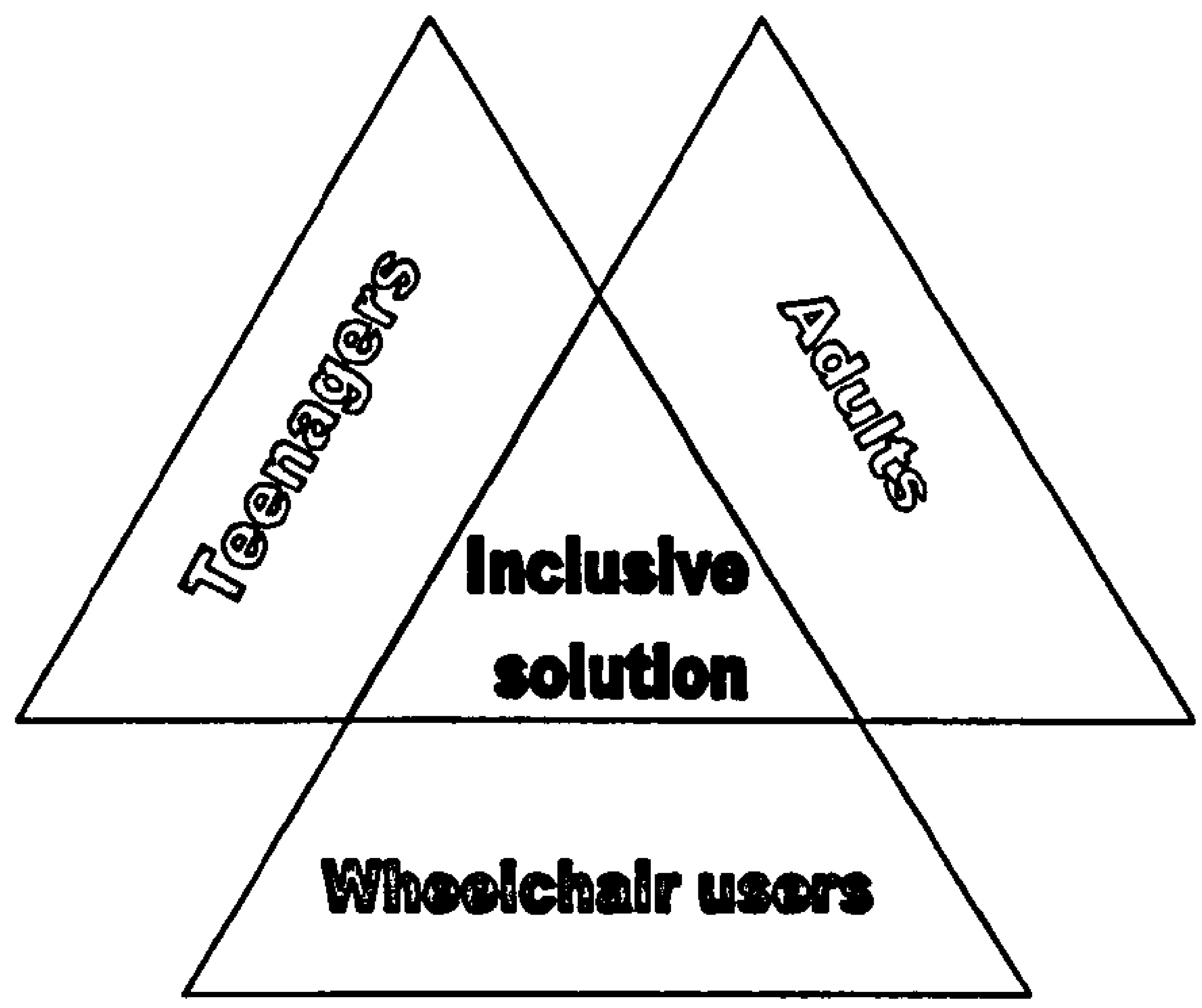


Figure 2-24 Blending design ergonomics data for inclusive bench design.

In writing about inclusive design in a paper entitled, 'Design for all: designing for the motion impaired user', Clarkson and Keates (1999) point out that in 'designing for all', subtle changes are needed in the designer's perception of the end user. They said: *'Rather than differentiating between able-bodied users and those with impairments of any sort, the users should be viewed as a continuum of varied abilities'*. It is in the spirit of this recommendation that this research has been undertaken, and for each of the three groups above, a single solution should emerge.

2.5 Conclusions from the literature review

The literature review has shown that that there are a number of fundamental issues, which need to be addressed. While some of these issues are outside the scope of this research some will be addressed. Workbench design has changed very little over the centuries, and not even with all the technological advancement and scientific know-how, has it changed in recent decades. Websites abound which offer what are called 'ergonomic workstations' and benches but they are limited in their accessibility and physical structure. Apart from Landis (1998) there is very little on engineering or woodwork benches, and while some designs are very fine examples, they are generally customised to suit a narrow range of users. Most of the innovations on workbench design for the disciplines under consideration are rooted in the past.

A scrutiny of the benches in the workshops in England two hundred years ago, and in Sweden over a century ago, reveals that we could walk into any such workshops now and find almost exact matches. Neither would we find any, which were wheelchair user accessible. The fact that Mandel, (1997) found that while Scandinavian children had grown while ISO standard heights for school desks had moved downward, speaks volumes. While school benches in practical classrooms do not appear to have dropped in height, they certainly have not increased (Department of Education and Science, Furniture Specifications for Ireland).

What is very obvious is that MSDs and RSIs are rife, not just in the adult population but also in the school going population, (Marras, 2000; CCOSH, 1998; Mandal, 1997). While several studies have been undertaken, which investigated the ergonomics of school furniture design few were on teenagers and the literature search produced none on workbench design. This is in spite of the fact that research shows that there is significant evidence of MSDs in second level school-goers, with about one third having regular low back pain. The evidence shows that where ergonomic intervention does take place that significant improvements can be made both in the adult and school going population as well as for wheelchair users. However the evidence also shows that not enough research is being undertaken in this area, particularly for school going children, and is seen by many as inappropriate for WUs. Methods of subjective evaluation in the gathering of ergonomic data has been successfully used by a number of researchers, (Dimov, et al., 2000; Genaidy and Karwowski, 1993, Cameron, 1996; Drury, 1987). This allows ergonomic intervention in a manner, which is flexible and subject interactive. Body mapping, visual analogue scales and subjective height and endurance evaluations appeared to be very effective evaluation tools, (Straker, 1999).

Discomfort is seen as a more accurate measure of incorrect posture than pain, and is more easily understood.

Several short evaluation methods have been developed for posture and discomfort analysis, such as RULA (rapid upper limb assessment), McAtamney and Corlett (1993); REBA (rapid entire body assessment) at Cornell University, (2001); LUBA (loading on upper body assessment), Kee and Karwoeski, (2001), and DAS (discomfort assessment surveys) are all well established part of the ergonomic evaluation toolkit.

Little effort has been made to integrate wheelchair users into the industrial work environment, and consequently little has been done apart from recent work by O'Herlihy, 2003; and O'Herlihy and Gaughran, 2002. Ergonomic and anthropometric data is as scarce for wheelchair users as workbench users.

Universal Design (UD) and inclusive design approaches to workbench design requires that new ergonomic data is gathered and applied in design solutions. Inclusive design should not compromise usability by the intended user population nor should it compromise on aesthetics. Solutions, which are clinical or medical in appearance, are not liked. Any solution should function well in being fit-for-purpose, should reduce body part discomfort, and should be fully accessible.

Chapter 3 will discuss the design of experiments relating to wheelchair users, the ergonomic outcomes and a comparative analysis and evaluation of surrogate wheelchair users at workbenches.

3 WHEELCHAIR USERS AND SURROGATES BEST-FIT WORKING HEIGHTS, PRODUCTIVITY AND ENDURANCE

3.1 Introduction

The question to be answered in this chapter of the thesis is: Can surrogates be used to establish ergonomic data for wheelchair users?

In answering this question a comparative analysis of the results of an identical test-bank from a group of wheelchair users (WUs) and a group of surrogate users wheelchair (SWUs) will be made. The data collected from a previous study on WUs only, undertaken at the University of Limerick in 2002, will be used to determine the validity of using SWUs in establishing ergonomic data. The raw data from the WU test-group was used with the agreement of Eoin O'Herlihy and was published by O'Herlihy and Gaughran (2002[2]). The WU study group consisted of 12 wheelchair users undergoing a bank of bench process/manipulative tests. The data from eleven of this group was used, as one test subject was unable to complete some elements of the test-bank because of dexterity problems. The complete test took 3 to 3.5 hours to complete.

The surrogate group of eleven subjects were all volunteers and were chosen to approximately match the WU group. The group consisted of five females and six males. The WU group was made up of four females and seven males. A test permit was sought and approved by the Ethics Committee in the University of Limerick.

3.2 The method

A best-fit working height has a major bearing on the comfort of any worker. This is as important for wheelchair users as it is for the able-bodied. Four elements were combined to establish an ergonomic best-fit, Body part discomfort (BPD), endurance evaluation, subjective height ratings and efficiency.

The experiments were designed to test the following null hypotheses:

1. Psychomotor skills will not be affected by working height.
2. Completion times will not be affected by working height.
3. BPD will not be affected by working height.
4. Endurance will not be affected by working height.
5. SWUs cannot be used instead of WUs
6. There is no best-fit difference between male and female WUs/SWUs

The study was a repeated measures design with the primary factor of working height condition. The condition working height had five levels of working height plus the existing bench height (6 heights in total). The study makeup was 11 subjects, at 6 working heights, for 7 tasks.

3.3 Experimental design

3.3.1 Completion times, body part discomfort (BPD) and estimated endurance times

This section of the experiment aimed to analyse the effect of workbench design and working heights on psychomotor skills, BPD and estimated endurance time. The tests were carried out at six levels on a specially designed test-rig. Delleman (1999), in his study of sewing machine operators, used height increments of 50mm (3 only), and these were deemed suitable for the purpose of this testing. The available bench height of the rig was determined as a measure, which at it's lowest would be the subjects knee height and at its highest the 200 mm above knee height. The rig also represented the normal engineering bench, which was 800 mm high, and inaccessible (did not have knee/leg clearance. A preliminary survey of 10 wheelchair users revealed that to them knee clearance at any work-station, was a critical factor. Elbow heights would be part of the data collection so that it could be determined whether there was a correlation between elbow and knee heights for ergonomic best fit.

The bench heights and processes were randomised so as to eliminate any learning sequence effect. Table 3-1 shows the bench test-rig heights and coding.

Table 3-1 Working height treatments and order code

Code	Work height
1	Existing Workbench
2	KH
3	KH + 50mm
4	KH + 100mm
5	KH + 150mm
6	KH + 200mm

A subjective questionnaire was designed to assess different aspects of the workbench. The questionnaire used modified versions of Drurys and Coury (1982) and Shackel et al (1969) rating scales in the study of chair design. The anchors used were the same as those used by Drury and Coury (1982) and Shakel et al., (1969), for all but one of the rating scales. The rating scores were then used as the dependent variable.

3.3.2 Body part discomfort (BPD)

For BPD each operator was asked to rate their body part discomfort in eighteen regions shown on a diagram of the rear view of a human upper body (Figure 3-1), modified from Corlett and Bishop 1976 and Delleman 1999). Each subject completed the rating on the BPD map at the conclusion of the test-bank for each height. The scoring was '0' for no discomfort and '5' for extreme discomfort. They also used a visual analogue scale to express their 'subjective height evaluation'. The latter was done by placing a tick at a point along a 100 mm line. The '0' point was the extreme low, the highest point '10' was the extreme high position and the mid point '5' was the 'ideal height'.

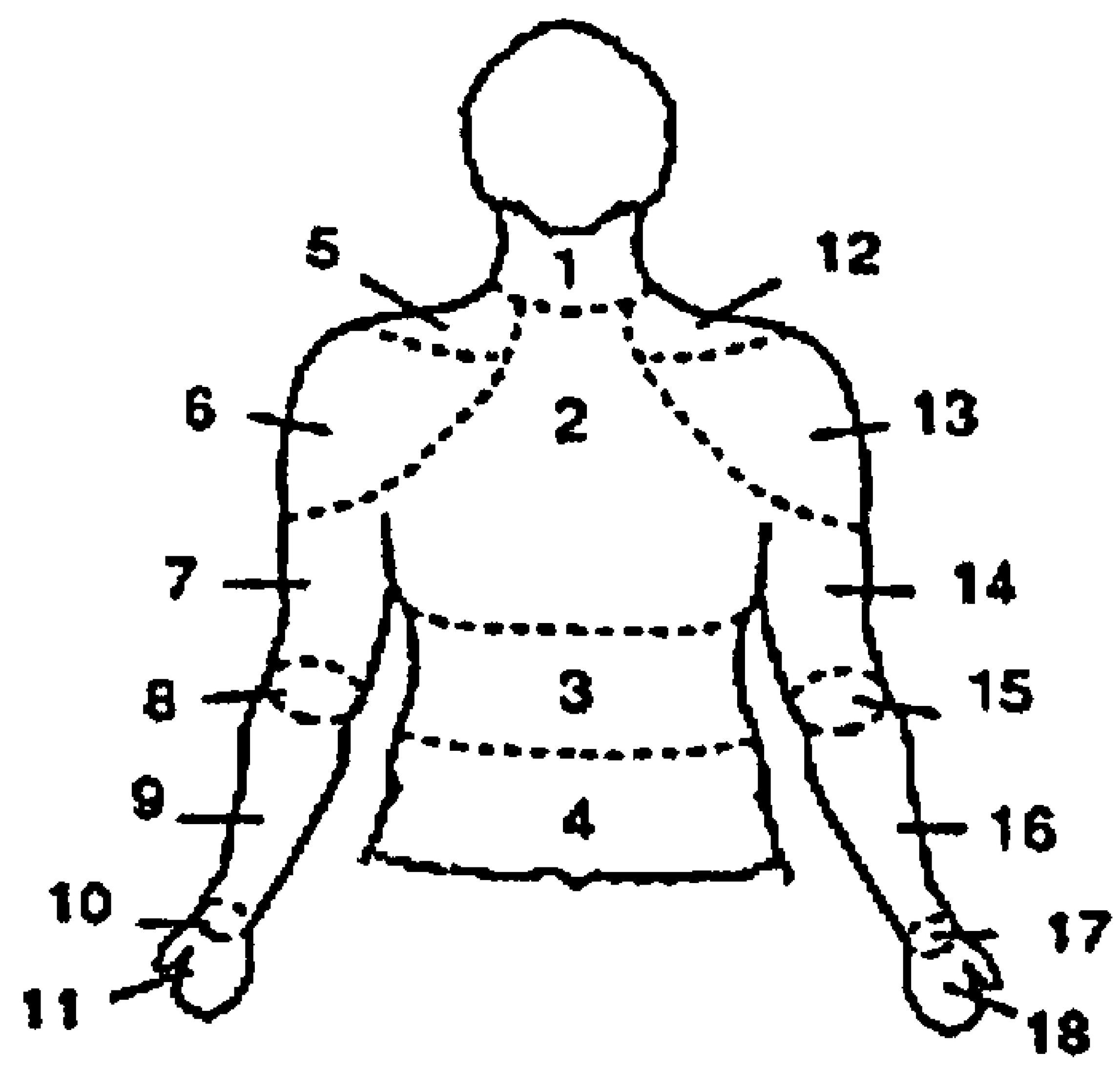


Figure 3-1 The body map (rear view) used for BPD

On beginning the next test height subjects were asked to express if they still had any discomfort on any of the body parts. They were usually fully recovered before proceeding to the next height. If any discomfort was present at the beginning of the test bank, this score was subtracted from the end score. The resulting score for each region was the dependent variable.

3.3.3 Estimated endurance time

Using the same method as Delleman (1999), the operator was asked to estimate on the basis of their perceptions, how long they could operate at each level of the bench height, doing this type of work, (1= less than 2 hours (h), 2 = 2-4, 3 = 4-6h, 4 = 6-8h, 5 = More than 8h). The estimated endurance time was used as the dependent variable.

3.3.4 Completion times

Table 3-2 indicates how the scoring system worked, for each of the psychomotor and industrial tasks. For each subject the score times were recorded and used as dependent variables. Subjects and the working height the independent variables.

Table 3-2 How the scores for each task were calculated

Test	Test Name	Value
1	Three Pin Plug Assembly	Total time to assemble three electric plugtops.
2	One Hole Test	The largest throughput in three trials (Trials one minute).
3	Small Tapping Task	Number of pairs of taps within the targets after 30 seconds.
4	Purdue Pegboard	Total no. of pins for left + right + both (pairs) (30 seconds) and total for assembly (60 seconds).
5	Grooved Pegboard	Total time to complete Pegboard (in seconds).
6	MRMT	Time to complete four trials
7	Large Tapping Task	Number of pairs of taps within the targets after 30 seconds.

3.3.5 Psychomotor skills and industrial tasks tested

A number of standard tests were available to examine aspects of the psychomotor abilities. The following tests were deemed suitable to assess the skills, which were identified as being required by manual operators. A total of five psychomotor skills and two industrial tasks were used as part of this study, (see illustrations of test bank elements in Appendix E).

To test manipulation dexterity the Grooved Pegboard was used. Pegs, which have a key along one side, must be rotated to match the hole before they can be inserted into a test board which consists of 25 holes with slots randomly positioned. The subject is required to fill the board as quickly as possible with their dominant hand first and then with their non-dominant hand.

The work of Fitts (1954) is replicated by the Small Tapping Task, which measures the speed of simple ballistic movement. The test itself consists of a sheet with two rectangles, 150mm high and 10mm wide, at a centre distance of 160mm. To assess the speed of simple ballistic movements, subjects are required to place as many dots as possible within the rectangle within a thirty second period. The Large Tapping Task is similar to the small tapping task but the centre distance of the two rectangles is increased to 1000mm and the width of the rectangle is now 30mm. The test is designed to measure gross motor movement.

To test manual dexterity the Minnesota Rate of Manipulation Test (MRMT) is used. The test is broken into two sections, turning and placing and both measure manual dexterity. It measures finger rate of manipulation. The subject was required to fill the board working from left to right for the first row and right to left on the second row and so on. For the first row, the subject was also required to fill the holes by lifting the block with the left hand, turning it over and placing it back in the right hand. This was alternated for the second row. The board was filled four times and the times were noted and recorded and aggregated for analysis.

The Purdue pegboard has been widely used to aid in the selection of employees for jobs that require fine and gross motor dexterity and co-ordination. It measures gross movements of hands, fingers and arms, and fingertip dexterity, as necessary in assembly tasks. For the test, the subjects are required to carry out four separate tasks. Firstly, test subjects are required to place as many pins as possible in the board with their dominant hand in a thirty second period. This is repeated for subject's non-dominant hand. The test is then repeated in the same manner except both hands are used simultaneously to fill both columns. The score is the number of pairs of pins, which are inserted into the board. The final part of the test requires the subjects to make an assembly that consists of a pin, a washer, a collar and a washer. The subject is required to complete as many of these assemblies as possible going from top to bottom in one minute.

It was essential to include some tasks that would be representative of industrial tasks. Two such industrial tasks that were evaluated in previous testing were, the one hole test (Tangney, 1998) and the three pin plug assembly task (Tangney, 1998; O' Sullivan and Gallwey, 2001).

The main feature of the one hole test is that it accurately reflects four basic elements (reach, grasp, move and position) of a pick and place operation (Salvendy, 1973). A modified version of the one hole test, similar to that carried out by Tangney (1998) was used as one of the industrial tasks. Tangney found that after three trials the learning effect reached its maximum. Hence it was decided that three blocks of one-minute trials would be sufficient and the largest score obtained was selected as the test value.

Tangney also discussed, the inconsistent nature of the return mechanism of the pin and believes that a modification of the system should be made. Analysis of this problem found that loading a number of pins into the machine before commencing the test, eliminated the problem. The test itself consists of grasping one pre-positioned pin (3mm in diameter and 25.4mm long), moving it 178mm in a 45° direction away from the body, positioning it into a hole with close tolerances and reaching to grasp the next pre-positioned pin.

The three-pin plug assembly task is a simplified and modified version of a simulated industrial task studied by O'Sullivan and Gallwey (2001) and Tangney (1998). To ensure realism in the workplace, the task mimicked that carried out by O'Sullivan and Gallwey (2001). The subjects completed a total of three three-pin plug assemblies, after completing a number of practice runs. Each of the eight components of the plugs was positioned in bins on convenient arc on the table surface, a jig was positioned in front of the subject for holding the components during assembly. Table 3-3 below shows the sequence of the required assemblies.

Table 3-3 Method of assembly of the three-pin plug-top

No	Task Element
1	Reach for base.
2	Place base on jig.
3	Reach for earth pin and insert into base.
4	Reach for live pin and insert into base.
5	Reach for neutral pin and insert into base.
6	Reach for fuse holder and insert into base.
7	Grasp fuse and insert into holder.
8	Reach for grip and insert into base.
9	Reach for cover and place on assembly.
10	Reach for closing screw and thread in with fingers.
11	Reach for screwdriver and tighten assembly.
12	Release assembly.

3.3.5.1 Test apparatus

In designing the test rig a number of important elements were identified, and included. These included, a minimum work surface dimensions of 900 x 600mm (1200mm x 700mm was used); a fully accessible work area; easily adjustable heights, and simple attachments to emulate an existing bench. Figures 3-2 show the trial test rig telescopic column. The column design was a motorised, rack and pinion. The height range was 600mm to 1100mm the cantilevered work surface was fixed to a cranked bracket to allow a lower working height if necessary. The column had a lift capacity of 2,000N.

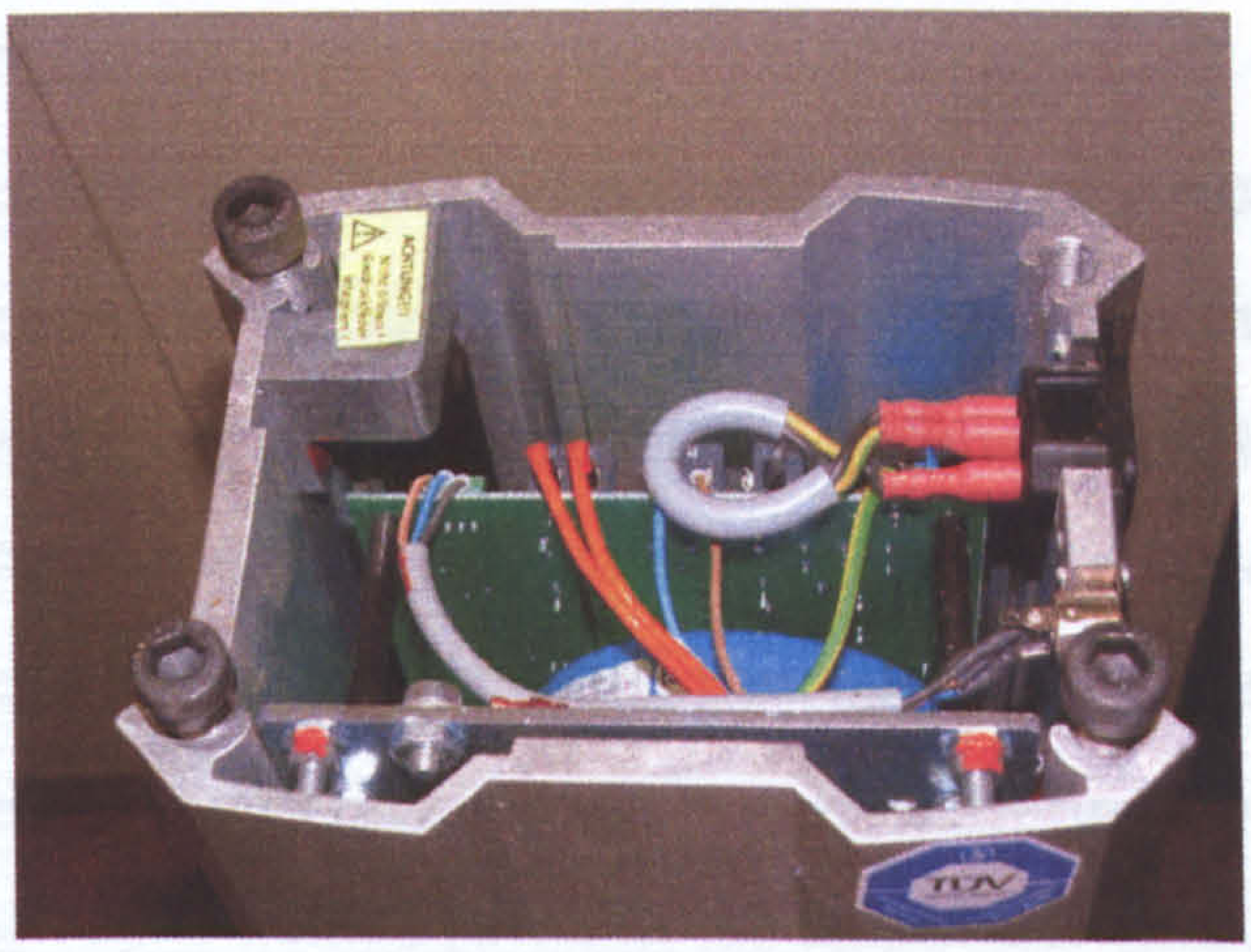


Figure 3-2 The telescopic lift column

The psychomotor test-bank as described earlier, including a Minnesota Rate of Manipulation Test board, a Grooved Peg board, a Purdue Pegboard, a One Hole test, a supply of prepared large and small tap (ballistic and gross motor skills) test sheets, and a binned supply of electric plug-tops, the assembly jig and a Phillips screwdriver. For recording: a BPD map scales, estimated endurance times and height rating scales, a stopwatch, and a time/number recording matrix. A Holtain anthropometer was used to collect anthropometric details. The test time was three to three-and-a-half hours.

3.3.5.2 Subjects

Eight male and four female WUs, all volunteers, were used as the first test group. The second group of eleven surrogates, included six males and five females, again all were volunteers. All subjects were reasonable fit. The qualifying level of physical ability for the WUs, was that they should be capable of manually propelling themselves in their wheelchair. The WUs all used their own wheelchairs. The SWUs all used the same wheelchair, which was adjustable to suit their body/leg size to a comfortable fit.

3.3.5.3 Procedure

A number of pilot tests were used to ensure that the test procedure worked and to estimate overall time and rest/recovery periods. At the beginning of each session, the subject was given a full oral explanation of the experimental procedure, read the experiment briefing and signed a detailed consent form. The initial questionnaire was filled out at the beginning to establish personal details, and whether they were sufficiently fit to undergo the test. They were informed that they could withdraw from the test at any time, and without explanation; (no subject did).

Four anthropometric characteristics were measured in the sitting position in the wheelchair, including stature, shoulder height, elbow height and knee height (KH). The KH was used to determine the heights for the five for the workbench rig. The sequence of the procedure was:

1. Determine if there was any BPD before the test began.
2. Set the work height and perform the seven elements of the test bank (randomised).
3. Subjects complete BPD scale, Height evaluation scale, and estimated endurance time.
4. Subjects repeat the above steps for other levels (again ramdomised).

3.3.6 Descriptive statistics for WUs and SWUs

The descriptive statistics show the details and comparisons for the WUs and the SWUs. The knee height range for WUs was 94mm and for SWUs 71mm, with a standard deviation of 29.65 and 25.71 respectively. The elbow height range for WUs was 157mm, and for SWUs 112mm, with standard deviations of

43.1 and 32.99 respectively. Because all surrogates used the same wheelchair there was likely to be less variation in the anthropometric data. The minimum age for both sub groups was 19 years with a maximum age for WU of 56 years and for SWUs 58 years. Table 3-4 shows the details.

Table 3-4 Descriptive statistics wheelchair users and surrogates

Age	WU	SWU	Males	Females	WU Males	WU Females	SWU Males	SWU Females
N	11	11	13	9	7	4	6	5
mean	33.64	29.91	35.54	26.33	36.43	28.75	34.5	24.4
Std.Dev.	15.17	14.1	15.47	11.42	14.33	17.52	18.04	4.51
min	19	19	19	19	20	19	19	20
Q1	20.5	20	22	20	24.5	19.75	20.5	20
median	27	24	32	21	34	20.5	27	24
Q3	48	30.5	50	29	48	29.5	50	29
max	56	58	58	55	56	55	58	29
Missing Vls.	0	0	0	0	0	0	0	0

3.4 Analysis of the data

3.4.1 The effects of working height on BPD

BPD was measured on eighteen body part regions (based on Corlett and Bishop 1976) for wheelchair users, after they had completed all seven tasks at each level of working height. Analysis of the test data revealed that KH+100 was identified as resulting in least discomfort among subjects, while KH+0 resulted in the greatest discomfort. It also shows that, as the working height deviates upward or downward from KH+100, that BPD increases. Figure 3.3 shows the mean discomfort for all 18, body parts for the WUs. This indicates that a height of 100mm above knee height (KH+100) produces the least amount of discomfort.

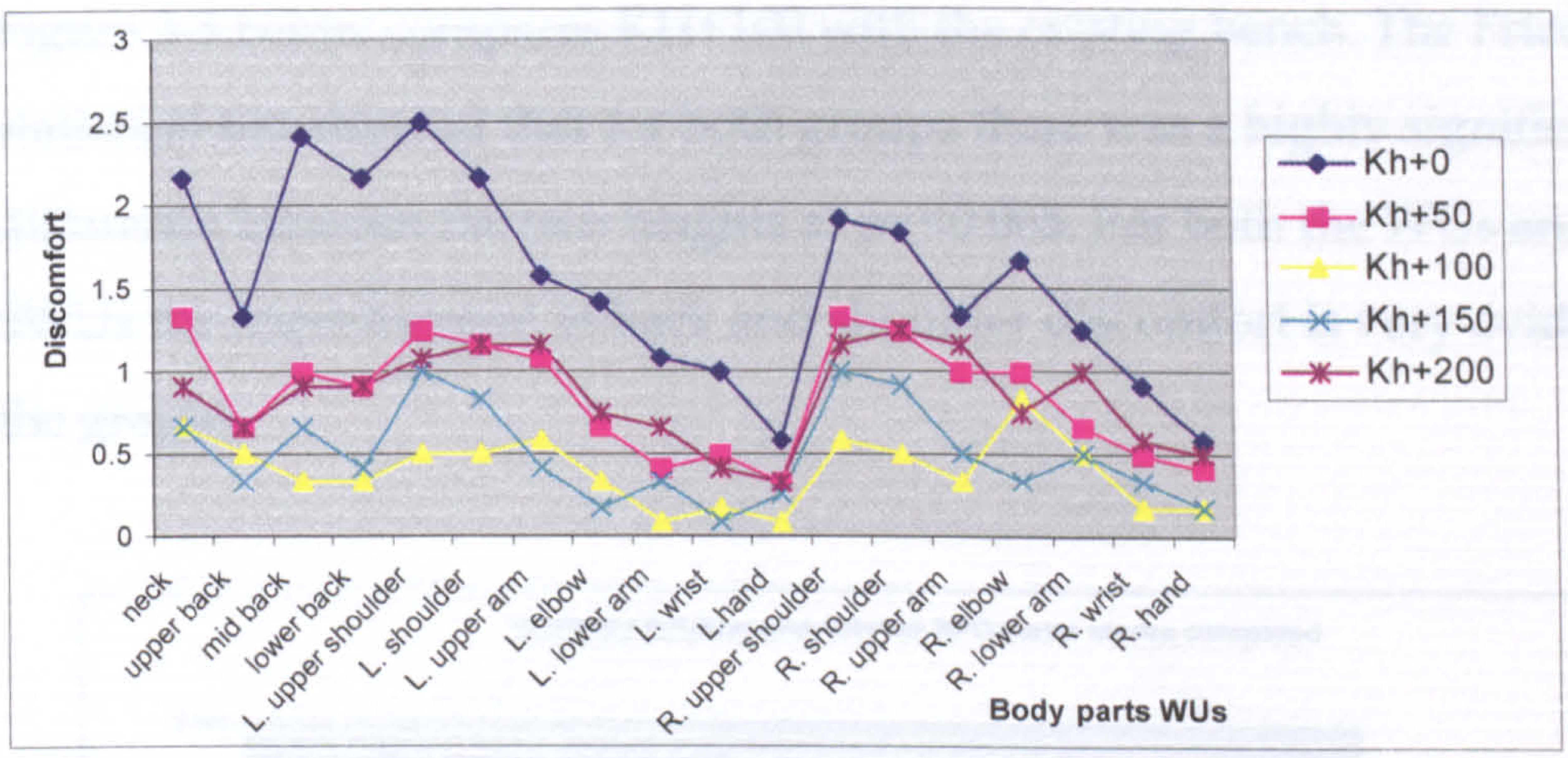


Figure 3-3 Body part scores for the five bench heights for WUs

Figure 3-4 below shows a similar graphic for the SWUs. Again the KH+100 height produces the best results for comfort. Knee height (KH+00) is the least comfortable, as is also the case for the WU sub-group.

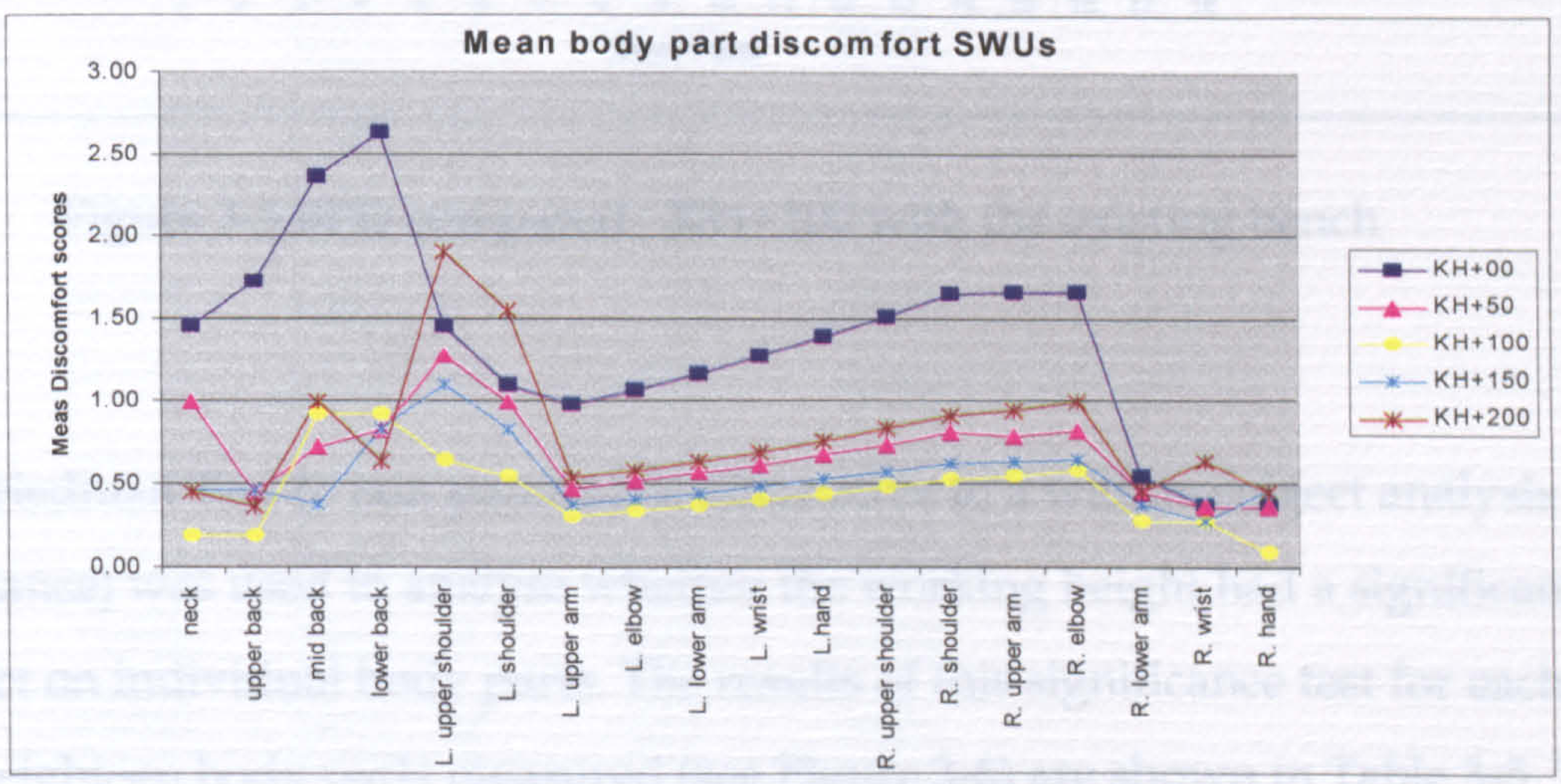


Figure 3-4 Body part scores for the five bench heights for SWUs

Comparing the two graphs above shows that there is a good correlation between BPD generally, for WUs and SWUs, and particularly for least and greatest BPD. Discomfort was measured on a zero to five scale on the Y-axis, where zero indicated 'no discomfort' and five indicated 'severe discomfort'.

Figure 3-5 below compares KH+100 with the existing bench. The Friedman statistical test showed that for both groups there was a highly significant difference between the two heights at p=<0.005. For both the WUs and the SWUs the improvement in back and shoulder discomfort is very evident from the graphs.

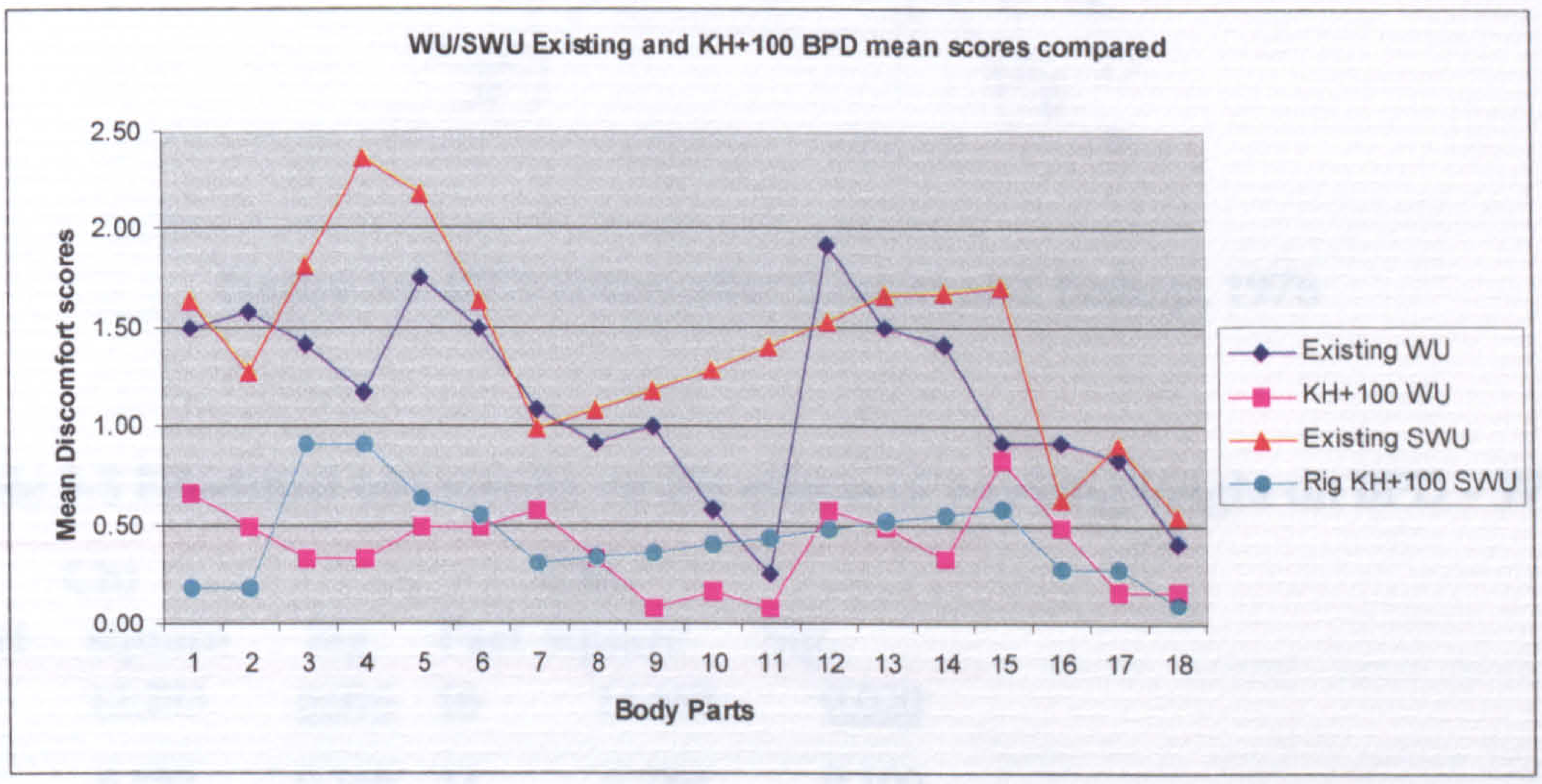


Figure 3-5 BPD compared - KH+100 with the existing bench

A Friedman Test (a non parametric alternative to a within-subject analysis of variance) was used to analyse whether the working height had a significant effect on individual body parts. The results of this significance test for each of the eighteen body parts measured (see Figure 3-6) are shown in Table 3-5. The statistically significant parts (<0.05) are underlined. Tables 3-5 and 3-6 below show the full analysis for each body part.

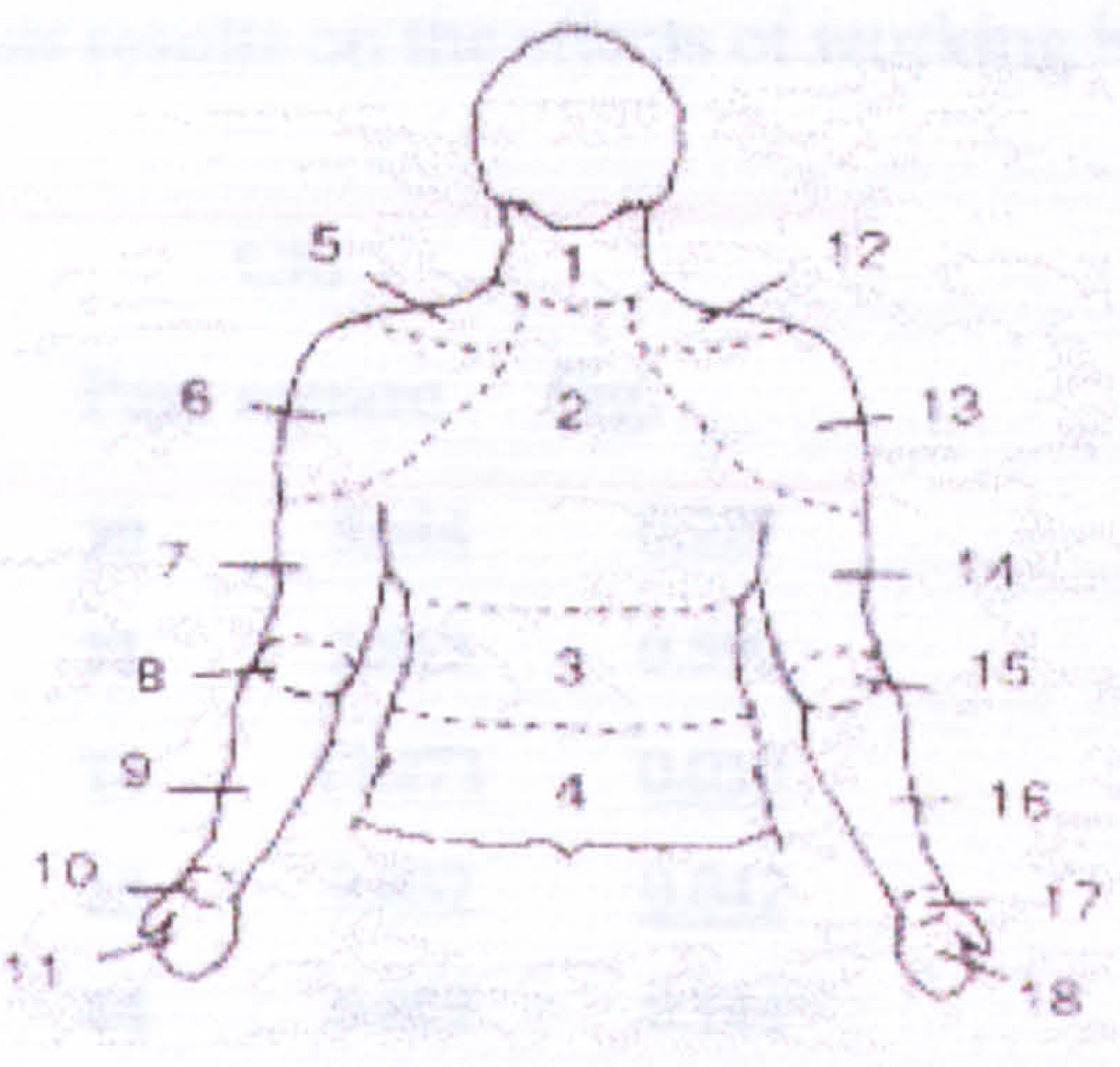


Figure 3-6 BPD zones after Corlett and Bishop, 1976

Table 3-5 Friedman test results on the effects of working height on BPD - WUs.

Part	Chi square	Sig.	Part	Chi square	Sig.
1	12.233	0.016	**10**	11.688	0.020
2	6.452	0.168	**11**	7.789	0.100
3	17.972	0.001	**12**	10.094	0.069
4	20.058	0.000	**13**	10.359	0.035
5	19.789	0.001	**14**	9.521	0.049
6	12.134	0.016	**15**	8.500	0.075
7	7.51	0.186	**16**	4.388	0.356
8	12.989	0.011	**17**	7.273	0.122
9	12.092	0.017	**18**	4.89	0.618

The results in Table 3.5 indicate that the working height had a significant effect on ten of the body parts tested, confirming the importance of best-fit working heights in order to reduce discomfort, and as a result reduce the likelihood of MSD in the long term. Body parts 3, 4 and 5, the waist, lower back were highly significant statistically for WUs.

Table 3-6 Friedman test results on the effects of working height on BPD - SWUs

Part	Chi square	Sig.	Part	Chi square	Sig.
1	12.672	0.013	10	5.644	0.227
2	17.824	0.001	11	2.813	0.590
3	21.161	0.000	12	13.271	0.010
4	20.275	0.000	13	9.932	0.042
5	14.521	0.006	14	6.852	0.144
6	9.096	0.590	15	1.114	0.892
7	9.442	0.510	16	1.429	0.839
8	5.134	0.274	17	4.247	0.374
9	1.778	0.777	18	6.540	0.162

For the SWUs, parts 2, 3, 4 and 5, upper back, waist, lower back and left shoulder had greatest statistical significance. Parts 3, 4, and 5 were highly significant (P=<0.001/6) to both groups.

The BPD line graphs for the WU (Figure 3-3), and SWU (Figure 3-4) groups and for both (Figure 3-5), are similar, and when subjected to comparative statistical analysis show no significant difference.

The results of the analysis show that there was a significant effect on ten of the body parts tested, most notably all back regions and the shoulders, for the WU group and there were seven body parts showing significant discomfort for the SWU group.

Five of the effected body parts are common to both groups. The neck did present a problem for the surrogates, but did not for the WU group. Body part 13 and 14 registered significant discomfort for the WU group but did not for the SWU group. The general discomfort for the total cohort is registered in the shoulders and back. Therefore the preferred height of KH+100 contributes to neutralising body posture for seated workers whether WUs or SWUs. A Wilcoxon Signed Ranks (WSR) test also showed that there was a BPD concentration in the back for both groups. Body parts 3, 5, 6, 12, 13 and 14 has significant discomfort for the WUs and for the SWUs parts 1, 2, 4, 5, 6 and 12. BP 5, 6, and 12 were common to both groups. Confirming the results of the Friedman test. The analysis of the total group is seen in Table 3.7 below.

Table 3-7 Analysis of total cohort (WUs + SWUs)

	Friedman Test All Body Parts			Wilcoxon Sign-Rank Test of Existing versus KH+100	
variable	Chi Square	Degrees of Freedom	p-value	Test statistics	p-value
bpd1	18.67	5	0.002	2.5	0.002
bpd2	23.16	5	0	2.5	0.002
bpd3	24.28	5	0	0	0.031
bpd4	27.58	5	0	5	0.003
bpd5	18.89	5	0.002	3	0.001
bpd6	21.38	5	0.001	0	0
bpd7	7.51	5	0.186	11	0.049
bpd8	15.05	5	0.01	0	0.008
bpd9	15.24	5	0.009	2	0.016
bpd10	12.08	5	0.034	0	0.016
bpd11	5.56	5	0.352	0	0.125
bpd12	21.3	5	0.001	3	0.001
bpd13	15.88	5	0.007	0	0.004
bpd14	13.69	5	0.018	6	0.008
bpd15	12.75	5	0.026	8	0.117
bpd16	7.65	5	0.177	3.5	0.055
bpd17	12.98	5	0.024	0	0.031
bpd18	4.4	5	0.493	0	0.062
Agg BPD	32.92	5	0	1.5	0

Applying the WSR to male/female BPD it was found that males registered significant BPD on eleven parts, and females on five parts. Five of the male body parts were significant at just under p=0.05. There was a gender correlation for the neck, the upper and lower back, and the right shoulder. It can therefore be said that male and female workers PBD is effected by variations in bench height.

Delleman and Dul (2002), and Lowe et al., (2001) used the sum of the body part scores to arrive at an aggregate BPD score. WSR test produced highly significant for the aggregate BPD relating to bench height, with a significance level of p=0.006 for the WUs and p=0.001 for the SWUs. As some body parts record a zero score, it is particularly useful to arrive at a general discomfort score as an indicator of a best-fit height.

On the issue of *gender* there was found to be no significance difference between male and female aggregate BPD. Both sub-groups had a significance level of p=<0.01. The null hypothesis for gender difference in BPD for bench working heights is upheld.

The results of the analysis showed that WUs and SWUs both had significant BPD as a result of bench working height, and there was no significant difference between the two sub-groups. It is therefore concluded that SWUs may be used in place of WUs in determining BPD in relation to bench working heights. So the surrogate versus wheelchair user null hypothesis is rejected.

3.4.2 The effects of working height on estimated endurance times

Figures 3-7 and 3-8 below, graphs the mean estimated endurance times for both groups, while operating at various working heights. On the Y axis below; 1 indicates 'less than two hours', 2 is 'two to four hours', 3 indicates 'four to six hours' and 4 indicates 'six to eight hours.

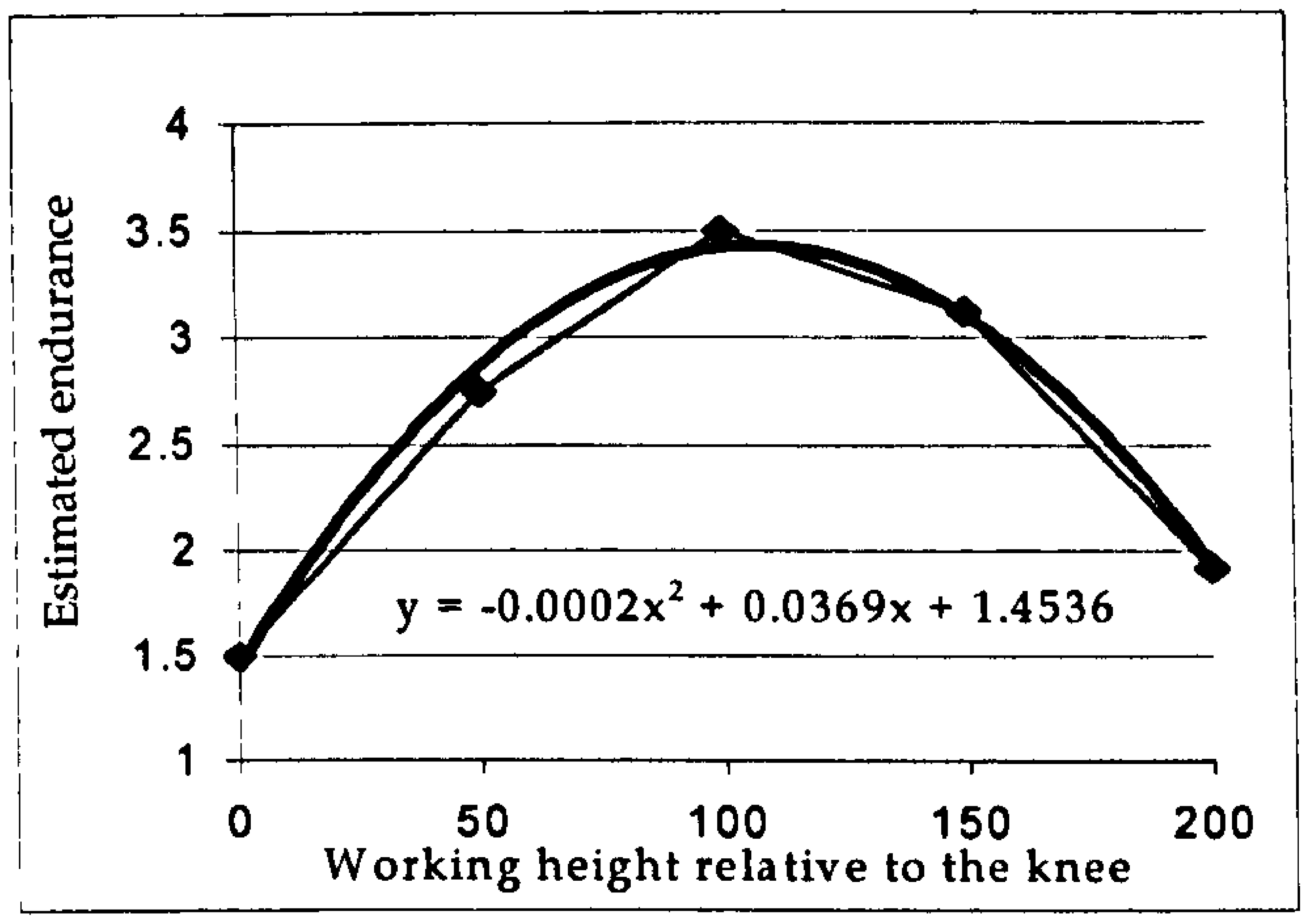


Figure 3-7 Endurance graph wheelchair users

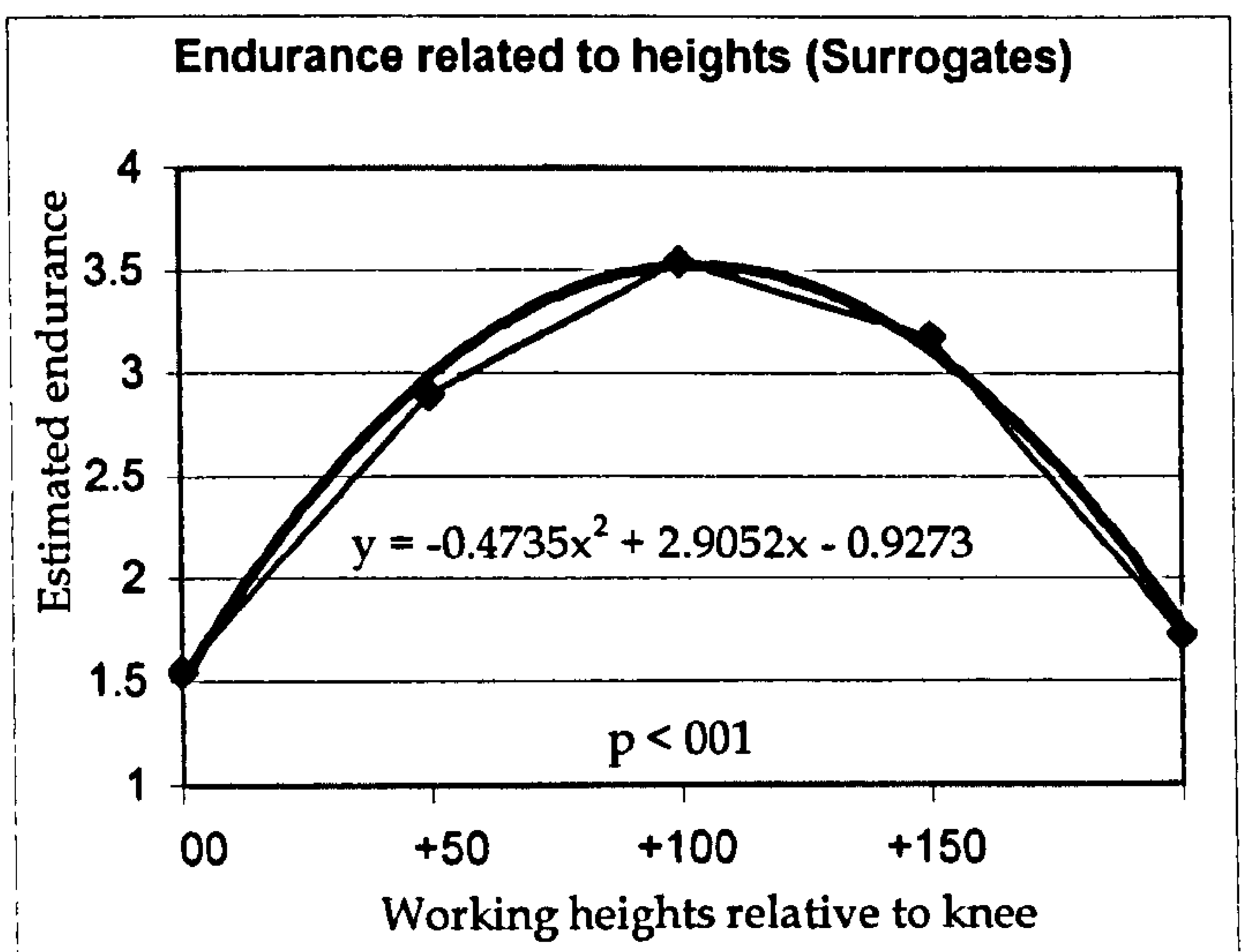


Figure 3-8 Endurance graph surrogate wheelchair users

The graphs, may be used to predict estimated endurance times relative to working height above the KH of the wheelchair user, as well as for surrogates. As there was found to be no statistical significance between the endurance for both groups ($p > 0.05$), then it is appropriate to use surrogates to determine endurance. However differences in BPD may need to be considered as this might have a significant affect during prolonged activities. The data collected was based on the test-subjects estimated time that they felt they could spend doing the type of activity associated with the test bank. A comparative analysis of the curves and their values show that there is no significant factor-of-difference between WUs and SWUs associated with endurance. The endurance analysis for the whole cohort is seen in Table 3-8, and the box-plot Figure 3-9 shows that for the total cohort, the highest estimation is for KH+100, with KH+150 a close next best, with the exception of one out lying score.

Table 3-8 Friedman and Wilcoxon tests on endurance

Friedman test for Endurance				**Wilcoxon SR, KH+100 v Extn.**	
variable	Chi Square	Degrees of Freedom	p-value	Test statistics	p value
endurance	88.83	5	<0.001	210	<0.001

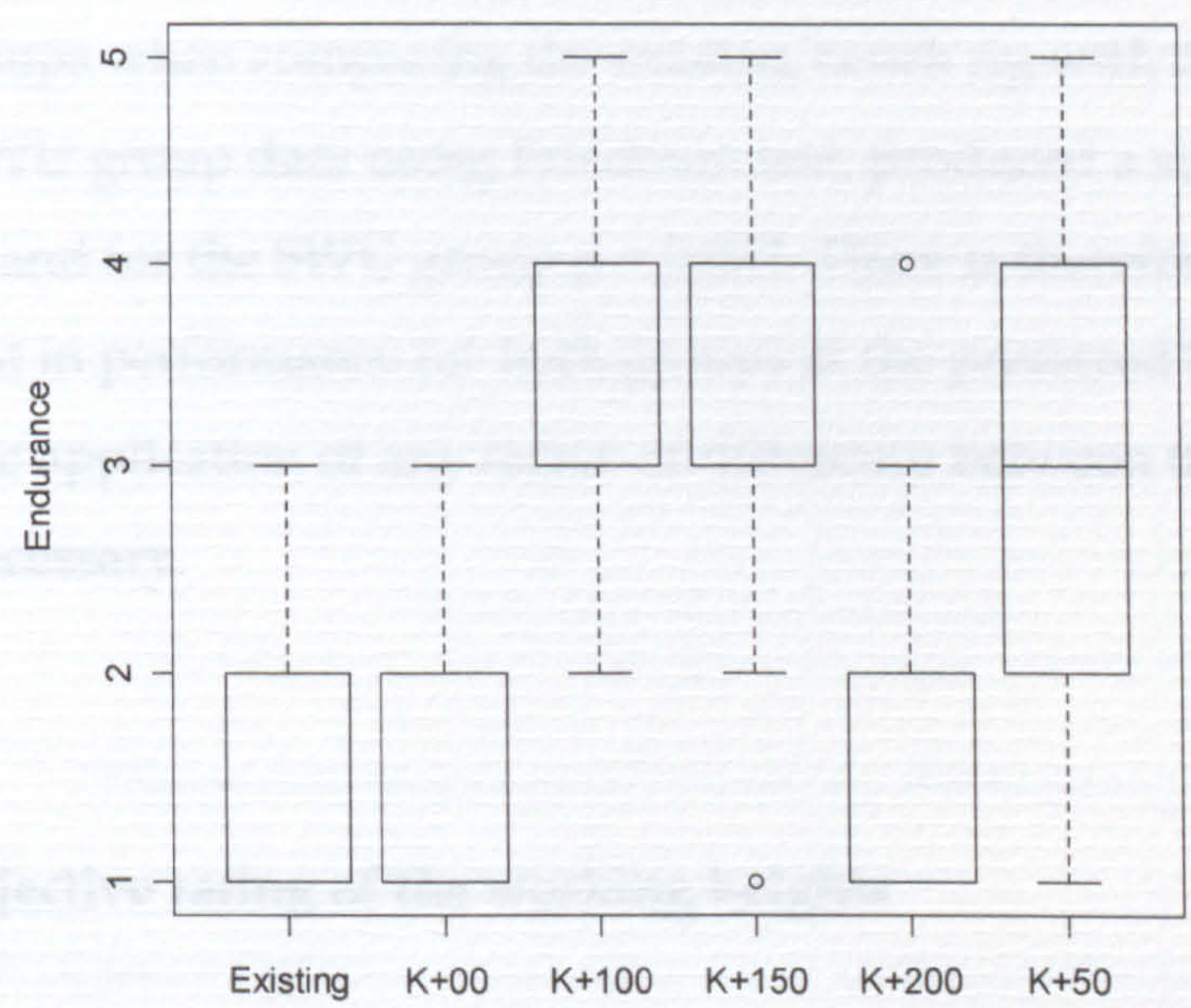


Figure 3-9 Box-plot on endurance

The results of the mean estimated endurance time indicate that subjects will work on average two hours (1.75) on the existing workbench, while they will work six hours (3.5) on the KH+100 (accessible) height (100mm above knee level). A Wilcoxon non-parametric test was used to identify whether the populations had the same means. The results (p=0.001), indicate that there was a positive increase in endurance, resulting from working at KH+100.

Bench height has a significant effect on endurance, therefore the null hypothesis for endurance must be rejected.

3.4.3 The effects of working height on completion time

The data revealed that working height does not have a significant effect on completion time for tasks with the exception of the one-hole test. There is however a significant improvement on completion times for both the WU and the SWU groups when comparing the existing bench rig with the KH+100 rig. Analysis of WU group data using Friedman test, produced a significance value of p = 0.010, and for the SWU group p = 0.002. There is therefore a significant improvement in performance for both groups at the preferred bench height, and again the application of any factor-of-difference between the groups was seen as unnecessary.

3.4.3.1 Subjective rating of the working heights

Subjects rated the working height upon completion of the test-bank, at each level. Figure 3.9 below shows the mean results of these ratings, for the WU group, using error bars with a confidence limit of 95%. Zero on the Y-axis indicates a working height of 'too low' 5 is 'adequate' and 10 is 'too high'.

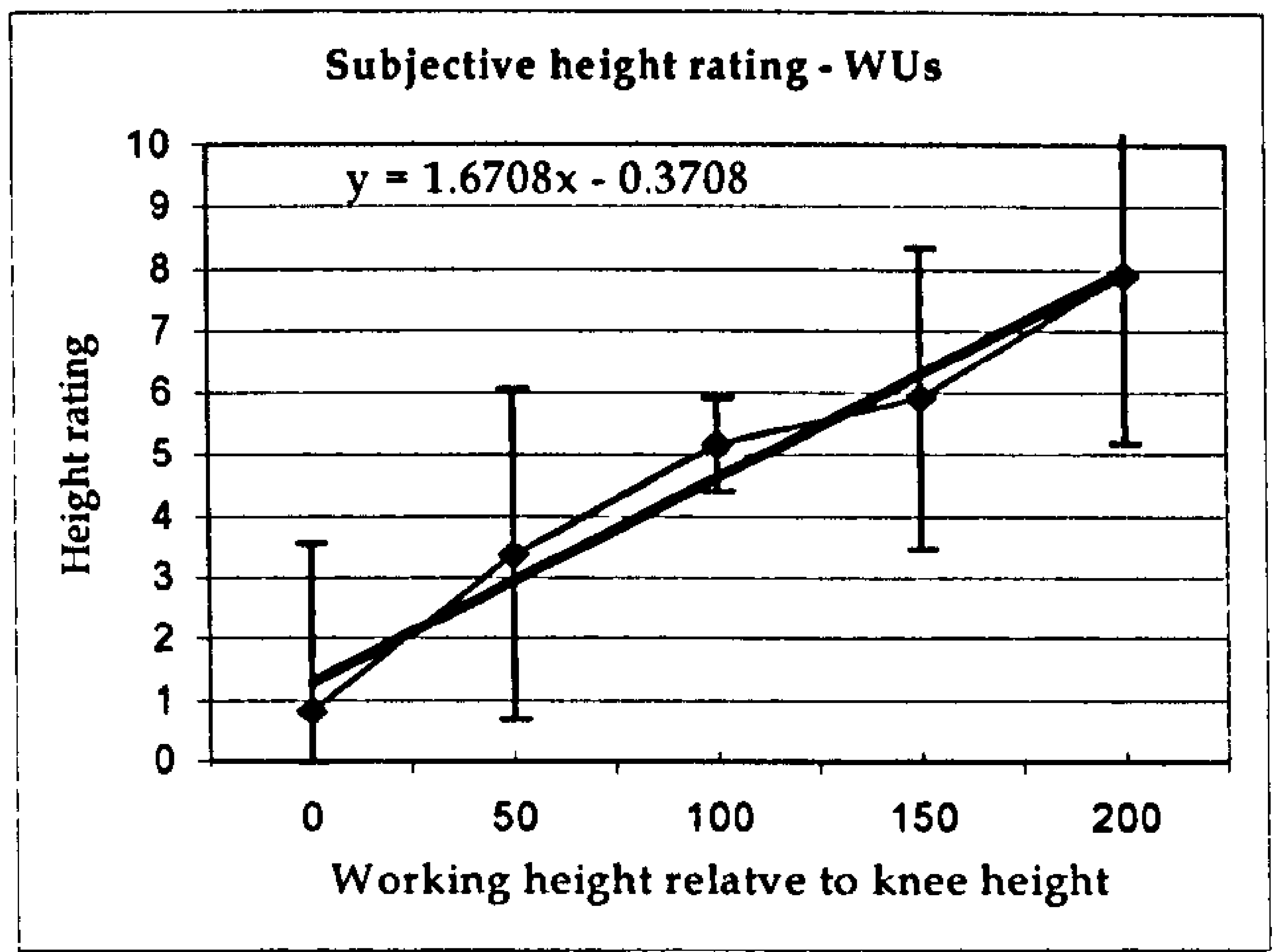


Figure 3-10 Work heights rating - WU group.

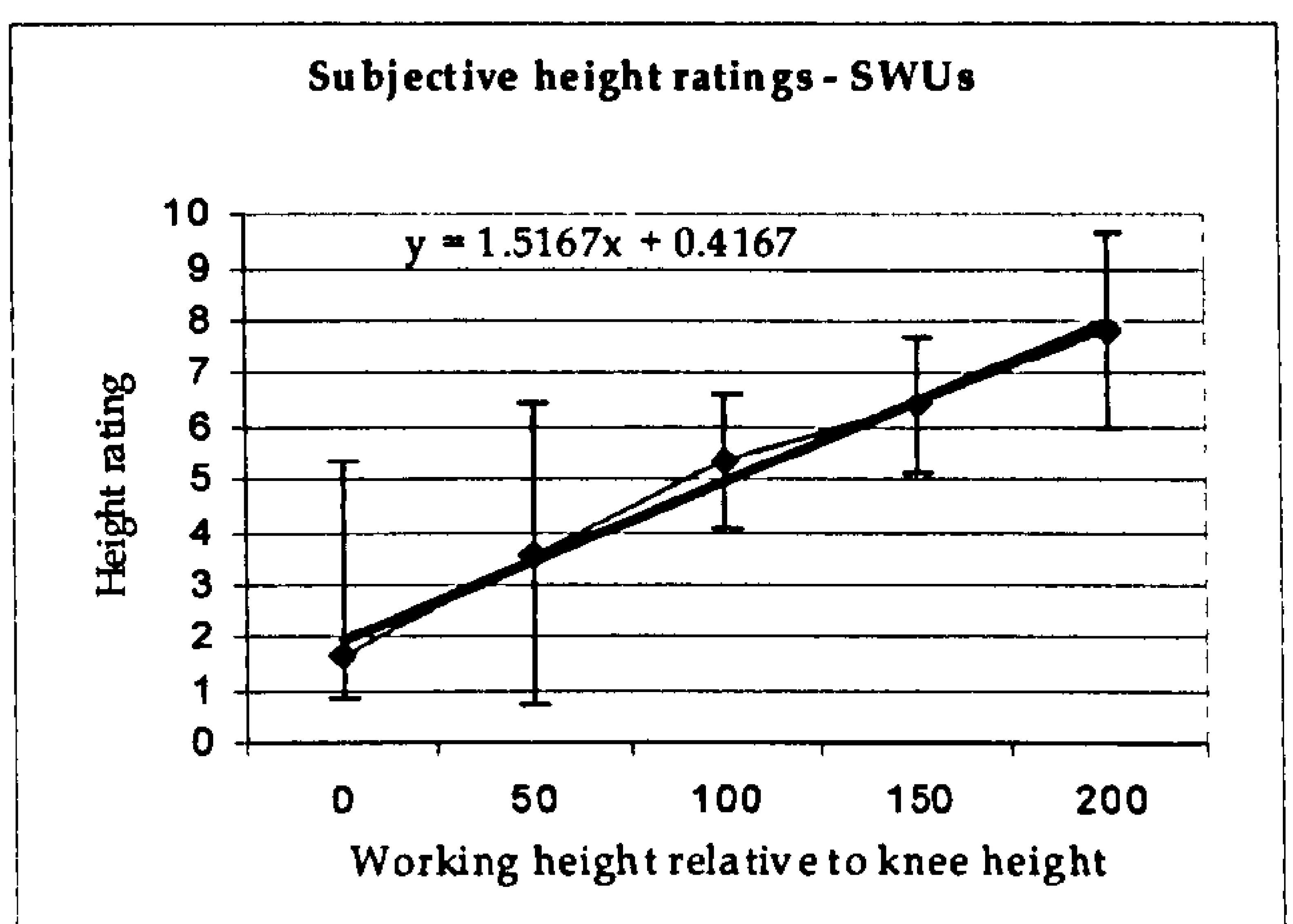


Figure 3-11 Work heights rating - SWU group.

The residuals of the ANOVA model failed the Anderson-Darling normality test with a p-value of zero therefore nonparametric tests were used.

These results indicated that the working height had a significant effect on the subjects rating ($p<0.001$) for both groups, as seen in Figures 3-9 and 3-10. The results suggest that there is a near perfect correlation between working height, and rating as $r = 0.97$ and 0.99, show that a positive linear relationship exists between ratings for both groups. The preferred height graph is very similar for both groups, producing a highly significant p value for the SWU group of, p=<0.001, and for the WU group a value of p=<0.001. As was seen, for both groups, the identified, preferred working height of KH+100 significantly contributed to the reduction of BPD.

Overall, there is no necessity to apply a factor-of difference for working heights, between the two groups, as the subjective rating was almost identical for both.

3.4.3.2 Existing versus preferred height

The results of the mean estimated endurance time indicate that subjects will work on average two hours (1.75) on the existing workbench, while they will work six hours (3-5) on the preferred accessible height (100mm above knee level). A Wilcoxon non-parametric test was used to identify whether the populations had the same means. The results (p=0.002), indicates that there was a positive increase in endurance, resulting from working at KH+100. The test subjects were also more comfortable at KH+100, with significantly reduces BPD (see Figure 3-5).

Figure 3-12 shows the test rig set up to emulate the existing bench, while Figure 3-13 shows the very non-neutral body position, of a subject working on the assembly task at this setting. For all other heights, with the exception of KH+00, subjects were able to sit under the cantilevered bench top.

Figure 3-12 The rig set up to emulate the Existing bench

Figure 3-13 Test subject in a very awkward body posture

A comparative analysis of the anthropometric data for elbow height, and knee height, showed that there was no correlation between them for wheelchair users. Therefore knee height and elbow height is not interchangeable.

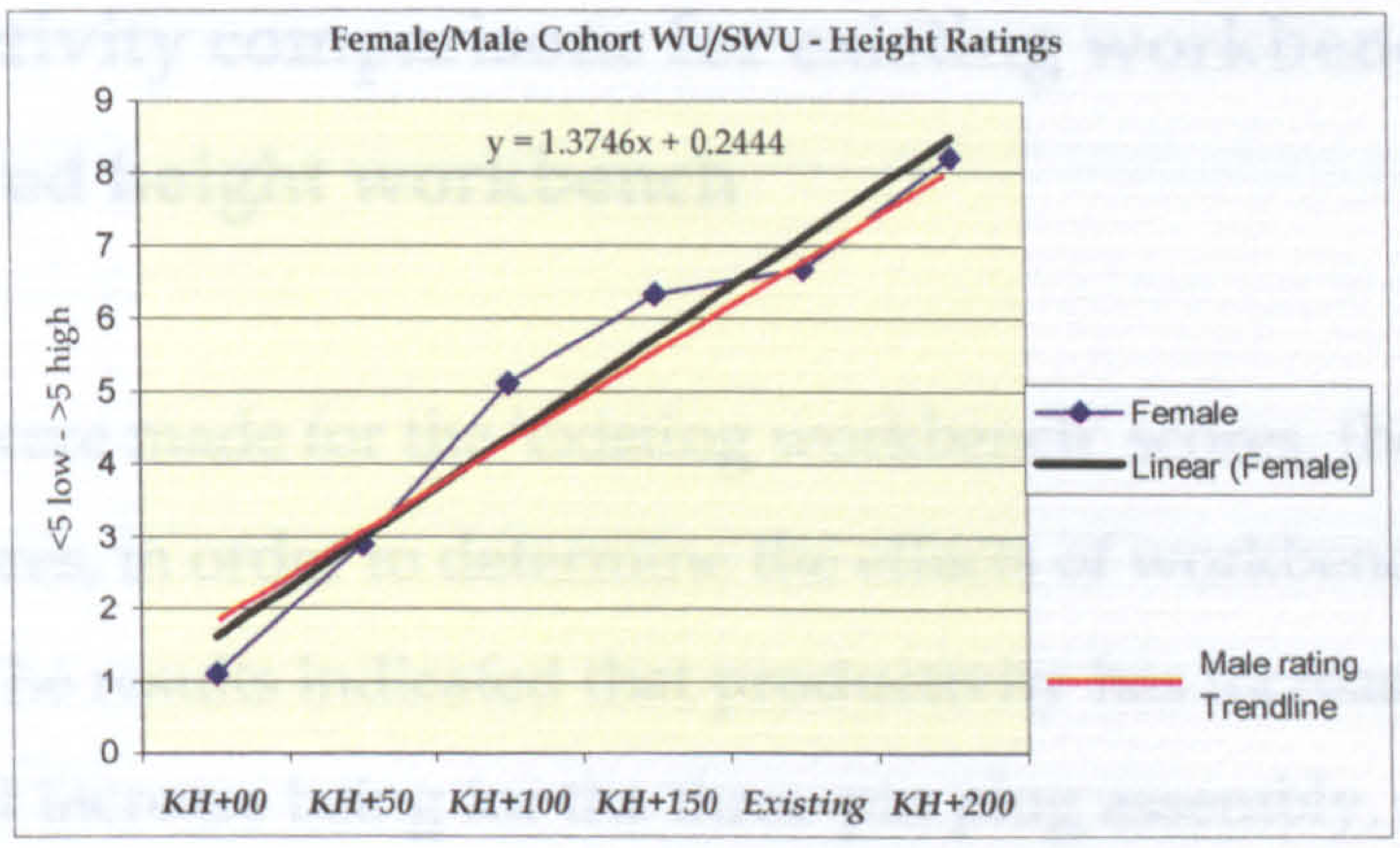


Figure 3-14 Female height rating with male trend-line

Figure 3-14 shows that there is no significant difference, between male and female height ratings. The lower limits on the graphs are similar but the females are less tolerant of the upper heights. The preferred height of KN+100 is almost right on the ideal line ('5') for both. Figure 3-15 shows the height ratings for the males.

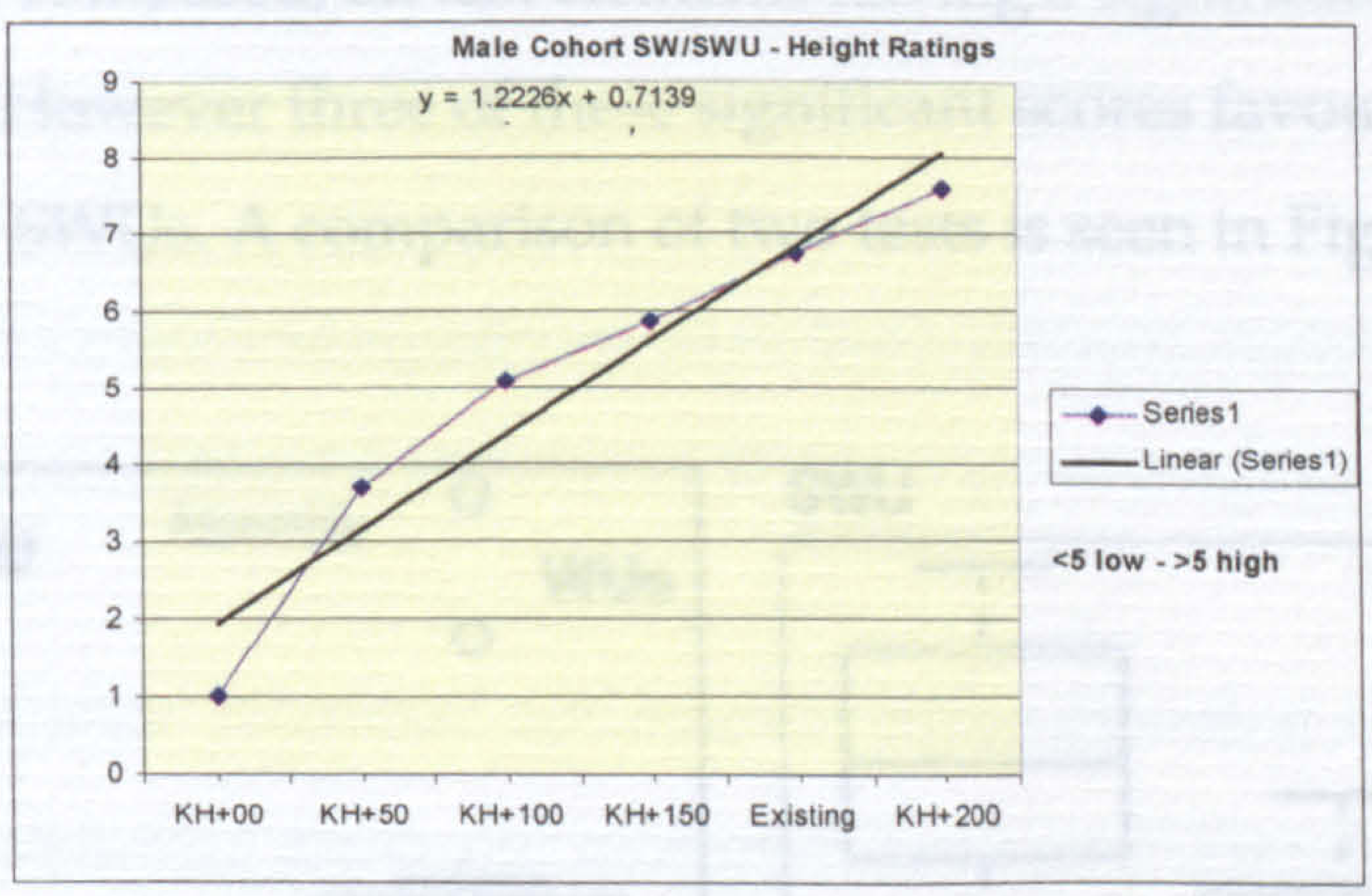


Figure 3-15 Male height rating

3.4.4 Productivity comparisons for existing workbench and preferred height workbench

Comparisons were made for the 'existing workbench' scores, the 'best-fit' workbench scores, in order to determine the effects of workbench design on productivity. The results indicated that productivity has increased in all tasks with the largest increase being for the three-pin plug assembly, and the MRMT test. The results of all tests show that there was a significant difference for all completion times, with the exception of the grooved pegboard, as a result of working on different bench heights for WUs. A similar increase in productivity was established for the SWU group at the KH+100 bench height. This improved productivity for the three pin electric plug-top and was highly significant for both groups.

Bench height appeared to have a significant impact on productivity when WUs and SWUs were compared, all test elements having a significance value of p=0.005 or less. However three of these significant scores favoured the WUs, and four for the SWUs. A comparison of two tests is seen in Figure 3-16.

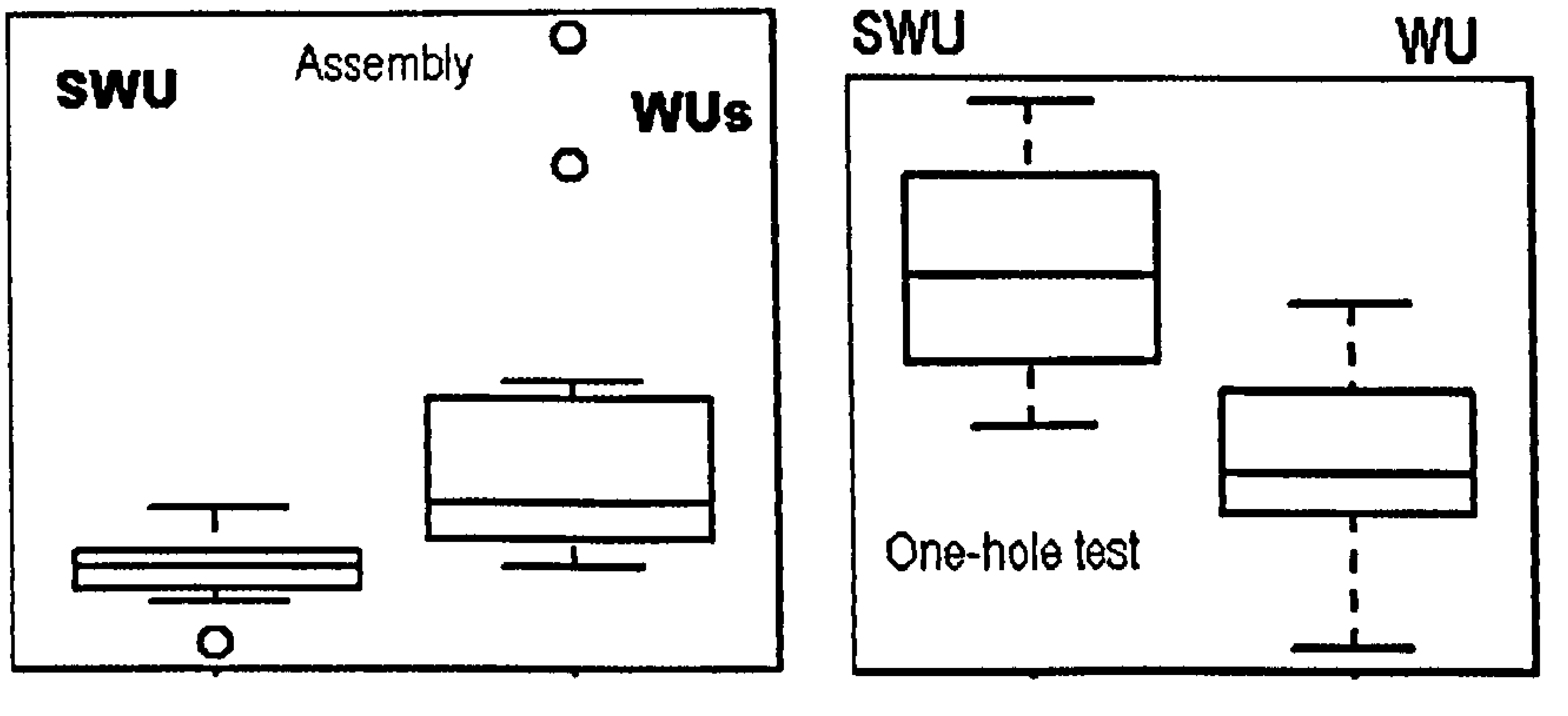


Figure 3-16 Efficiency box-plots for WUs and SWUs.

We can therefore conclude that while the best performance is at KH+100 this is not significant. Neither is there any significance when we compare the males with the females within the group. Applying, the Wilcoxon Signed Rank test, as seen in Table 3.9, shows that all test elements fall well short of the significance level, p=0.05.

The null hypothesis that bench height does not affect efficiency, is upheld.

3.5 Discussion

The research set out to establish a best-fit working heights for wheelchair users at psychomotor/industrial tasks and to determine if surrogate wheelchair users may also be used in establishing the data. The following conclusions were seen as significant:

- The most appropriate height for wheelchair users (including surrogate wheelchair users) was found to be at Knee Height plus 100 millimetres, i.e. KH+100;
- working at this height significantly reduced body part discomfort, and improved productivity (though not significantly);
- endurance curves and equations have been devised which will allow the calculation of estimated endurance for a range of heights;
- moving from the identified optimum in either direction will result in reduced endurance times and increased body part discomfort;
- the comparisons between working at the existing/traditional engineering bench, and the best-fit KH+100 bench produces highly significant statistical evidence of reduced body part discomfort, and improved productivity and work endurance times;

- there was a distinct correlation between the WU group and the SWU group in nearly all facets of the test results, with the exception of some elements of BPD. There was however, a good match, in the BPD analysis of back and shoulders for both groups and also for the aggregate BPD;

- there was no significant differences between male and female sub-groups, in efficiency, endurance or in height rating

- there appears to be no reason why surrogate wheelchair users may not be used as test subjects in research relating to bench design to accommodate wheelchair users at industrial tasks. The research also suggests that it is appropriate to mix test groups;

- the research has extended ergonomic test methodology and data for wheelchair users at workbenches, as well as their career options.

Chapter 4 will discuss the test results for able-bodied bench users.

4 THE ABLE-BODIED TEST COHORT BEST-FIT WORKING HEIGHTS, PRODUCTIVITY AND ENDURANCE.

Chapter 4 discusses the methodology for the design of experiments relating to the three subgroups of the able-bodied test subjects. The demographics of the test subjects is discussed and the test bank and evaluation methods are selected based on previous ergonomic data collection design methods. The design of the test-rig results from a pilot pre-test analysis of a cross section of potential users. The timing, location and makeup of the subgroups is discussed. Approval for the testing was sought from The Ethics Committee of the University of Limerick and was granted.

It was decided that a total cohort of sixty subjects would be adequate for the purpose of testing. There were three sub-groups who would be included in the cohort and a gender balance would also be a necessary element of the groups. The sub groups were chosen from regular users of benches. Adult bench users formed one sub-group, and school going young people, who work at benches in technologies classrooms, were also included. The school going subjects were selected from first year and senior classes at second level.
The adult group consisted of 10 males and ten females, the senior student group consisted of 11 males and 9 females, and the junior group were distributed, 10 males and 10 females. All were volunteers.

All, the adult group had some experience of working at engineering and/or woodwork benches. The average bench experience was 12.5 years, with the least experience being 3 years and the greatest being over 45 years. For some of those included, this experience was part-time. The senior school students had an average of four years (part-time) experience and the junior students just over 3 months (part-time). These three sub-groups will be referred to as the 'Adult', 'Senior' and 'Junior' groups in future discussion. The data and analysis will also be addressed in that order. Table 4.1 below gives the summary statistics for the total cohort.

4.1 Summary Statistics

Table 4-1 Summary statistics for the able-bodied cohort

Total	*Age*	*Stature*	*Elbow Height*
N	60.00	60.00	60.00
mean	19.42	1691.33	1062.80
Std.Dev.	8.63	103.83	73.65
min	12.42	1442.00	890.00
Q1	13.83	1619.75	1005.00
median	16.21	1689.00	1059.00
Q3	21.29	1761.50	1105.00
max	59.67	1985.00	1265.00
missing values	0.00	0.00	0.00

The stature range for the total cohort was 543mm as can be calculated from Table 4-1. The box-plots, below, illustrate the statistical comparisons. Figure 4-1 show the box-plots for age, stature, and elbow height.

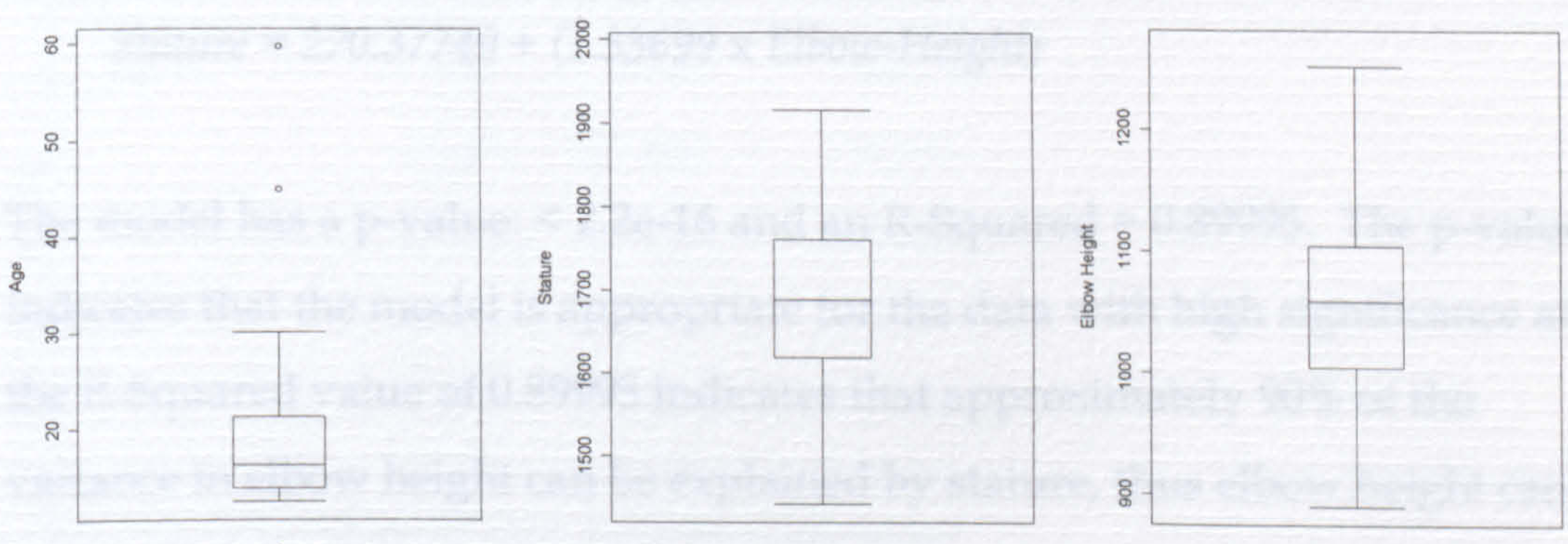


Figure 4-1 Boxplots for able-bodied cohort

The data analysis for the total cohort showed no relationship between age and stature, but showed a strong linear relationship for elbow height and stature, with the exception of a few outliers as seen in the scatter-plot in Figure 4-1.

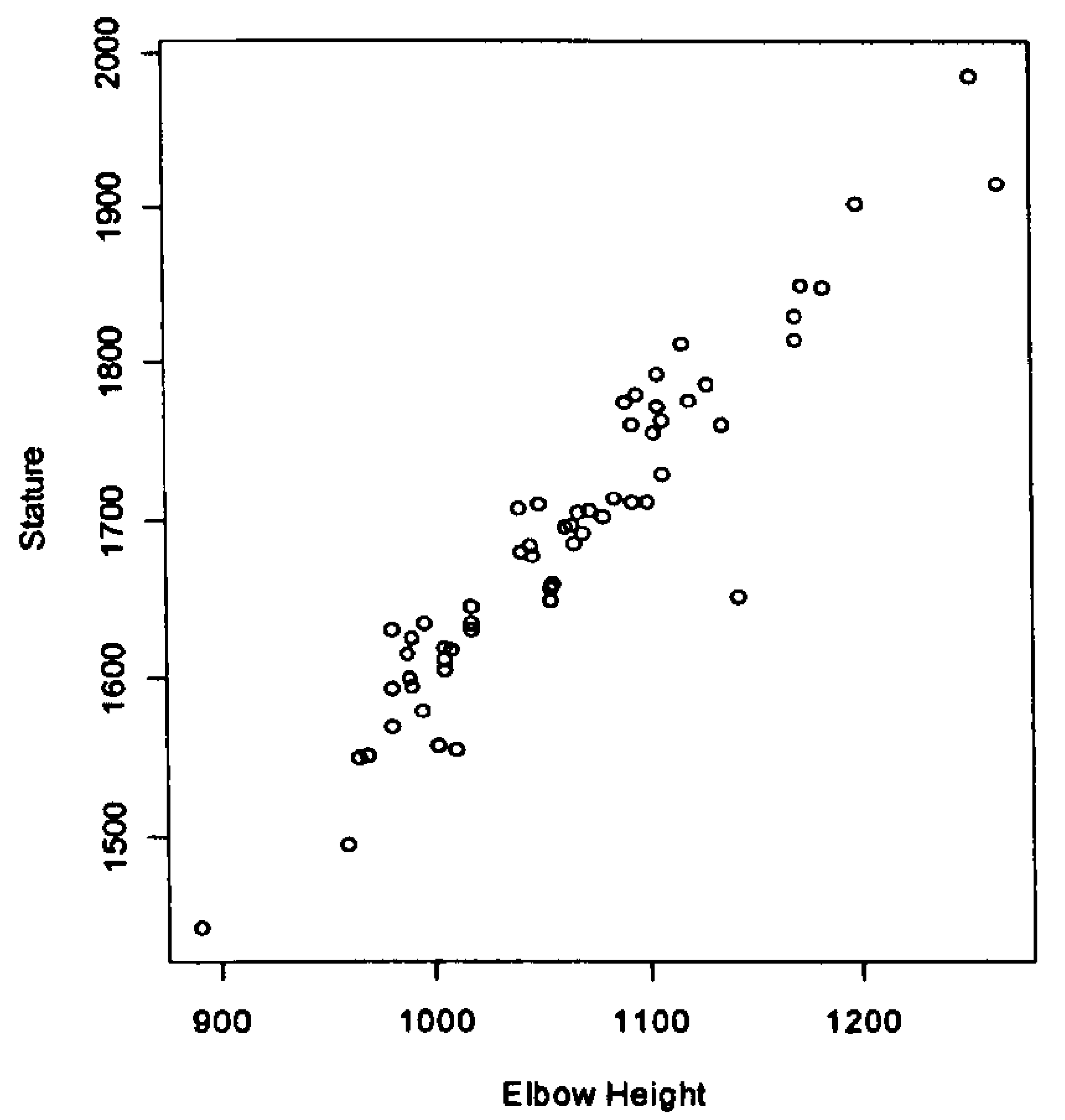


Figure 4-2 Scatter-plots for able-bodied cohorts

From the scatter-plot of elbow-height against stature it is clear that elbow-height and Stature are strongly linearly related; a linear regression was carried out resulting in the model:

$$Stature = 270.37749 + (1.33699 \times Elbow\text{-}Height)$$

The model has a p-value: < 2.2e-16 and an R-Squared = 0.89995. The p-value indicates that the model is appropriate for the data with high significance and the R-Squared value of 0.89995 indicates that approximately 90% of the variance in elbow height can be explained by stature, thus elbow height can be predicted from stature accurately implying that they are interchangeable measures.

Tables 4-2 and 4-3 show the summary statistics according to gender. The summary statistics for each of the sub-groups will be given at the beginning of the analysis for each of the three groups. The total cohort was made up of 31 male subjects and 29 female subjects. As some of the adult males used in the tests were very experienced, this resulted in a higher standard deviation for age between males and females.

Table 4-2 summary Statistics for able-bodied males

Males	*Age*	*Stature*	*Elbow*
N	31.00	31.00	31.00
mean	20.28	1718.19	1079.23
Std.Dev.	10.59	116.96	85.62
min	12.42	1442.00	890.00
Q1	13.62	1634.00	1011.50
median	16.25	1712.00	1090.00
Q3	22.04	1783.50	1124.00
max	59.67	1985.00	1265.00

Table 4-3 Summary statistics for able-bodied females

Females	*Age*	*Stature*	*Elbow*
N	29.00	29.00	29.00
mean	18.50	1662.62	1045.24
Std.Dev.	5.93	80.05	54.39
min	12.50	1552.00	969.00
Q1	13.83	1612.00	1005.00
median	16.17	1652.00	1046.00
Q3	20.75	1702.00	1080.00
max	30.17	1902.00	1199.00

4.1.1 Summary statistics for able-bodied subjects by demographic and gender

Tables below show the subject demographics for age, stature and elbow height. Table 4-4 for age, 4-5 for stature and 4-6 for elbow height.

Table 4-4 Age demographic

Age	*Adult Males*	*Adult Females*	*Senior Males*	*Senior Females*	*Junior Males*	*Junior Females*
N	10	10	11	9	10	10
mean	31.733	25.574	16.280	16.315	13.225	13.383
Std.Dev.	12.355	4.410	0.4834	0.5919	0.4565	0.5094
min	20.5	19.833	15.417	15.333	12.417	12.5
Q1	23.520	21.042	16	16	13.042	12.979
median	27.208	27.75	16.25	16.167	13.167	13.583
Q3	34.645	29.146	16.583	16.417	13.375	13.833
max	59.666	30.167	17.083	17.417	14	13.833

Table 4-5 Stature demographic

Stature	*Adult Males*	*Adult Females*	*Senior Males*	*Senior Females*	*Junior Males*	*Junior Females*
N	10	10	11	9	10	10
mean	1792.9	1659.8	1753.27	1726.22	1604.9	1608.2
Std.Dev.	43.92	47.752	108.829	100.20	92.416	37.240
min	1712	1580	1606	1552	1442	1555
Q1	1766.25	1626.5	1698.5	1678	1561	1576.25
median	1790	1666	1708	1714	1621	1615.5
Q3	1826.25	1700.5	1777.5	1772	1635	1634
max	1850	1712	1985	1902	1761	1657

Table 4-6 Elbow-height demographic

Elbow Height	Adult Males	Adult Females	Senior Males	Senior Females	Junior Males	Junior Females
N	10	10	11	9	10	10
mean	1135.9	1047.4	1101	1081.778	998.6	1010.2
Std.Dev.	33.989	48.92	82.952	61.816	65.289	26.649
min	1100	988	1005	969	890	980
Q1	1105.5	1008	1056.5	1056	968.75	993
median	1124	1045.5	1073	1085	988.5	1006.5
Q3	1170	1075.5	1101.5	1105	1012.5	1015.25
max	1183	1143	1265	1199	1135	1055

4.1.2 Questions to be answered from the tests

This Chapter will discuss the answers to the following questions:

- Can Body Part Discomfort (BPD), be reduced by identifying a best-fit bench working height?
- Can work endurance be estimated and extended?
- Are there gender differences for bench requirements?
- Does a young teenager whose stature corresponds to that of an adult have the same bench ergonomics requirements?

The tests will be discussed in the sequence Adult, Seniors and Juniors, then appropriate comparisons will be made between the sub-groups.

4.1.3 The method

As already discussed, a best-fit working height has a major bearing on the comfort of any worker. While this has obvious relevance to adults working at benches, whether in their chosen profession or as hobbyists, the not-so-obvious bench user, is in the second level school system, in technology, engineering, woodwork, and other practical classrooms. Two of the subgroups are school based, junior students and senior students. Four elements were again combined to establish an ergonomic best-fit: Body Part Discomfort (BPD), endurance evaluation, subjective height ratings and efficiency.

The experiments were designed to test the following null hypotheses:

1. BPD will not be affected by working height.
2. Endurance will not be affected by working height.
3. The test cohort will not have a preferred subjective height rating
4. Efficiency will not be affected by working height.
5. There are no best-fit differences between male and female bench users.
6. The ergonomic requirements for young school bench users will be different from the requirements of adults.

The study was a repeated measures design with the primary factor of working height condition. The condition working height had four levels of working height plus the existing bench height (5 heights in total). The range of heights, were arrived at through pilot tests, undertaken by ten, experienced bench users who tested heights, higher and lower to those selected. The eliminated heights were deemed much too high or much too low, and were set in relation to elbow height. The study makeup was 60 subjects (3 x 20), at 5 working heights, for 5 tasks.

4.2 Experimental design

4.2.1 Body part discomfort (BPD), endurance and efficiency

This area of the research aimed to analyse the effect of workbench heights on bench processing skills, for BPD and estimated endurance time and efficiency. The tests were carried out at five levels on a specially designed test-rig.

Again (as in Chapter 3) Delleman's (1999), height variations of 50mm were deemed suitable for the purpose of the testing. The variable bench height of the rig was determined as a measure, which at it's lowest would be 250 mm below the subjects elbow height, and at its highest, 100 mm below elbow height. The rig also represented the normal engineering bench, which was 800 mm high, and this fixed height would be up to 465 mm below the tallest subject's elbow. Anthropometric data for elbow heights and stature was collected. The bench heights and processes were randomised so as to eliminate any learning sequence effect. Table 4.7 shows the bench test-rig heights and coding.

Table 4-7 Working height treatments and order code

Code	Work height
1	Existing Workbench
2	Elbow height minus 100 mm (E-100)
3	E-150 mm
4	E-200mm
5	E-250mm

A subjective questionnaire was designed to assess different aspects of the workbench. The questionnaire used modified versions of Drurys and Coury (1982) and Shackel et al (1969) rating scales in the study of chair design. The anchors used were the same as those used by Drury and Coury (1982) and Shakel et al., (1969), for all but one of the rating scales. The rating scores were then used as the dependent variable.

4.2.2 Body part discomfort (BPD)

For BPD each test subject was asked to rate their body part discomfort in twenty-five regions shown on a diagram of the rear view of a human body (Figure 4-3), modified from (Corlett and Bishop, 1976 and Delleman, 1999). Each subject completed the rating on the BPD map at the conclusion of the test-bank for each height. The scoring was '0' for no discomfort and '5' for extreme discomfort. They recorded their score on the grid beside the BPD map. Any special comments were entered by the test supervisor.

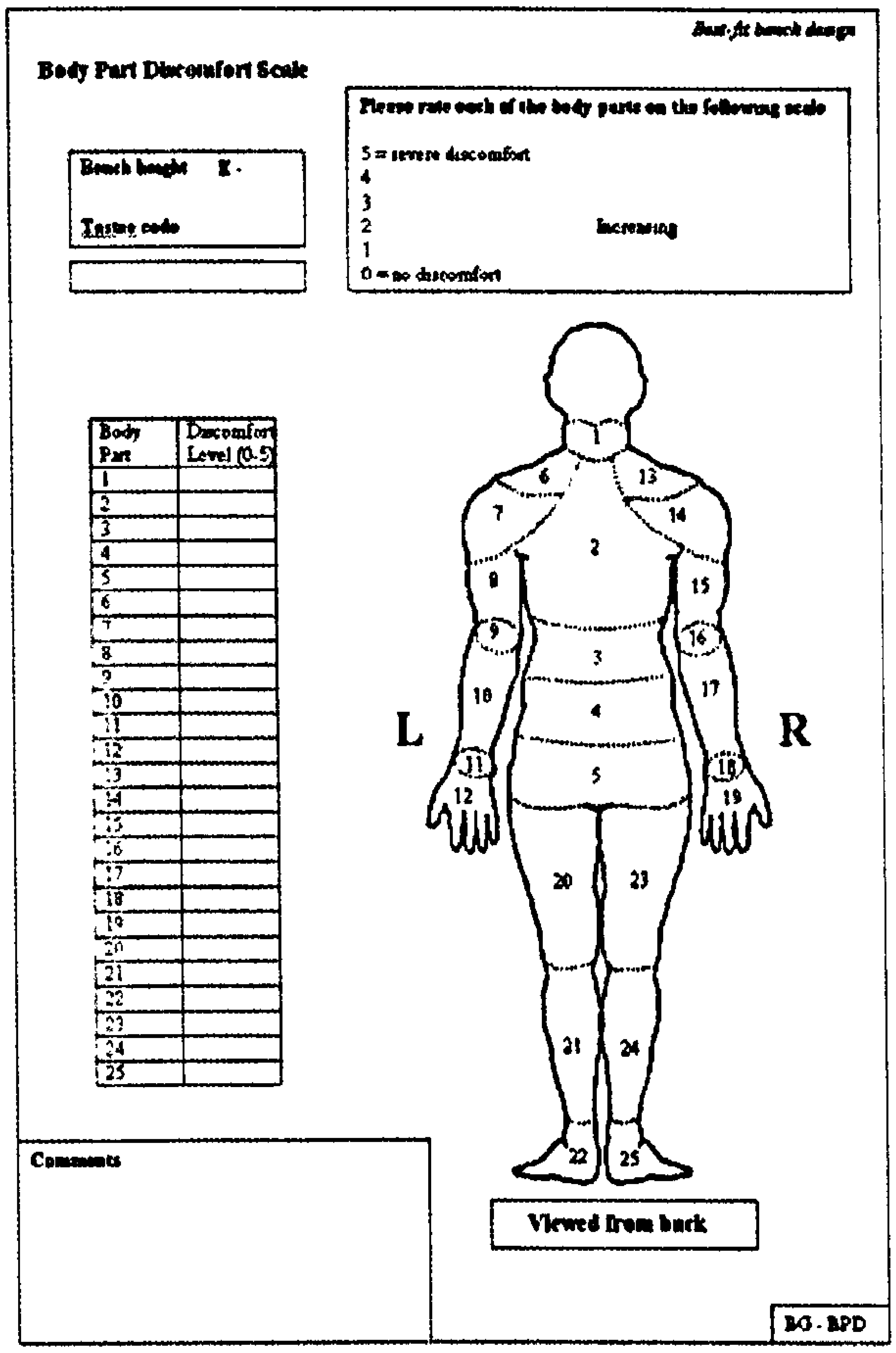


Figure 4-3 The body map (rear view) used for BPD

On beginning the next test, height subjects were asked to express if they still had any discomfort on any of the body parts. They were usually fully recovered before proceeding to the next height. If any discomfort was present at the beginning of the test bank, this score was subtracted from the end score. The resulting score for each region was the dependent variable.

4.2.2.1 Estimated endurance time

Using the Delleman (1999) model, the operator was asked to estimate on the basis of their perceptions, how long they could operate at each level of the bench height, doing this type of work, (1= less than2 hours (h), 2 = 2-4h, 3 = 4-

6h, 4 = 6-8h, 5 = more than 8h). The estimated endurance time was used as the dependent variable. Their endurance rating was entered as a numerical value, 1 to 5.

4.2.2.2 Completion times and number scoring

Table 4-8 indicates the scoring system, for each of the bench processing tasks. For each subject the score times were recorded and used as dependent variables. Subjects and the working height were the independent variables. All scores were recorded by the tester.

Table 4-8 Processing tasks and scoring

Task	Task Name	Time measured in minutes
1	Three Pin Plug Assembly	Total time to assemble three electric plugtops.
2	Wood planing	Time taken to mark out and plane off 2.5 mm from a 350 x 30 piece.
3	Wood Sawing	Time taken to mark out and cut a piece 30 mm x 30 mm, and rip-cut the piece 50 mm deep.
4	Metal filing	Time taken to mark out and file 6 mm at a 45° angle on 6 mm MS
5	Metal sawing	Time taken to mark out and hacksaw 12 mm deep on 6 mm MS

4.2.3 The skills selected for the test

Eight experienced bench workers in the metal and woodworking skills were asked to list the most common processes when working at a bench. The top three for metalwork were filing, metal sawing, and assembly, and for woodworking, planing and saw cutting. As assembly is a task common to both disciplines, this would be part of the task bank. It was decided to confine the test bank to five elements to allow the test to be complete in 1.5 hours per subject. None of the test elements required a high degree of skill and therefore could be undertaken by inexperienced subjects. Quality of execution would not be tested.

The test elements would fall between the categories of light and heavy work as described by Kroemer and Grandjean (2000). The assembly task was in the category of light, and the others were in the category of light/heavy work.

4.2.3.1 The bench tasks

Manual dexterity skills were required for each task. The plugtop test was discussed in the last chapter and was identical in procedure and requirements. Wood planing requires quite a non-neutral posture, where both arms are pushing in conjunction with feet in a fixes position, the hips moving in the direction of the plane (parallel to the bench), and the back in flexion and torsion. It is therefore necessary to adjust to the most comfortable posture when planing. Wood sawing has one arm and shoulder almost static (the work holding hand), and most of the work is done with the cutting hand, arm and shoulder. There is some back flexion.

Metal sawing uses both arms, with the dominant arm/hand having the greatest work-load. The hips are oblique to the bench and the back is flexed and slightly twisted (in torsion). Metal filing requires more downward pressure than for sawing, with the body position much the same, but usually the back is more flexed.

4.2.3.2 Subjective height evaluation scoring

At the end of each test bank at a particular height the subjects were asked to give a subjective height evaluation rating for that height (Berquer et al., 2002; Straker, 1999). They used a visual analogue scale to express their 'subjective height evaluation'. The latter was done, by placing a tick at a point along a 100 mm line. The '0' point was the extreme low, the highest point '10' was the extreme high position and the mid point '5' was the 'ideal height'.

4.2.4 The test apparatus

The same telescopic column was used for the bench as for the test described in Chapter 3, but the table top was enlarged and moved to a more central position to reduce the strain on the column. The cranked bracket was replaced with a level frame, which was designed to cantilever for working in a seated position. A vice 90 mm high was fitted as this was the mean between a typical engineering vice (180 mm high), and a woodworking bench vice which is normally flush (level) with the bench top. The test rig is shown in Figure 4-4.

Figure 4-4 The test rig ready for use

The height range for the bench was 500mm, from 650 mm at the lowest level to 1,050 mm fully raised. Using the anthropometric data for the 5^{th} percentile and the 95^{th} percentile (Pheasant, 1998), this gave a good margin at either end of the elbow heights.

4.2.5 The procedure

A number of pilot tests were used to ensure that the test procedure worked and to estimate overall time and rest/recovery periods. At the beginning of each session, the subject was given a full oral explanation of the experimental procedure, read the experiment briefing and signed a detailed consent form. The initial questionnaire was filled out at the beginning to establish personal details, and whether they were sufficiently fit to undergo the test. They were informed that they could withdraw from the test at any time, and without explanation, (no subject did).

Two anthropometric characteristics were measured, the stature and the subjects elbow height. The elbow height was used to determine the heights for the four heights of the workbench rig. The fifth height was the fixed height of the typical engineering and woodwork bench, 800 mm.

The sequence of the procedure was:

1. Determine if there was any BPD before the test began.
2. Set the work height and perform the five elements of the test bank (randomised).
3. Subjects complete BPD scale, Height evaluation scale, and estimated endurance time.
4. Subjects repeat the above steps for other levels (again randomised).

All adults and some seniors were tested in the ergonomics laboratory, at the University of Limerick, and all the remainder were tested at Castletroy Community College.

Chapter 5 will discuss the data and analysis for the three sub groups.

5 THE EFFECTS OF WORKING HEIGHT ON BPD, ENDURANCE AND EFFICIENCY

The data will be analysed and discussed, starting with adults the senior students and finally junior students.

5.1 The adult test group

The Test Cohort

The adult test group constituted one third of the able bodied test subjects. The group consisted of ten females and ten males. They were all experienced bench process users including fitters, workshop technicians, joiners, cabinet makers, woodwork, metalwork and technology teachers and three hobbyists. The mean age was 28.65 and the standard deviation was 9.57. The mean stature of the group was 1726 mm (Standard Deviation 81.6). The 5th percentile (female) stature was 1580 mm and the 95th percentile (male) stature was 1850 mm. The summary statistics for the group are seen in Table 5-1.

Table 5-1 Summary Statistics of able-bodied adults

	Age	*Stature*	*Elbow*
N	20	20	20
mean	28.654	1726.35	1091.65
Std.Dev.	9.566	81.583	61.171
min	19.833	1580	988
Q1	21.708	1673	1047.75
median	27.75	1712	1101.5
Q3	30.042	1788.5	1131.75
max	59.667	1850	1183
missing values	0	0	0

The group was tested on the trial rig described in the previous section. The five test heights were randomised, as were the five bench processes, so as to eliminate any learning effect. Subjects completed a pre-test questionnaire to establish suitability and signed a consent form. The test procedure was fully explained to all and they were reminded that they could exit the test at any time.

5.1.1 The effects of working height on BPD

The BPD was measured as described in Chapters 3 and 4. Scores were derived from the body map of 25 body parts. Figure 5-1 below shows the mean BPD for all bench heights tested. E-250 and the existing bench produce the greatest discomfort and E-150 the least. The discomfort is particularly expressed in the back for these heights and in the shoulders for E-100.

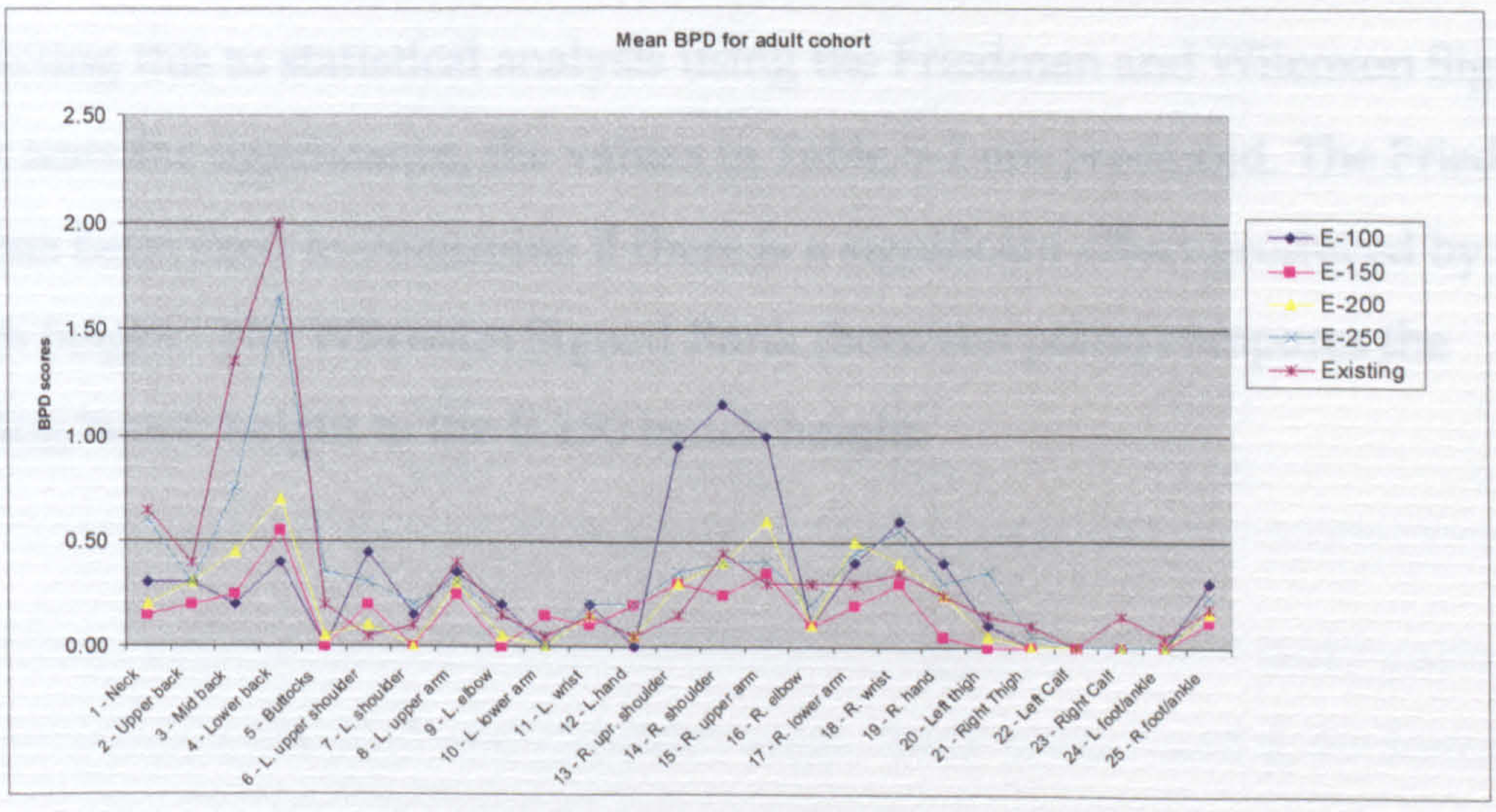


Figure 5-1 BPD means for all heights tested.

When the back and shoulder zones are separated out (Figure 5-2) we see that the height E-150 produces a good compromise height, by reducing significantly the back discomfort for E-250 and the Existing heights, as well as the shoulder discomfort for E-100. The discomfort is least in the non-dominant shoulder and in the legs. As the height levels move away from the E-150 height, aggregate discomfort increases at all levels.

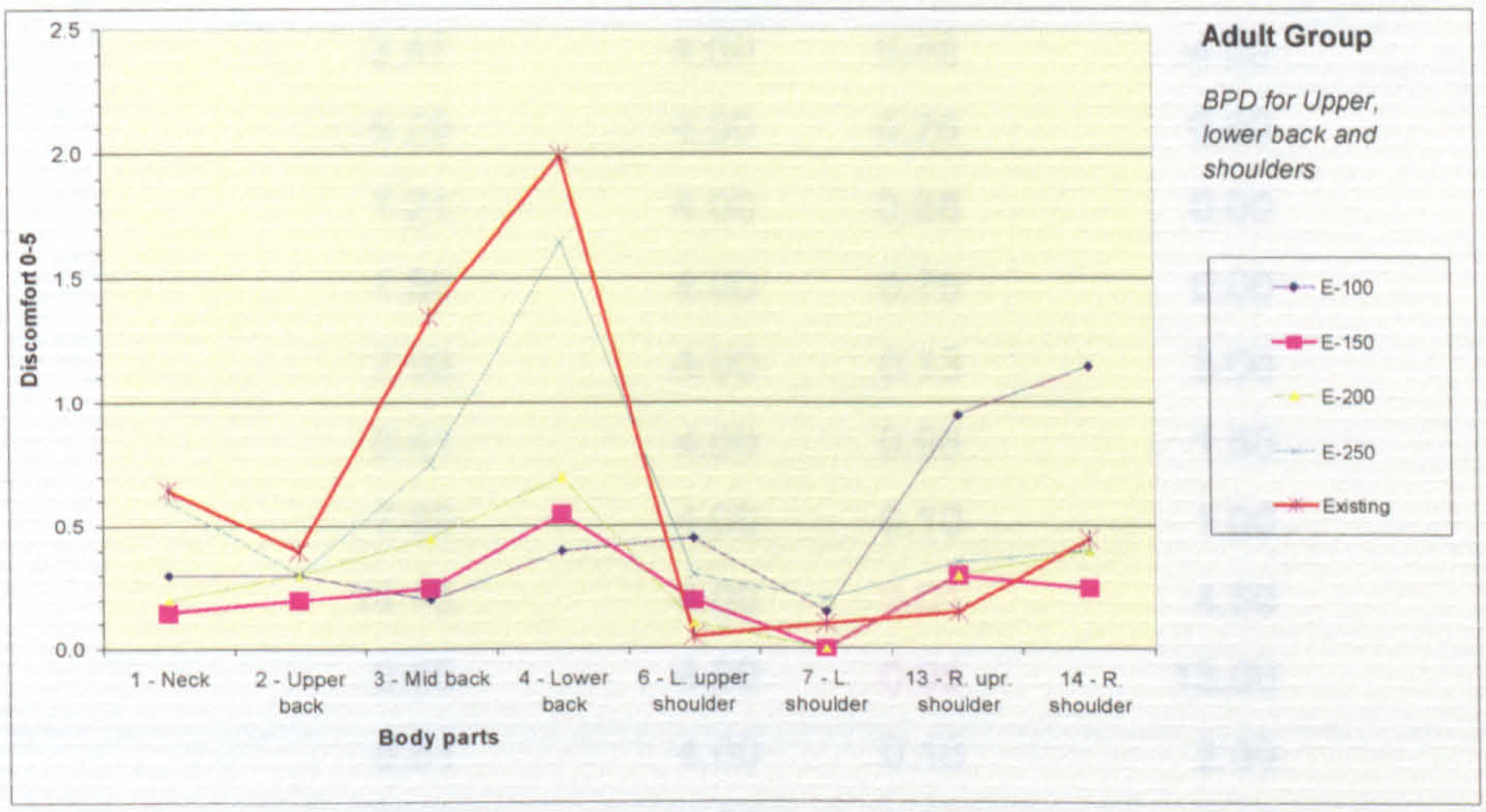


Figure 5-2 BPD for back and shoulder zones.

Subjecting this to statistical analysis using the Friedman and Wilcoxon Signed Rank tests for significance, the values in Table 5-2 are produced. The Friedman test has been used to determine if there is a significant effect produced by the bench height. The Wilcoxon Signed Rank (between pairs) compares the existing bench height to the E-150 bench height.

Table 5-2 Friedman and Wilcoxon Signed Rank tests results

VARIABLE BEING TESTED	FRIEDMAN TEST RESULTS, TESTING IF BENCH HEIGHT HAS A SIGNIFICANT EFFECT ON VARIABLE			WILCOXON SIGNED RANK TEST RESULTS, COMPARISON BETWEEN E-150 AND EXISTING BENCH HEIGHTS	
variable	Chi Square	Degrees of Freedom	Significance	Test Statistic	Significance
bpd1	12.14	4.00	0.02	3.00	0.09
bpd2	6.60	4.00	0.16	3.00	0.06
bpd3	25.91	4.00	0.00	0.00	0.00
bpd4	29.89	4.00	0.00	1.00	0.00
bpd5	7.14	4.00	0.13	0.00	0.50
bpd6	3.47	4.00	0.48	4.50	0.75
bpd7	5.29	4.00	0.26	0.00	1.00
bpd8	1.21	4.00	0.88	0.00	1.00
bpd9	1.86	4.00	0.76	0.00	1.00
bpd10	7.08	4.00	0.13	3.00	0.50
bpd11	0.41	4.00	0.98	1.50	1.50
bpd12	7.89	4.00	0.10	1.00	1.00
bpd13	14.15	4.00	0.01	4.50	0.75
bpd14	9.55	4.00	0.05	13.00	0.56
bpd15	6.61	4.00	0.16	2.50	1.00
bpd16	2.03	4.00	0.73	2.50	1.00
bpd17	1.09	4.00	0.90	3.00	1.25
bpd18	1.45	4.00	0.84	3.00	1.25
bpd19	4.00	4.00	0.41	0.00	1.00
bpd20	8.73	4.00	0.07	0.00	0.50
bpd21	4.00	4.00	0.41	0.00	1.00
bpd22	NA	4.00	NA	NA	NA
bpd23	4.00	4.00	0.41	0.00	1.00
bpd24	4.00	4.00	0.41	0.00	1.00
bpd25	4.00	4.00	0.41	0.00	1.00

As can be seen the test for height effect shows significance in 5 body parts concentrated in the back and shoulder areas. Body parts 3 and 4, the lower back, had highly significant values at p=<0.001. The other three were BP 1, the neck, and BP 13 and 14 the dominant right shoulder.

Looking at the aggregate scores (Lowe et al., 2001; Delleman and Dul, 2002) for each test height gives a clear picture of the comparisons of each level for BPD. The E-150 has the minimum score and the existing height has the highest score (Figure 5-3).

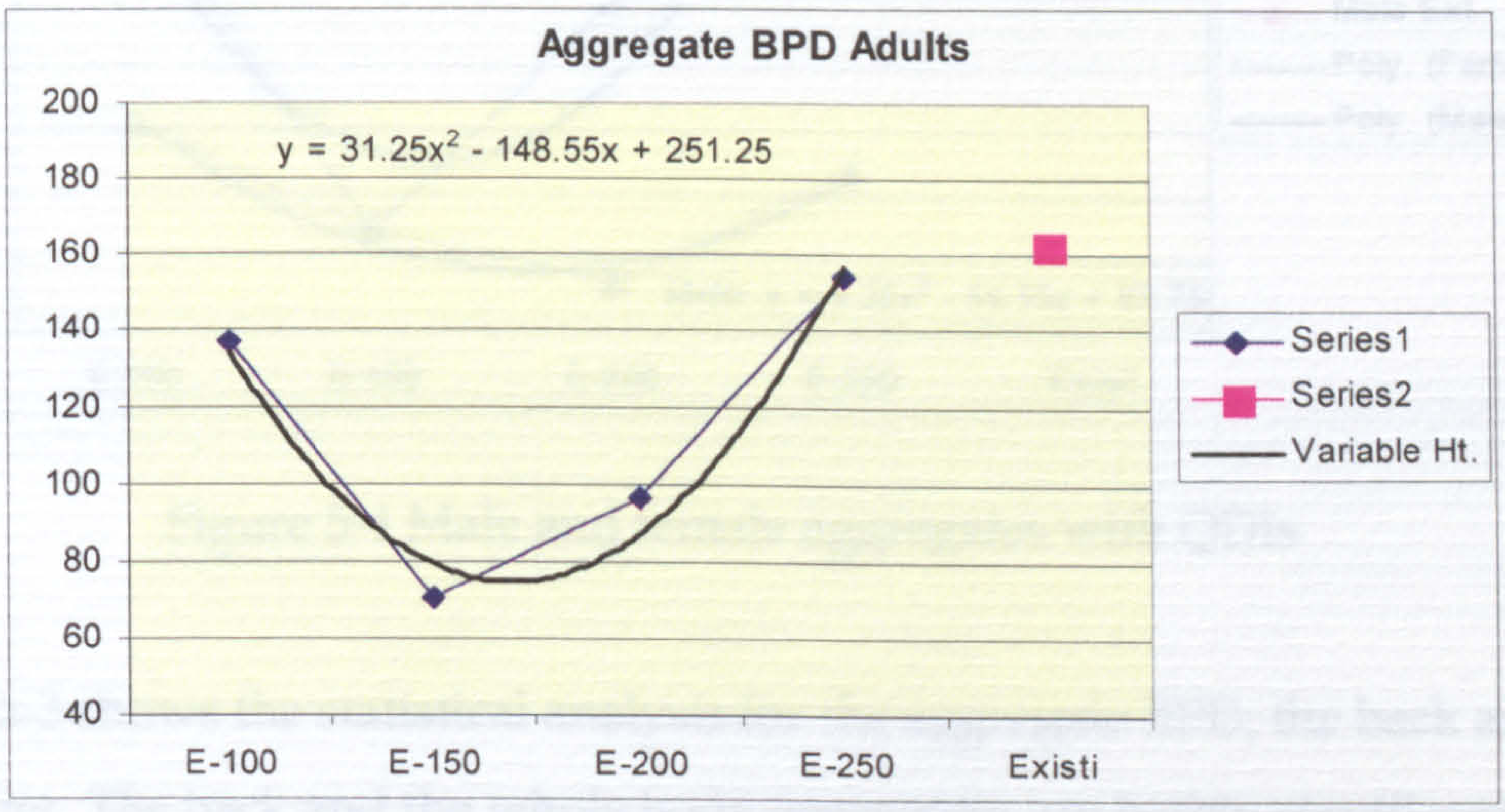


Figure 5-3 Aggregate BPD with QDI

The quadratic equation may be used to predict the general discomfort at any level, to give a 'quadratic discomfort indicator', (QDI), See Figure 5-3.

When the male and female aggregate scores are separated a new picture emerges (Figure 5-4). While the aggregate BPD is exactly the same for the E-150 level the curve moves away much more sharply for the females as the curve goes above and below E-150. We can therefore conclude that the male bench position in relation to BPD is far more robust than for the adult females, Figure 5-4. It is also worth noting that the Existing bench produced less BPD for the females than did the E-250 level. This resulted from the Existing level falling between the E-200 and E-250 levels.

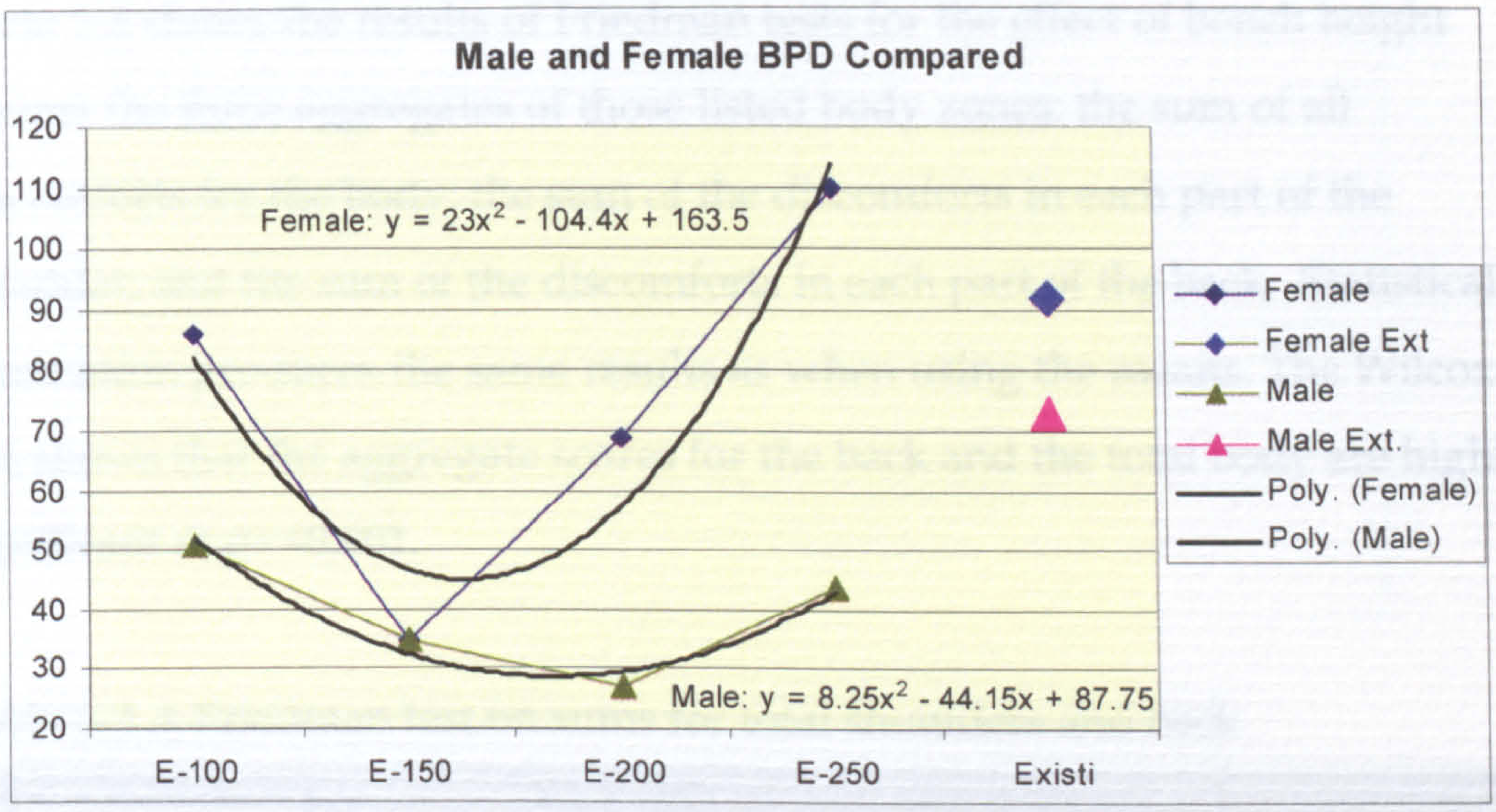


Figure 5-4 Male and female aggregates with QDIs

Table 5-3 shows the statistical analysis for the aggregate BPD, the back and the shoulder. The back and the whole body aggregates are highly significant at p=<0.001 and the shoulder has a significance of P=0.03. The table shows that for the Wilcoxon Signed rank test that there is a highly significant p value for back parts 3 and 4 at P=<0.001, and there is significance in shoulder discomfort. BPD for 3,4, and aggregate is illustrated in Figure 5-5, which shows the effects of bench height in comfort for the areas under consideration.

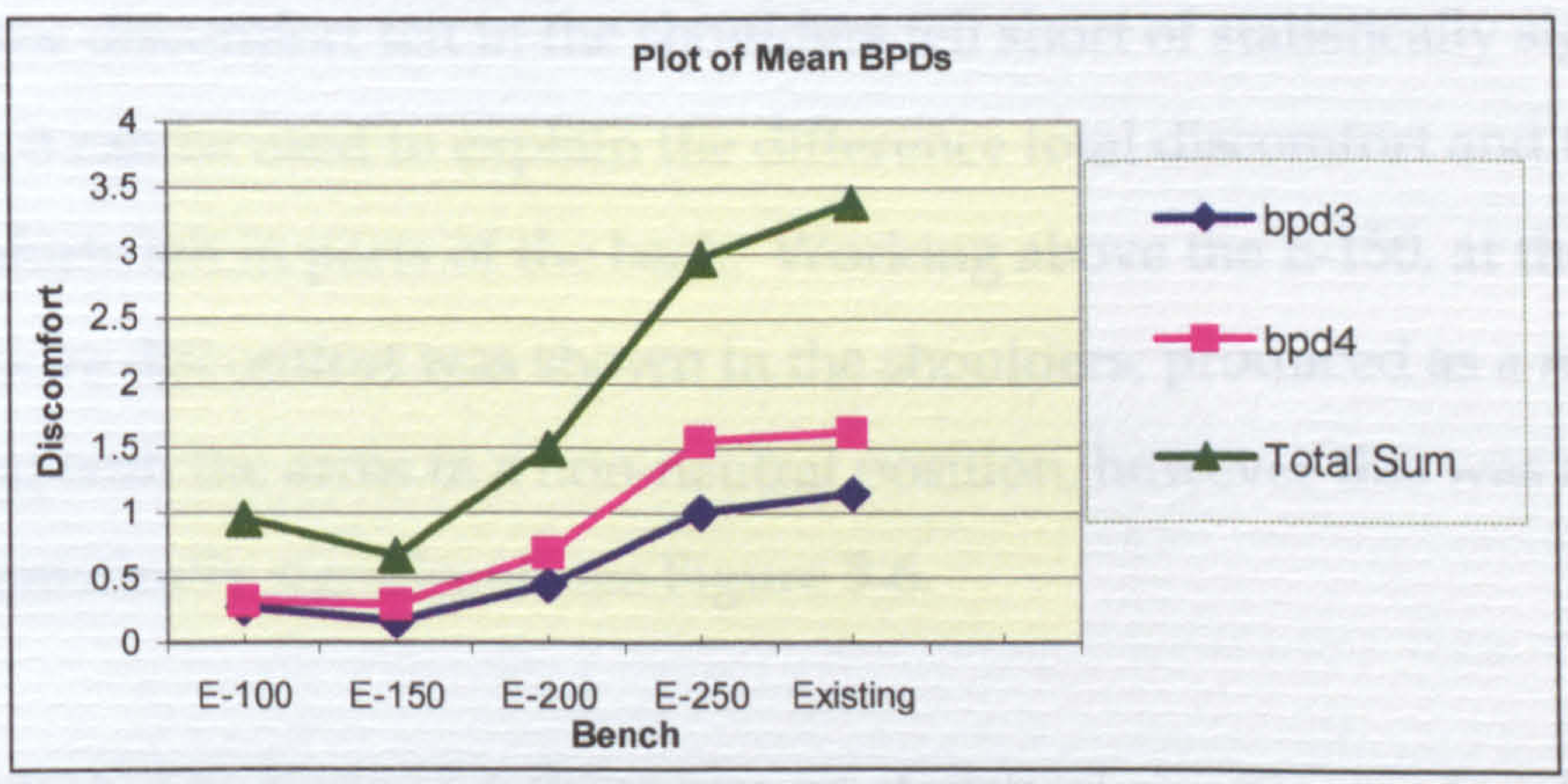


Figure 5-5 Back areas 3 and 4 and total sum

Table 5-3 shows the results of Friedman tests for the effect of bench height against the three aggregates of those listed body zones: the sum of all discomforts for the body; the sum of the discomforts in each part of the shoulder; and the sum of the discomforts in each part of the back. Statistically, summation produces the same results as when using the means. The Wilcoxon test shows that the aggregate scores for the back and the total body are highly significant at p=<0.001.

Table 5-3 A Friedman test on sums for total shoulders and back

	Friedman			Wilcoxon	
variable	Chi Square	Degrees of Freedom	Significance	Test Statistic	Significance E-150 v Extn.
AggBpd	30.47	4.00	0.00	4.50	0.00
Shoulders	11.19	4.00	0.03	32.00	0.95
Back	39.40	4.00	0.00	1.50	0.00

The body parts found to be statistically significantly effected by the height of the bench were PB3 and BP4, i.e. the middle (p = .002) and lower back (p = .002). The total sum of body part discomforts, was found to be highly statistically significantly effected by the height of the bench (p = .006). While the discomfort felt in the shoulders fell short of statistically significant (p = .159), it can be used to explain the difference total discomfort and the discomforts felt in parts of the back. Working above the E-150, at the E-100 level, more discomfort was shown in the shoulders, produced as a result of working with the arms in a non-neutral position, however this was not enough to be statistically significant, see Figure 5-6.

As illustrated in Figure 5-6 there was no statistical significance for shoulder discomfort when comparing the E-150 height with the Existing bench height.

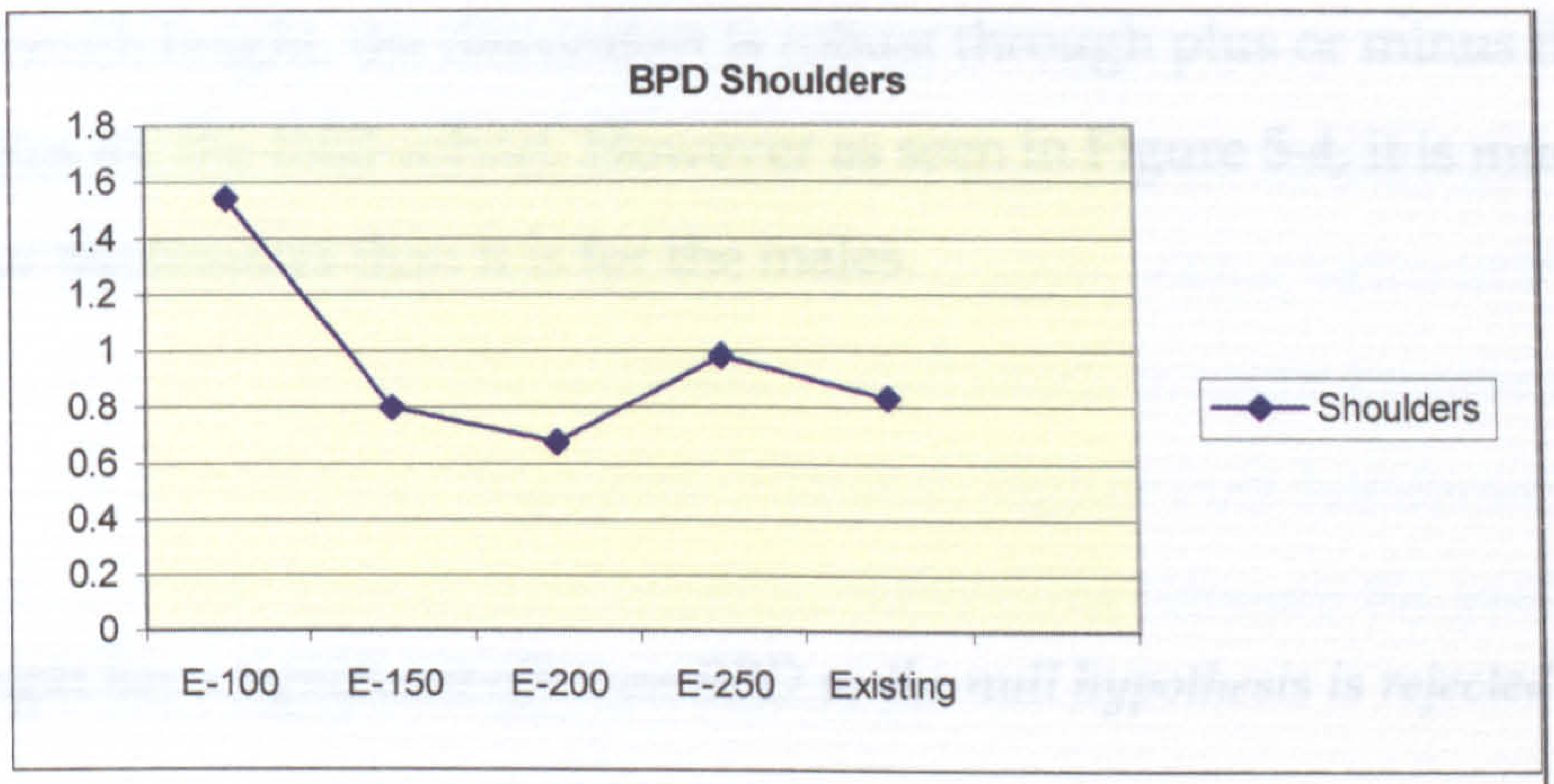


Figure 5-6 Shoulder discomfort at the five levels

Bpd13 and Bpd14 show discomfort at the E-100 level suggesting discomfort in the working shoulder, likely due to working in a non-neutral posture when the bench is too high. Table 5-4 shows the comparison of the E-100 level with both the Existing and the E-150 levels.

Table 5-4 BPD for 13 and 14 and compared working heights

	Test Statistic	*Significance*	
Bpd13	28	0.016	Comparing E-100 to Existing
Bpd13	29	0.163	Comparing E-100 to E-150
Bpd14	29.5	0.125	Comparing E-100 to Existing
Bpd14	28	0.016	Comparing E-100 to E-150

From the above table of Wilcoxon Sign-Rank tests we can see that for BP13 there is a significant difference in discomfort between E-100 and the Existing bench, with E-100 having more discomfort than the Existing bench height.

The total discomfort for E-150 is significantly different to the Existing bench height; total discomfort with a Mann-Whitney U of 70 corresponding to a p-value of $P=<0.001$. While the E-150 level is more comfortable than all other levels, comparing it to its neighbouring bench heights E-100 and E-200 we find no significant differences. There are however significant differences in discomforts between E-150 and E-250, suggesting that while E-150 is the optimal bench height, the discomfort is robust through plus or minus fifty millimetres for the total cohort. However as seen in Figure 5-4, it is much less robust for the females than it is for the males.

Bench height has a significant effect on BPD so the null hypothesis is rejected.

5.1.2 Endurance

Endurance was measured as a subjective estimate for each height after completing the test bank at that height. Subjects were asked; "How long do you feel you could endure working at this height, doing this type of work?" The subjects responded in groups of hours, which were coded as in Table 5-5 below.

Table 5-5 Endurance Groupings*

Code	Time
5	<2 hours
4	2-4 hours
3	4-6 hours
2	6-8 hours
1	<8 hours

* inverse of WUs

The 1 to 5 Scale was then used to record the score. The heights recording the least working time were E-100, E-250 and the Existing bench height. The Friedman nonparametric test was used to analyse the results. The mean rank for E-150, is significantly lower than all others, see Table 5-4

Application of the Friedman test for statistical significance indicates a highly significant difference for E-150 with all other heights, with a value of P=<0.001. The Friedman test shows that endurance estimations between heights is highly significant at p=<0.001 and using the Wilcoxon Signed rank test shows a very high statistical significance for endurance differences between the preferred E-150 and the Existing bench height (Table 5-6).

Table 5-6 Friedman and Wilcoxon Signed Rank tests results

Friedman test between heights				*Wilcoxon SR E-150 V Existing*	
variable	*Chi Square*	*Degrees of Freedom*	*Significa nce*	*Test Statistic*	*Significance*
endurance	60.35	4.00	p=<0.001	0.00	p=<0.001

The Graph shown in Figure 5-7 below, has used the mean endurance time estimates. A trendline has been added and a quadratic equation, which allows the calculation of estimated endurance in relation to the bench height below elbow height.

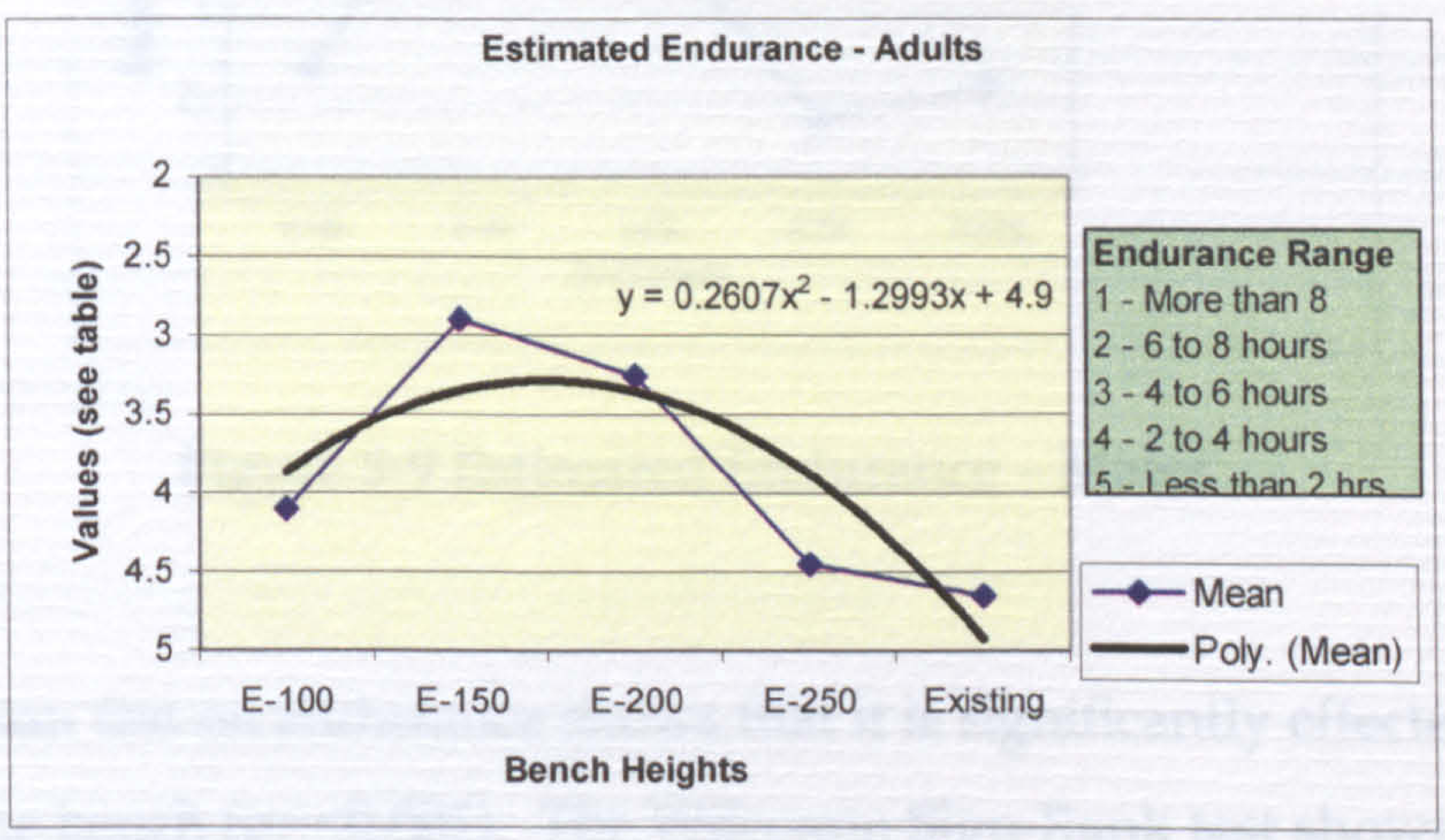


Figure 5-7 Mean Estimated Endurance Graph

It is of interest to note, that while BPD for females generally exceeds that for males (see under BPD analysis), their endurance estimates exceed that for the males, see Figures 5-8 and 5-9 below.

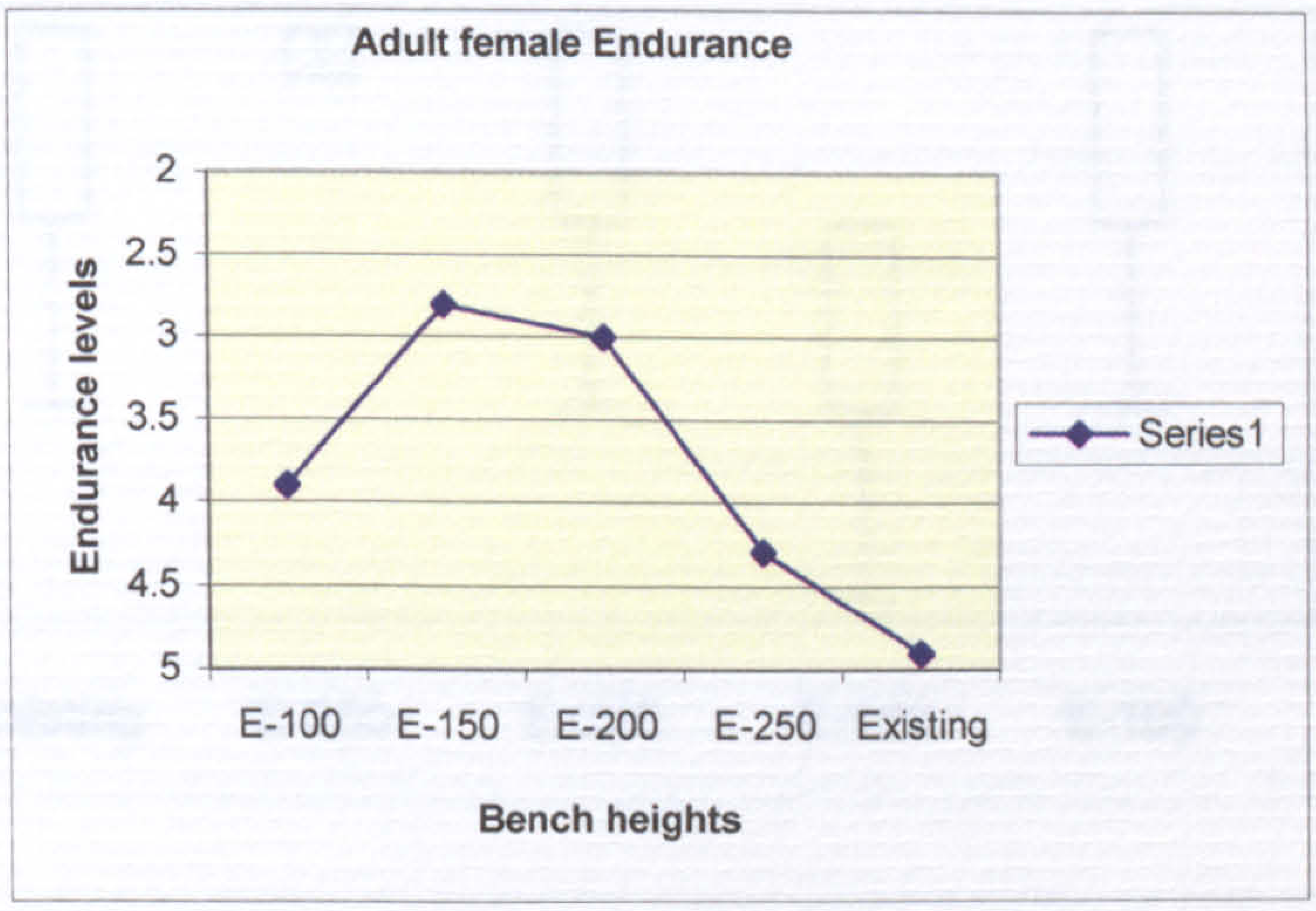


Figure 5-8 Estimated Endurance - Females

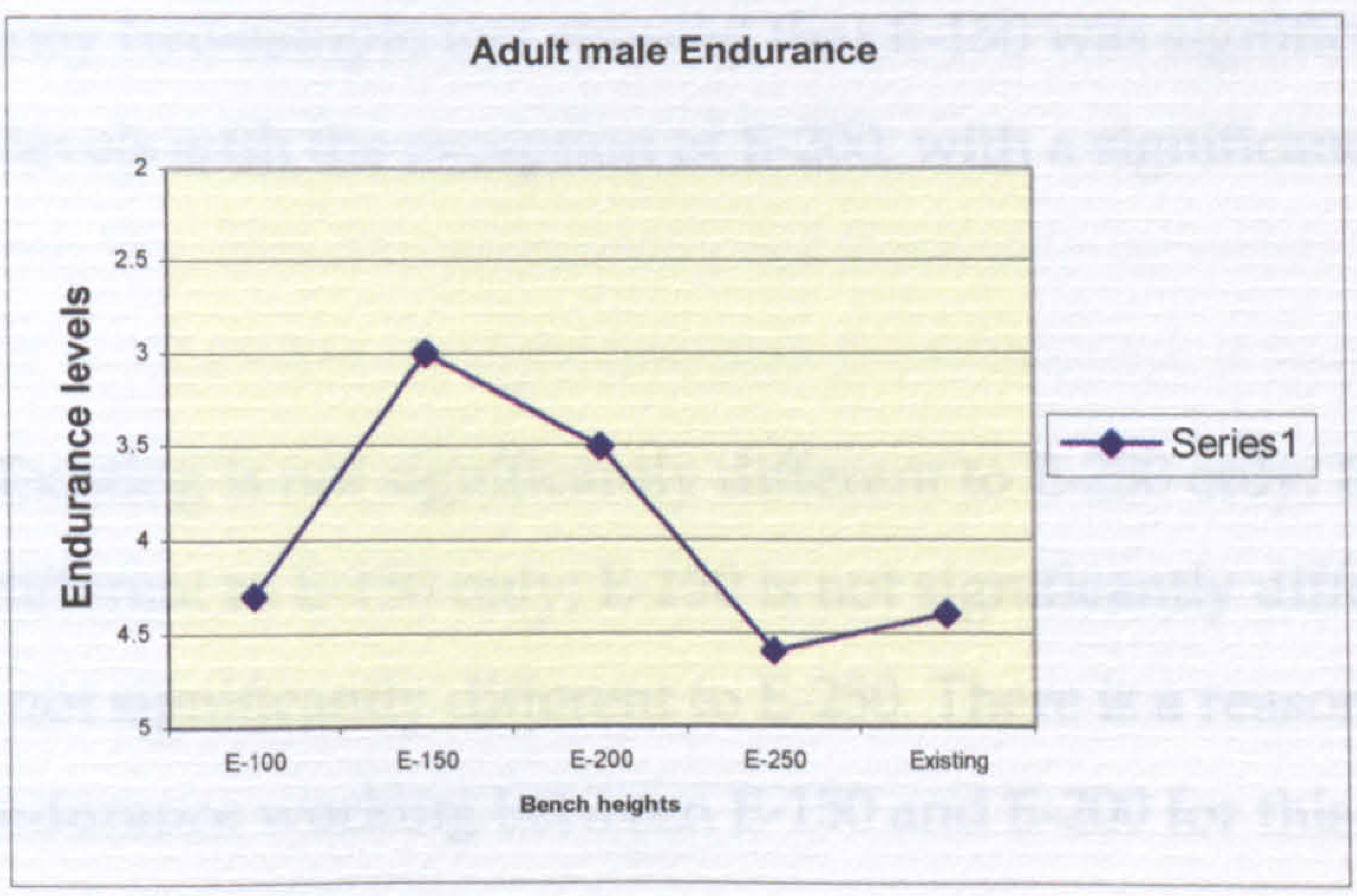


Figure 5-9 Estimated Endurance - Males

The Friedman test on endurance shows that it is significantly effected by the height of the bench (p=<0.001). The Wilcoxon Sign-Rank test shows that E-150 results in a significantly different endurance level to the endurance at the existing height. E-150 can be seen from the boxplot to have the highest endurance (lowest number on the scale used).

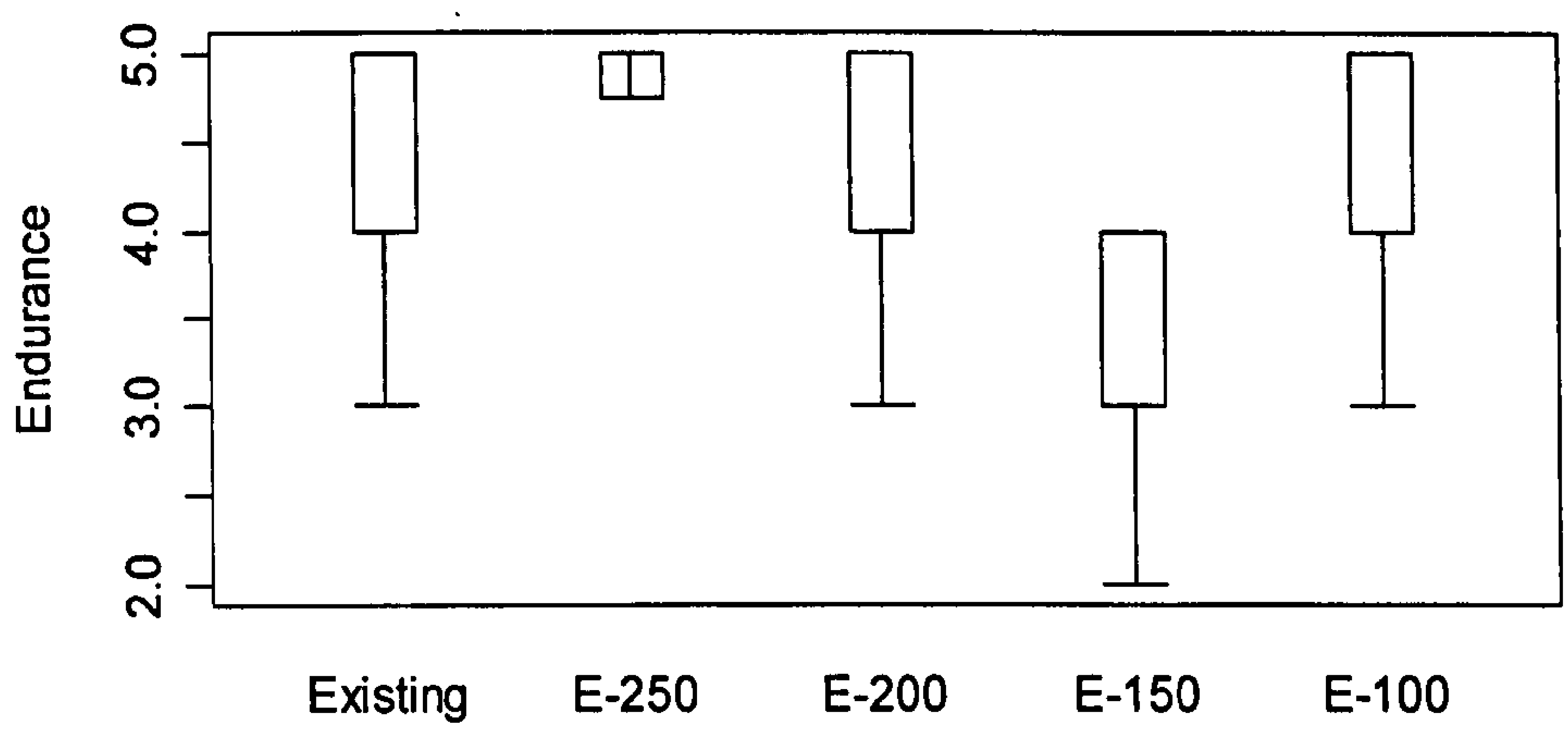


Figure 5-10 Box-plot showing endurance is significantly better at E-150.

A Mann-Whitney two-sample test showed that E-150 was significantly better than all other levels with the exception of E-200, with a significance value of p=0.149.

In summary: Existing is not significantly different to E-250 only; E-200 is not significantly different to E-150 only; E-150 is not significantly different to E-200 only, E-100 is not significantly different to E-250. There is a reasonably robust position for endurance working between E-150 and E-200 for this type of bench processing.

Bench height has a significant effect on endurance.

5.1.3 Overall subjective height ratings

Of all the variables drawn from the sample, bench height was the only one to have a significant effect on the overall subjective height response. Using the one-way ANOVA (analysis of variance with one response and one treatment) with overall subjective height as response and bench height as the treatment the following table of ANOVA results was obtained.

The significance value from the table tells us that the subjects gave significantly different overall satisfaction rates for different bench heights. The R Squared value of .712 tells us that bench height accounts for 71% of the subjects' opinion of the variability in opinions on each bench. No other variables were deemed to add enough extra information to the model to be relevant.

The normal probability plot (Figure 5-11), and the summary of descriptive statistics of the residuals below, confirm that the data satisfies the assumptions necessary for an ANOVA test sufficiently for the test to be valid; the normal probability plot is close to a straight line and the histogram is approximately normal. The p-value for the Anderson-Darling statistic ($p = 0.138$) does not suggest that the residuals are significantly non-normal (Figure 5.12).

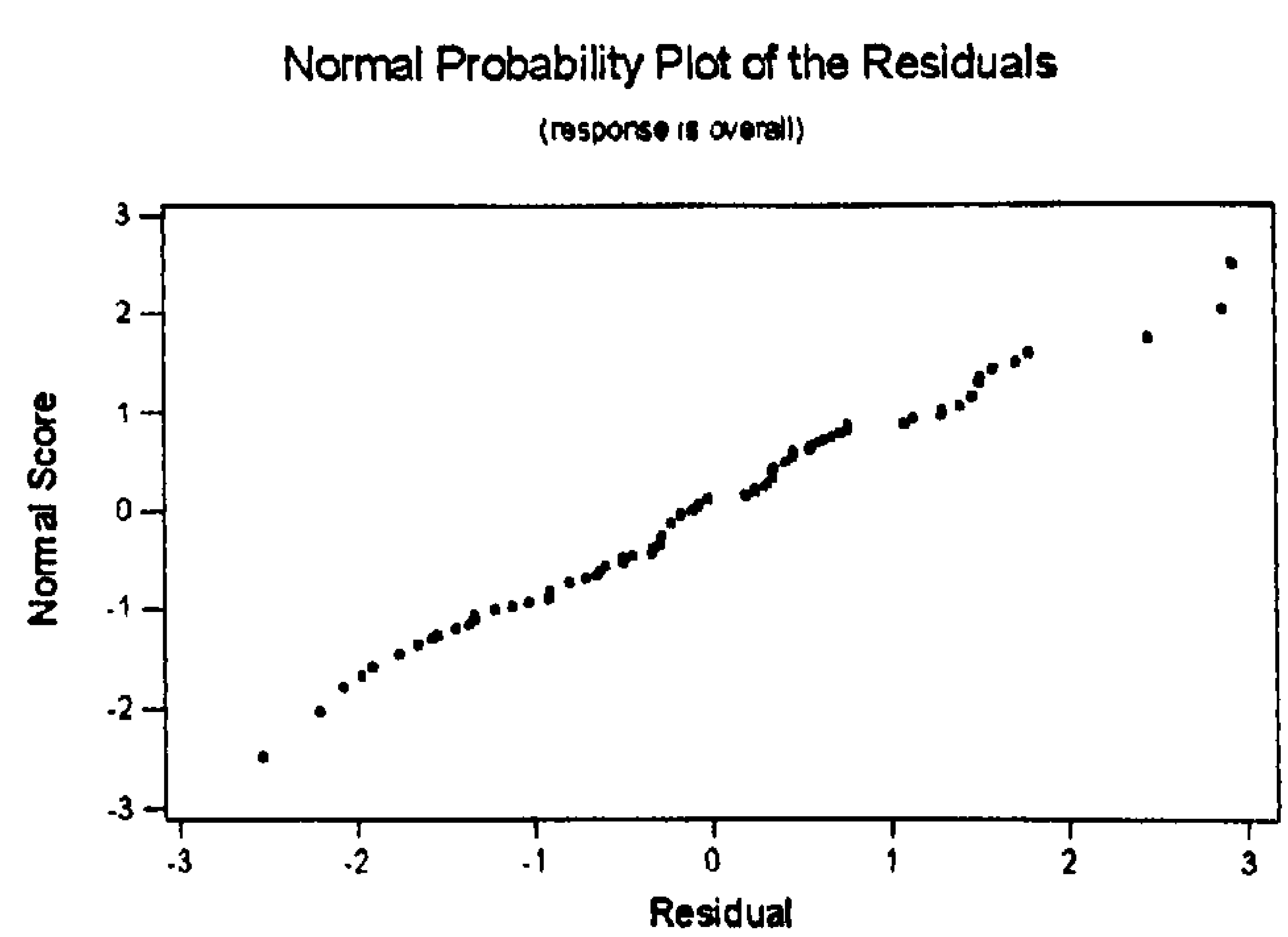


Figure 5-11 Probability plot of residuals

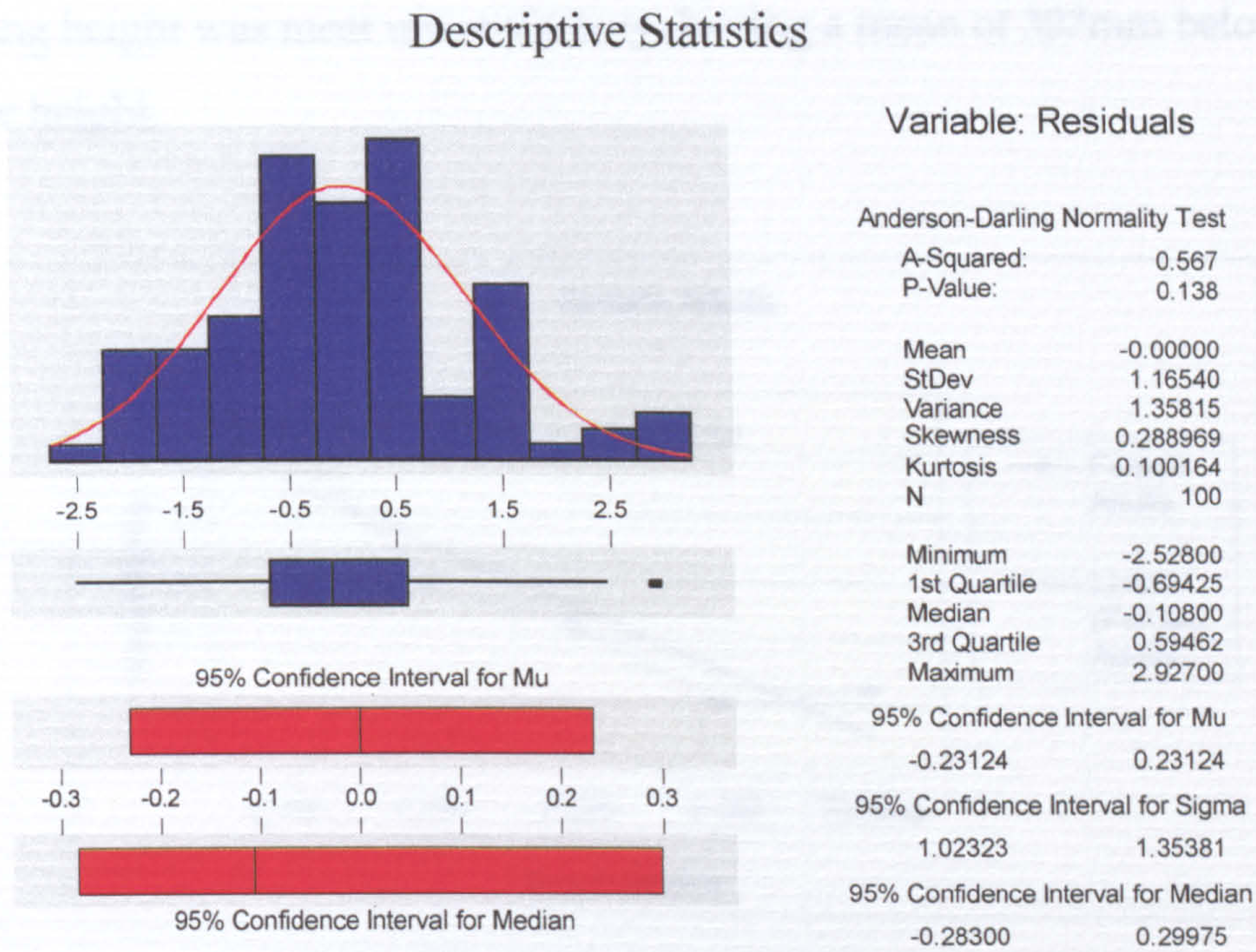


Figure 5-12 The Anderson Darling normality test

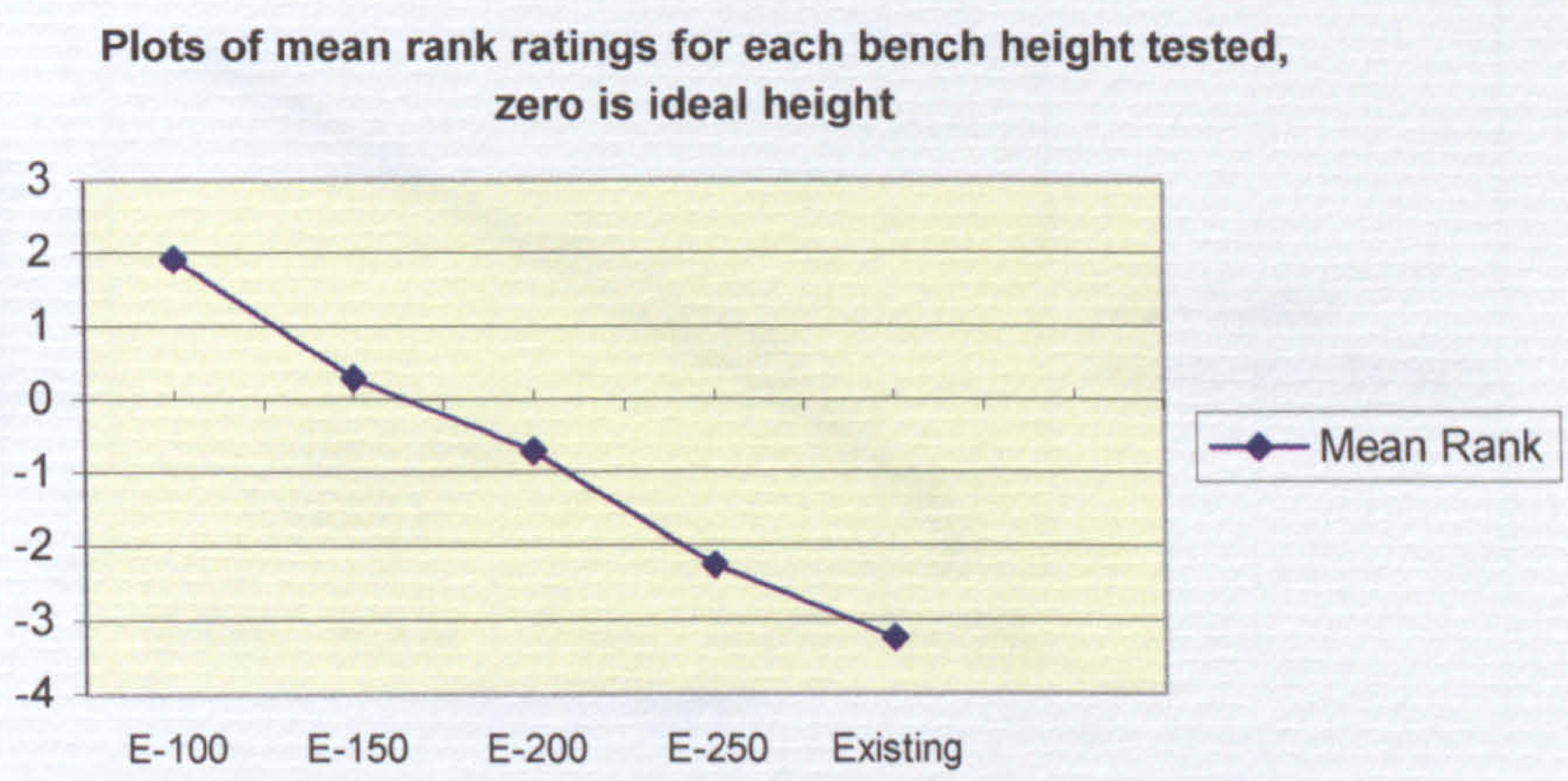


Figure 5-13 Height ratings

From the graph it can be seen that as the height moves above and below the 'ideal' of E-150 the level of satisfaction decreases in an almost straight line. Analysis of the data shows however that females found less dissatisfaction with the existing bench height than did the males. This is because the Existing height was nearer to their elbow height (at E-220mm) than the E-250 level. A comparison of the graphs at Figures 5-14 and 5-15 below also show that the existing height was most unsatisfactory, having a mean of 307mm below elbow height.

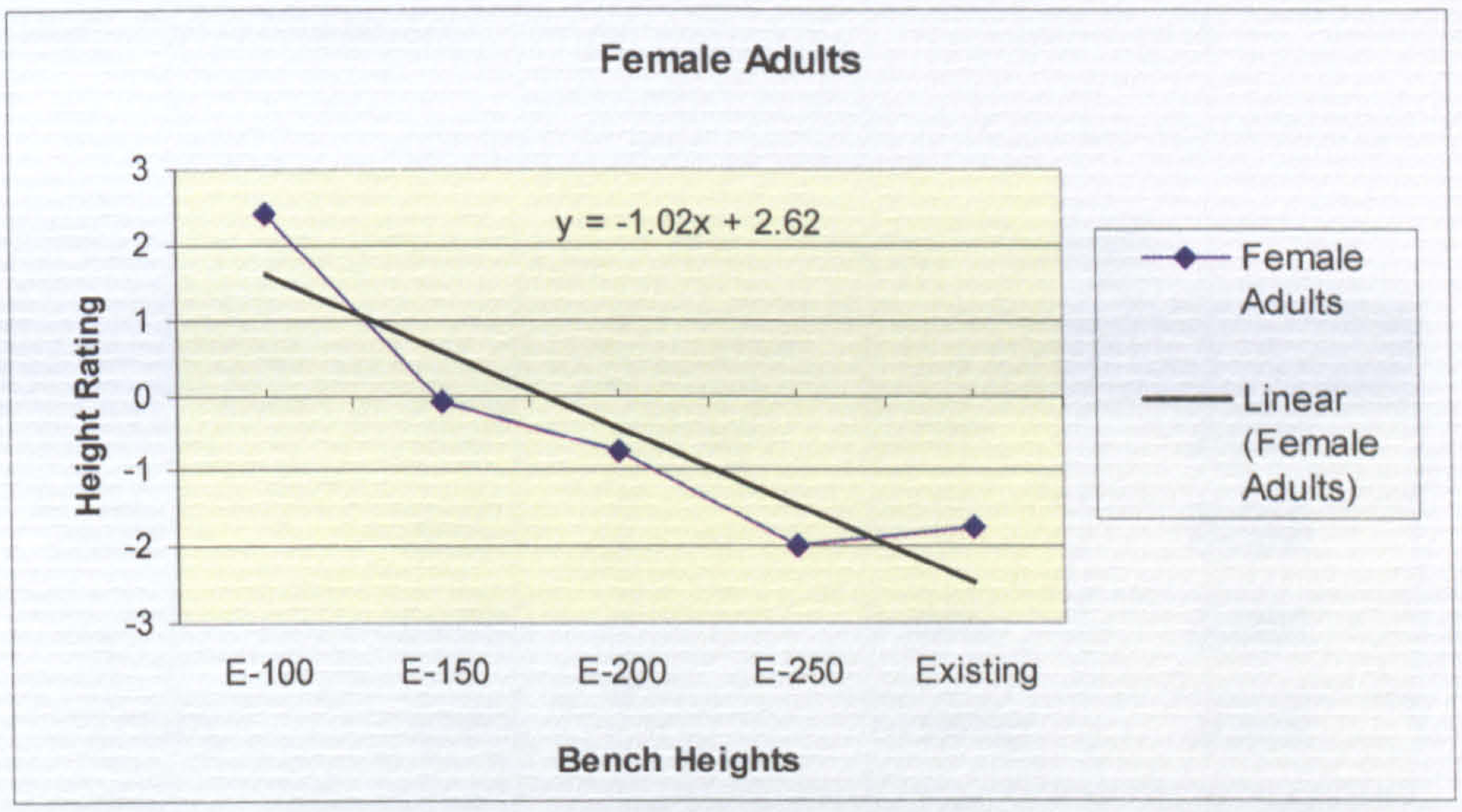


Figure 5-14 Female height ratings

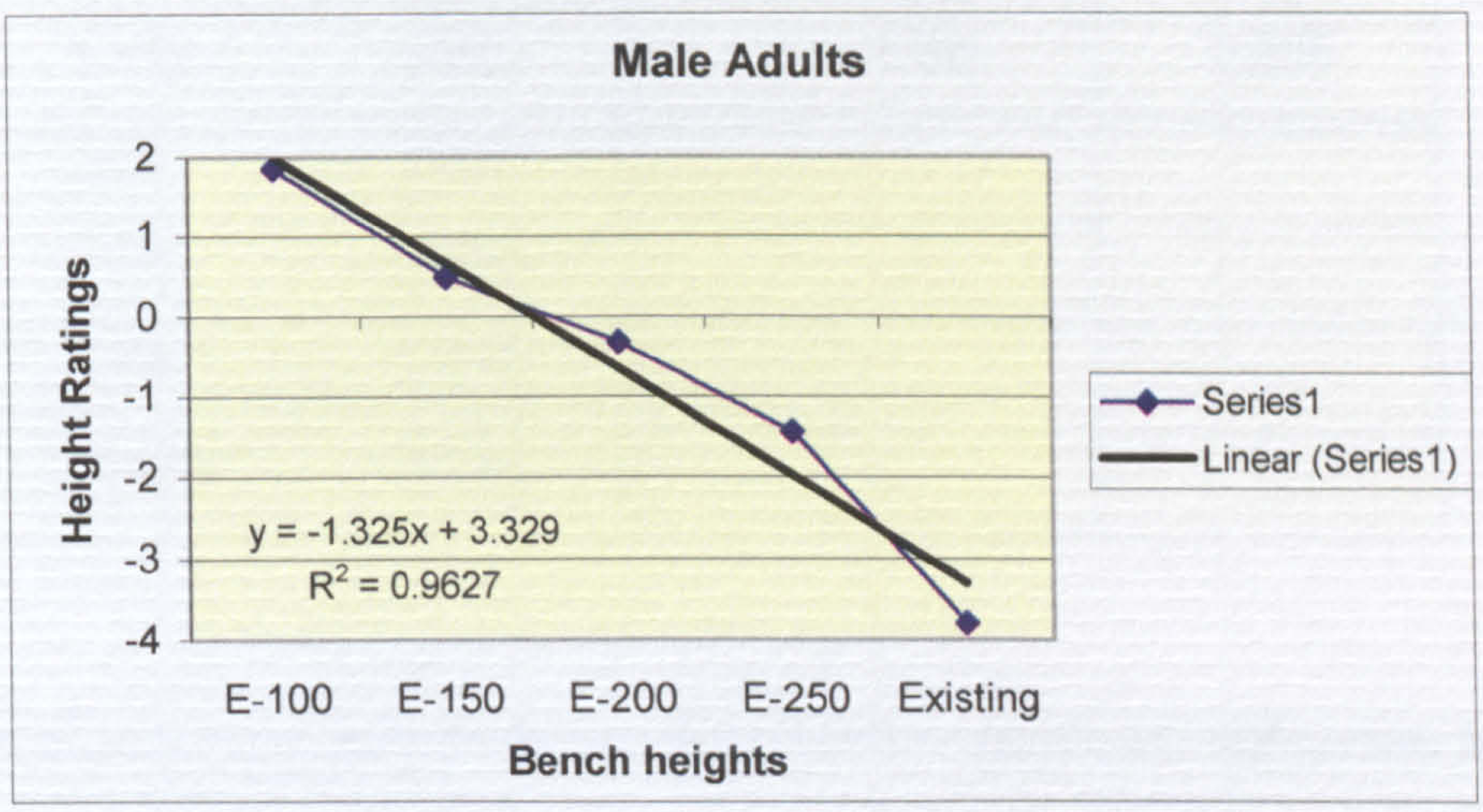


Figure 5-15 Male height ratings

It will also be noticed that for the female sub-group, the E-100 level presented a greater level of dissatisfaction for the females than for the males. While the trendlines are almost parallel, the male graph line lies mainly on the negative side of the of the '0' or ideal axis.

Applying Tukey's method, the subjective ratings to each possible pair of bench heights, were tested for significant differences, each bench height is compared with all others, see Table 5-7.

Table 5-7 Tukey's multiple comparisons of height ratings

Bench-code		*Significance*	*Bench-code*		*Significance*
E-100	E-150	*0.000*	**E-250**	E-100	*0.000*
	E-200	*0.000*		E-150	*0.000*
	E-250	*0.000*		E-200	*0.001*
	Existing	*0.000*		Existing	*0.078*
E-150	E-100	*0.000*	**Existing**	E-100	*0.000*
	E-200	*0.069*		E-150	*0.000*
	E-250	*0.000*		E-200	*0.000*
	Existing	*0.000*		E-250	*0.078*
E-200	E-100	*0.000*			
	E-150	*0.069*			
	E-250	*0.001*			
	Existing	*0.000*			

The analysis showed that there is a statistically significant difference between all heights ($p=<0.001$) with the exception of E-150 and E-200, and E-250 and the Existing height.

Summary

The bench height E-150 has the most satisfactory mean overall subjective height rating. A bench height of E-200 will not have a significantly lower

mean overall subjective height rating, whereas E-100 and E-250 heights do have a significantly lower mean overall subjective height rating.
The conclusion is that the optimum height is E-150 and the neighbouring height of E-200 is not significantly worse, however the existing bench heights and the E-100 and E-250 bench heights were found to be significantly worse than both E-150 and E-200.

5.1.4 Individual subjective height ratings

Each of the processes, were individually rated to determine whether such process ratings were more or less important than the general bench height rating. Applying an ANOVA test indicated that the process was less important than the general bench height. The bench rating having a significance level of p=<0.001 and the process having an insignificant level of less than the required p=0.05, see Table 5-8.

Table 5-8 Comparisons of height rating (tests between-subjects effects)

Variable	*Significance*
Bench height	P=<0.001
Process height	P=0.395
Bench v Process	P=0.268

The above ANOVA finds process not to be a significant factor of the subject's ratings of each bench. The interaction between bench-height and process is shown not to be significant at p=0.268.

Summary

The above ANOVA table finds bench height to be a significant factor on the individual subjective ratings, however the R Squared value is less than the R Squared value for the overall subjective height rating; this suggests that the individual ratings should be dropped in favour of the overall ratings, which give bench height a more important role in determining a subject's satisfaction with a particular bench.

5.1.5 Efficiency

All tasks were stop-watch timed, so as to make a comparison of tasks for each bench height. The Friedman and Wilcoxon Signed Rank tests, were used to analyse the data. The results are shown in Table 5-9.

Table 5-9 Bench Height and efficiency - adults

Friedman Test				*Wilcoxon Sign Rank Test between E-150 and Existing*	
Process	Chi Square	Degrees of Freedom	p-value	Test statistic	p-value
assembly	14.52	4	0.006	47	0.029
metalsaw	6.52	4	0.164	70	0.772
metfiling	1.5	4	0.827	66.5	0.156
planing	9.28	4	0.055	114	0.749
woodsaw	6.14	4	0.189	108	0.615

Bench height does not affect the efficiency of planing, wood and metal sawing and metal filing. The Friedman test shows us that bench height affects the efficiency of assembly. The Wilcoxon sign-rank test shows that the efficiency of assembly at a working height of E-150 is significantly different to the efficiency at the existing working height, with E-150 being the most efficient.

Table 5-10 shows the analysis results for the Friedman test (height/process), and the Wilcoxon Signed Rank test for comparison of the E-150 and the Existing levels, for male adults.

Table 5-10 Bench height and efficiency - adult males

Friedman Test				Sign Rank Test between E-150 and Existing	
Process	Chi Square	Degrees of Fredom	p.value	Test statistic	p.value
assembly	5.77	4	0.217	14	0.182
metalsaw	4.5	4	0.342	14.5	0.664
metfiling	3.41	4	0.491	24	0.75
planing	4.87	4	0.301	25	0.846
woodsaw	8.06	4	0.089	21	0.541

Table 5-11, below shows the results of the same tests applied to the adult female cohort.

Table 5-11 Bench-height and efficiency - adult females

Friedman Test				Sign Rank Test between E-150 and Existing	
Process	Chi Square	Degrees of Fredom	p.value	Test statistic	p.value
assembly	10.05	4	0.04	9.5	0.066
metalsaw	3.2	4	0.526	21.5	0.922
metfiling	1.5	4	0.826	12	0.131
planing	5.24	4	0.264	33	0.609
woodsaw	3.27	4	0.514	31.5	0.305

As can be seen for adult females there is significance for the assembly task as an effect of bench height, with a p-value of 0.04. The effect of bench height on efficiency is not statistically as evident when the adults are separated by gender. However when the male female comparison is made for processes at the E-150 and Existing heights it was found that for four processes there was a highly significant difference in favour of the males, see Table 5-12.

Table 5-12 Adult gender comparisons

Sign Rank Test between E-150 v Existing		
Process	Test statistic	p-value
Metalsaw	2321	<0.001
Metfiling	2264.5	<0.001
Planing	1767.5	<0.001
Woodsaw	2210	<0.001

The Table shows that for metal sawing, metal filing, planing and wood-sawing, there is a significant difference between the results for males and females for each of these four processes. However for the gender sub-groups and the total cohort, *bench height does not significantly influence efficiency.*

5.1.6 Summary

As stated in the design of experiments, the order of the test for height and process was randomised, in order to block the effect of learning. Subjects were timed for each process and these were compared for each height. Observing the subjects work at the various heights, it was noted that while they appeared less comfortable and were working in non-neutral body postures, they nevertheless worked harder to compensate, seemingly ignoring the bench height. Both parametric and non-parametric tests on efficiency against bench height found bench height not to have a statistically significant effect on efficiency. Therefore while there was some differences, for example E-150 was more efficient than E-100, neither this nor any of the other combinations were statistically significant. As the statistical analysis failed to reject the null hypothesis, *it is concluded that bench height has no effect on efficiency for the adult group.*

As has been shown however, Body Part Discomfort (BPD), does have a significant difference depending on working height. This is likely to lead to fatigue over a prolonged period and it is expected, will add to the efficiency differences so that they may become significant.

5.2 The senior students test group

The Test Cohort

The senior test group constituted one third of the able bodied test subjects. The group consisted of nine females and eleven males. They were all technology classroom bench process users with an average of four years experience. The mean age was 16.3 years and the standard deviation was just 0.5 years. The mean stature of the group was 1741 mm (15 mm taller than the Adult Group), the Standard Deviation 103.2 mm. The 5th percentile (female) stature was 1552 mm and the 95th percentile (male) stature was 1985 mm. That is 135 mm taller than the tallest adult tested. The tallest female in this group was 52 mm taller than the tallest male adult tested. The summary statistics for the group are seen in Table 5.13.

Table 5-13 Summary statistics of able-bodied seniors

	Age	*Stature*	*Elbow*
N	20	20	20
mean	16.29578	1741.1	1092.35
Std.Dev.	0.520429	103.2075	72.9847
min	15.333	1552	969
Q1	16	1685.5	1053.5
median	16.20833	1711	1079
Q3	16.52083	1776.25	1105.75
max	17.41667	1985	1265
missing values	0	0	0

The group was tested on the trial rig described in the previous section. The five test heights were randomised as before, as were the five bench processes so as to eliminate any learning effect. Subjects completed a pre-test questionnaire to establish suitability and signed a consent form. The test procedure was fully explained to all and they were reminded that they could exit the test at any time.

5.2.1 Analysis of the data

5.2.1.1 The effects of working height on BPD

The BPD was measured as described in Chapters 3 and 4. Scores were derived from the body map of 25 body parts. Figure 5-1 below shows the mean BPD for all bench heights tested. Again, E-250 and the existing bench produced the greatest discomfort and E-150 the least. The discomfort is particularly expressed in the back for these heights and in the shoulders for E-100. There also was some hand/wrist discomfort. Figure 5-16 shows the mean BPD for the group.

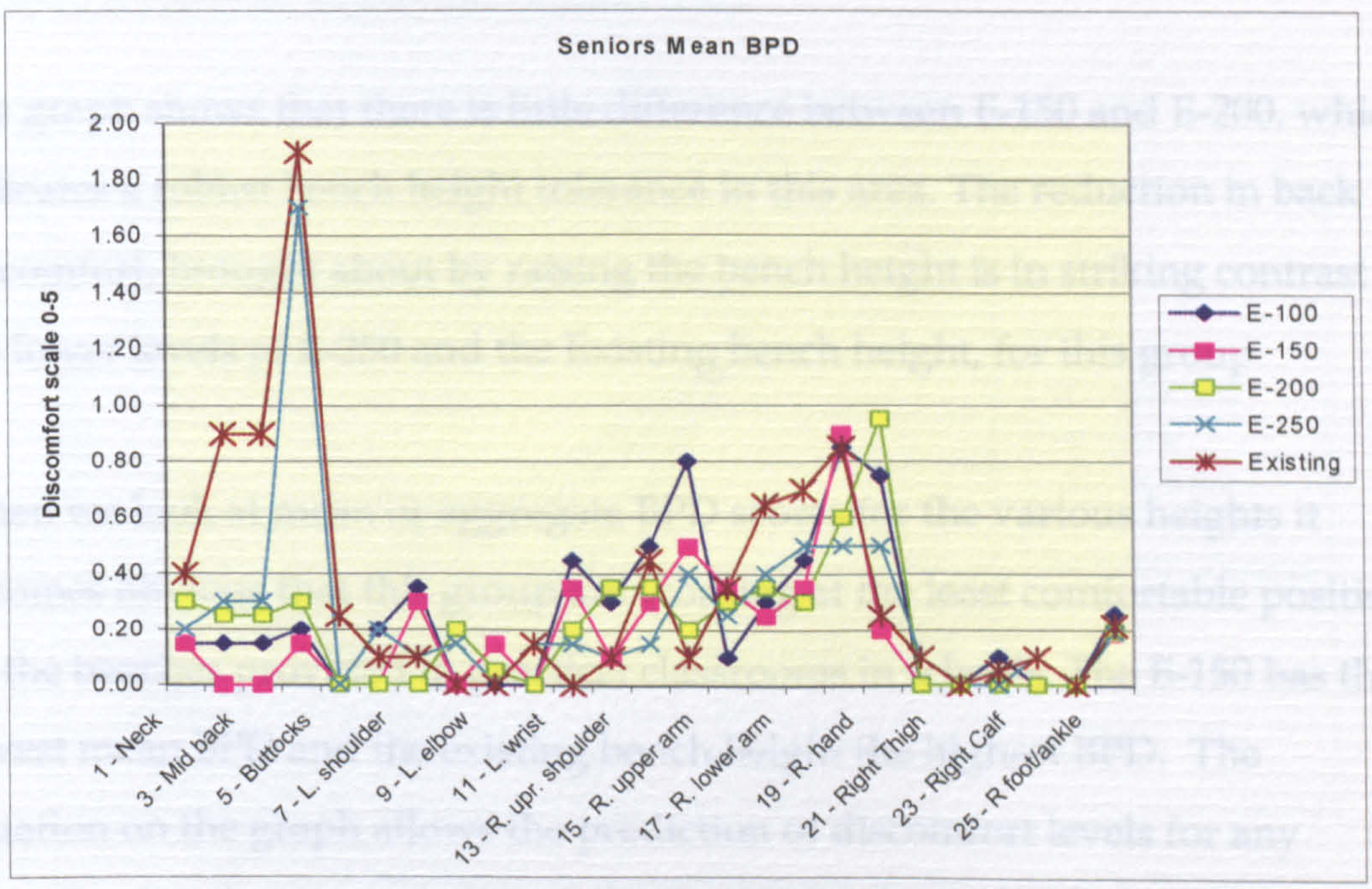


Figure 5-16 Mean BPD for the seniors

As can be seen, the back again has significant discomfort. The areas of the neck, back, and shoulders are shown in Figure 5-17. E-150 produced the most satisfactory result, but this however is with the sacrifice of some shoulder comfort, although not significantly so.

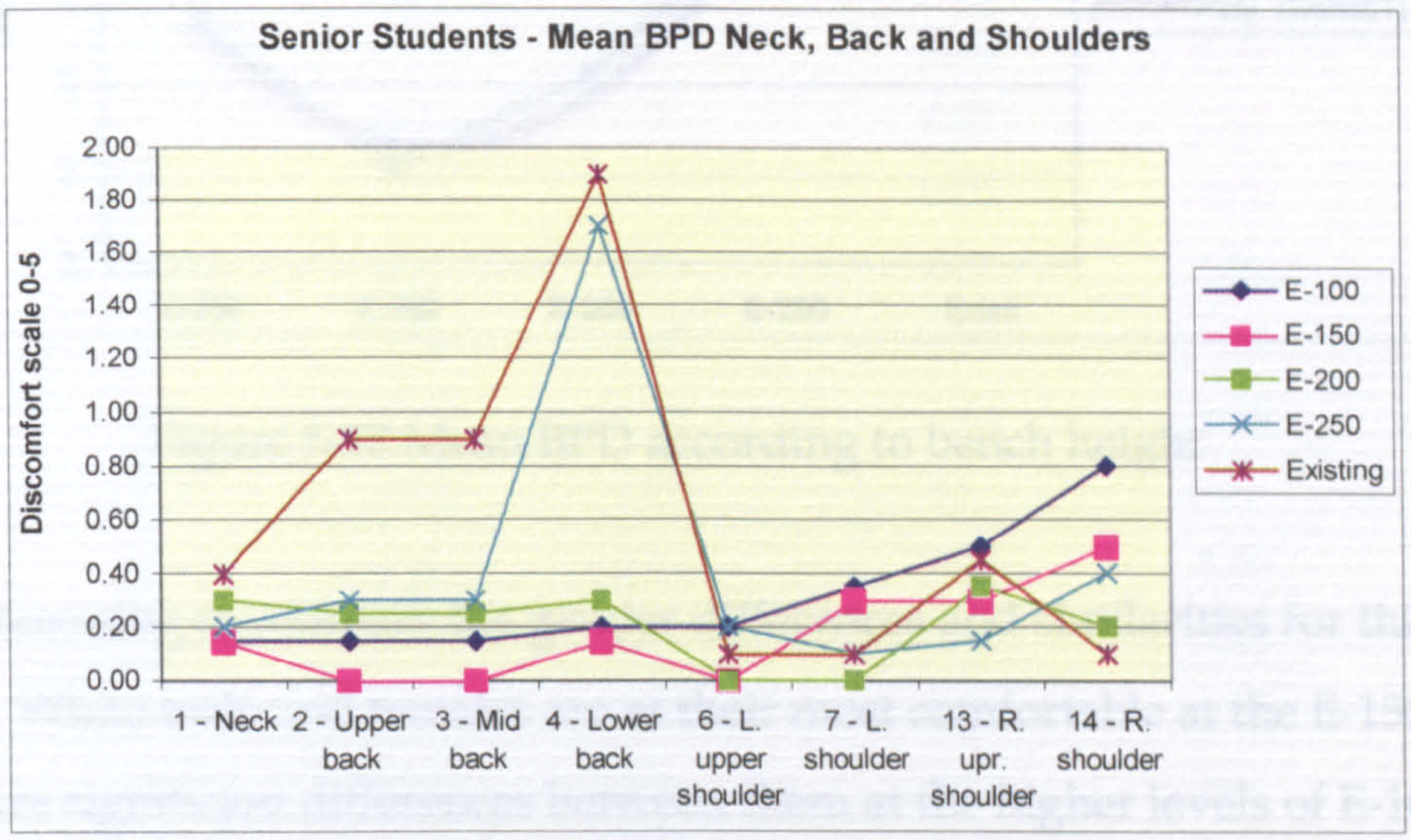


Figure 5-17 BPD for neck back and shoulders

The graph shows that there is little difference between E-150 and E-200, which indicates a robust bench height tolerance in this area. The reduction in back discomfort, brought about by raising the bench height is in striking contrast to the lower levels of E-250 and the Existing bench height, for this group.

When we look at mean or aggregate BPD scores for the various heights it becomes obvious that this group are working at the least comfortable position on the benches provided in practical classrooms in schools. The E-150 has the lowest mean BPD and the existing bench height the highest BPD. The equation on the graph allows the prediction of discomfort levels for any particular height chosen within the range. Figure 5-18 illustrates the contrast between the existing bench height and the others in the test bank. The Existing bench was more than 300 mm below elbow height for this group.

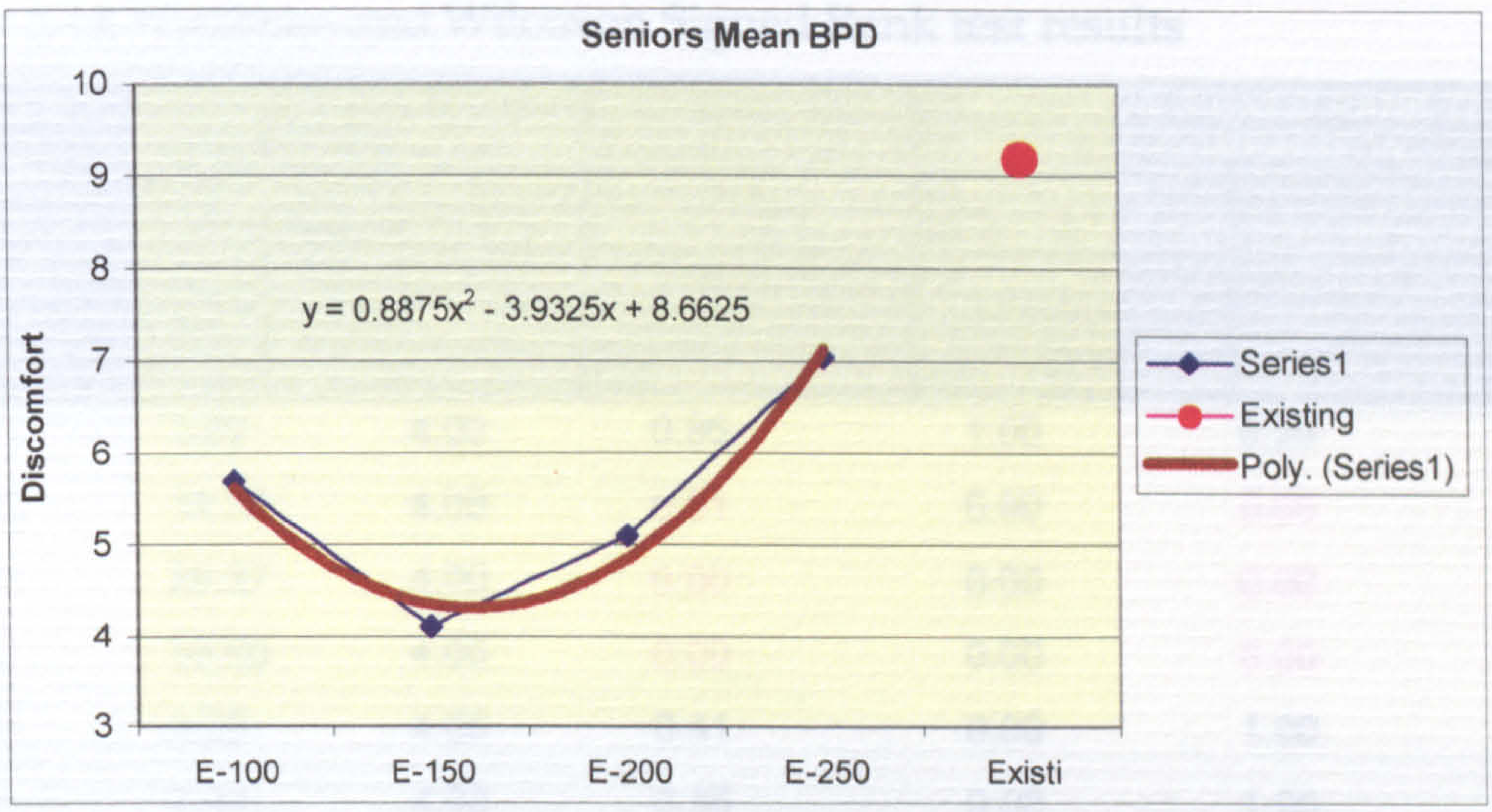


Figure 5-18 Mean BPD according to bench height

It is interesting to compare the gender differences and similarities for this group. While male and females are at their most comfortable at the E-150 level, there are significant differences between them at the higher levels of E-100 and E-150, but the BPD almost converges at E-250. Both had greatest discomfort at the Existing bench height (see Figure 5-19).

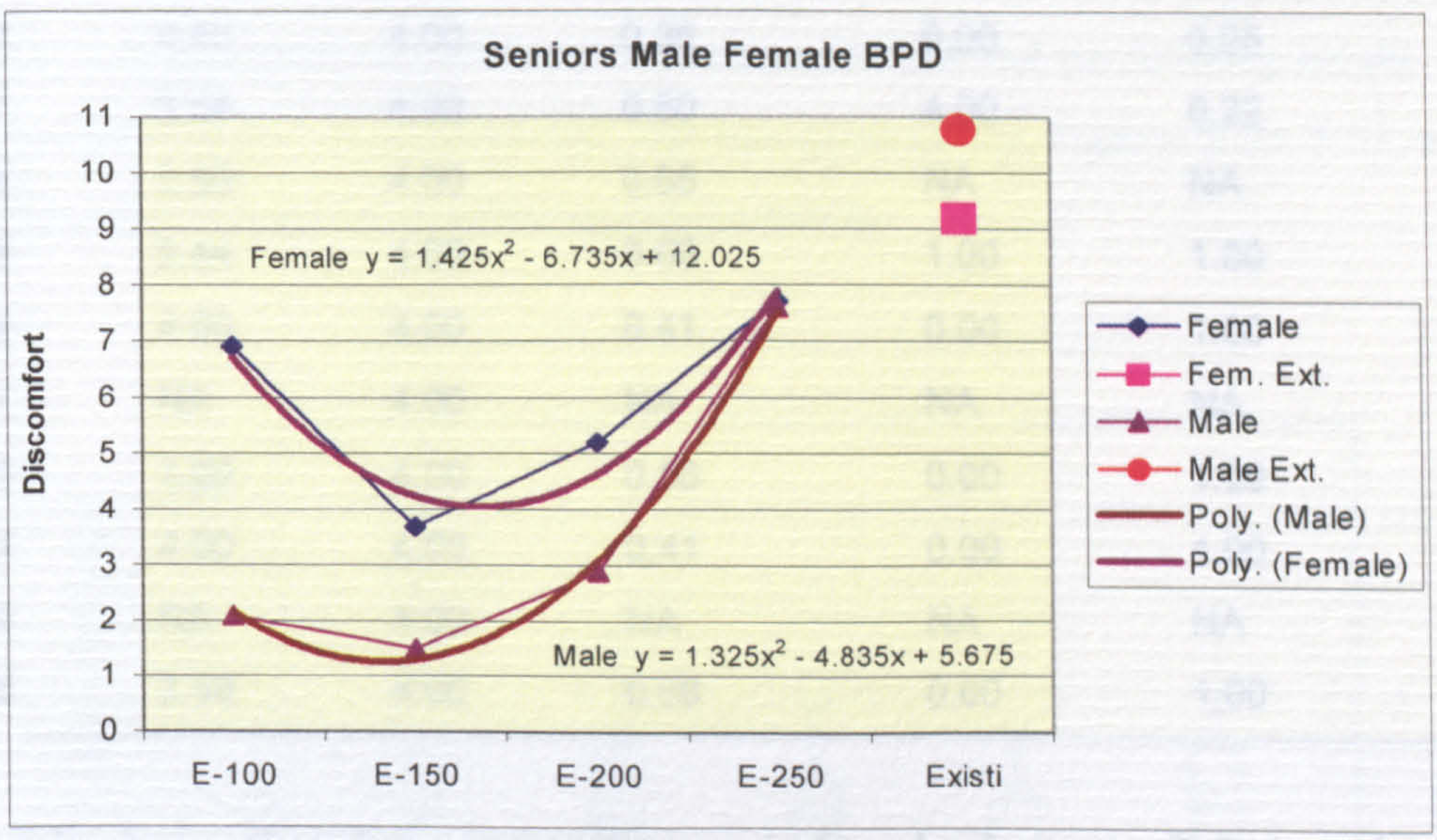


Figure 5-19 Mean male and female BPD for bench height

The table below, Table 5-14, represents the results from the Friedman and Wilcoxon Signed-Rank tests.

Table 5-14 Friedman and Wilcoxon Signed Rank test results

VARIABLE BEING TESTED	FRIEDMAN TEST RESULTS, TESTING IF BENCH HEIGHT HAS A SIGNIFICANT EFFECT ON VARIABLE			WILCOXON SIGNED RANK TEST RESULTS, COMPARISON BETWEEN E-150 AND EXISTING BENCH HEIGHTS	
variable	Chi Square	Degrees of Freedom	Significance	Test Statistic	Significance
bpd1	1.29	4.00	0.86	1.00	0.25
bpd2	14.76	4.00	0.01	0.00	0.03
bpd3	29.37	4.00	0.00	0.00	0.00
bpd4	39.65	4.00	0.00	0.00	0.00
bpd5	4.00	4.00	0.41	0.00	1.00
bpd6	4.44	4.00	0.35	0.00	1.00
bpd7	5.57	4.00	0.23	3.00	0.50
bpd8	2.46	4.00	0.65	NA	NA
bpd9	4.00	4.00	0.41	1.00	1.00
bpd10	4.00	4.00	0.41	0.00	1.00
bpd11	5.62	4.00	0.23	3.00	0.50
bpd12	4.00	4.00	0.41	NA	NA
bpd13	2.11	4.00	0.72	4.00	0.50
bpd14	9.64	4.00	0.05	15.00	0.06
bpd15	4.62	4.00	0.33	1.00	1.00
bpd16	4.40	4.00	0.36	0.00	0.25
bpd17	3.34	4.00	0.50	4.00	0.22
bpd18	2.50	4.00	0.65	NA	NA
bpd19	2.44	4.00	0.66	1.00	1.00
bpd20	4.00	4.00	0.41	0.00	1.00
bpd21	NA	4.00	NA	NA	NA
bpd22	3.00	4.00	0.56	0.00	1.00
bpd23	4.00	4.00	0.41	0.00	1.00
bpd24	NA	4.00	NA	NA	NA
bpd25	2.40	4.00	0.66	0.00	1.00

The table shows that there is significance in four body parts, 2, 3, 4, and 14, the back and shoulders. Body parts 3, and 4 are highly significant at p=<0.001. All these areas proved significant when the Wilcoxon Signed Rank test was applied to test between E-150 and the Existing height, with the exception of BP14 (the right shoulder), which was just under significance at p=0.06.

The aggregates for the whole body, the back and the shoulders were tested in the same way. Table 5-15 below shows the results. The aggregate body part discomfort (ABPD), and the back aggregate, show very high significance, with a p value of p=<0.001, for the effect of the variable and for the compared effect between E-150 and the Existing height.

Table 5-15 Test results for aggregate BPDs

VARIABLE BEING TESTED		FRIEDMAN TEST RESULTS, TESTING IF BENCH HEIGHT HAS A SIGNIFICANT EFFECT ON VARIABLE		WILCOXON SIGNED RANK TEST RESULTS, COMPARISON BETWEEN E-150 AND EXISTING BENCH HEIGHTS	
variable	*Chi Square*	*Degrees of Freedom*	*Significance*	*Test Statistic*	*Significance*
Agg. BPD	31.49	4.00	0.00	5.50	0.00
Shoulders	6.04	4.00	0.20	18.00	0.59
Back	50.16	4.00	0.00	0.00	0.00

The shoulders, while showing some discomfort, did not have statistical significance for either the height variable or between the preferred height and the Existing height, with p values of 0.02 and 0.59 respectively. The box-plots below, Figures 5-20, 5-21, and 5-22 illustrate the comparisons of the aggregate BPDs.

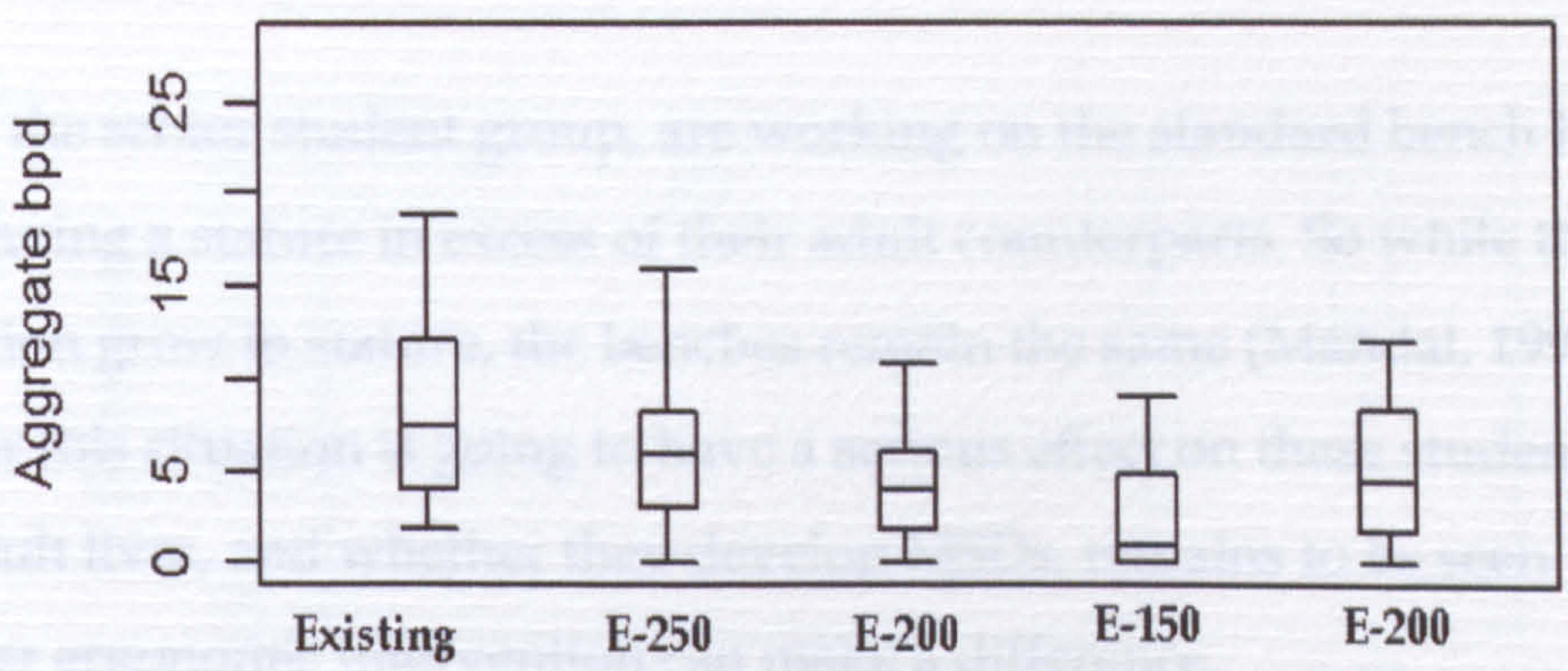


Figure 5-20 Aggregate BPD seniors

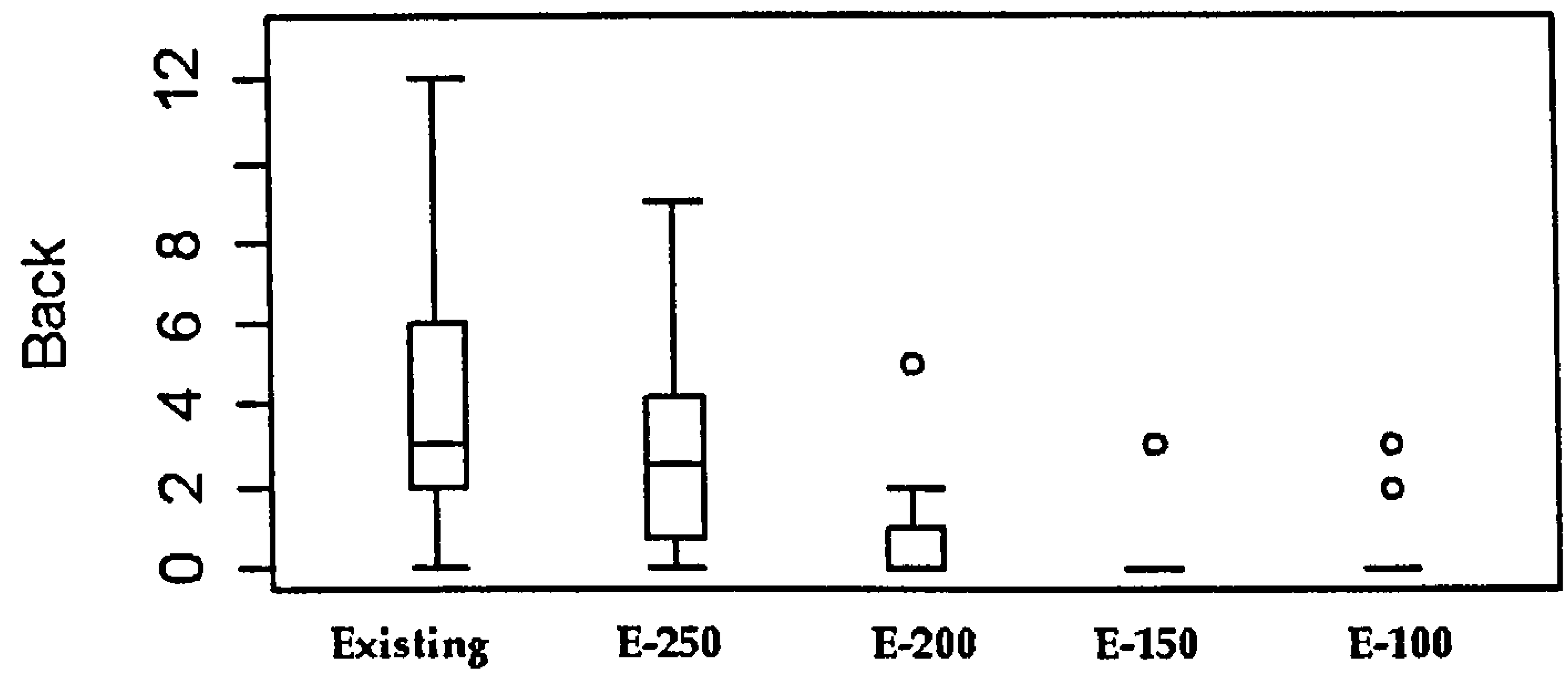


Figure 5-21 Aggregate back BPD seniors

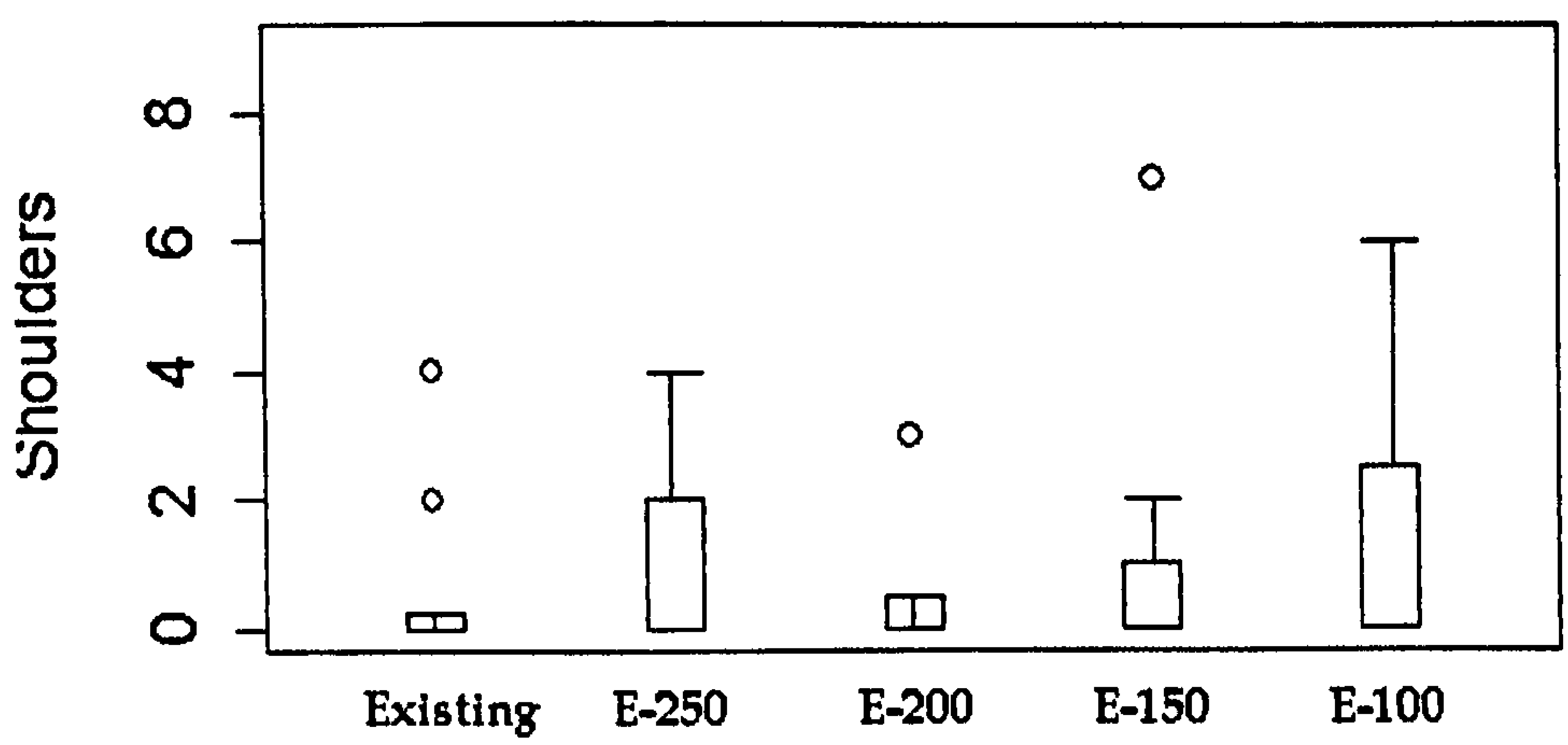


Figure 5-22 Boxplot of shoulder BPD seniors

Most of the senior student group, are working on the standard bench height, while having a stature in excess of their adult counterparts. So while the user population grow in stature, the benches remain the same (Mandal, 1997). Whether this situation is going to have a serious effect on these students in their adult lives, and whether they develop MSDs, remains to be seen. However ergonomic intervention can make a difference.

As has been shown, bench height has a very significant effect on the comfort/discomfort of the senior student group.

5.2.1.2 Endurance

Endurance was measured as a subjective estimate for each height after completing the test bank at that height. Subjects were asked; "How long do you feel you could endure working at this height, doing this type of work?" The subjects responded in groups of hours, which were coded as in Table 5.5

The Friedman test on endurance shows that it is significantly effected by the height of the bench. The application of the Wilcoxon Sign-Rank test shows that E-150 results in a significantly different (better) endurance level than the Existing bench height, see Table 5.13.

Table 5-16 Friedman and Wilcoxon Signed Rank tests results

Friedman test between heights				Wilcoxon SR E-150 V Existing	
variable	*Chi Square*	*Degrees of Freedom*	*Significance*	*Test Statistic*	*Significance*
endurance	28.08	4.00	p=<0.001	0.00	p=<0.001

The box-plot below, Figure 5.23, shows the E-150 level to be better for endurance than all others, the lowest number score indicates the longest endurance.

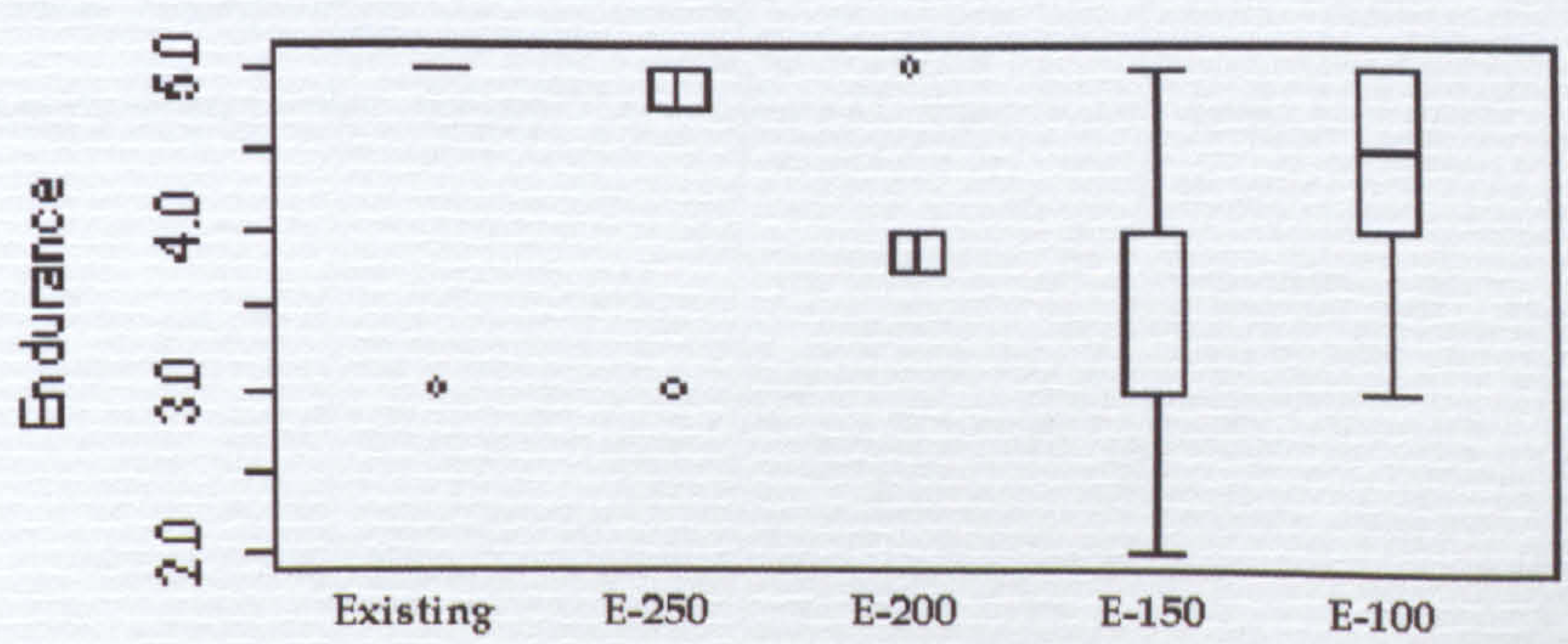


Figure 5-23 Endurance box-plot - seniors

Figure 5-24 below illustrates the mean endurance estimates, and a quadratic equation has been added. This allows the estimation of endurance for a particular height this may be termed the quadratic endurance indicator (QEI).

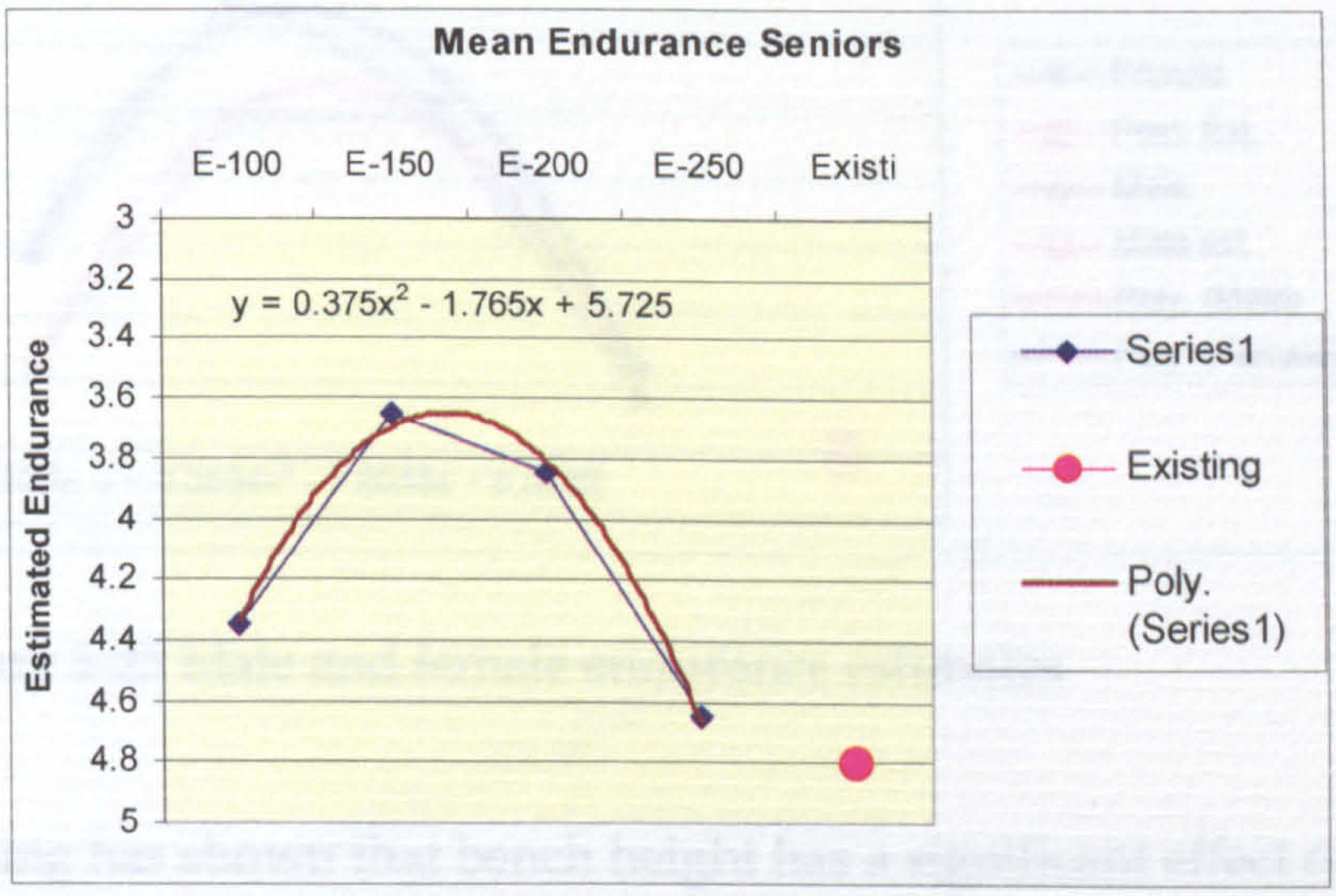


Figure 5-24 Mean endurance graph with QEI

The gender comparison at Figure 5-25 shows the endurance curves for the male and female sub-groups. It is interesting to note that while there are not significant differences in endurance estimates, the females like their cognate adult group, have a longer endurance estimate than the males, while having a higher aggregate BPD.

The E-250 and Existing levels are almost the same for males and females, and as can be seen, these two levels have the lowest endurance estimate.

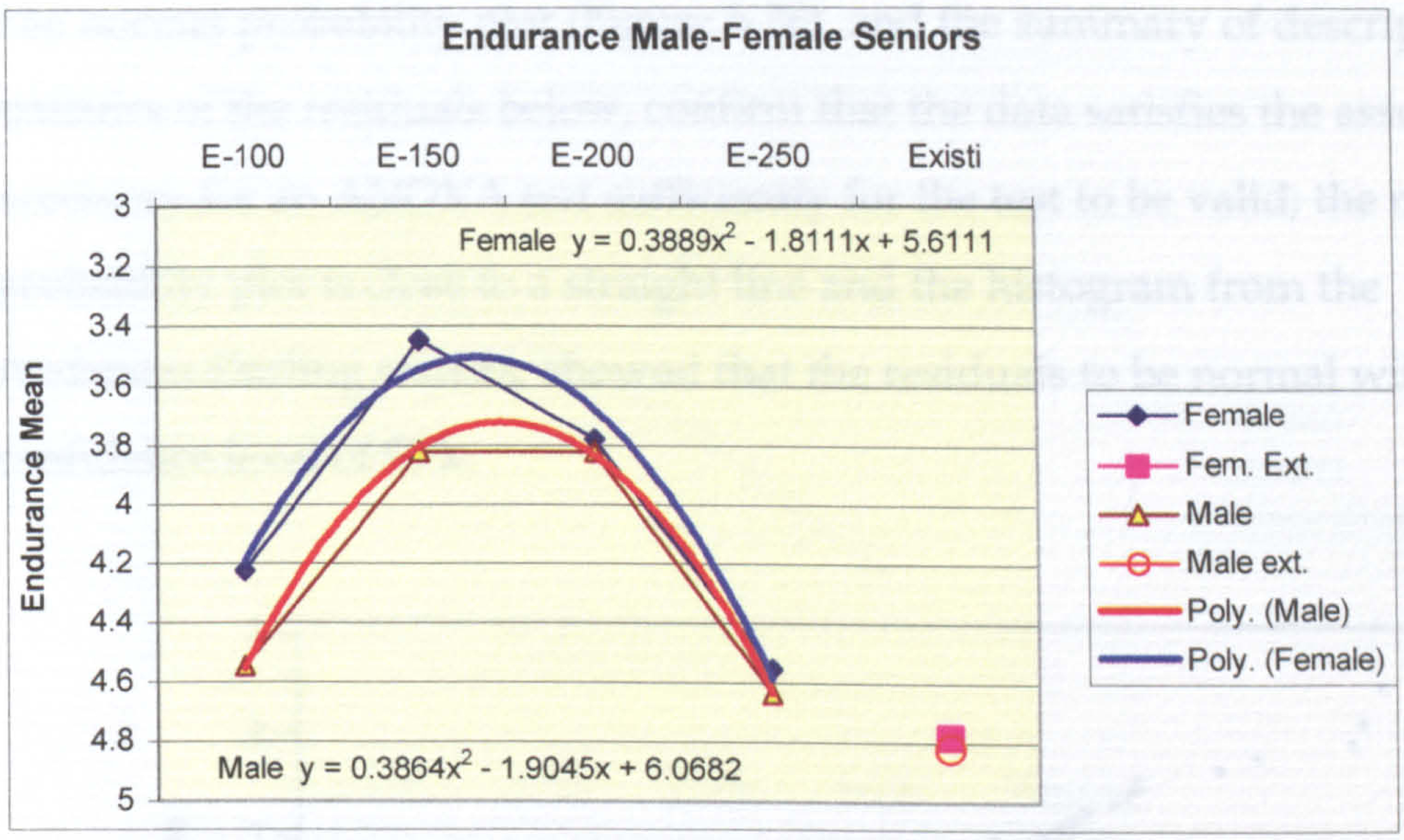


Figure 5-25 Male and female endurance estimates

The foregoing has shown that bench height has a significant effect on endurance estimates and the findings concur that the best estimate is for E-150 and which has the lowest BPD.

Based on the evidence presented, the null hypothesis that endurance is not effected by bench height, must be rejected.

5.2.1.3 Overall subjective height ratings

The significance value from the analysis tells us that the subjects gave significantly different overall satisfaction rates for different bench heights. No other variables were deemed to add enough extra information to the model to be relevant. The R squared value for process (from individual height ratings) was lower than the R squared value for overall height rating and therefore was of less significance.

The normal probability plot (Figure 5-26), and the summary of descriptive statistics of the residuals below, confirm that the data satisfies the assumptions necessary for an ANOVA test sufficiently for the test to be valid; the normal probability plot is close to a straight line and the histogram from the Anderson-Darling statistic showed that the residuals to be normal with a confidence level of 95%.

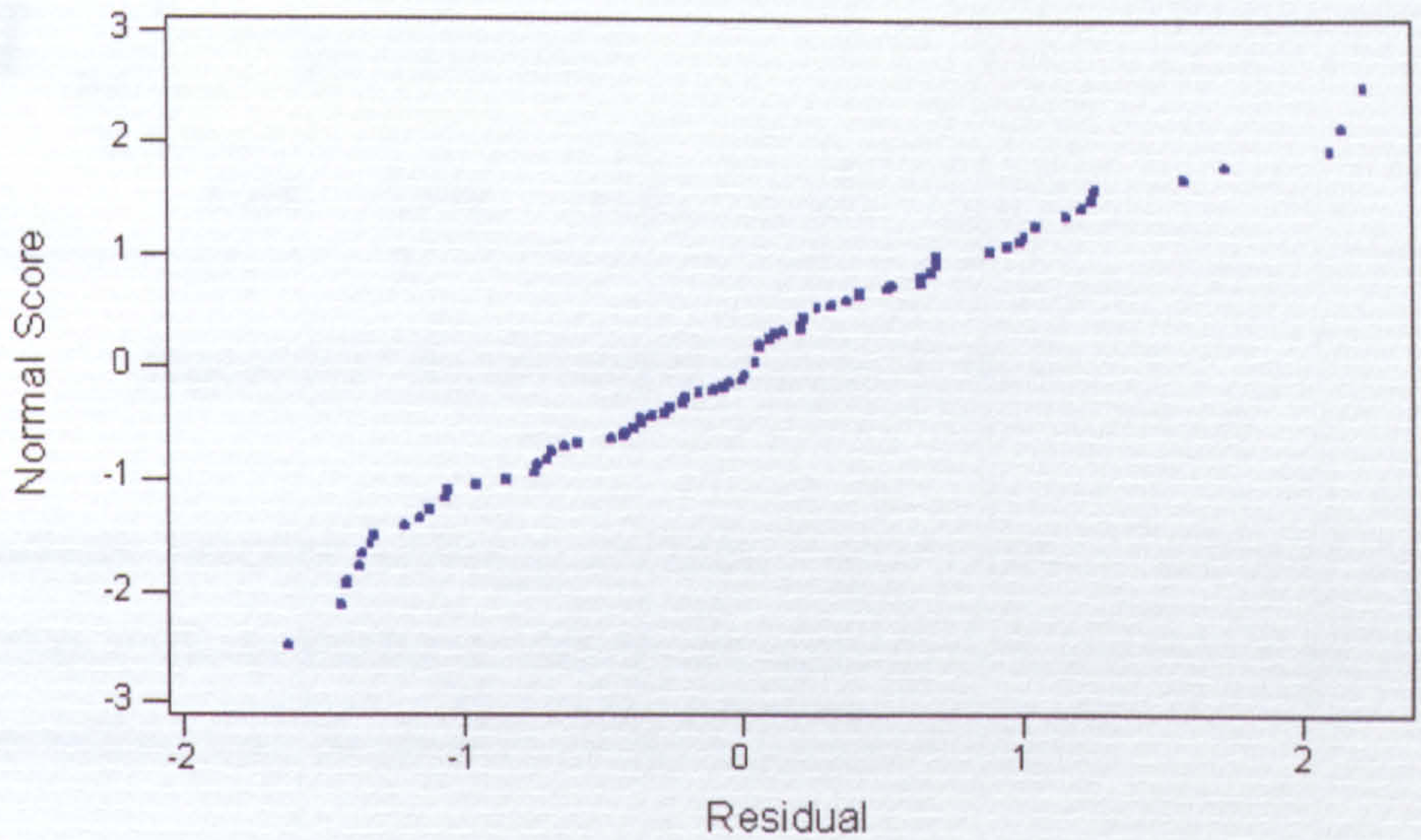


Figure 5-26 The normal probability plot of residuals

Applying Tukey's test of multiple comparisons showed that all heights were significantly different in height rating with the exception of E-150 and E-200, with a p value of 0.125. All other comparisons produced a highly significant value of P=<0.001.

The graph below, Figure 5-27, shows the mean general bench height ratings. As heights move away from the '0' line they fall into a straight line graph. Again the E-150 height falls nearest to the 'ideal' height rating. E-100 is significantly too high and E-250, and the Existing height are rated extremely too low. Existing is the worst height.

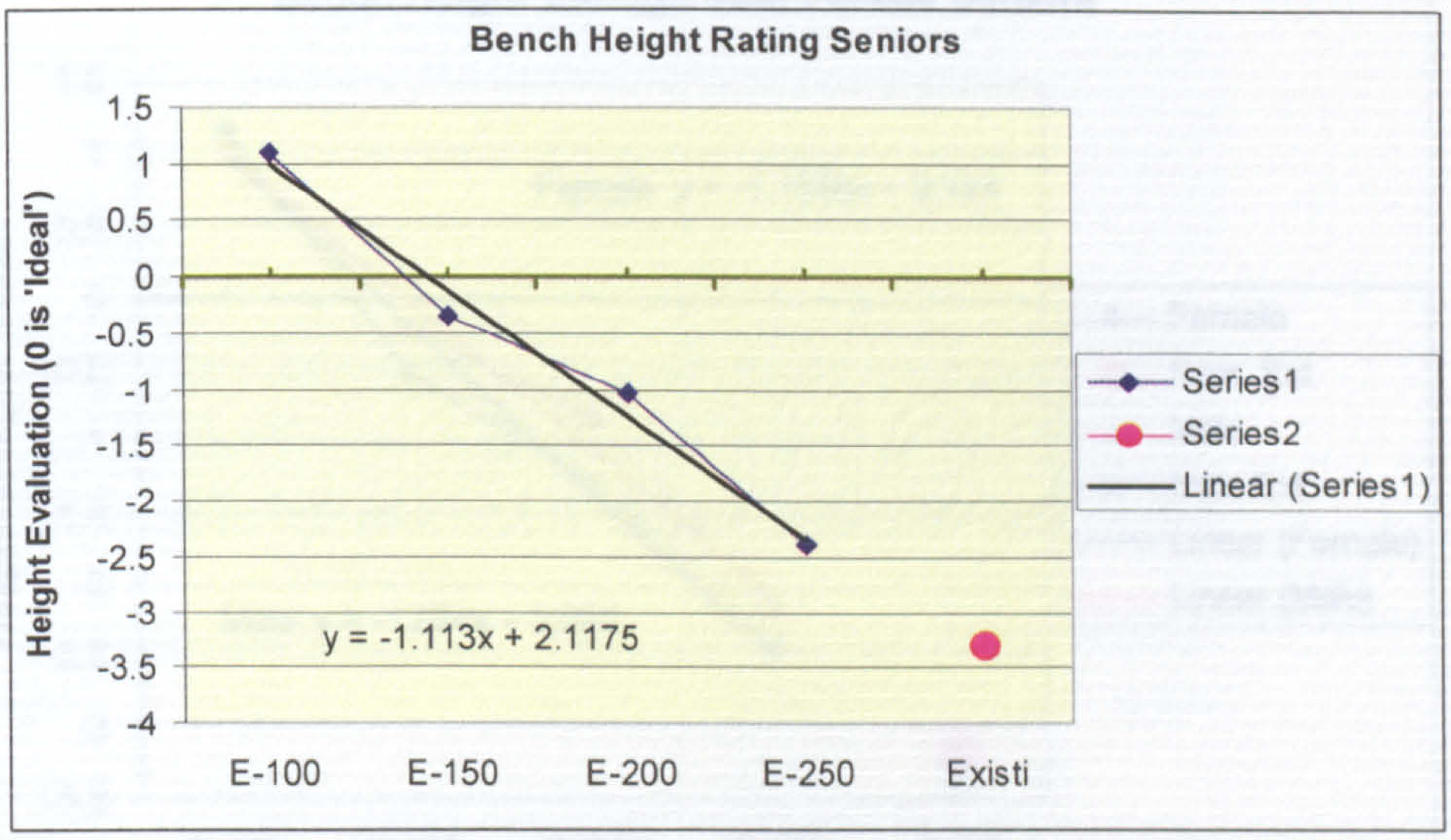


Figure 5-27 Bench height ratings - seniors

The quadratic function added to the graph may be used to determine a satisfaction level according to height, the quadratic satisfaction indicator (QSI) or the trendline may be used to obtain a graphical result.

Gender comparisons for height rating show from the plots of the mean ratings that male and female ratings fall into an almost straight line, as can be seen from the close proximity of the trendlines to the data points. Figure 5-28 shows the male/female comparisons. As can be seen each deviates little from the total seniors cohort, nor is there any significance in gender difference. Height ratings are significant for all comparisons, as with the total cohort, again with the exception of the E-150 and E-200, which were not rated significantly different.

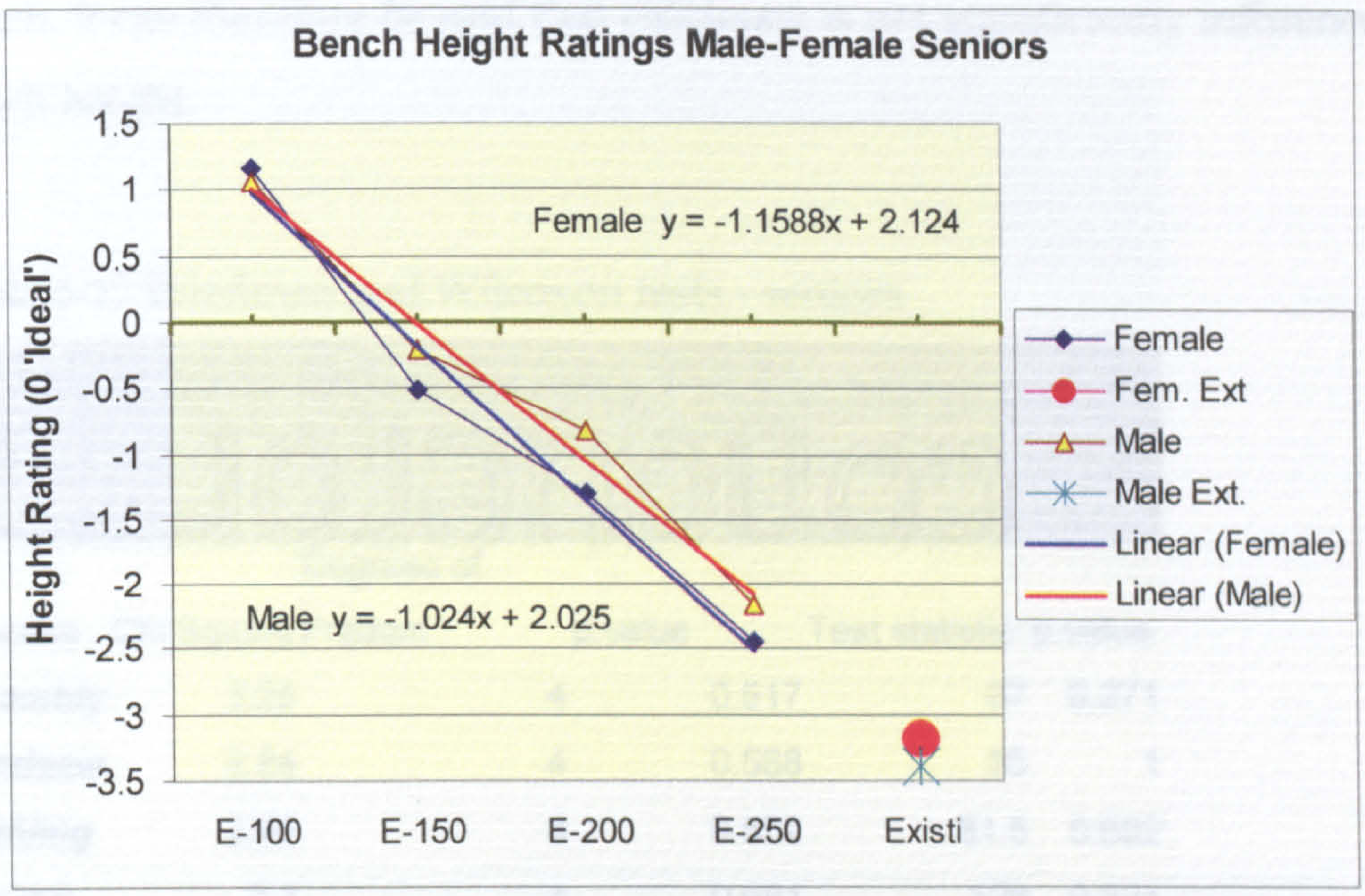


Figure 5-28 Gender comparisons for height ratings - seniors

Height rating is a significant factor in the satisfaction with any particular bench height. Ratings for individual processes proved less important than the overall rating and as a result should be superseded by the overall rating which plays a more important role in determining a subjects satisfaction with a particular bench.

Bench height plays an important role in user satisfaction.

5.2.1.4 Efficiency

Efficiency was tested in exactly the same manner as for the Adult group described in 5.1.6. Tasks and heights were randomised and all processes were stop-watch timed. Table 5-17, below shows that there are no significant values for efficiency against bench height, as all p values exceed 0.05. Neither is there any significance when comparing performance at E-150 with the Existing bench. It can therefore be said that efficiency is not significantly influenced by bench height.

Table 5-17 Friedman and Wilcoxon tests - seniors

Friedman Test				Wilcoxon Sign Rank Test between E-150 and Existing	
Process	Chi Square	Degrees of Fredom	p.value	Test statistic	p.value
assembly	3.25	4	0.517	67	0.271
metalsaw	2.94	4	0.568	85	1
metfiling	2.42	4	0.659	81.5	0.602
planing	2.3	4	0.681	126	0.221
woodsaw	1.25	4	0.87	109	0.588

When we examine efficiency according to gender the same picture emerges, none of the processes have a p value of less than 0.05 in any of the comparisons made. See Tables 5-18 and 5-19 below.

Table 5-18 Significance values - senior males

Friedman Test				Sign Rank Test between E-150 and Existing	
Process	Chi Square	Degrees of Fredom	p.value	Test statistic	p.value
assembly	3.7	4	0.448	23.5	0.427
metalsaw	1.89	4	0.755	35	0.475
metfiling	2.39	4	0.664	31.5	0.915
planing	2.21	4	0.698	47	0.24
woodsaw	0.58	4	0.965	32	0.952

Table 5-19 Significance values - senior females

Friedman Test				*Sign Rank Test between E-150 and Existing*	
Process	Chi Square	Degrees of Fredom	p.value	Test statistic	p.value
assembly	3.22	4	0.521	12	0.461
metalsaw	1.41	4	0.842	14	0.641
metfiling	1.3	4	0.862	13	0.547
planing	1.34	4	0.854	22	0.641
woodsaw	1.89	4	0.757	21	0.742

However when between-gender comparisons were made, it was found that there were highly significant p values for three processes, metal sawing, metal filing and wood sawing. The male advantage in efficiency was probably due to strength factors. Table 5-20 below shows the p values for the five processes. Since there were no significant effects across bench heights, then the analysis of the efficiency data for all bench heights together was used for gender comparison.

Table 5-20 Seniors gender comparisons

	Sign Rank Test between E-150 and Existing	
Process	Test statistic	p.value
assembly	977	0.071
metalsaw	1749	0
metfiling	1624	0.007
planing	1269.5	0.825
woodsaw	1803.5	0

Planing and assembly are the only processes in which there was no significant difference between the efficiency of males and females.

5.2.1.5 Summary

The analysis of the data shows that for the processes undertaken at the various heights, bench height did not have a significant effect on efficiency. However observing some very tall test subjects when working at the various tasks, and noting their discomfort at some of the heights and especially the Existing height, it was evident that with all groups they appeared to ignore the discomfort in order to complete the task on hand. While this is praiseworthy, it is not a reason for failing to meet the ergonomic needs of young people whose body is not yet mature and who may cause damage that will manifest itself in the future.

However, as the statistical analysis failed to reject the null hypothesis, and *it is concluded that bench height has no effect on efficiency for the senior student group.*

5.3 The junior students test group

The Test Cohort

The junior test group constituted one third of the able bodied test subjects. The group consisted of ten females and ten males. They were all technology classroom bench process users with an average of three to four months experience. Their mean age was 13.3 years and the standard deviation was 0.48 years. The mean stature of the group was 1607 mm and the Standard Deviation 49 mm. The 5th percentile (male) stature was 1442 mm and the 95th percentile (male) stature was 1761 mm. The summary statistics for the group are seen in Table 5-21.

Table 5-21 Summary statistics of Able-bodied juniors

	age	stature	elbow
N	20	20	20
mean	13.304	1606.55	1004.4
Std.Dev.	0.4778	68.596	48.898
min	12.417	1442	890
Q1	12.979	1567	980
median	13.208	1617.5	999
Q3	13.833	1635.25	1017.25
max	14	1761	1135
missing values	0	0	0

The group was tested on the trial rig, as with the adults and seniors. The five test heights were randomised as before, as were the five bench processes so as to eliminate any learning effect. Subjects completed a pre-test questionnaire to establish suitability and signed a consent form. The test procedure was fully explained to all and they were reminded that they could exit the test at any time. All students including the seniors had parental consent to participate in the test.

5.3.1 Analysis of the data

5.3.1.1 The effects of working height on BPD

The BPD was measured as described in Chapters 3 and 4. Scores were derived from the body map of 25 body parts. Figure 5.1 below shows the mean BPD for all bench heights tested. Again, E-250 and the existing bench produced the greatest discomfort and E-150 the least. The discomfort is particularly expressed in the back for these heights and in the shoulders for E-100. There also was some hand/wrist discomfort. Figure 5-29 shows the mean BPD for the group.

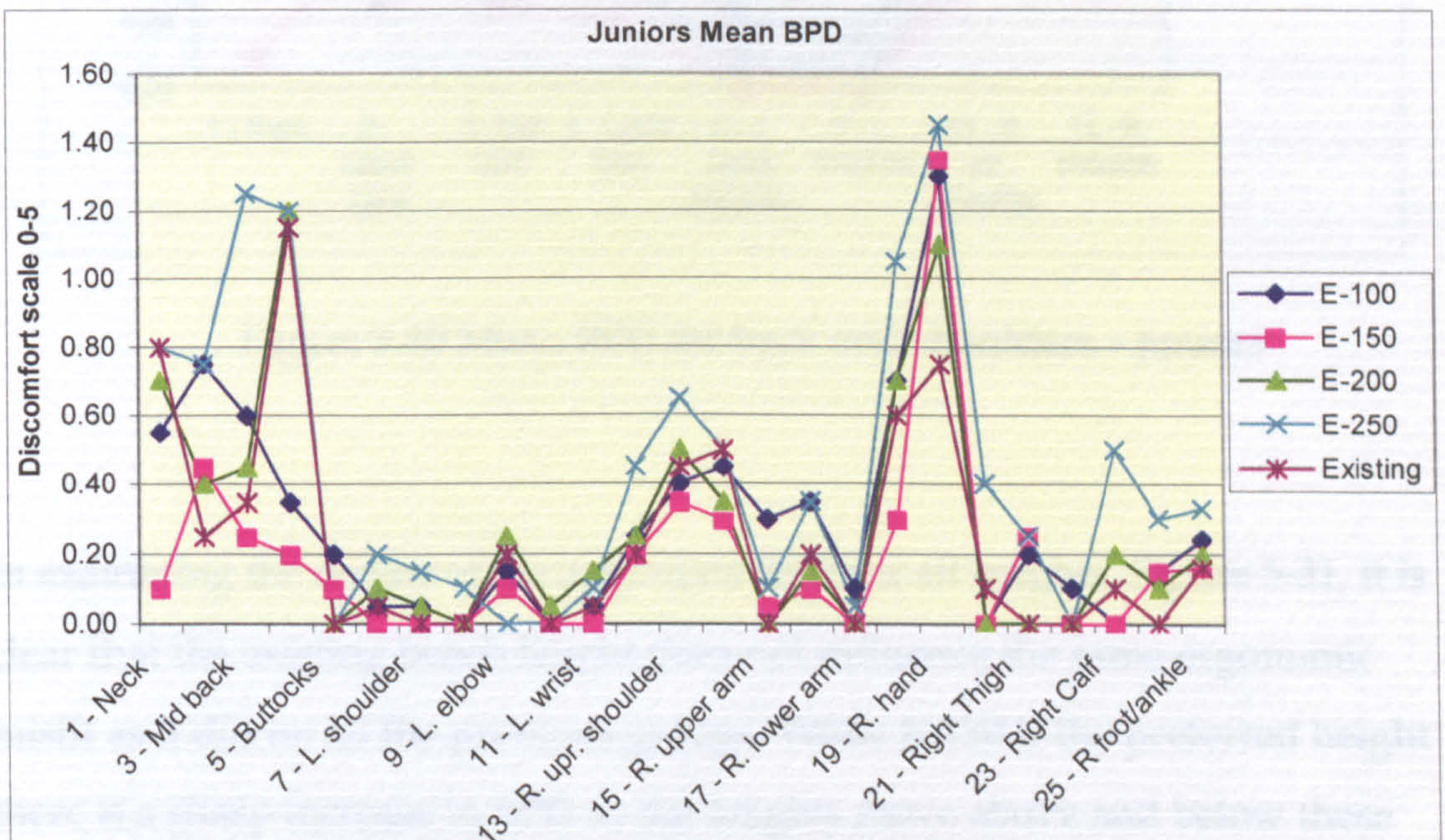


Figure 5-29 Mean BPD for all heights - juniors

As can be seen from the graph a new element enters here. The hand and wrist discomfort exceeds both the back and the shoulders. While shoulder and back discomfort is greatly reduced at E-150, the hand and wrist discomfort is not. This is likely due to the tooling being an ergonomic bad fit, and the fact that the hands and wrist are well under developed. The isolation of the back and shoulder areas as seen in Figure 5-30 below show the influence once again of the E-150 working height, which has significantly reduced the discomfort in these areas.

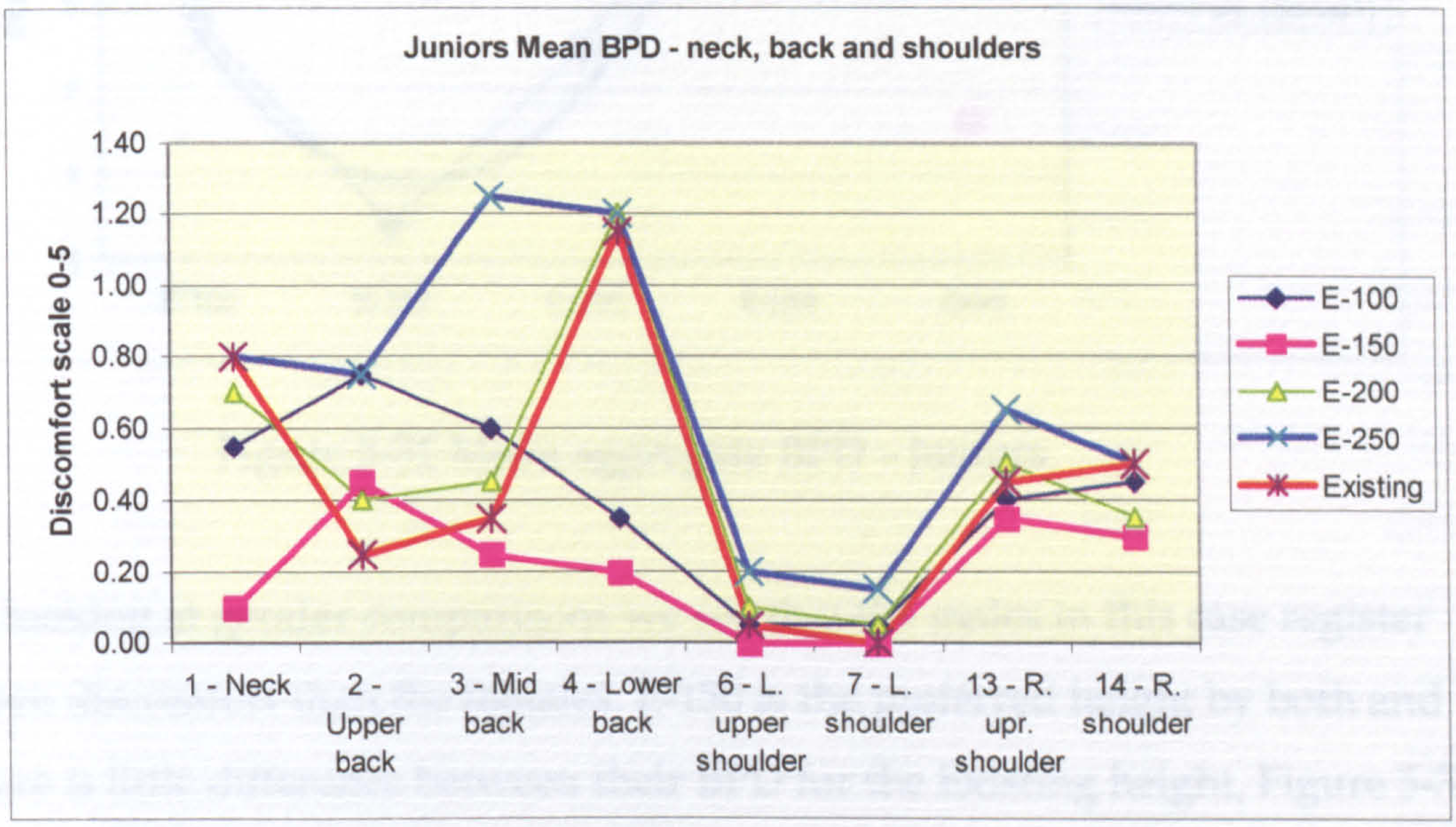


Figure 5-30 Mean BPD for back and shoulders - juniors

In examining the means of the aggregate BPD for all heights, Figure 5-31, it is clear that the existing bench height does not influence the same ergonomic misfit as it did on all the previous groups. While E-150 is the preferred height there is a sharp increase in BPD as the heights move above and below these heights, see Figure 5-30. E-250 is worst, and there is no significant difference between the E-100 height and the E-200 height. Discomfort levels do not differ significantly between the Existing height and either E-150 and E-200.

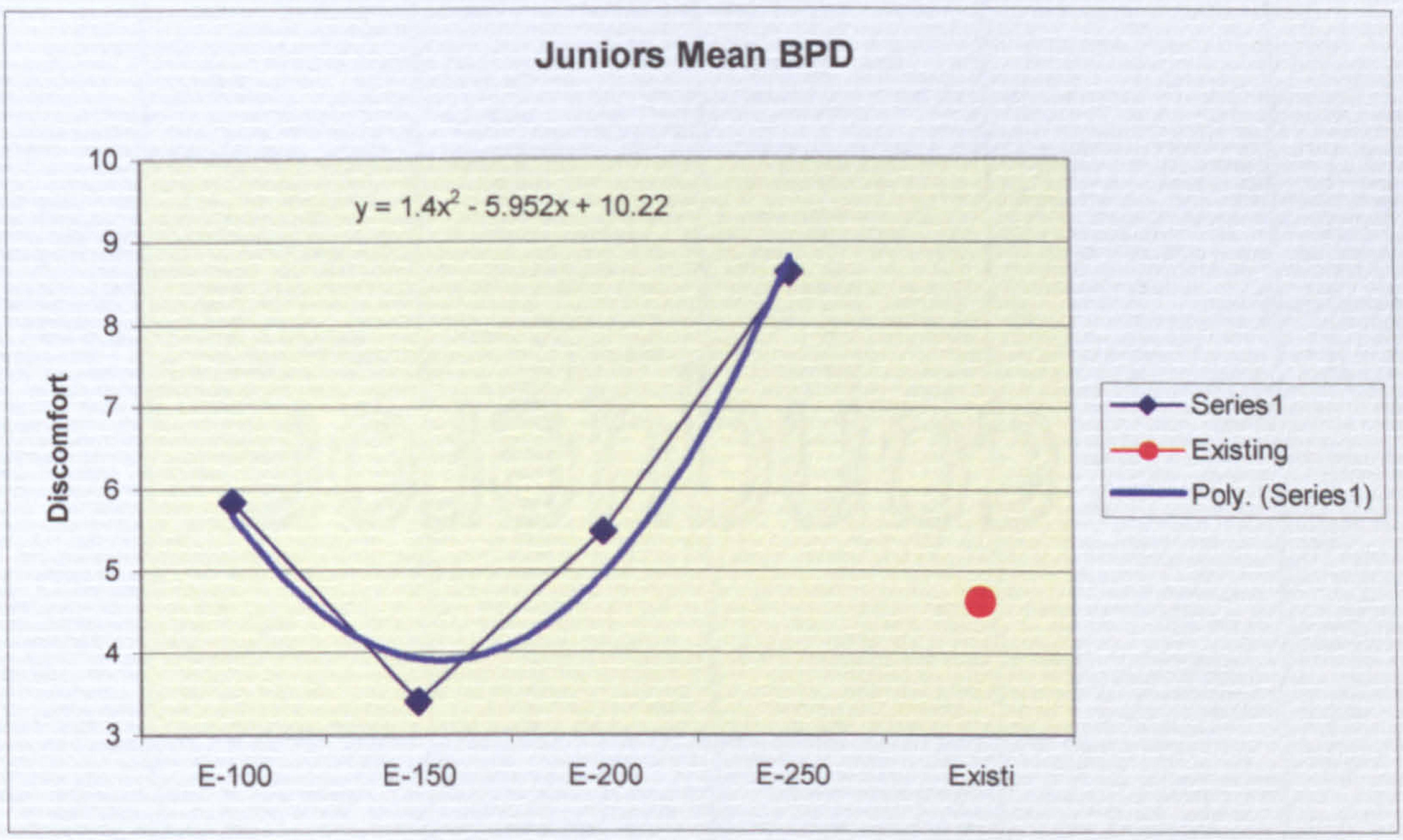


Figure 5-31 Mean aggregate BPD – juniors

In looking at gender comparisons we see that the males in this case register more discomfort than the females. E-150 is the preferred height by both and there is little difference between their BPD for the Existing height, Figure 5-32.

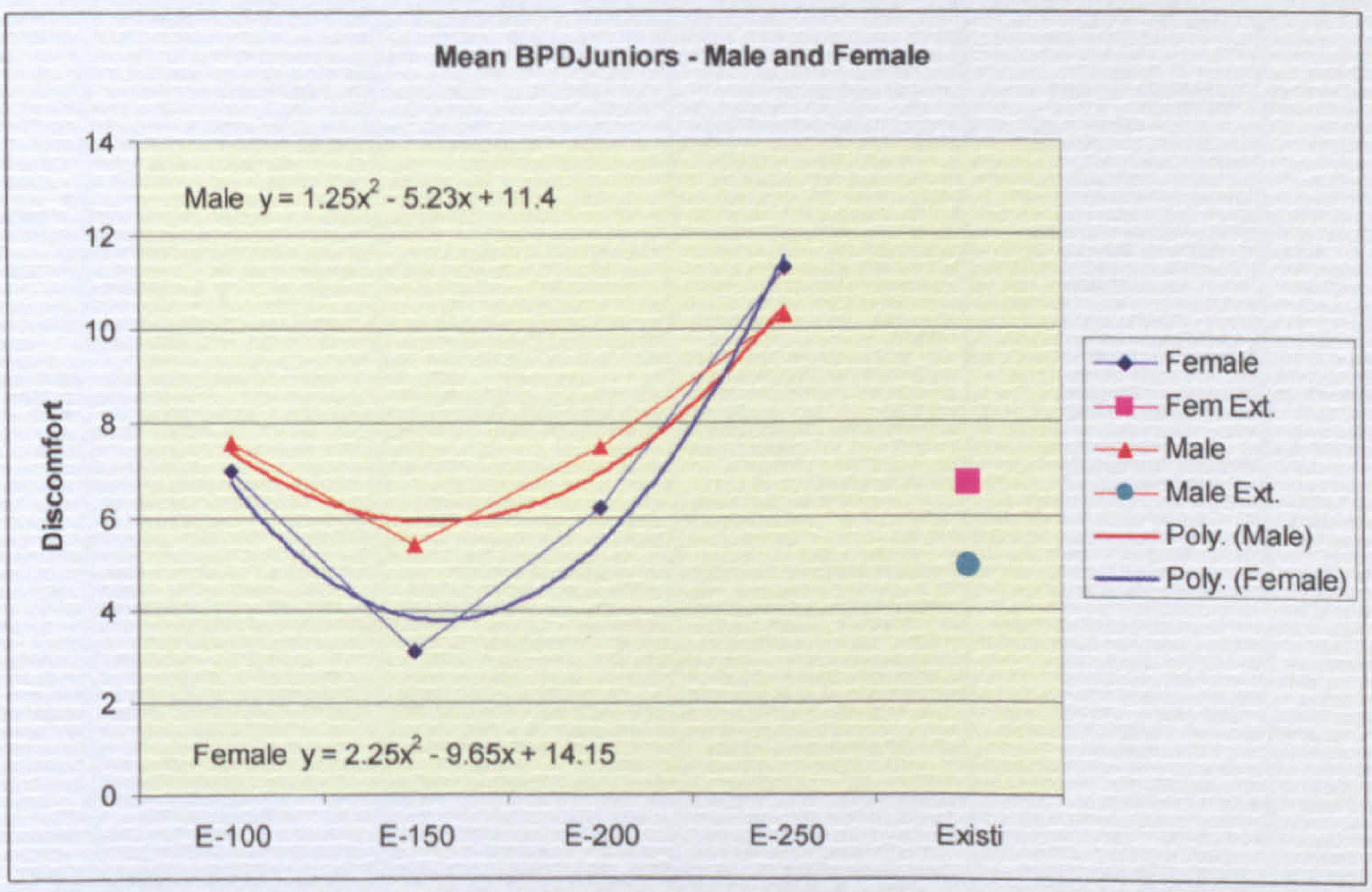


Figure 5-32 Gender BPD comparisons – juniors

Table 5-22 The results from the Friedman and Wilcoxon Signed-Rank tests.

VARIABLE BEING TESTED	FRIEDMAN TEST RESULTS, TESTING IF BENCH HEIGHT HAS A SIGNIFICANT EFFECT ON VARIABLE			WILCOXON SIGNED RANK TEST RESULTS, COMPARISON BETWEEN E-150 AND EXISTING BENCH HEIGHTS	
Variable	***Chi Square***	***Degrees of Freedom***	***Significance***	***Test Statistics***	***Significance***
bpd1	5.57	4.00	0.23	3.50	0.03
bpd2	4.68	4.00	0.32	7.00	0.50
bpd3	11.57	4.00	0.02	2.50	1.00
bpd4	6.63	4.00	0.16	7.50	0.04
bpd5	3.50	4.00	0.48	3.00	0.50
bpd6	2.80	4.00	0.59	0.00	1.00
bpd7	2.40	4.00	0.66	NA	NA
bpd8	4.00	4.00	0.41	NA	NA
bpd9	6.50	4.00	0.17	0.00	0.50
bpd10	4.00	4.00	0.41	NA	NA
bpd11	7.56	4.00	0.11	0.00	1.00
bpd12	1.48	4.00	0.83	NA	NA
bpd13	4.35	4.00	0.36	0.00	1.00
bpd14	2.84	4.00	0.59	9.00	0.88
bpd15	8.50	4.00	0.08	1.00	1.00
bpd16	4.79	4.00	0.31	1.50	0.75
bpd17	3.00	4.00	0.56	NA	NA
bpd18	12.06	4.00	0.02	6.00	0.44
bpd19	0.20	4.00	1.00	62.50	0.08
bpd20	9.71	4.00	0.05	0.00	1.00
bpd21	3.67	4.00	0.45	3.00	0.50
bpd22	4.00	4.00	0.41	NA	NA
bpd23	14.00	4.00	0.01	0.00	1.00
bpd24	4.36	4.00	0.36	1.00	1.00
bpd25	5.86	4.00	0.21	0.00	1.00

In Table 5-22 each row represents the results of both:

1. A Friedman test, used to test if there was any significant change in the response variable due to the changes in bench heights and
2. A Wilcoxon Signed-Rank test, used to test for a significant difference between the preferred E-150 bench height, and the Existing bench height.

As can be seen body parts 3, 18, 20, and 23, show significant discomfort due to the changes in bench height. This group uniquely showed significant discomfort in BP20 and 23, the thighs. While, because of their lower mean stature they show less back discomfort than the adults or senior students. Also as reflected in Figure 5-29, they had significant discomfort on BP18, the right wrist.

The analysis of the compared heights of E-150 and the Existing height show that there was significant discomfort in two body parts, BP1 and BP4, the neck and the lower back.

Table 5-23 below shows the aggregates for the total body (ABPD), the shoulders and the back. The Friedman test on the effect of bench height on the variables, show that the APBD is highly significant at a p value of <0.001. These levels include the E-250 height, which is, for this group much lower in relation to their elbow height than the Existing bench height. This is evidenced in the Wilcoxon Signed Rank (WSR) test, which shows no significance between the E-150 and the Existing bench height.

There is no significance reflected in either the Friedman or the WSR tests for the shoulders, both falling well short of the 0.05 level. As with the ABPD there is a high level of significance for bench heights, at $p=<0.001$, but not for the compared E-150 and the Existing bench height, see Table 5-23.

Table 5-23 The aggregate BP analysis results

VARIABLE BEING TESTED	FRIEDMAN TEST RESULTS, TESTING IF BENCH HEIGHT HAS A SIGNIFICANT EFFECT ON VARIABLE			WILCOXON SIGNED RANK TEST RESULTS, COMPARISON BETWEEN E-150 AND EXISTING BENCH HEIGHTS	
Variable	Chi Square	Degrees of Freedom	Significance	Test Statistics	Significance
Agg. BPD	23.15	4.00	0.00	41.00	0.17
Shoulders	2.93	4.00	0.57	12.00	0.77
Back	23.28	4.00	0.00	25.50	0.09

Table 5-24 below shows the gender comparisons for the three aggregates, total-body, back and shoulders.

Table 5-24 Aggregate comparisons male and female

VARIABLE BEING TESTED		FRIEDMAN TEST RESULTS, TESTING IF BENCH HEIGHT HAS A SIGNIFICANT EFFECT ON VARIABLE			WILCOXON SIGNED RANK TEST RESULTS, COMPARISON BETWEEN E-150 AND EXISTING BENCH HEIGHTS	
Variable		Chi Square	Degrees of Freedom	Significance	Test Statistics	Significance
Agg. BPD	M	7.12	4	0.13	22.5	0.547
Agg. BPD	F	15.62	4	0.004	1	0.016
Back	M	7.1	4	0.131	5.5	1
Back	F	26.27	4	0.000	7.5	0.039
Shoulders	M	0.96	4	0.915	5	0.5
Shoulders	F	1.63	4	0.804	2	0.375

In Table 5.24, we see that for the males the analysis reveals that there is no significant discomfort in any of the areas, either for the bench heights against the variable or for the Wilcoxon test between E-150 and Existing height. For the females however, the total body and the back aggregates are highly significant, at p=0.001 and P=0.004 respectively. The Wilcoxon test also shows significance in these two areas for the E-150 and the Existing height comparison. The shoulders do not register any significance for either.

A different picture emerges from this group in some respects. While the Existing bench height does not cause serious discomfort problems for the group (except for the taller test subjects and the female back), the analysis shows that bench height has a significant effect on discomfort levels. This group is also reflecting discomfort in the dominant hand and wrist, and would likely benefit from ergonomic intervention on the design of hand tools to suit their strength and hand anthropometry. There is also significant discomfort in the thighs relating to bench height, and this unique factor could benefit from further study.

For the Junior test group, it has been shown that bench height has a significant effect on BPD.
Females suffered more discomfort than males.

5.3.1.2 Endurance

In the same manner as for the other groups, endurance was measured as a subjective estimate for each height after completing the test bank at that height. Subjects were asked; "How long do you feel you could endure working at this height, doing this type of work?" The subjects responded in groups of hours, which were coded as in Table 5-5.

The Friedman test on endurance shows that it is highly significantly effected by the height of the bench. The application of the Wilcoxon Sign-Rank test shows that E-150 results in a significantly different (better) endurance estimate level than the Existing bench height, see Table 5-25.

Table 5-25 Friedman and WSR tests results on the endurance variable

VARIABLE BEING TESTED	FRIEDMAN TEST RESULTS, TESTING IF BENCH HEIGHT HAS A SIGNIFICANT EFFECT ON VARIABLE			WILCOXON SIGNED RANK TEST RESULTS, COMPARISON BETWEEN E-150 AND EXISTING BENCH HEIGHTS	
Variable	Chi Square	Degrees of Freedom	Significance	Test Statistics	Significance
endurance	29.44	4.00	P=<0/001	6.50	P=<0.001
Endurance Male	15.21	4	0.004	4	0.062
Endurance Female	19.51	4	0.001	0	0.016

Figure 5-33 shows graphically, the relationship of endurance to the various bench heights. While there are significant differences in endurance estimates, there is little difference between the E-100, the E-200 and the Existing levels. Again the E-150 scores best for endurance.

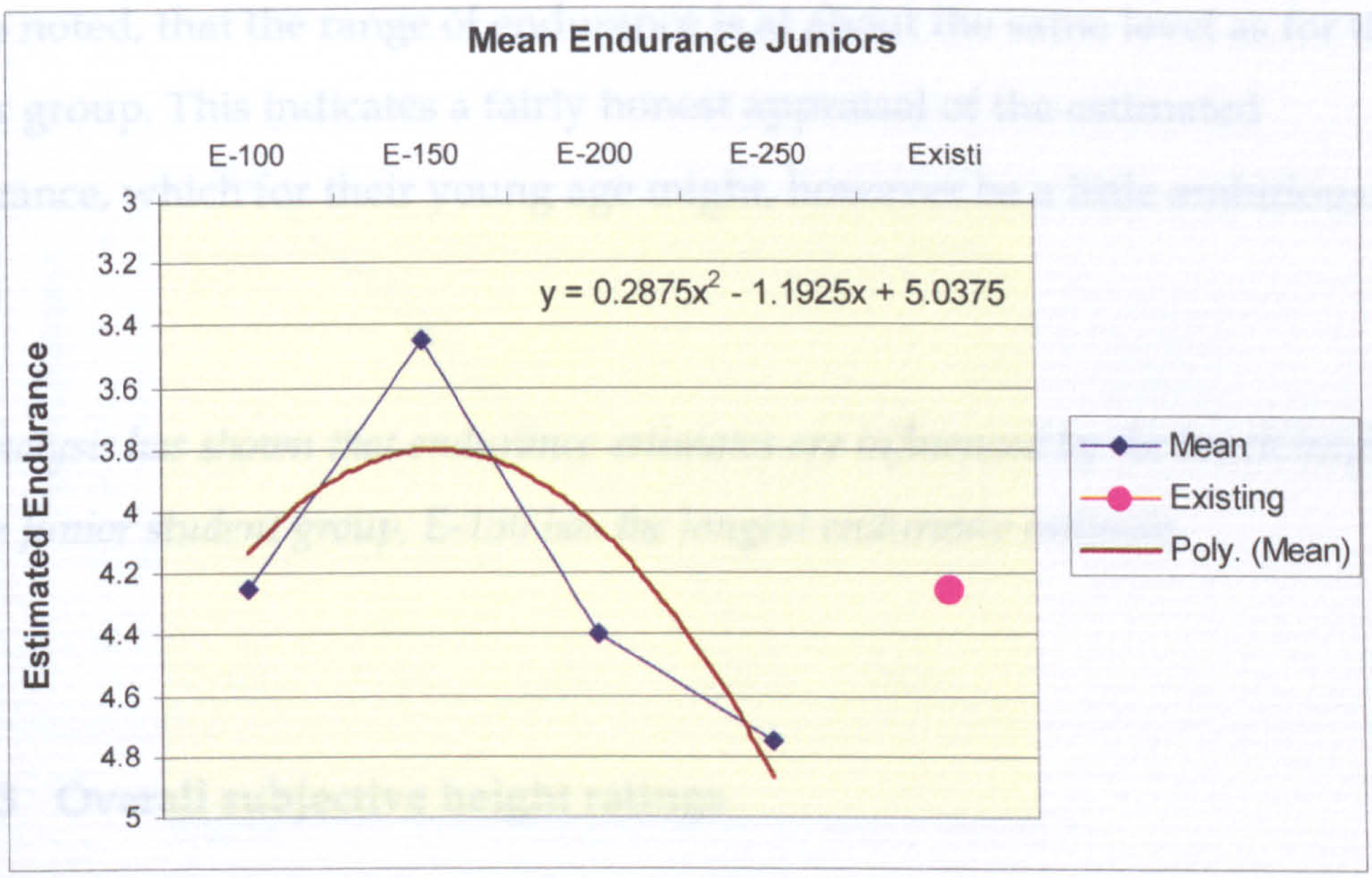


Figure 5-33 Endurance estimates – juniors

Figure 5-34 shows the male/female relationship for endurance and conforms to the statistical analysis seen in Table 5-25 above. While the two run in almost parallel, the male endurance score is longer generally.

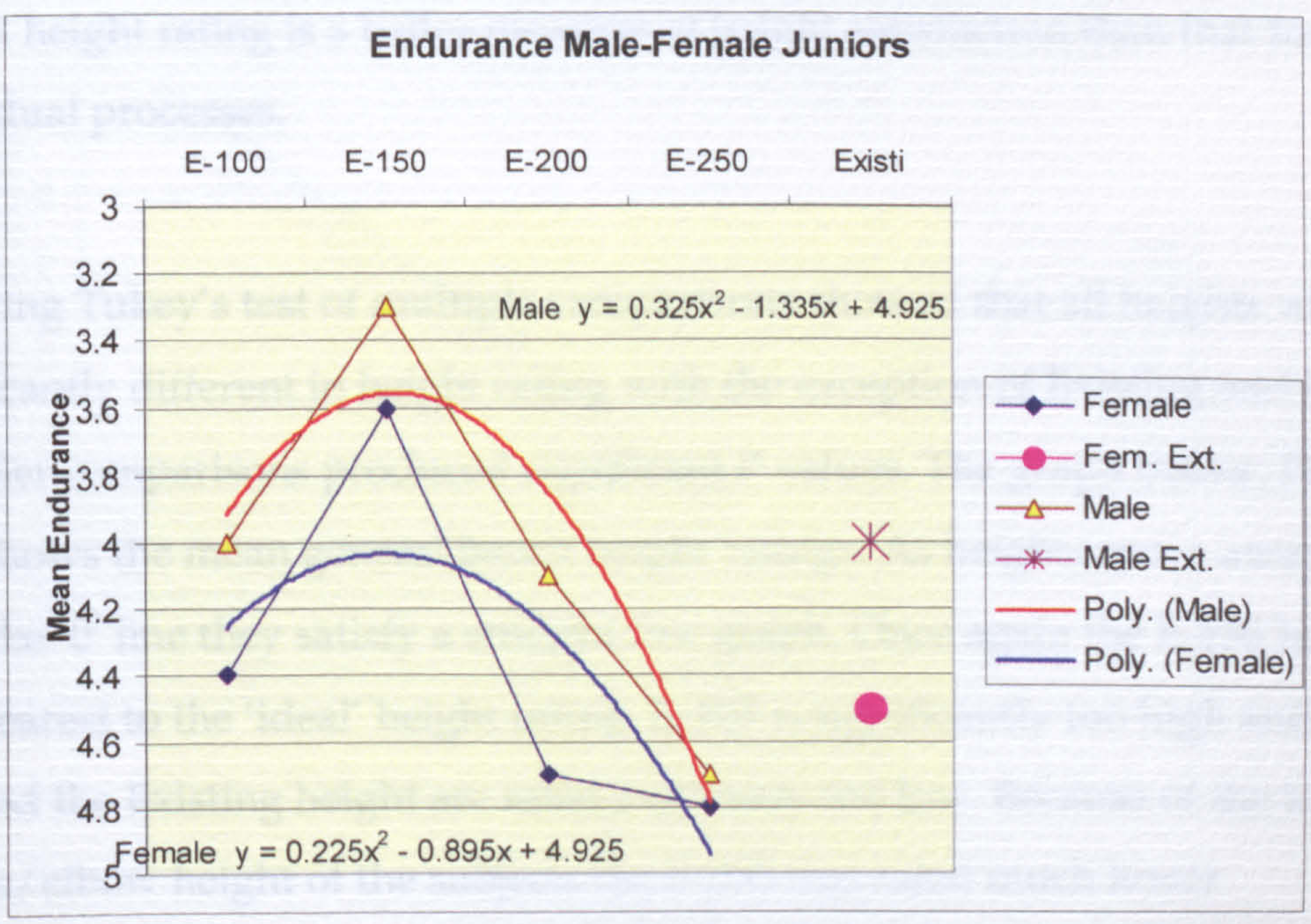


Figure 5-34 Male and female endurance comparisons

It was noted, that the range of endurance is at about the same level as for the senior group. This indicates a fairly honest appraisal of the estimated endurance, which for their young age might, however be a little ambitious.

The analysis has shown that endurance estimates are influenced by the bench height and for the Junior student group, E-150 has the longest endurance estimate.

5.3.1.3 Overall subjective height ratings

The data did not satisfy the assumptions of ANOVA so the data was analysed using non-parametric Kruskal-Wallis and Tukey tests. The significance value from the analysis shows that the subjects gave significantly different overall satisfaction rates for different bench heights. The overall rating for subjective bench height had a significance value of P=<0.001. The value for the individual processes subjective height rating had a p value of 0.74, showing that the overall height rating is a better measure of height satisfaction than that for individual processes.

Applying Tukey's test of multiple comparisons showed that all heights were significantly different in height rating with the exception of Existing and E-200. All other comparisons produced significant P values. The graph below, Figure 5.35, shows the mean general bench height ratings. As heights move away from the '0' line they satisfy a straight-line graph. Once again the E-150 height falls nearest to the 'ideal' height rating. E-100 is significantly too high and E-250, and the Existing height are rated extremely too low. Because of the lower stature/elbow height of the subjects the E-250 was rated much lower than the rating for the Existing bench height. An equation for height satisfaction indication appears on the graph.

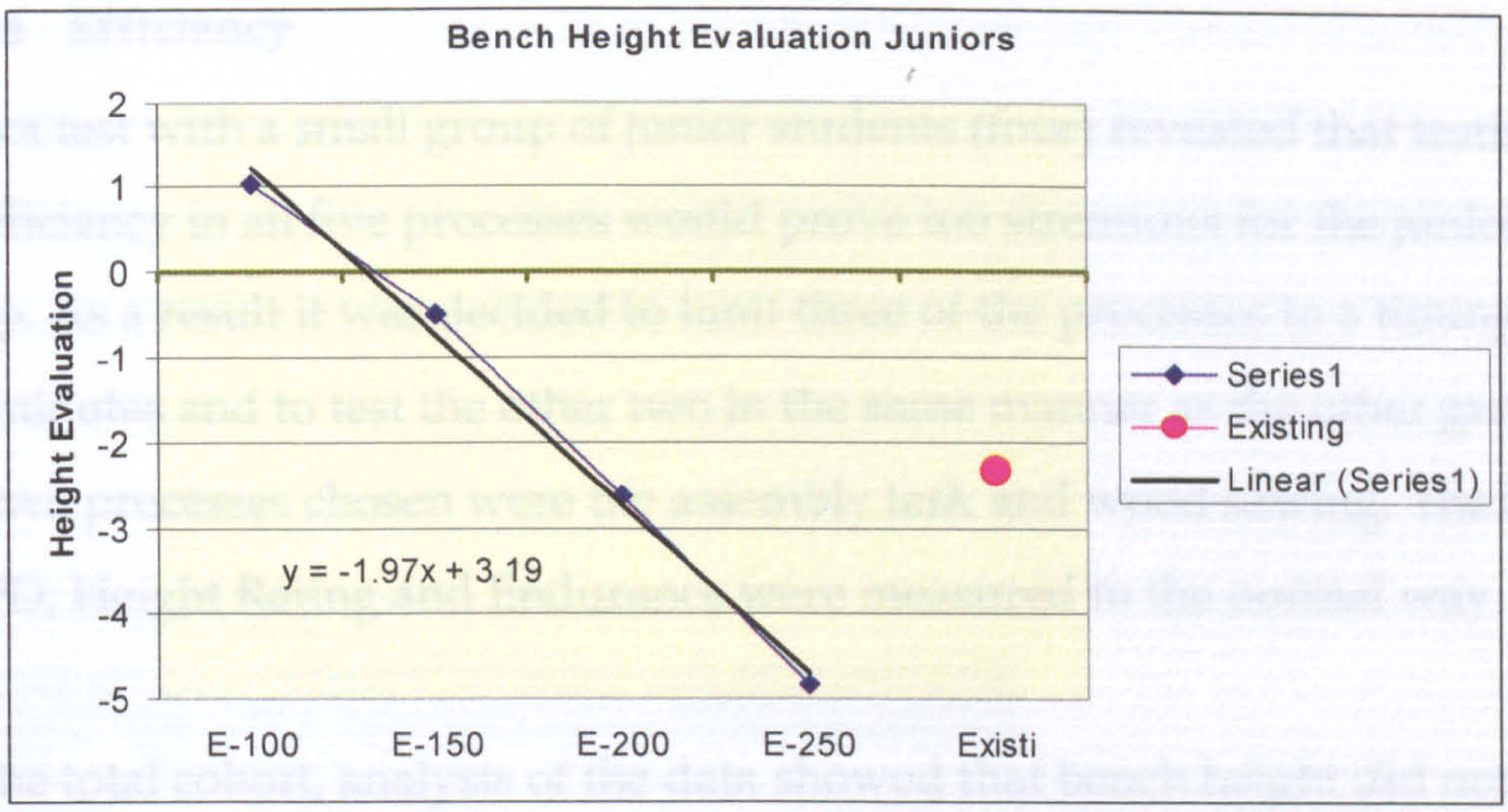


Figure 5-35 Mean height evaluations – juniors

In Figure 5-36 we see the comparisons of male and female juniors for bench height rating. There was no statistical significance between the males and females for any of the heights. Application of the Wilcoxon rank Sum gave a value of P=>0.66.

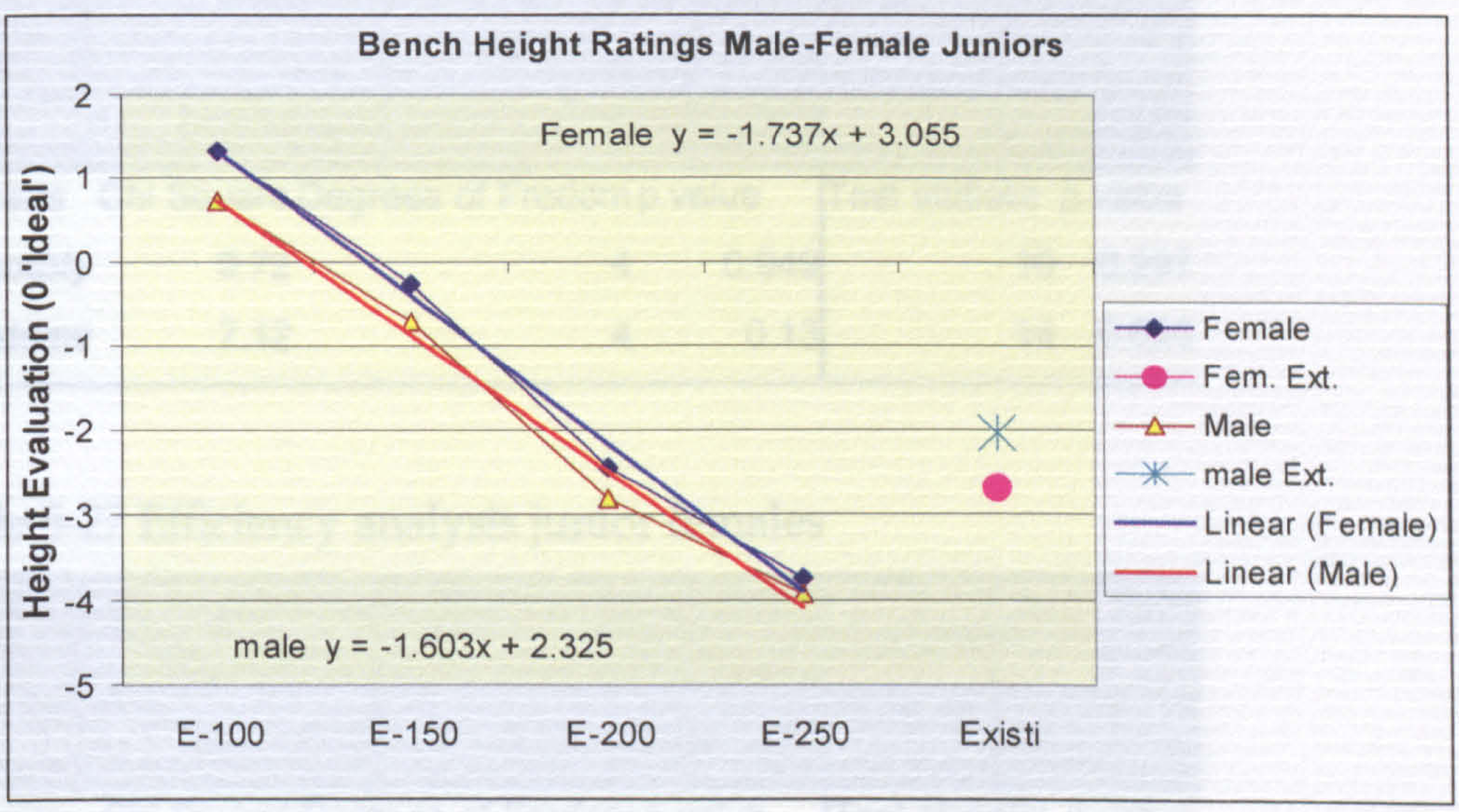


Figure 5-36 Mean height ratings males and females

The overall height rating was statistically significant for the juniors and superseded the rating for individual processes. E-150 was best and E-250 was worst.

5.3.1.4 Efficiency

A pilot test with a small group of junior students (four) revealed that testing for efficiency in all five processes would prove too strenuous for the junior group. As a result it was decided to limit three of the processes to a timing of two minutes and to test the other two in the same manner as the other groups. The two processes chosen were the assembly task and wood sawing. The areas of BPD, Height Rating and Endurance were measured in the normal way.

For the total cohort, analysis of the data showed that bench height did not have a significant effect on efficiency, having a value of p=0.72. Tables 5-26 and 5-27 below shows the Friedman and Wilcoxon tests results for males and females for efficiency, for the processes measured. None of the p values are significant, for either the bench heights or the compared Existing height with the preferred E-150 height.

Table 5-26 Efficiency analysis junior males

Friedman Test				*Sign Rank Test between E-150 and Existing*	
Process	Chi Square	Degrees of Fredom	p.value	Test statistic	p.value
assembly	0.72	4	0.949	10	0.297
woodsaw	7.12	4	0.13	14	0.625

Table 5-27 Efficiency analysis junior females

Friedman Test				*Sign Rank Test between E-150 and Existing*	
Process	Chi Square	Degrees of Fredom	p.value	Test statistic	p.value
assembly	5.31	4	0.257	24	0.75
woodsaw	3.49	4	0.479	30	0.826

Looking at the gender comparisons for the junior group (Table 5-28), with the application of the WSR test we find that there is no significance for the assembly process (p=0.632). However wood sawing does have a significant value of p=0.005, showing the males to be more efficient than the females for this process.

Table 5-28 Juniors gender comparisons

Sign Rank Test between E-150 and Existing		
Process	Test statistic	p.value
assembly	1319.5	0.632
woodsaw	1658.5	0.005

There is a difference in efficiency between males and females for wood sawing but not for assembly. *On-the-whole bench height did not significantly affect efficiency.*

5.4 Synthesis of test findings

5.4.1 Groups of similar stature compared (adult/adolescent)

In order to establish whether juniors/seniors who are of similar stature to adults, have the same ergonomic requirements, a number of comparison tests were undertaken. The analysis of the data relating to, adult males with senior males and adult females with senior females, found no significant differences in any area. The adult males and senior males, five each in similar stature range were compared. These were the following subject numbers:

Adult males = 3,6,7,8,9

Senior males = 21,22,28,29,30

The Exact Wilcoxon Sum rank test was used for all comparisons, the results are in Table 5-29 below, and are for the Existing and the E-150 bench heights.

Table 5-29 Comparisons for similar stature - male adults/seniors

Response	p-value (Ext./E-150)
Height rating	0.3095/0.3016
Aggregate BPD	0.1429/0.5952
Endurance	>0.999/0.2778

Four each from the female adults and seniors were of similar stature. The test subject numbers are seen below.

Adult Females = 14, 16, 17,19

Senior Females = 32, 35, 37, 38

Again the Exact Wilcoxon Sum rank test was used for all comparisons, the results are in Table 5-30 below, and are for the Existing and the E-150 bench heights. Here again there were no significant differences found. The efficiency response was not tested as it proved not to have significance for bench heights in all previous tests. The same applied to the male group.

Table 5-30 Comparisons for similar stature - female adults/seniors

Response	*p-value (Ext./E-150)*
Height rating	0.6857/0.3016
Aggregate BPD	0.5714/0.8286
Endurance	>0.999/0.7429

There were no male juniors of sufficient stature to compare with the adults. Four of the tallest junior females were compared with the smaller adult females. The same test was applied for the same responses and bench heights. The results are to be seen in Table 5-31. Again there were no significant p-values, with the exception of endurance for E-150, which favoured the adults. The test subject numbers compared were:

Adult females = 52,55,5, 59

Junior females = 11,13,15,18

Table 5-31 Comparisons for similar stature - female adults/juniors

Response	*p-value (Ext./E-150)*
Height rating	0.8857/0.1714
Aggregate BPD	0.9714/0.8857
Endurance	>0.999/0.02857

The samples of test subjects in the comparisons above, between adults and young people are small in number, and therefore the results of the analysis cannot be considered conclusive. However, the results do suggest that it may be possible to interchange, or mix data between 12 to 18 year olds and adults. Further analysis using greater numbers, may confirm this, and a more thorough investigation would produce more robust results.

5.4.2 The test bank used

The adaptation of the RULA (Rapid Upper Limb Assessment) system (McAtamney and Corlett, 1993; Delleman, 2000; Brodie and Wells 1997), to the whole body, along with the assessment tools like DAS (Lowe et al., 2001), and the VAS (visual analogue scales, Straker, 1999), worked well together to give ergonomic feedback on people working at benches, whether wheelchair users, able-bodied adolescents or adults.

The test bank chosen as a result of previous experience and pilot tests worked very well in establishing the raw data and was quite manageable in the context of a 'rapid response' ergonomic evaluation of the subjects. Both test rigs were very satisfactory and were well within the ranges of tall and small stature test subjects. The rig for the wheelchair users was designed to work at lower levels and had the same adjustment range.

The test subjects afforded a broad range of statures both in wheelchairs and for able-bodied subjects. The 5^{th} and 95^{th} percentiles were easily catered for and this has possibly extended to the 99^{th} percentile in stature, and as seen in 5.4.1 if we are able to use smaller adolescents in place of adults, the 1^{st} percentile is also catered for.

5.4.3 Significant anthropometric and ergonomic findings

The literature review has established that school going young people have not been tested for this nature of work before, as they are seen as being outside the user population for workbenches. This research has established ergonomic criteria, which can make a significant contribution to the musculo-skelatal health of these young people, and thereby reduce the risk of encountering RSI problems in the future. It has also contributed to the broadening of career options in areas, which were hitherto unexplored for wheelchair users.

It has also been established that in spite of the increase in stature in the bench using population, bench design for this type of work has remained unchanged for centuries.

Among the important elements established, in the areas of anthropometric and ergonomic data are:

- Best-fit heights have been established for a range of users;
- wheelchair users and surrogates work more comfortably at a height of 100 mm above knee height, KH+100;
- surrogate wheelchair users may be used to establish ergonomic data for bench processing;
- able-bodied users work more comfortably at a height of 150 mm below elbow height, E-150;
- nearly all wheelchair users had previously worked at inaccessible benches, where awkward postures for them is the 'norm';
- all but the smallest test subjects are working on benches, which force them to work in awkward postures. This is particularly dangerous for adolescents whose body is still in the development stage;
- the tallest test subject was 1985 mm and the highest elbow height was 1265 mm (not the same subject), a massive 465 mm above the typical bench height;
- there was a difference of 543 mm between the smallest junior male stature and the tallest senior male stature. And this has implications for a universal design solution;
- the mean knee height for the WU/SWU cohort was 648 mm and the lowest height was 576 mm;
- comparisons between adult and adolescent test subjects have been made, which suggest ergonomic compatibility, however, further ergonomic exploration is required, in order to confirm this;
- it has been shown that robust working heights exist for most bench users and where the requirements are less robust, as with female bench users, this will need to be catered for;

- the research has established that an ergonomic best-fit bench will significantly reduce BPD and increase endurance time, which will likely in the long term significantly increase productivity. This must be considered true as less time lost from work due to MSDs and RSIs will significantly improve productivity.

In spite of all the analysis of workstation ergonomics in recent decades, not a single publication was found on this type of bench processing, although some were found on cognate activities such as welding and sewing machine operation, and none whatsoever on school going children/adolescents at workbench activities.

This research project covered a broader range of workbench users than any research heretofore, (12 to 18 year olds, adults and wheelchair users). None of the test subjects had ever worked on an adjustable bench. Yet this is an important piece of equipment in the workshop or practical classroom. It is particularly important for young school-goers, where there is such a broad range of statures, for the user population. First year students in second level schools will use benches, which are too low for the majority of them at that time. The same student, possibly now 500mm taller will work at this same bench five years later.

The typical bench height in use in schools is 800 mm, and some are as low as 770 mm. None, of the benches in over thirty schools visited had a bench that was wheelchair user accessible. During this study, in one school where a wheelchair user was observed working in a practical classroom, when she needed to use the saw or chisel she raised herself up to sit on the arm of the wheelchair, so as to gain access. When she was interviewed after class, and was asked; 'if she would like a lower accessible bench'? she answered no! Reason? As a teenager she would not want to be any different from her peers than she had to be. However if there were some adjustable benches in every classroom, which were used as required by students of short or tall stature, or wheelchair users, then that would be seen as normal practice.

The latest specification for future orders of school furniture provided by the Department of Education and Science (Republic of Ireland), has at last given recognition to the fact that young people grow between the ages of 12 and 18. However, the height specification for a junior workbench is now 780 mm and for senior classrooms 850 mm. However, if we subtract 150 mm from the *mean* elbow height for junior females, they require a bench height of 860 mm, i.e. 80 mm higher, and this is without taking into consideration the 95%ile. For the senior male students the mean elbow height was 1101 mm, and working at the optimum for the *average* means a bench height of 951 mm. This is 100 mm higher than the proposed standard. The differences between maximum and minimum elbow heights, for the subjects tested was 375 mm.

5.4.3.1 Summary findings

- There is a general (and unacceptable) high level of discomfort for nearly all bench users working at the current bench provisions;
- across all the able-bodied test groups, a consensus best-fit height for this type of work has been established. This is 150 mm below elbow height. It is robust to plus 50 mm for the males but less so for the females;
- the best-fit height is supported by: the lowest level of BPD, the preferred height of the user group, and the estimated endurance;
- while efficiency was not significantly effected by bench height, it is envisaged that significantly reduced BPD will result in less work absence in the long term because of developed MSDs/RSIs, which in turn must improve productivity;

- wheelchair users will work comfortably at an accessible bench, which is 100 mm above knee height. This height is reasonably robust to a height of plus or minus 50 mm;
- wheelchair users can appropriately work in engineering environments.
- while quality was not a factor in testing, an improved postural position can only positively impact on quality;
- ergonomic intervention for this type of bench activity is almost non-existent, and particularly urgent for schools;
- while there are some significant gender differences in BPD and efficiency, and to a lesser extent endurance this does not appear to have impacted on the preferred/best-fit height;
- the lowest elbow height for any of the wheelchair users tested was 576 mm (a very small test subject), and the greatest elbow height for any of the able-bodied test subjects was 1265 mm (a very tall subject).

In consideration of the above, a set of criteria has emerged, which informs the design of an improved universal/inclusive design solution, for a more robust test-rig and first prototype workbench. This aims to satisfy the ergonomic requirements of all of the above categories of bench users. Chapter 6 will discuss the inclusive solution.

6 TOWARDS AN INCLUSIVE DESIGN SOLUTION

As discussed in 2.4 of this Thesis, inclusive design by its nature endeavours to provide for as broad a user population as is practicable. The test-rig used for all elements of the testing associated with this research project, worked very well in all respects. However the telescopic column had a light, rack and pinion mechanism, which while capable of raising 2,000N, had nevertheless a small gearing surface contact, and therefore if it were subjected to the rigours of everyday use over an extended period of time, would likely malfunction. As a continuum of the research then, a more robust and inclusive test-rig was designed, which would also provide a first prototype for further development. To meet the criteria for the range of users tested, as described earlier, requires that the bench should be:

Safely usable by all;
Fit for the purpose intended;
Not identifiably associated with any one group;
Robust in construction and appearance;
Able to satisfy the principles of UD.

If we then consider the above criteria in relation to the seven recognised principles of universal design and decide which of these a new inclusive bench design must satisfy, which of the seven are not required? Working through the list below as the principles are normally presented, it becomes apparent that to varying degrees all the conditions need to be met. Neither is it necessary to approach the process in the numerical order of the principles. In fact it is likely in this case, as we wish to include wheelchair users in the user cohort, that the seventh principle; 'size and space for approach and use', might need to be the first under consideration, and be modified to read, 'size, space and *shape* for approach and use'. The seven principles (from the Center for Universal Design at North Carolina State University; www.design.ncsu.edu/cud) listed below underpinned the bench design approach.

1. *Equitable use;*
2. *flexibility in use;*
3. *simple, intuitive use;*
4. *perceptible information;*
5. *tolerance for error;*
6. *low physical effort; and*
7. *size and space for approach and use.*

The first stage is to *define the problem.* Albert Einstein said that: *'the definition of a problem is more important than its solution'.* The development and use of the test-rigs, both the cantilevered model for the WUs, and the centre-column model, used for the able-bodied test subjects, has significantly informed the development of an improved universal model. While this problem had been defined to a large extent due to observation, perceived needs, and pilot studies, it nevertheless became more refined as the testing on the test bench/rig proceeded.

When, for wheelchair users the bench moved away from their preferred height, the discomfort due to awkward body posture was apparent. If it was too low, one hand had to be used for balance (surrogates could assist with leg muscles), too high and shoulder and arm discomfort increased. The observations of wheelchair users endeavouring to work at a 'normal' bench, reinforced the 'exclusion' attitude that has prevailed for too long. The same can be said of a young man, almost 2 metres tall and stooping to work on a bench better suited to a person who is perhaps half a metre shorter. One of the young women tested had a stature in excess of 1.9 metres (almost 6' 3"), and when the test bench was lowered to the typical bench height of 800 mm from one of the higher levels, she could not believe that this was the bench height at which she normally worked. Therefore, recording the data of people from the 1st to the 99th percentile, and confirming the hypotheses by analysis of the data, has clearly defines the problem.

The problem definition therefore was:
Design an inclusive workbench/test-rig, which will be adjustable, to include work-surface heights which will accommodate wheelchair users at it's lowest level, and the 99th percentile stature male at the upper level. The work-surface height should be easily adjustable to meet the needs of the users for all heights in this range. It should be: safely usable by all, not identifiably associated with any one user group, robust in construction; and be able to satisfy the principles of UD.

According to Pheasant (1998), the 5th percentile seated person (female) requites a minimum work surface height of 635 mm to allow leg clearance, and if this person is on a wheelchair then this can be increased (minimum + 100 mm). As the lowest knee level recorded for the wheelchair users anthropometric data was 576 mm, we can safely assume that this subject was well below the 5th percentile. Bar and Galluzzo (1999), give lab station work heights for wheelchair using school going young people, and uses a range from 760 mm up, They also suggest that knee clearance for older children should be a minimum of 685 mm. There are no dimensions to be found for workbench users in wheelchairs.

As the tallest person measured for establishing the anthropometric data for the able-bodied subjects was 1985 mm tall, then this person was above the 99th percentile stature for males of 1930 mm, (Goldsmith, 2000).

In establishing the range of adjustability, the lowest knee height of 576 mm, plus the 100 mm above knee height, gave a lowest requirement of 676 mm, and as there was no significant difference in BPD between KH+100 and KH+150, a tolerance of plus 50 mm was assumed. This meant that the maximum low-level height should not exceed 726 mm. At the upper end of the scale it was necessary to accommodate a test subject with an elbow height of 1,265 mm. Allowing for 150 mm below elbow (E-150) this gave a height of 1,105 mm. As there was no significant difference for adult users between the E-150 level and the E-200 level, this gives a tolerance of minus 50 mm. The minimum high-level arrived at is now is 1,055 mm.

The bench top needed to have a surface area which satisfied ergonomic requirements. It was decided to use the dimensions recommended by Kroemer and Grandjean (2000), as seen in Figure 6.1 below. This shows the 5th percentile but there was a need to extend the width to accommodate the 'occasional reach' zone as well as the taller, long reach user. The size requirement for the work-surface was 1,600 mm long and a minimum of 750 mm wide.

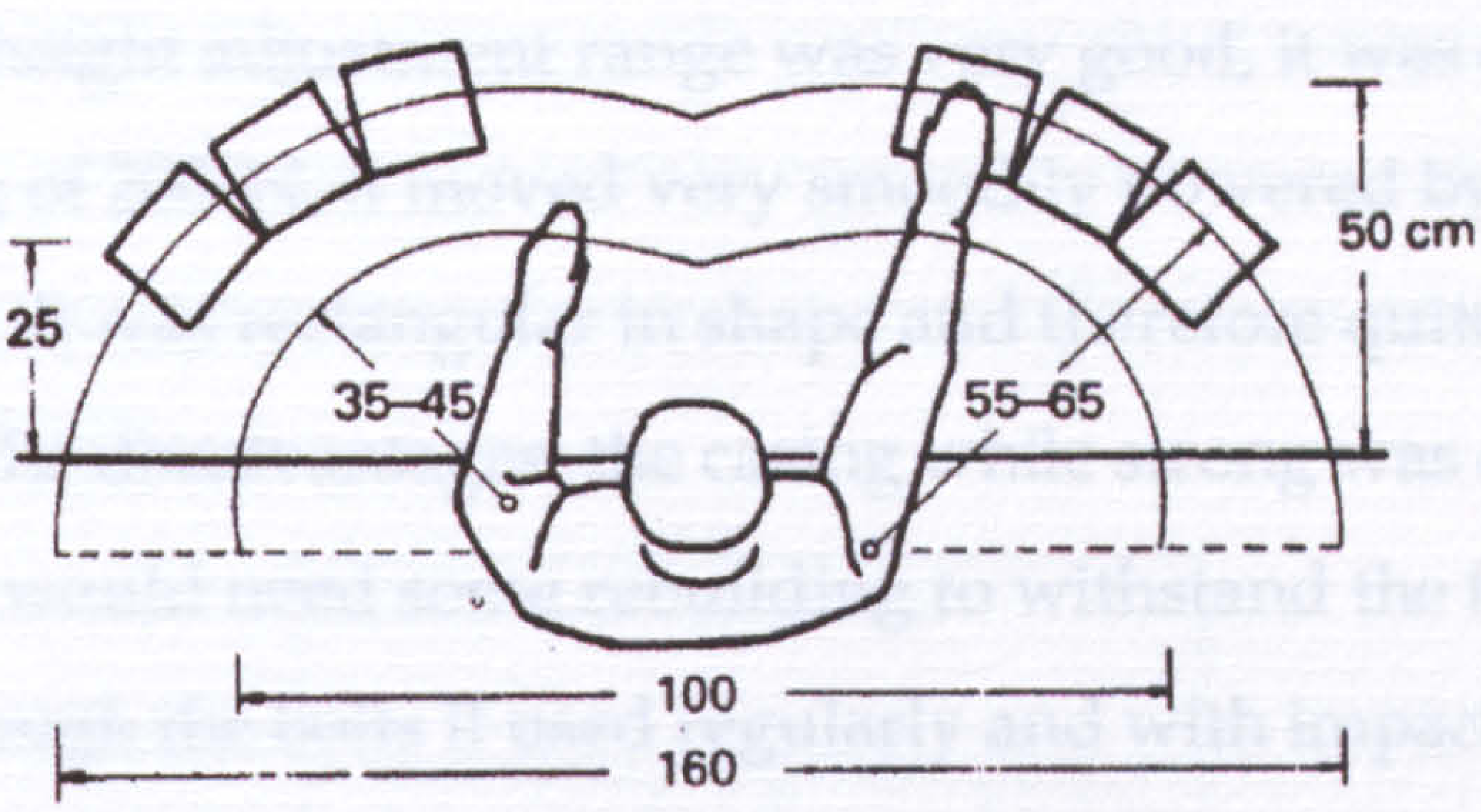


Figure 6-1 Horizontal arc of grasp and working area.

The measurements taken from the wheelchair users for leg-depth clearance show that 600 mm is satisfactory. The overall image of an improved inclusive test-rig and a first prototype bench had emerged! The cantilevered drinking UD fountain at Figure 6-2 illustrated the principle.

Figure 6-2 A UD drinking fountain

6.1 The inclusive bench/test-rig developed

The development of the solution, needed in addition to the above primary considerations, to include the practicalities of manufacture and engineering. In deciding to make the bench adjustable, this had to have ease of use, and function effectively. The rise and fall mechanism could have several approaches. Light bench models with four telescopic, hydraulically controlled legs were considered but proved too flimsy for the purpose, and did not have the best 'optics', in the expectations of a bench for this type of work. The telescopic column used for the test bench was considered, and it met most of the criteria. It's height adjustment range was very good, it was capable of taking a loading of 2000N, it moved very smoothly powered by a well designed motor. It was rectangular in shape and therefore quite resistant to torsion forces. The disadvantages: the casing while strong was constructed of aluminium and would need some rebuilding to withstand the forces transmitted through the bolts if used regularly and with impact loads; the rack and pinion movement had a small contact area at the gear teeth, which would wear over time, the estimated use without malfunction was one year.

It was decided to design a new lift column. Square box section was considered, which would cater for the torsion forces and could house a hydraulic ram. However after some thought it was seen as presenting difficulty in having the inner square tube run smoothly inside the outer tube, within tight tolerances. The box section is rather 'loose' on cross sectional tolerances, as well as for straightness. After some investigation this idea was eliminated. However the basic idea of a single, strong column, which was telescopic was retained. It was decided that it should be powered by a hydraulic ram.

The idea of a round telescopic arrangement, become more attractive. On investigation it was possible to purchase from stock, a 204 mm outside diameter tube, with a 12.7 mm wall thickness and a pre-polished inner surface. An inner tube of similar wall thickness but finished on the outside was also available. However the nearest stock size to the inner diameter, was 144 mm outside diameter. This limited the possibility of using smooth running 'feathers' between the walls to control movement and to resist torsion.
The decision to make nylon inside/outside collars, which would convert the tubes into a smooth running piston, was seen as a good solution.

The accommodation sketch showing the section, with the final measurements, is seen in Figure 6-3. Silver-steel torsion bars were fitted to withstand rotational forces and these were housed in specially designed sleeves to increase the stability.

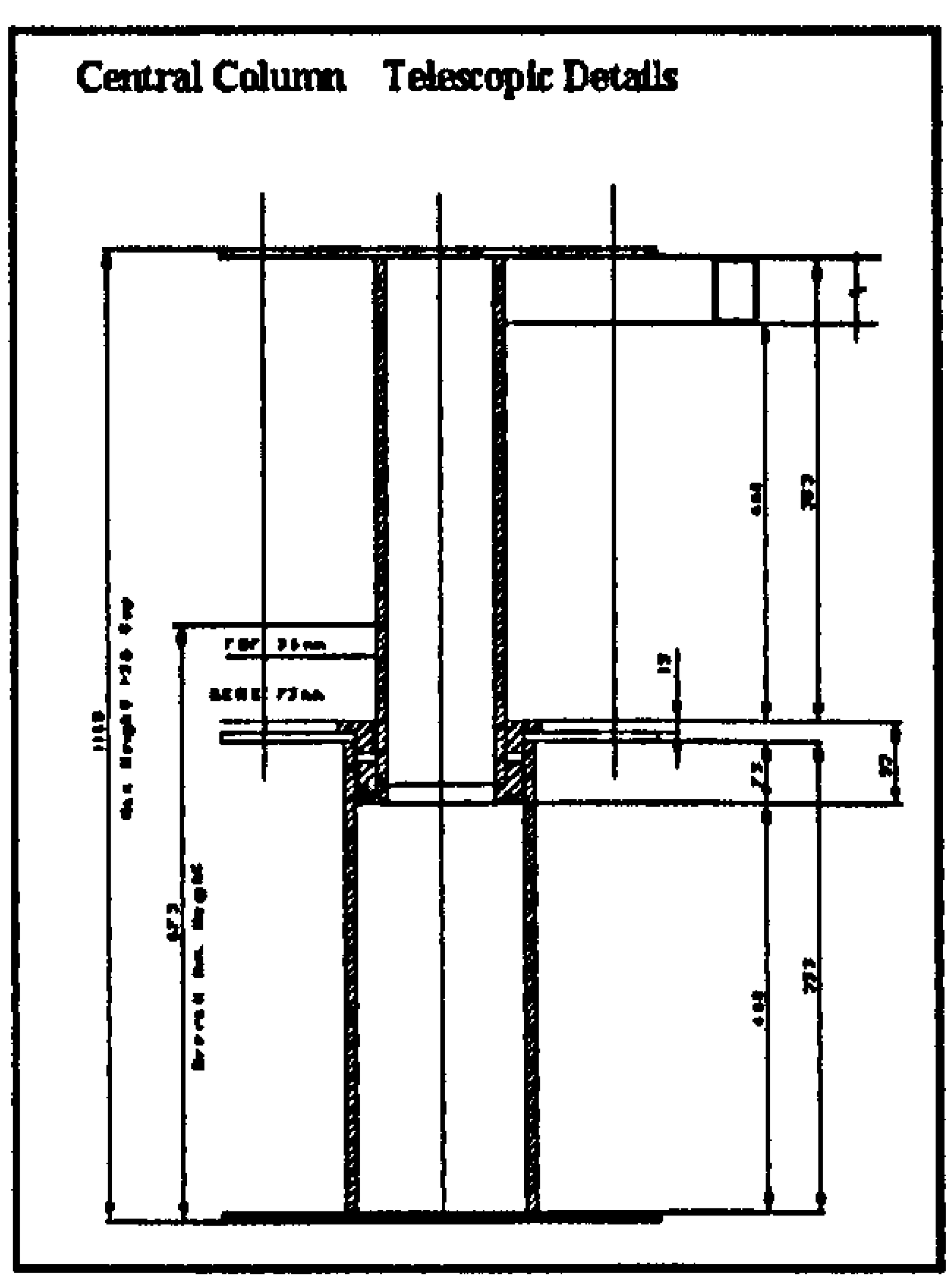


Figure 6-3 Design drawing for the telescopic column

The support arms needed to be shaped such as to accommodate the legs and feet supports of the wheelchair users. Test measurements showed that an inner clearance between the legs back-plate of 550 mm which was back 600 mm from the front edge of the of the bench. So as to give this clearance and to allow some overlap on the back of the bench, a bench width of 900 mm was arrived at. This gave the bench-top an overall size of 1,600 mm long and 900 mm wide. In order that the top would be 'self contained', i.e. the total thickness of the top should be self-supporting it was decided to construct it of laminated medium density fibreboard (MDF), with a grooved-in hardwood (beech) edging. The front and side views in Figure 6-4, show the bench at the lowest level, and Figure 6.6 shows the bench at the highest level.

WORKBENCH FULLY LOWERED

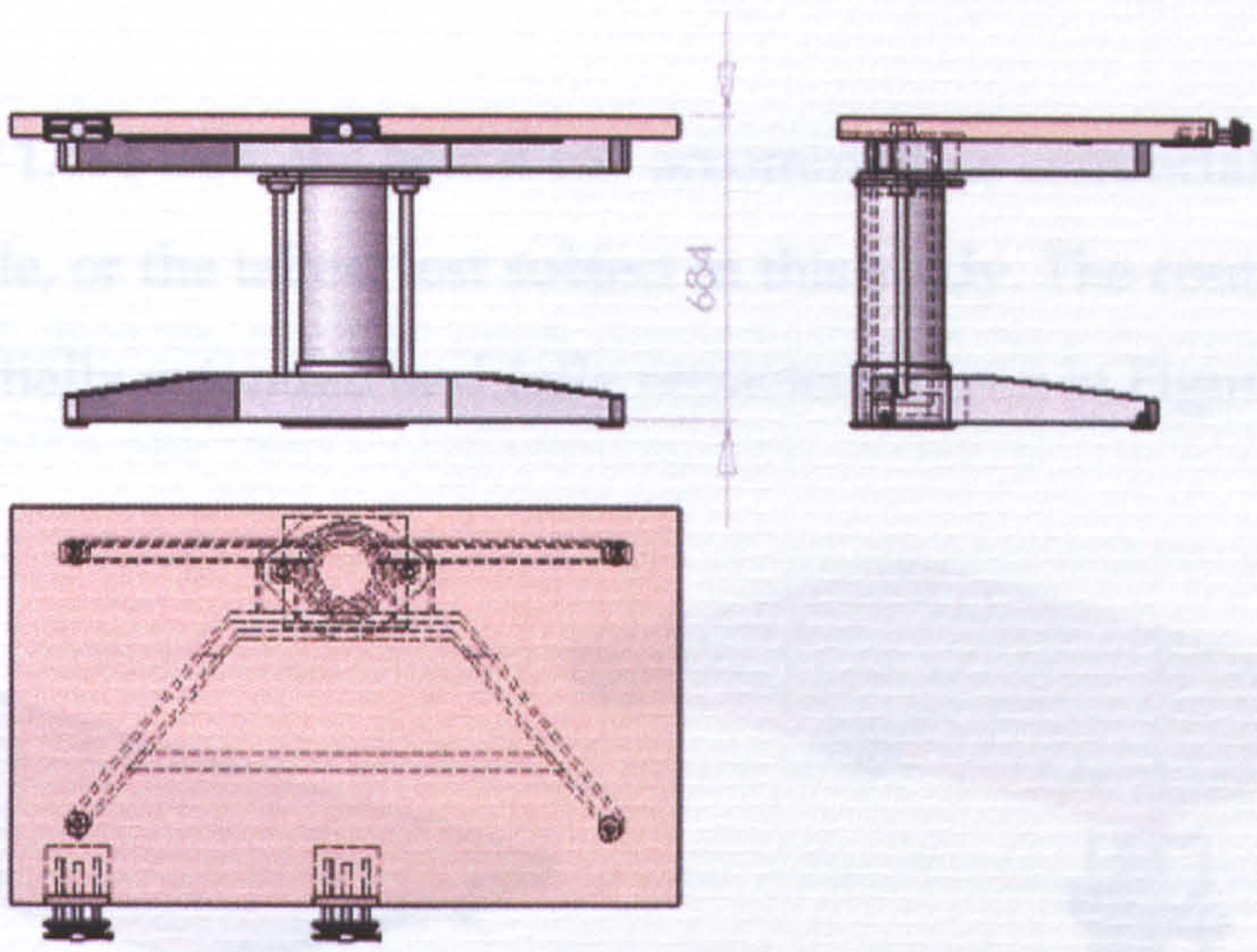


Figure 6-4 The inclusive bench fully lowered (height 684 mm)

With the bench at the lowest level, a height of 684 mm is possible, which will comfortably accommodate the wheelchair user with the minimum knee height. This is just 8 mm above the optimum, or 108 mm above the knee height. This may be adjusted by taking 10 mm from the shoulder of the nylon collar, but will then lose 10 mm on the overall height. At the other end of the spectrum, Figure 6-5 shows the height of the bench fully raised, to a height of 1,131 mm.

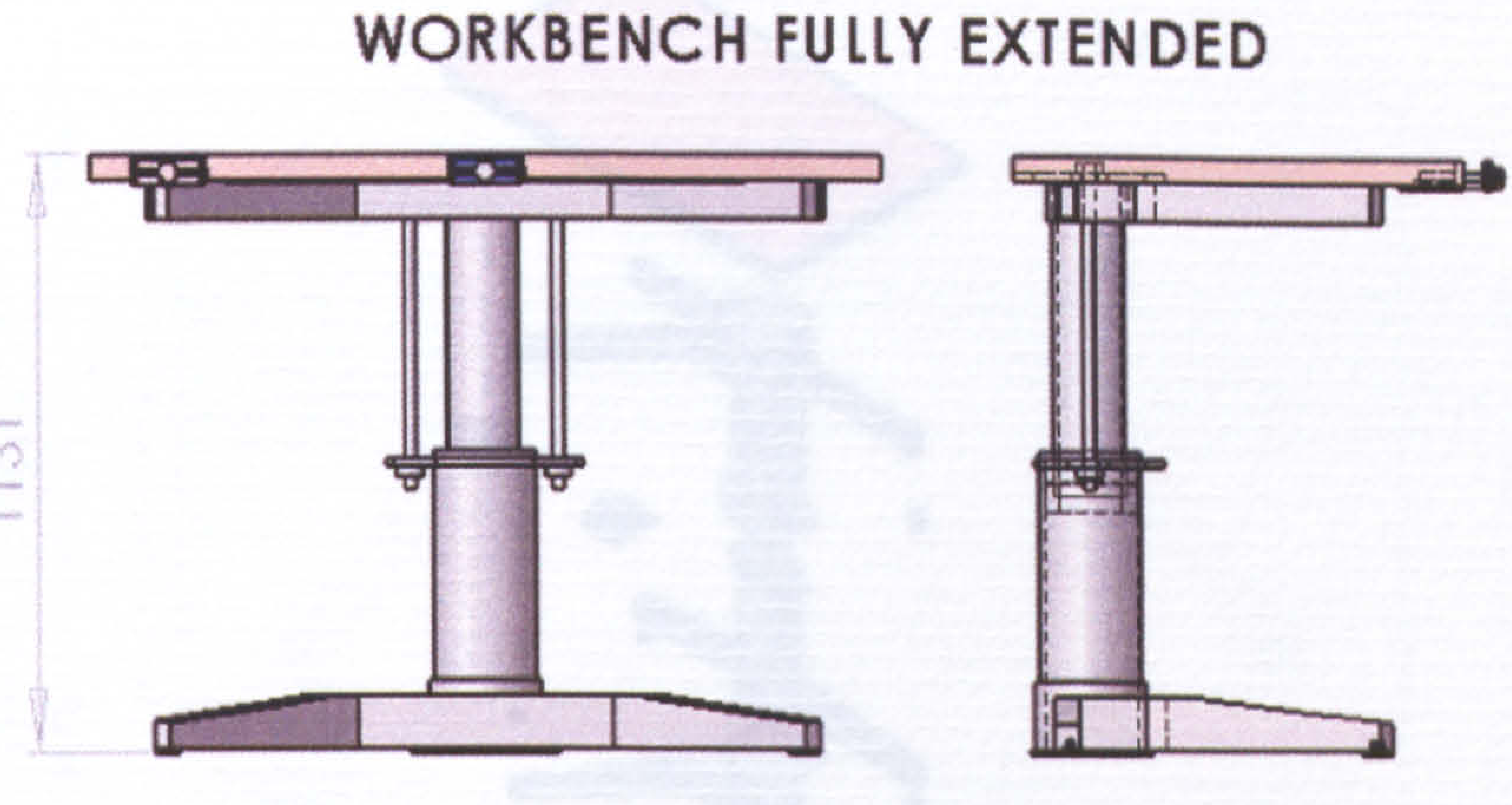


Figure 6-5 The inclusive bench fully raised (height 1,131 mm)

At a height of 1,131 mm, the bench can accommodate comfortably, the 99th percentile male, or the tallest test subject in this study. The contrast between the bench partially extended and fully retracted is seen in Figure 6-6.

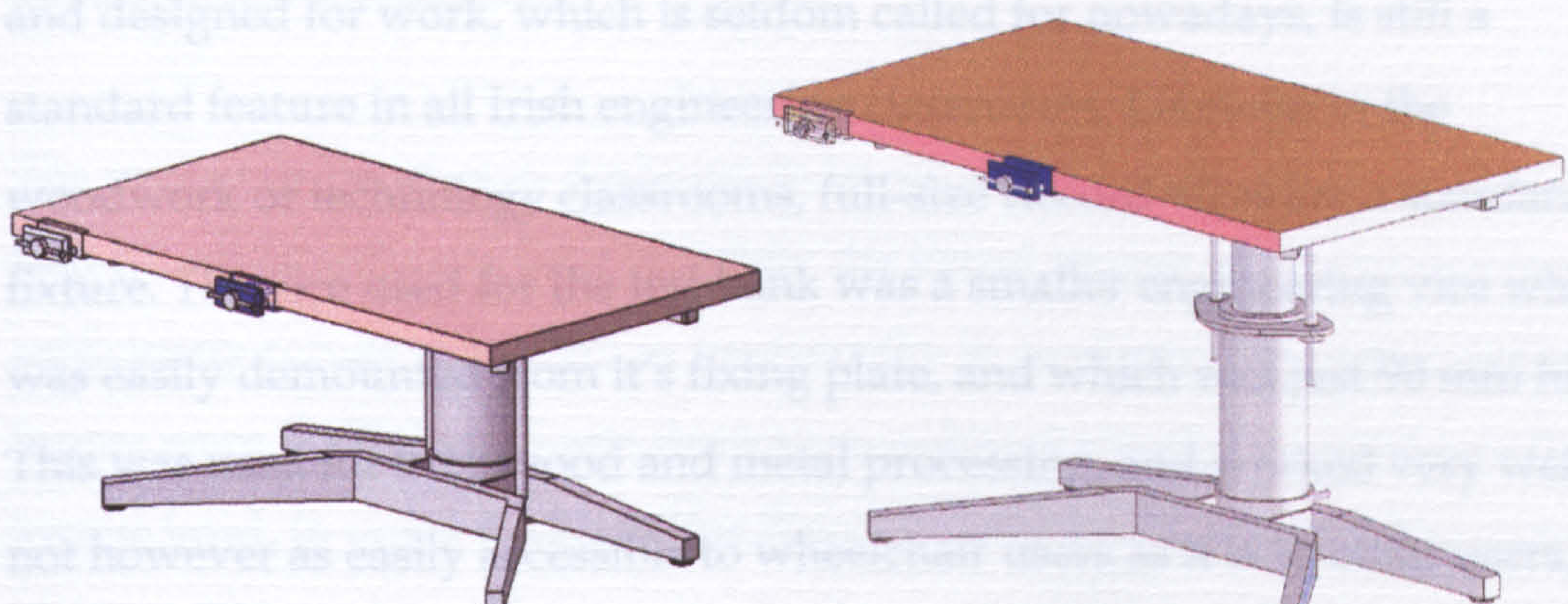


Figure 6-6 The auto-adjustable bench in two positions

The height adjustment to the bench is push-stick controlled. The motor, and the hydraulic pump are housed at the rear-underside of the bench. The control button is located on the underside and right, and is wired through the support beam. Figure 6-7 shows an exploded view of the main components of the bench.

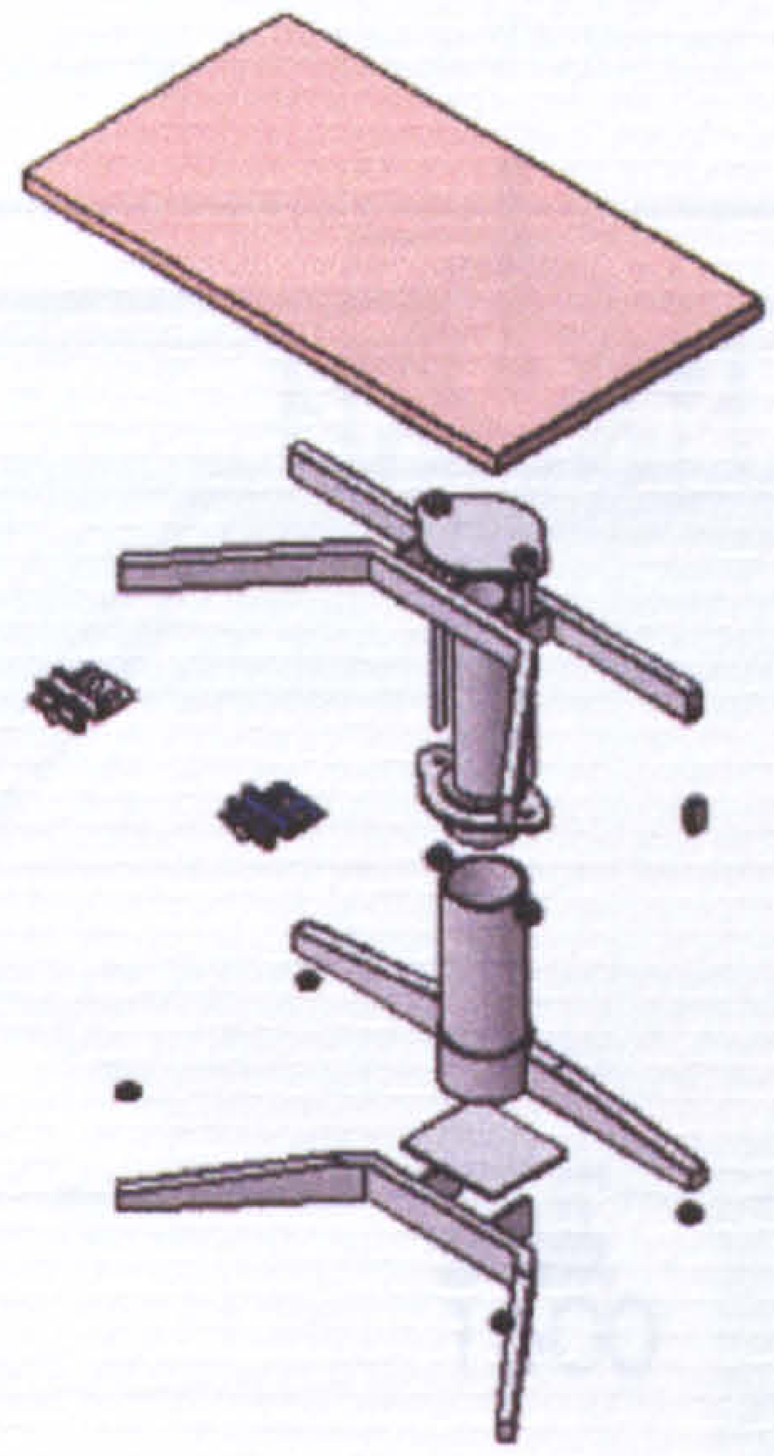


Figure 6-7 An exploded view of the main bench components

Work-holding devices, such as vices, are a standard part of most workbenchs. While in industry, the heavy engineering vice, which is 180 to 190 mm high, and designed for work, which is seldom called for nowadays, is still a standard feature in all Irish engineering classrooms. Likewise in the woodwork or technology classrooms, full-size Record vices are a standard fixture. The vice used for the test bank was a smaller engineering vice which was easily demounted from it's fixing plate, and which was just 90 mm high. This was used for both wood and metal processing, and worked very well. It is not however as easily accessible to wheelchair users as it is to other users, although the former did, in the fitting trials, use the vice without too much postural displacement. The vice shown in the prototype bench seen in plan below in Figure 6-8, is shown in two positions, middle and end. It is intended for removal, when not in use, or moved from one position to the other. The central position makes the bench more accessible to the wheelchair user without diminishing the effectiveness for the able-bodied user. It is suitable for holding wood, plastic or metal. It has a simple fixing plate and a quick release lever for removal. It finished flush with the bench-top. This vice has not yet been manufactured, but the 90 mm engineering vice is adequate for now. From the fixing plate to top the vice is 58 mm high.

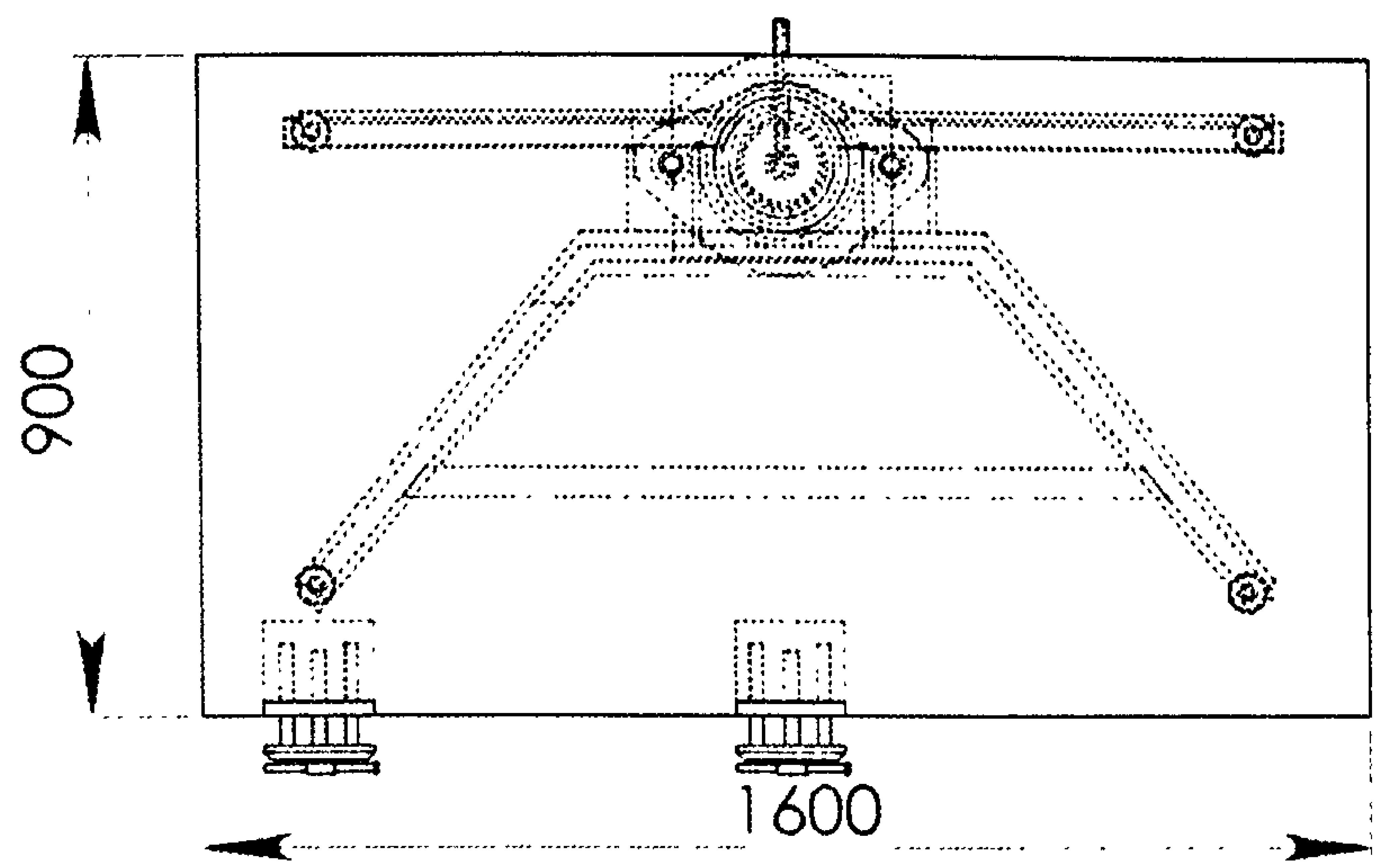


Figure 6-8 New vice design with alternative positions

The full set drawings for the bench, as well as a complete parts list are included in Appendix D.

The prototype bench was designed to be structurally safe, and an ergonomic best-fit, while endeavouring to satisfy the visual impact of a workbench, yet sufficiently robust to be seen as trustworthy in performance. Top support beams were limited to 75 mm deep so as not to obstruct the descent to the lowest level. In order to determine the structural safety and stability, a finite element (FE) analysis of the major loading points was undertaken. At the top, a vertical loading of 1,000N was applied along the front edge and the same at either end. A horizontal loading of 200N was applied to the vertical front edges to apply a torsion loading to the stabilising (torsion) bars. While much of the material was structurally stronger than mild steel, all material was treated as mild steel, for the purpose of testing.

Some of the results are seen below. Figures 6-9 and 6-10 showing the static displacement test. The displacement for a 1,000N edge loading was just in excess of 2 mm, and the factor of safety (FOS) was 5. Figure 6-11 shows the displacement for a torsion loading, with a FOS of 11. Other results appear in Appendix D.

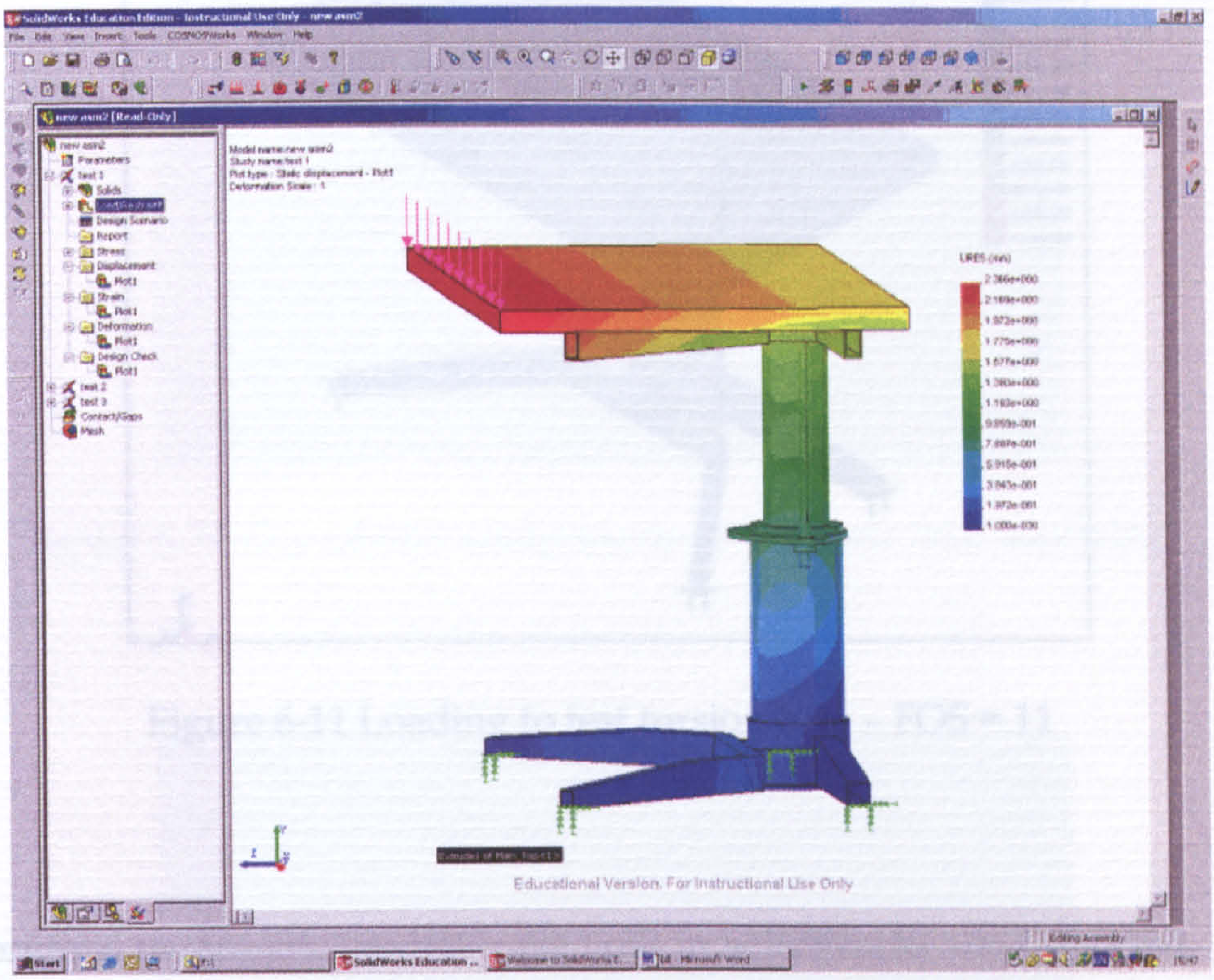


Figure 6-9 Stress for 1000Nfront edge loading - FOS 5.2

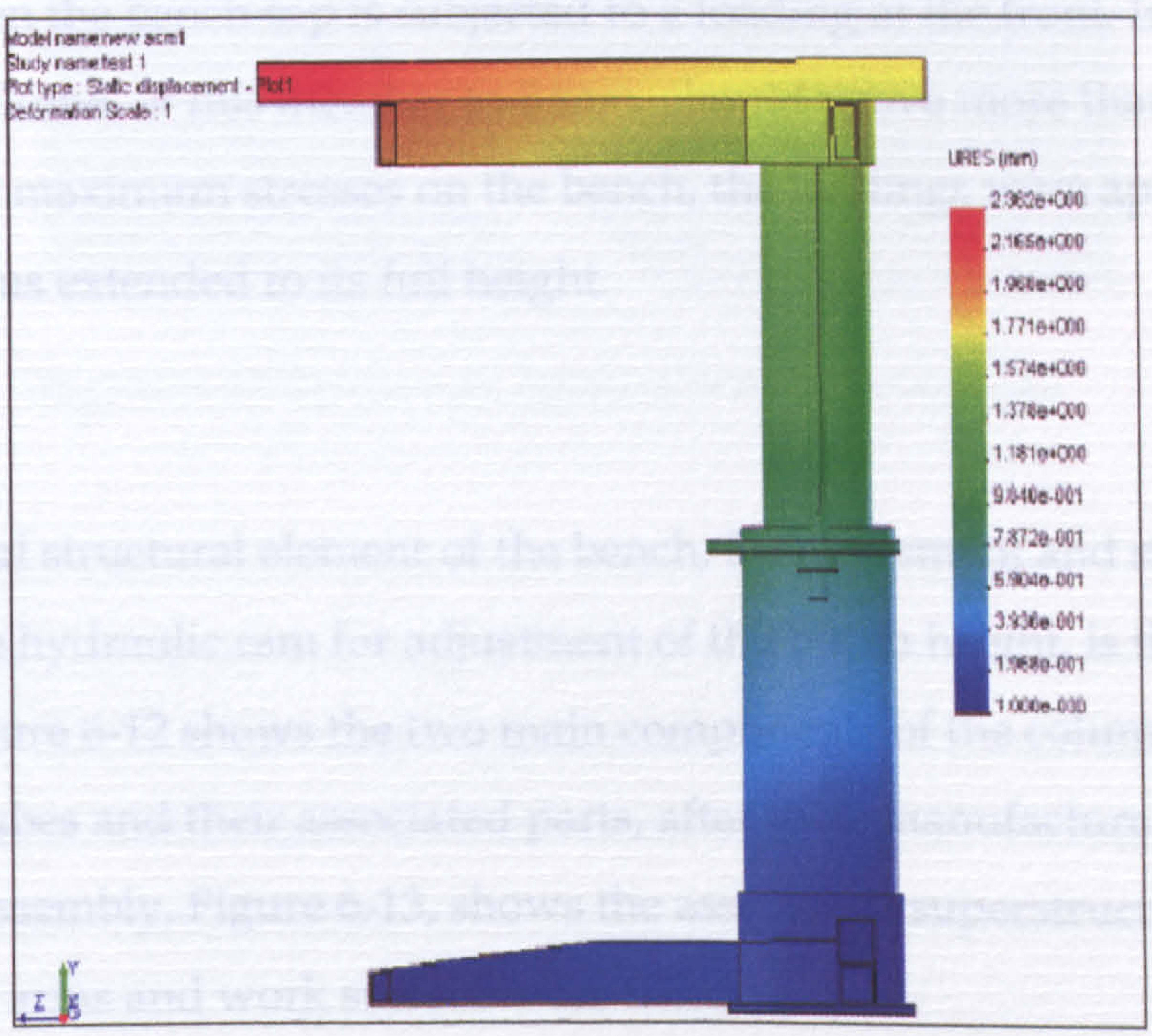


Figure 6-10 Static displacement test - reading 2.3 mm

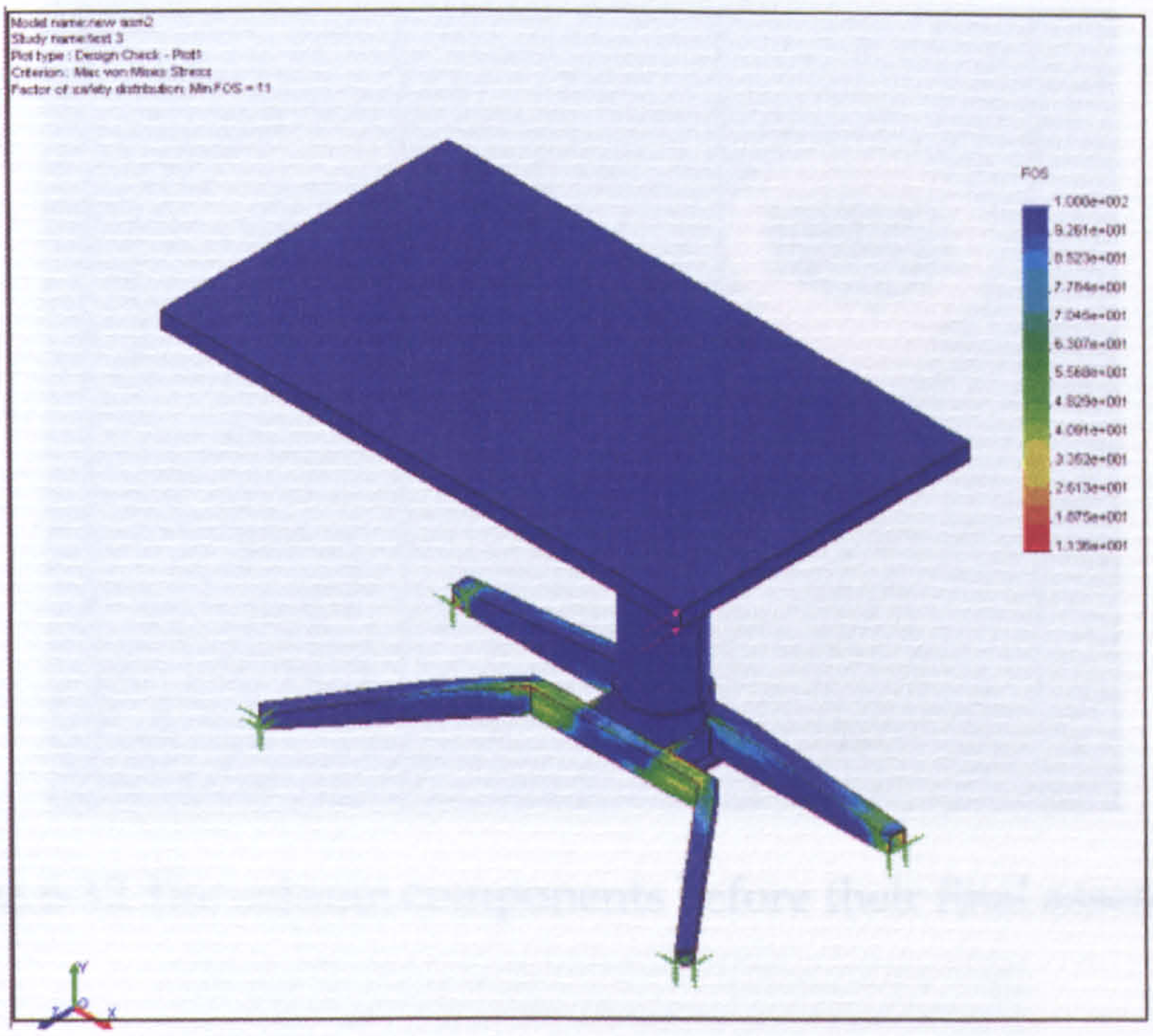


Figure 6-11 Loading to test torsion bars - FOS = 11

The original parametric models were built in SolidWorks and imported, meshed and tested in COSMOSworks. The traverse bar between between the front splayed supports, will need to be strengthened. This carried a torsion loading when the bench-top is subjected to a loading at the front. Increasing the wall thickness of this member to 5 mm, should prove more than enough. In order to test maximum stresses on the bench, the loadings were applied when the bench was extended to its full height.

The principal structural element of the bench, for movement and stability, and to house the hydraulic ram for adjustment of the bench height, is the telescopic column. Figure 6-12 shows the two main components of the column, the inner and outer tubes and their associated parts, after their manufacture and before their final assembly. Figure 6-13, shows the assembled superstructure before the support arms and work surface were fitted.

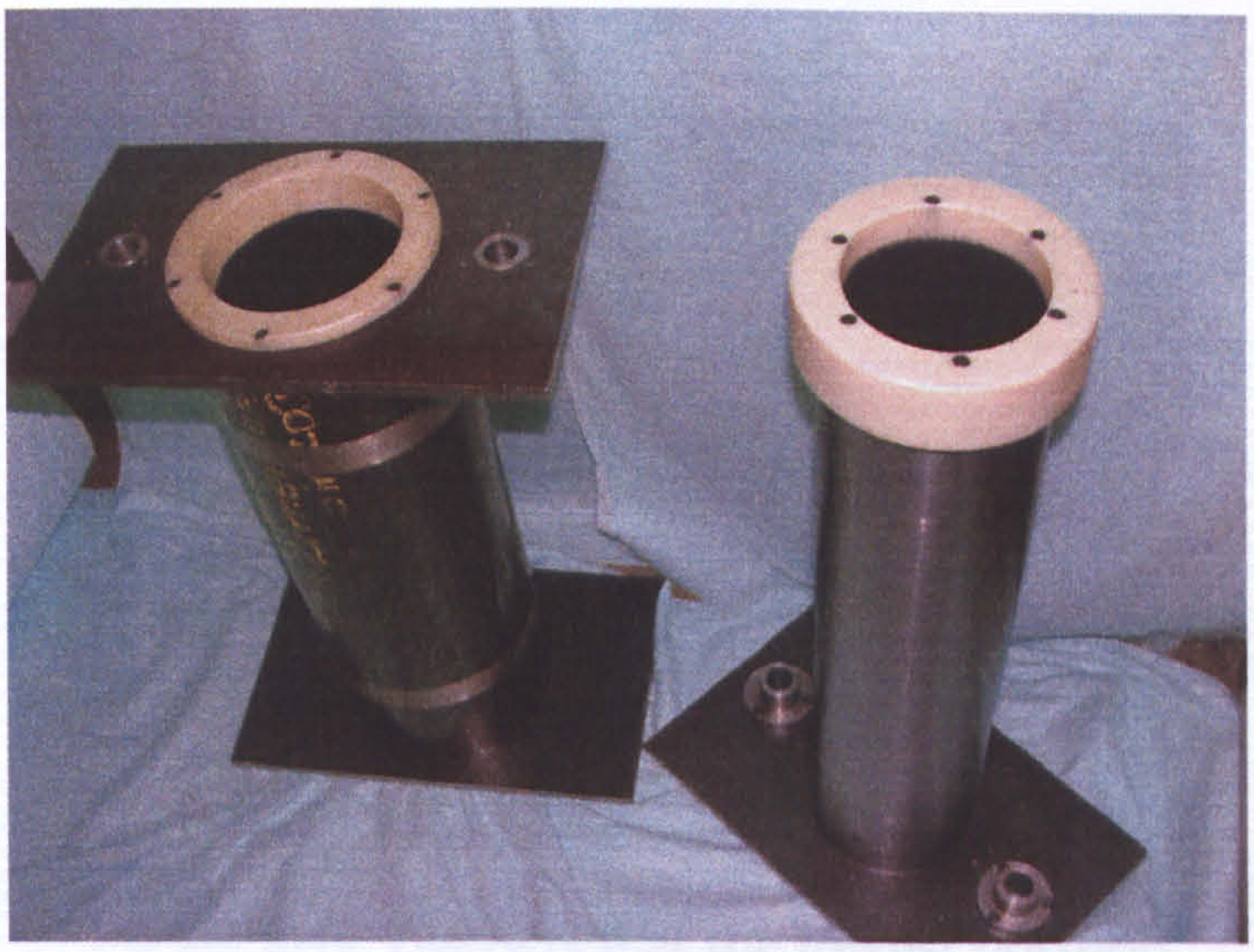


Figure 6-12 The column components before their final assembly

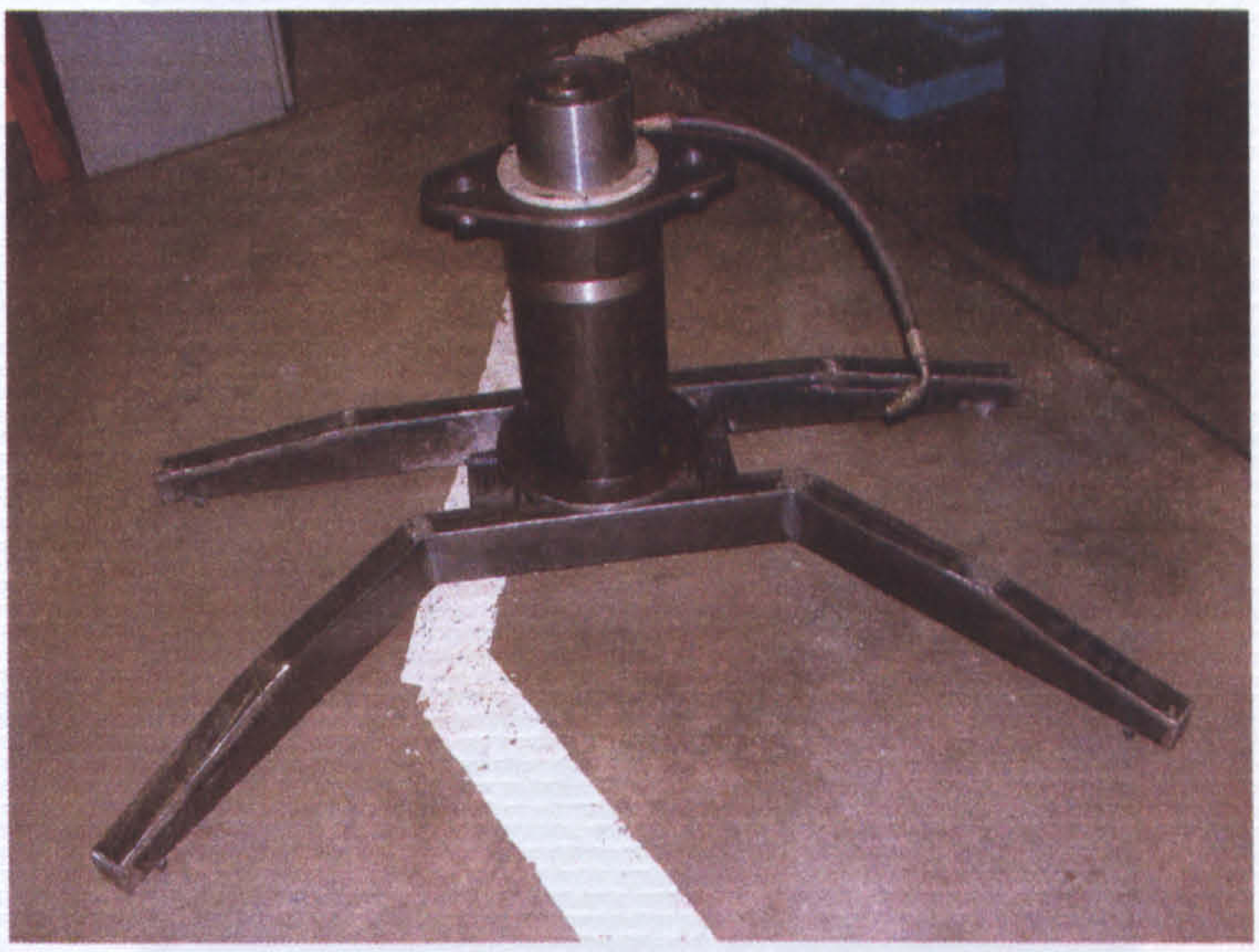


Figure 6-13 Telescopic column with support legs

The top support arms and laminated medium density fibreboard (MDF) top, were then fitted. The top was edged in hardwood to protect the edges of the work surface and to improve the appearance. Figure 6-14 shows the bench at the lowest level, while Figure 6-15 shows the column fully extended. The torsion bars are clearly visible, however the hydraulics as seen, are only on test connection.

Figure 6-14 The bench at the lowest position

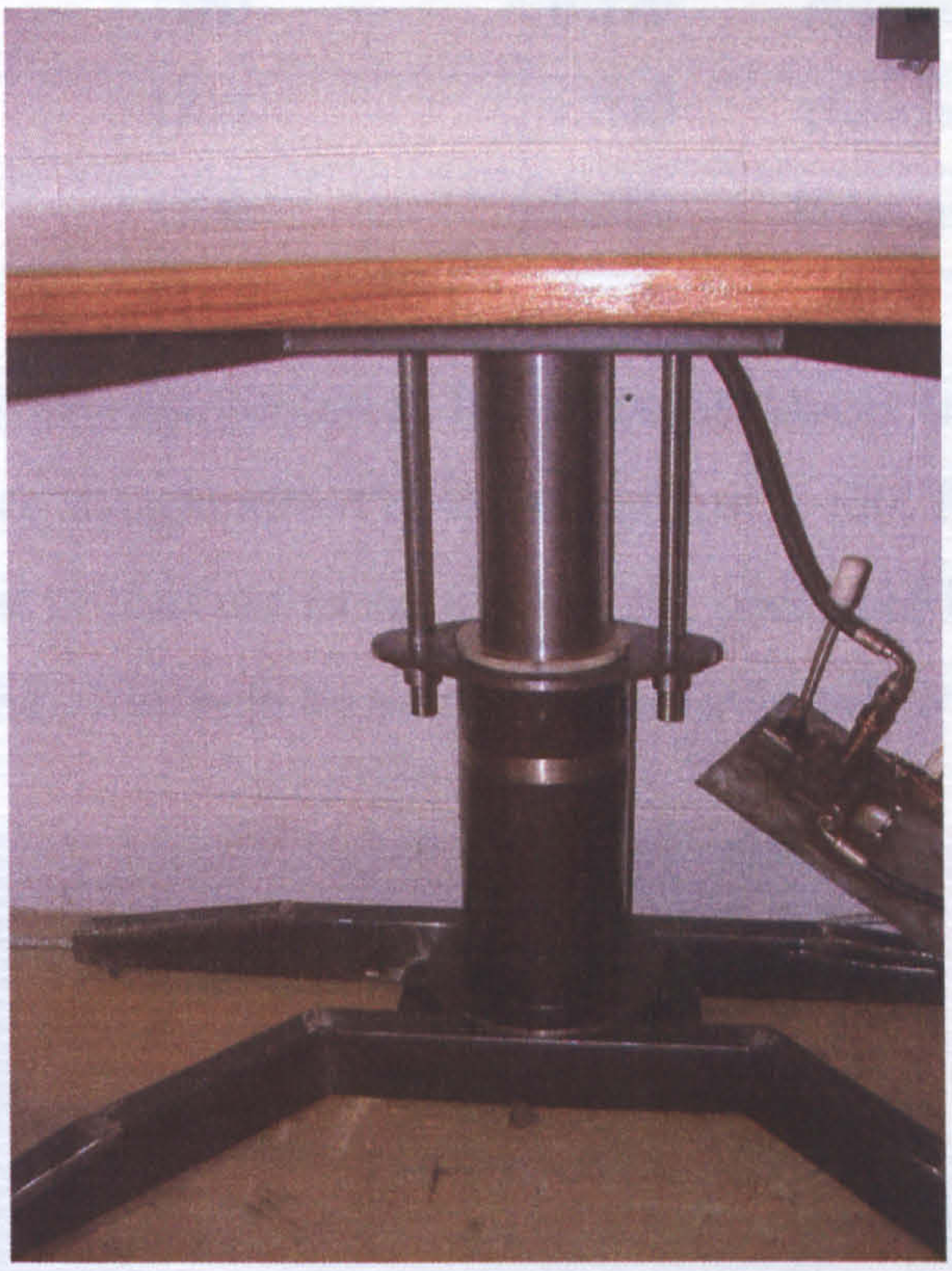


Figure 6-15 The telescopic column fully extended

Does it work? Four very tall males were trial-fitted, following testing and analysis, in the final design stage of the improved test-rig/prototype. All were in the 95th percentile (Pheasant, 1998, for British males) stature, and one of them was in the 99th percentile stature (Goldsmith, 2000). They were asked to work through the test processes at the E-150 height, and to make any fine adjustments to the height that they saw fit. Their optimum choices are shown in Table 6.1 below.

The levels at which they felt most comfortable were recorded in order to confirm if E-150 was the most satisfactory, and to ensure that the extended height of the prototype bench was adequate. All were experienced bench users.

Table 6-1 Post testing trial fits on taller users

Subject	*Stature*	*Elbow Height*	*Max comfort below elbow*
1	1920	1185	E-135 (Tolerance to E-150: + 15)
2	1905	1180	E-170 (Tolerance to E-150: - 20)
3	1985	1235	E-140 (Tolerance to E-150: +10)
4	1870	1200	E-150 (Tolerance to E-150: + 00)

As may be seen the average preferred height below elbow is 148.75 mm, a mere 1.25 mm above the identified best-fit height of E-150. The contrast in body posture of one of the trial-fit subjects, at the preferred height, and at the existing height of 800 mm, is to be seen in Figure 6-16 below.

Figure 6-16 The same worker at the Existing height (left) and at E-150.

The inclusive test-rig/prototype bench fulfils the design criteria very well. It has been tested for structural safety and fulfils these requirements quite satisfactorily, with one modification required to reduce torsion at the rear of the legs.

For wheelchair users the height of 100 mm above knee height has been enthusiastically received, and this height level has also been confirmed and reinforced by the surrogate wheelchair users. An element of safety needs further consideration here. If the WU is distracted, and has one of the greater knee heights, there is a danger of knee/thigh injury by the descending bench. This is an area, which requires further investigation. One solution, which could be researched, is to project a laser beam across between the support-frame arms, at the front. With the depth of the arms at 75 mm, the beam could be fixed as much as 70 mm from the bench soffite (under-surface), and if the beam is broken by the knees it cuts the movement immediately. A less sophisticated safety device is to use a steel dowel, inserted in an appropriate height-socket, in the column to stop the decent of the inner tube. Figure 6-17 shows a wheelchair user at the inclusive best-fit bench.

Figure 6-17 A wheelchair user at the inclusive bench

The more inclusive model, which has been developed, will allow further testing of wheelchair users at bench processing, and comparisons may be made with able-bodied users for the same test elements. Future testing may also include a study of the impact of the ergonomic best-fit, on the quality of work.

Consideration was given to tilting the top forward 15°, to make blueprint reading, using a laptop computer, drawing or writing, easier. However this was excluded because of complicating the design and considerably adding to the cost. Instead it is suggested that a folding, lightweight 'desktop', may be hung on the back of the bench and used as required.

At the beginning of this Chapter the criteria for the inclusive prototype bench were outlined. These were: *safely usable by all; fit for the purpose intended; not identifiably associated with any one group; of robust construction; and be able to satisfy the principles of UD.*

It is felt that these criteria have all been satisfied. The bench functions well, and is safe and robust in construction. Some work, however needs to be undertaken, to provide for a safe descent of the bench when being used by WUs, who may be adjusting it, while their legs are underneath. The bench does not look minority specific, but has appeal and functionality for all users. It satisfies the needs of a diverse range of users, and it is therefore an *inclusive solution,* which will function well as a test-rig for further research, and as a first prototype, ready for further development. It fulfils all the principles associated with universal design.

7 OVERALL CONCLUSIONS AND FUTURE WORK

The anthropometrics of humans and their ergonomic requirements are very diverse, and yet these diversities are very often ignored. This has been found to be particularly true when it comes to the workbenches people use, whether every day, or on a part-time regular basis. While the population in most parts of the world has grown in stature, very often, the equipment they use remains the same. This is not just of significance to the general user, but works (even if inadvertently) to exclude many users, in this case wheelchair users, and is quite ergonomically inadequate for a significant number of others. Not only is this a poor design strategy, but it is also makes little economic sense.

7.1 The cost of work related MSDs/RSIs

Work related Musculo-skeletal disorders (WRMSD) or work related repetitive strain injuries (WRRSI) have a huge impact on several fronts in the developed world. In spite of all the scientific, technological and economic advances, this problem still persists. Mark Boisnel addressed the delegates at the closing ceremony of 'European Week 2000', the theme of which was; Musculoskeletal Disorders'. He said; 'If we think in terms lower back pain, backache or pains in joints, we soon get the idea of the profound human dimension of this subject..... an average of 30% of European workers, or 44 million people in all suffer from some form of MSD'. Every year 600 million working days are lost in the EU due to occupational health problems, of which MSDs make up 30%. That is a huge 180 million working days.

The cost is not just the economic loss, which must include medical costs, but the cost in human suffering. Pheasant, (1998), in discussing the psychological as well as the physical suffering associated with MSDs/RSIs, points out that people with long standing RSI, show patterns of deviation from the psychological norm. He says: '...anxiety and depression that are so characteristic of the RSI victim are the consequences of that person's physical condition' (p149). Any contribution which, might lessen the impact of MSDs/RSIs is obviously worth pursuing. While there is no evidence of research into the effects on school going bench users as future MSD sufferers, there is evidence that one-third of them will suffer MSDs in later life. Their school desks, has been identified as one contributing factor. This thesis has considered ergonomic intervention on their use of workbenches.

In the introduction to this Thesis it was stated that several research questions would be addressed. One of the questions asked in relation to bench design was: Can body part discomfort (BPD) be reduced? The Thesis has discussed the effects of bench height on comfort, endurance, subjective height evaluation and performance. BPD impacts on all the other areas, and there is a correlation between it and the others. Therefore the recommendations for minimising BPD at workbenches can have some impact on reducing MSD now and in the future.

7.2 The main findings

The test banks devised worked very well to establish the data, and the test rig in both forms, i.e. cantilevered and centrally supported, provided the ideal test platform in all its variations. The heights, which were finally selected, were quite adequate to make the test comparisons and to control the time in relation to a 'rapid-response' feedback. The test groups were sufficiently diverse in age, stature, and ability to make a comparative evaluation of the data and to identify the particular and peculiar needs of each group.

7.2.1 Wheelchair users and surrogates

In Chapter 3 we discussed the possibility of using surrogate wheelchair users to determine ergonomic data, relating to workbenches. It has been shown that this is quite acceptable to use SWUs for this purpose. This has enabled the broadening of test cohorts or the using of surrogates only, for design ergonomic testing. It also afforded the opportunity to make gender comparisons relating to the bench activities discussed. The following has been achieved:

- The most appropriate height for wheelchair users (including surrogate wheelchair users) was found to be at Knee Height plus 100 millimetres, i.e. KH+100. Working at this height significantly reduced body part discomfort, and improved productivity (though not significantly).

- endurance curves and equations have been devised which will allow the calculation of estimated endurance for a range of heights. Moving from the identified optimum in either direction will result in reduced endurance times and increased body part discomfort. The non-neutral body positions, in which wheelchair users are forced to work at existing benches, would undoubtedly increase the likelihood of MSDs for them in the future;

- the comparisons between working at the existing/traditional engineering bench, and the best-fit KH+100 bench produces highly significant statistical evidence of reduced body part discomfort, and improved productivity and work endurance times;

- there was a distinct correlation between the WU group and the SWU group in nearly all facets of the test results, with the exception of some elements of BPD. There was however, a good match, in the BPD analysis of back and shoulders for both groups, as well as for the aggregate BPD. Aggregate BPD is seen as a very useful measure in relation to general best-fit trials;

- there was no significant differences between male and female sub-groups, in efficiency, endurance or in height rating;

- there appears to be no reason why surrogate wheelchair users may not be used as test subjects in research relating to bench design to accommodate wheelchair users at industrial tasks. The research also suggests that it appropriate to mix test groups;

- all of the surrogates tested, commented on the experience of working while seated in a wheelchair. None of them would look at wheelchair users in the same light as a result of that experience. They all said they would have much greater empathy with wheelchair users in future. In addition to undertaking the test bank series, some of them used the wheelchair to access other parts of the building, just to feel the experience. Most of them were generally more tired, especially the females at the conclusion of the test session.

The research has extended ergonomic test methodology and data for wheelchair users at workbenches. This research highlights to employers the capability of wheelchairs in work environments, where they were not traditionally seen. In an earlier survey associated with wheelchair accessibility in industry in Ireland, conducted at the University of Limerick in 2000, of 120 responses, not one of the companies employed a wheelchair user on the shop floor (O'Herlihy and Gaughran 2002[1]). Many commented that it was too unsafe, or that they had never considered the possibility. This research therefore opens up possibilities of career options not just in the minds of prospective employers, but also in the minds of the wheelchair users themselves. They have been empowered to consider career options, which in the past have been considered outside their level of capabilities.

7.2.2 The junior students

The area of ergonomic intervention on second level students in their first (or any other) year, relating to practical classroom activities appears not to have been explored by any researchers previously. The first year students of today are significantly taller than previous generations (some of them exceedingly so), yet the equipment has not changed or has moved even further away from their requirements. It must be recognised that these young people are the potential MSD sufferers of the future, and if an intervention can be made to provide more comfortable working conditions in technology and other practical classrooms, then the opportunity ought not to be missed. The following are the primary findings of this element of the research:

- The juniors preferred the bench height of E-150, and while they did not have significant aggregate BPD differences between this and the Existing height, they nevertheless increased in discomfort sharply as the bench moved above and below E-150. This is particularly important for the taller members of the cohort, because for them, the existing bench level may well be at or below the E-250 level as seen in figure 7-1 below.

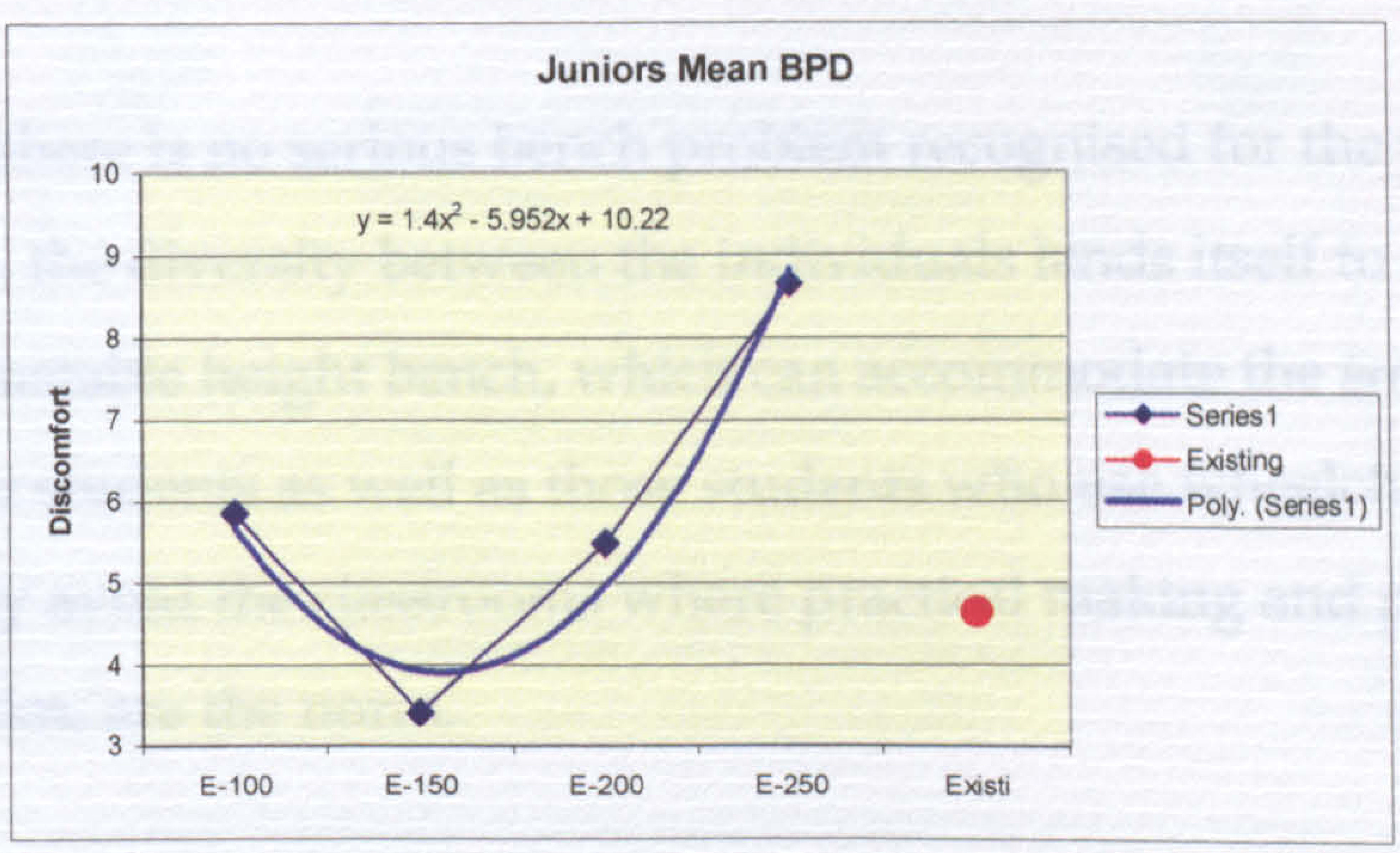


Figure 7-1 Aggregate BPD for the junior test group

There were differences in BPD for this group that will require future exploration. They were the only group to show significant BPD in the upper legs (thighs), and the BPD in hand and wrist was higher than the other groups. Some hand-tool redesign, to suit the ergonomics of smaller and physically less well developed hands and wrists, needs to be undertaken;

- even though there was not a great problem with the majority of them with the Existing bench height, they still judged the E-150 level to be the most comfortable, to have the longest estimated endurance, and it was their preferred height. Three of the tests elements of the test bank were limited to a two minute duration to combat fatigue, therefore only two test elements were used for this group for efficiency analysis. While one of these tested significant, overall it was found that bench height did not affect efficiency. However as already pointed out, prolonged working in uncomfortable positions is likely to impact on efficiency, and even though it was not part of this research study, there is likely to be an impact on quality of work;

- there were generally no significant differences found between males and females, for this group. Efficiency for the wood sawing test element was significantly better for the males at $p=0.005$;

- while there is no serious bench problem recognised for the junior cohort as a whole, the diversity between the individuals lends itself to recommending an adjustable height bench, which can accommodate the smaller and taller stature students as well as those students who use wheelchairs and who usually avoid the classrooms where practical making and processing activities, are the norm.

Figure 7-2 on the next page shows a colour-coded representation of BPD the principally effected zones for the junior students.

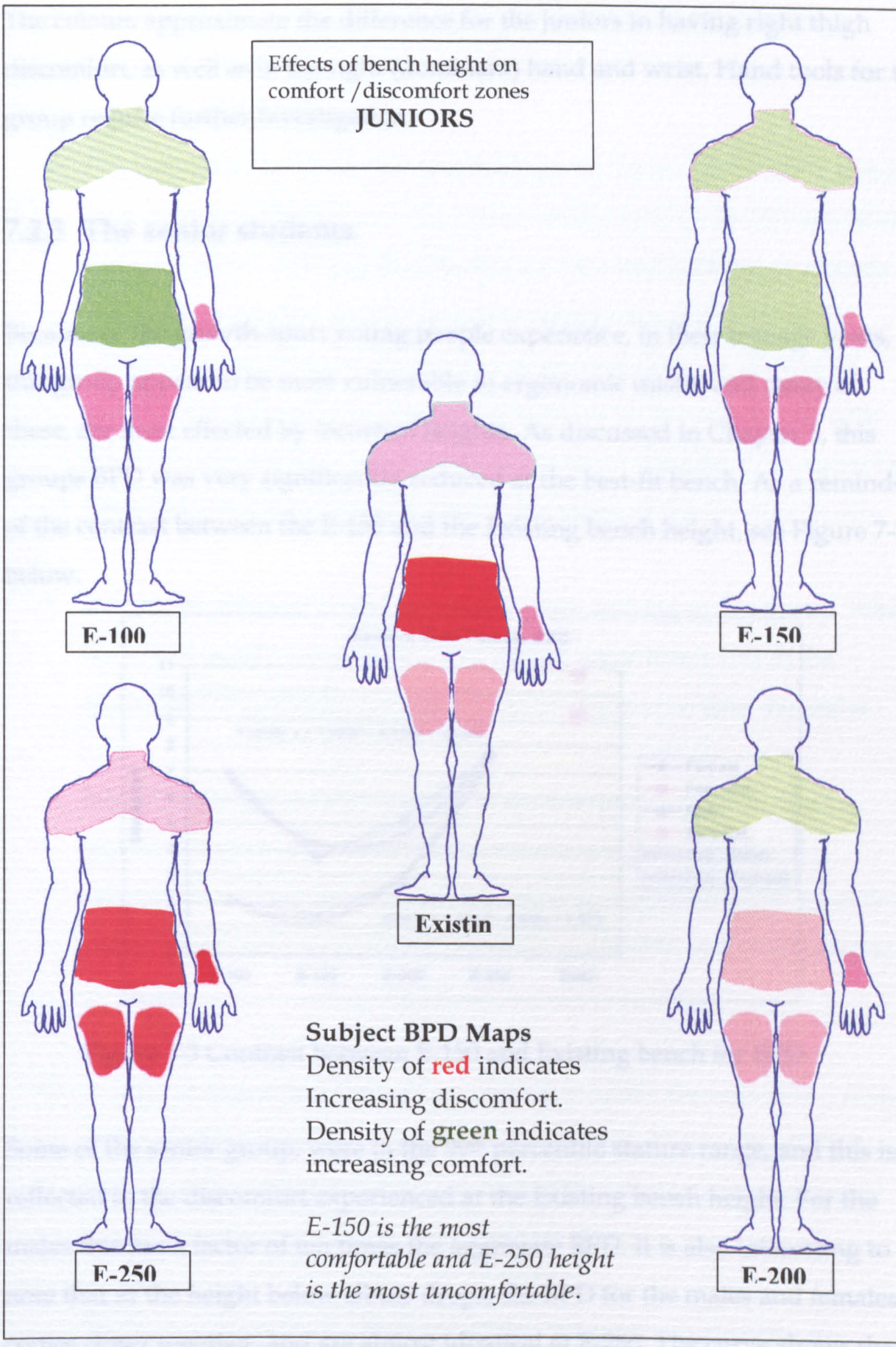


Figure 7-2 The comfortable and uncomfortable body zones colour-coded, for junior students

The colours approximate the difference for the juniors in having right thigh discomfort, as well as in the right (dominant) hand and wrist. Hand tools for this group require further investigation.

7.2.3 The senior students

Because of the growth-spurt young people experience, in their teenage years, this group appear to be most vulnerable to ergonomic misfit, and many of these, are most effected by incorrect heights. As discussed in Chapter 5, this groups BPD was very significantly reduced at the best-fit bench. As a reminder of the contrast between the E-150 and the Existing bench height, see Figure 7-3 below.

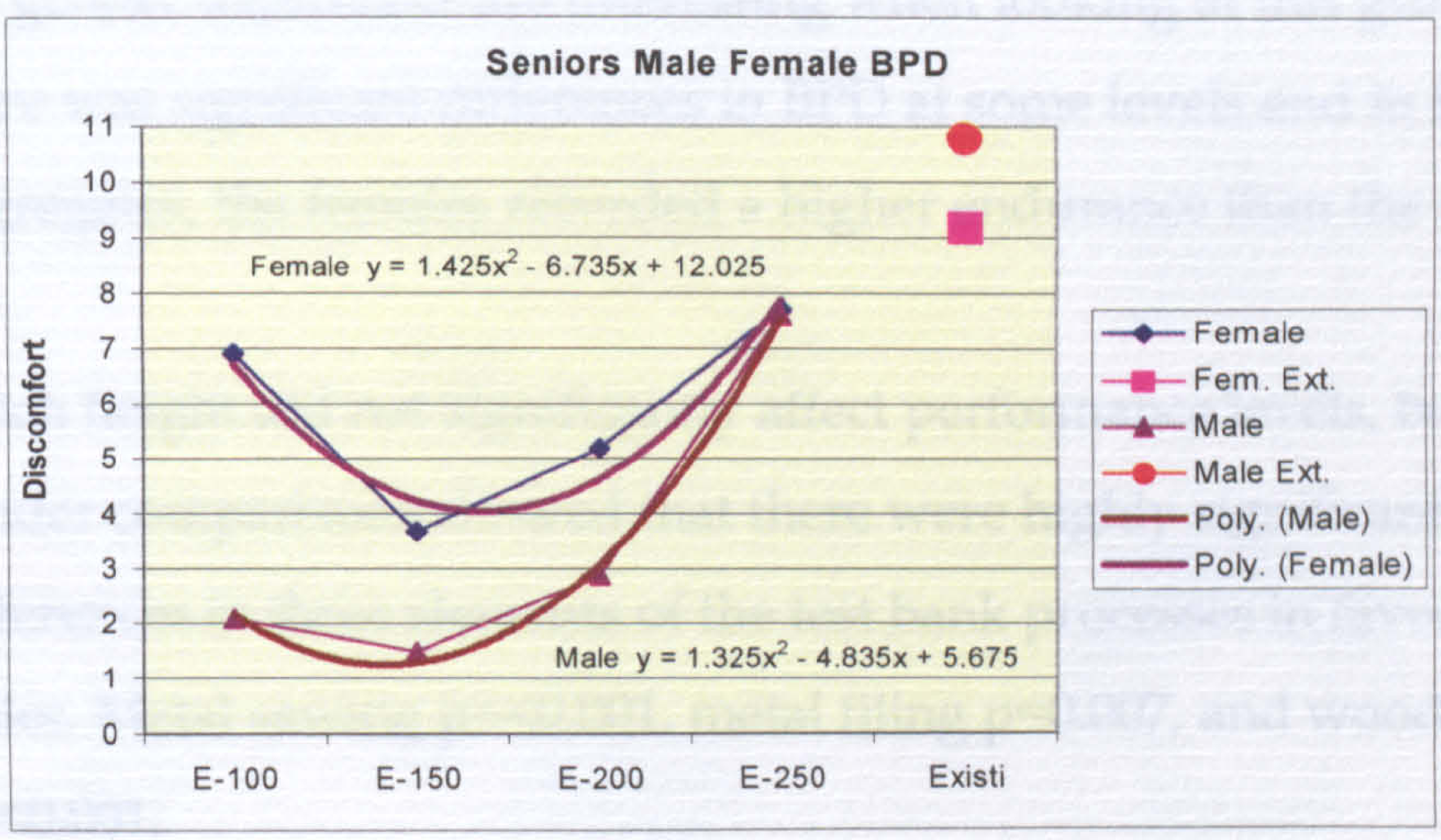


Figure 7-3 Contrast between E-150 and Existing bench for BPD

Some of the senior group, were in the 99th percentile stature range, and this is reflected in the discomfort experienced at the Existing bench height. For the males this has a factor of ten times the aggregate BPD. It is also interesting to note that as the height below elbow drops, the BPD for the males and females comes closer together, and are almost identical at E-250. The curve shows that this female group, has a robust working height working either side of the E-150 level, to plus or minus 25 mm. While the males BPD rises slowly at E-100, the BPD for the females rises quite sharply. The primary findings for this group are:

- The mean stature for the females in his group exceeded the adult female mean stature by 66 mm, and the tallest female senior was 190 mm taller than the tallest adult female. This has it's own implications, as regards work-height comfort. While the male seniors were shorter than the adults by approximately 50 mm, the upper end of the of the stature scale for the male seniors, shows that some of them were significantly taller than the adults. This accounts for some of the high BPD scores for this group, and magnifies the ergonomic misfit of the Existing bench;

- the gender differences are interesting when looking at this group. While there was significant differences in BPD at some levels and in the aggregates, the females recorded a higher endurance than the males;

- bench height did not significantly affect performance levels, but the gender comparisons showed that there were highly significant differences in three elements of the test bank processes in favour of the males. Metal sawing $p=<0.001$, metal filing $p=0.007$, and wood sawing $p=<0.001$;

- in spite of discomfort this group worked at nearly the same pace, even while working in quite awkward body postures. These school goers require urgent ergonomic intervention, if the practical classrooms are not to contribute to a future life of MSD suffering;

- the seniors rated the E-150 bench height the most comfortable, the preferred height, and scored it best for endurance, and as was seen in the last Chapter, the post test trial-fits showed that there is very little deviation from this measurement from people in the 99th percentile.

Figure 7-4 shows a colour-coded representation of BPD the principally effected zones for the senior students.

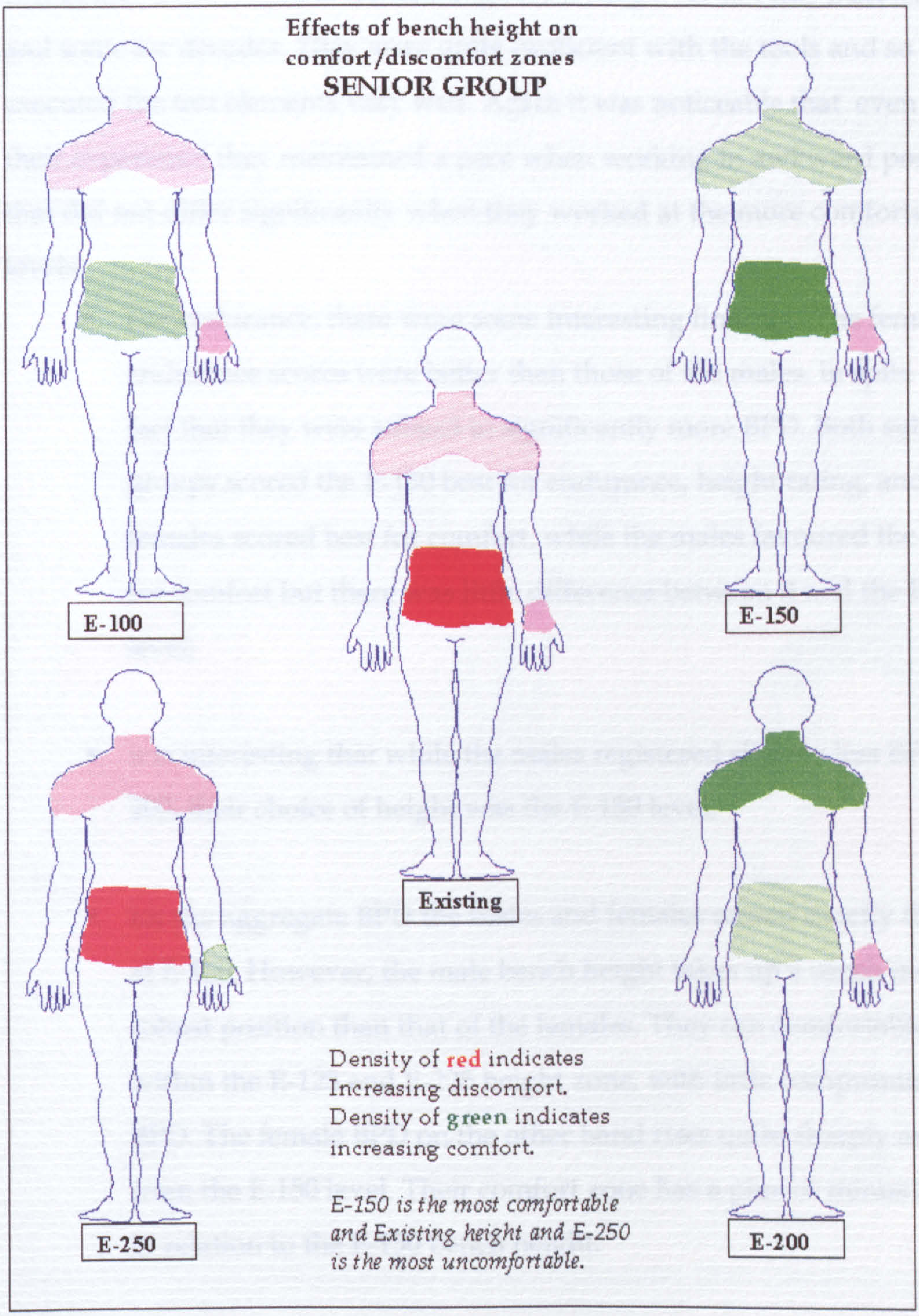


Figure 7-4 The comfortable and uncomfortable body zones colour-coded

7.2.4 The adult test group

These were a very experienced group, as described in 5.1. Most of these, male and female had worked at the existing bench height for not less than ten years, and some for decades. They were quite proficient with the tools and so executed the test elements very well. Again it was noticeable that even with their experience they maintained a pace when working in awkward postures, that did not differ significantly when they worked at the more comfortable levels.

- For endurance, there were some interesting findings. The female endurance scores were better than those of the males, in spite of the fact that they were subject to significantly more BPD. Both sub-groups scored the E-150 best for endurance, height rating, and the females scored best for comfort, while the males favoured the E-200 for comfort but there was little difference between it and the E-150, level;

- it is interesting that while the males registered slightly less BPD at E-200, their choice of height was the E-150 level;

- for the aggregate BPD the males and females scored exactly the same at E-150. However, the male bench height takes up a much more robust position than that of the females. They can comfortable work within the E-125 and E-225 height zone, with little compromise on BPD. The female BPD on the other hand rises quite sharply away from the E-150 level. Their comfort zone has a plus or minus 25 mm, in relation to the E-150 bench height.

Figure 7-5 on the next page shows a colour coded representation of BPD the principally effected zones for the adult test subjects.

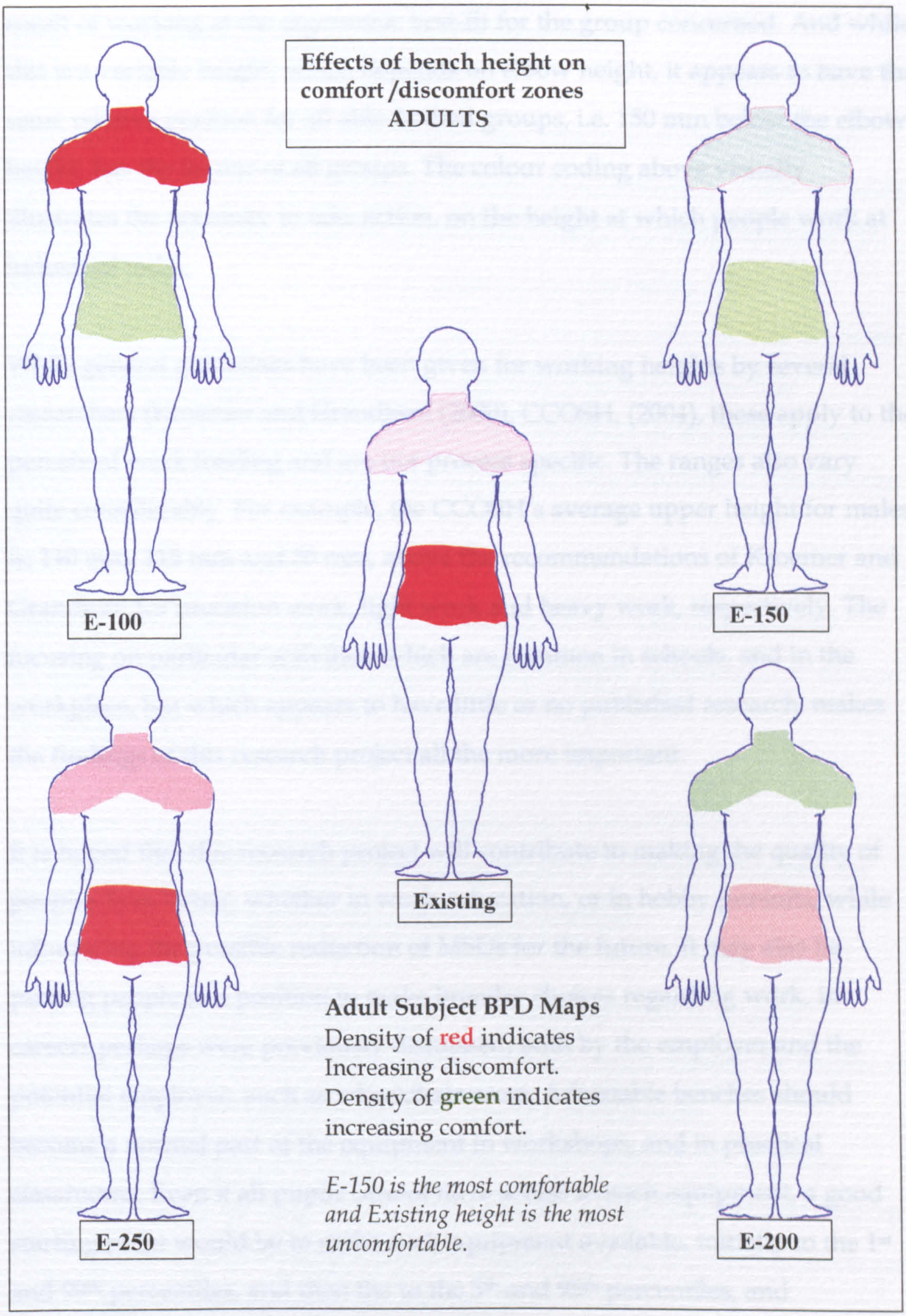


Figure 7-5 The adult comfortable and uncomfortable BPD zones identified.

Figures 7-2, 7-4 and 7-5 attempt to illustrate the effects of bench height on the comfort of the body zones. Some of the zones move from red to green as a result of working at the ergonomic best-fit for the group concerned. And while this is a variable height, which depends on elbow height, it appears to have the same relative position for all able-bodied groups, i.e. 150 mm below the elbow height, has the favour of all groups. The colour coding above visually illustrates the necessity to take action, on the height at which people work at industrial tasks.

While general guidelines have been given for working heights by several researchers (Kroemer and Grandjean (2000), CCOSH, (2004), these apply to the perceived work loading and are not process specific. The ranges also vary quite considerably. For example, the CCOSH's average upper height for males is; 110 mm, 115 mm and 50 mm, above the recommendations of Kroemer and Grandjean for precision work, light work and heavy work, respectively. The focusing on particular activities, which are common in schools, and in the workplace, but which appears to have little or no published research, makes the findings of this research project all the more important.

It is hoped that this research project will contribute to making the quality of peoples lives better, whether in work, education, or in hobby pursuits, while influencing the possible reduction of MSDs for the future. It may also be putting people in a position to make broader choices regarding work, in careers perhaps were previously dismissed, both by the employer and the potential employee, such as wheelchair users. Adjustable benches should become a normal part of the equipment in workshops, and in practical classrooms. Even if all pupils cannot have access to such equipment, a good starting point would be to make such equipment available, initially to the 1st and 99th percentiles, and then the to the 5th and 95th percentiles, and immediately to the minority who cannot access a bench at all, or in some cases may not be even able to access the room in which practical learning activities proceed, the wheelchair user.

7.2.5 Concluding comments and future work

This research project set out with the primary objective of determining an ergonomic-best-fit, for a broad range of users of workbenches. These included the young school going population (12-13 year olds), the senior students (16 plus years old), adults, and a cohort of surrogate wheelchair users. The research also endeavoured to determine, if adolescents who were of the same stature as adults, had the same bench ergonomics requirements. The secondary objective, which was completely dependant on the first, was to design a bench, which would suit the ergonomic requirements of this diverse group.

The research has identified the best-fit heights for the total cohort, while recognising the differences in relation to bench height ergonomics for each of the sub-groups.

Using the data from the *surrogate wheelchair users* in combination with preciously acquired raw data for a similar number of wheelchair users, we have been able to determine three important outcomes:

- Surrogates can be used in place of wheelchair users to acquire ergonomic data for workbenches, without compromising the results, or requiring to include in the data, a factor-of-difference;
- the combining of the two subgroups (WUs and SWUs), allow the exploration of other factors. For example, gender comparisons may be made, and the enlarged cohort allows more accurate conclusions to be drawn, from the analysis of the data;
- an ergonomic best-fit height of 100 mm above knee has been identified as the ideal working height for wheelchair users;

- the career options of wheelchair users are broadened, to the empowerment of wheelchair users, and possibly to the surprise of some employers.

The *junior student group* presented data, which was different from the other able bodied groups. The Existing bench does not present a major ergonomic misfit for the group in general. However, for the 5th and 95th percentiles of this group, the problems exist in relation to a mismatch between the very small or very tall individual. For them the outcomes include:

- Considerable discomfort in hand and wrist areas as well as in the thighs;
- significant discomfort differences to bench variations, but nor between the E-150 and the Existing height, because they are quite close to the same mean distance, below elbow height;
- the hand tools appear to be a considerable ergonomic mismatch for the younger users;
- E-150 is the ergonomic best-fit bench height for the group;
- the taller females in this group (a small sample), recorded no significant ergonomic differences, to female adults of similar stature. The males in this group could not be matched with a corresponding group of adults, because of height differences.

The *senior students* were identified, as being in the greatest 'MSD-for-the-future' danger zone. The 95th to the 99th percentile sub-group, both male and female are working in very ergonomically compromising body postures, at the existing workbenches. The following were the primary findings:

- As with their adult counterparts, the concentration of BPD was in the back, and this can be significantly reduced, by working at the identified best-fit height. There was also some excessive discomfort, in the hand and wrist areas which may need intervention through hand-tool redesign;

- their ergonomic-best-fit height for bench use is E-150. This is reasonably robust to plus or minus 30 mm;
- females working at the best-fit height are less comfortable than the males, but recorded a higher endurance score;
- for the small sample available, individuals in this group recorded no significant difference to adults of similar stature, for bench ergonomics requirements. For a robust conclusion further research in this area is required, using much larger samples.

The *adult test group,* most of whom, have been working at benches which are very much too low for their stature, were surprised at the level of comfort afforded, by adjusting the bench height to a better ergonomic match. Only one of these tested, a female of small stature, was able to work as well at the E-150 level as at an existing bench. The main findings for this group were:

- The existing bench height and the E-250 level presented the greatest discomfort levels, the BPD was mainly concentrated in the lower back;
- females registered far greater discomfort at all levels, with the exception of the E-150 level, the groups best-fit height, where males and females had identical BPD scores;
- in spite of recording greater discomfort, the endurance scores for the females were better than for the males;
- the male best-fit height is more robust than that of the females;
- bench height affects all the areas addressed to a significant degree, with the exception of efficiency. However, males were significantly more efficient than females.

Extending from the above the objective of designing a more inclusive workbench for a diverse range of users has been achieved. The bench works well, is fully adjustable to the needs of the broad range of users tested, and satisfies the 'optics' of a substantial workbench. It is hoped that the research outcomes, will influence the working conditions of all the bench using population the test groups represented, and that it impacts positively in some small way on the reducing of the MSD levels in the future.

7.2.6 Future work

There is a need to investigate the leg discomfort, in the junior cohort, which was not found in the other groups. This may because of muscular immaturity or perhaps they compensate with their legs to counter body flexion and torsion.

The hand-tools currently in use, do not suit the ergonomic requirements of either the junior or senior students. A range of ergonomic best-fit for hand-tools for young people, needs to be pursued.

Quality of work, resulting from ergonomic intervention for this type of work, has not been part of this research. It does however seem justified to say, that if an individual is more comfortable, they will produce better quality work. This needs investigation for schools and for industry.

In attempting to give a visual image of the changes in comfort levels for various working heights, an approximation of the colour changes relating to comfort levels have been used earlier in the thesis. It would be very beneficial to develop a colour spectrum, which could become the standard for varied levels of discomfort, such that in body mapping, where these could be applied accurately. This would not be just of benefit to ergonomic endeavours, but possibly also to the medical profession in identifying and treating MSDs and RSIs, and in perhaps identifying pain levels from accident injury.

It may also be of benefit to study the pedagogical impact of ergonomic intervention in practical classrooms.

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9 APPENDICES

9.1 Appendix A

9.1.1 Test and Evaluation Sheets

The BPD assessment sheet

Best-fit bench design

Body Part Discomfort Scale

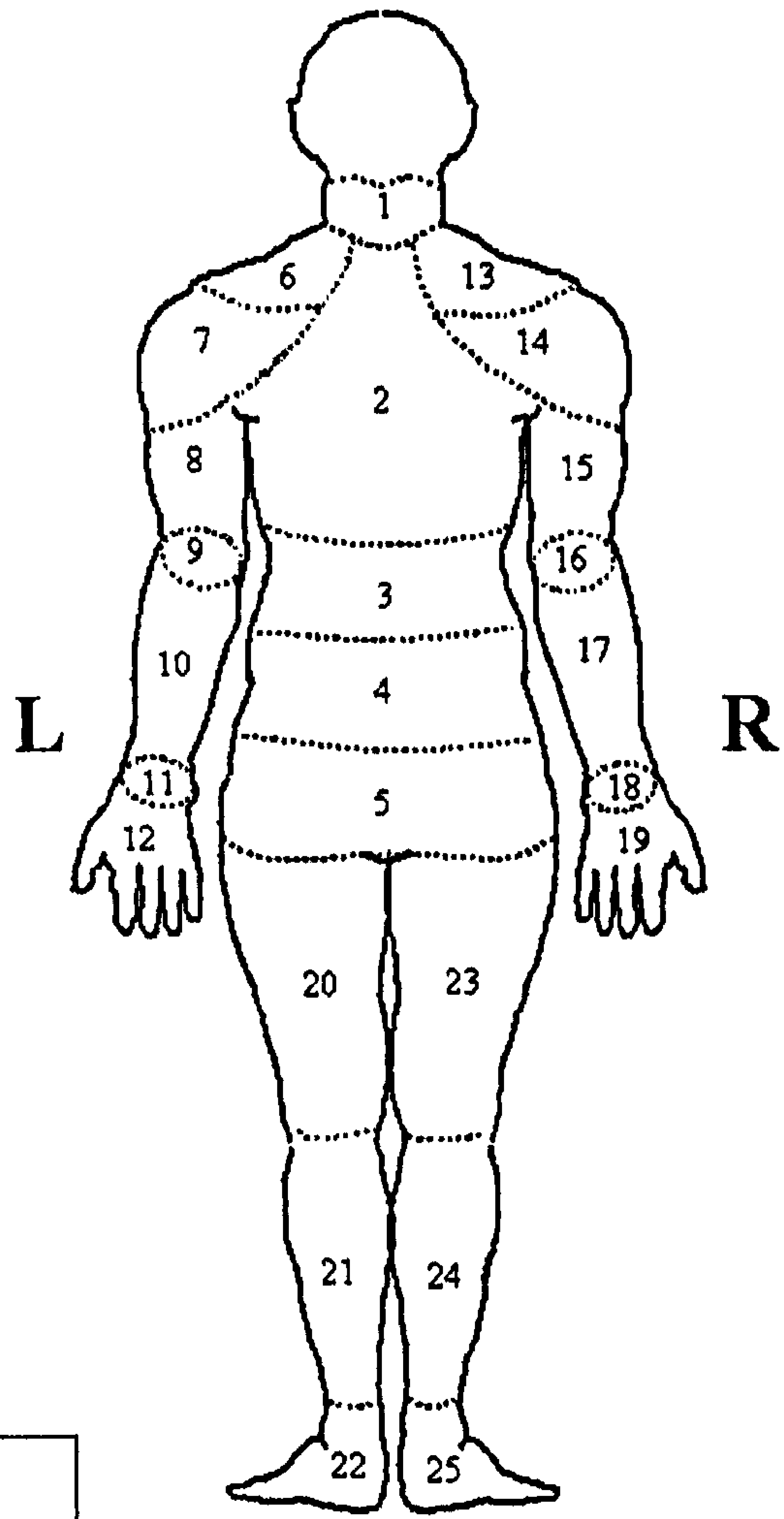
Please rate each of the body parts on the following scale

5 = severe discomfort
4
3
2 Increasing
1
0 = no discomfort

Bench height E -

Testee code

Body Part	Discomfort Level (0-5)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	
20	
21	
22	
23	
24	
25	



Viewed from back

Comments

BG - BPD

Department of Manufacturing & Operations Engineering

University of Limerick

PRE-TEST QUESTIONNAIRE

AME... Ref No.............................

ate of Birth: .... Age: ....

əst procedure................................

ɜ you are to be a subject in this laboratory, would you please complete the following ıestionnaire. Your co-operation in this is greatly appreciated.

Please tick appropriate box

	Yes	No
ıs the test procedure been fully explained to you?	☐	☐

ıy information contained herein will be treated as confidential

	Yes	No
• Has your doctor ever said that you have a heart Condition and that you should only do physical Activity recommended by a doctor?	☐	☐
• Do you feel pain in your chest when you do physical activity?	☐	☐
• In the past month, have you had chest pain when you were not doing physical activity?	☐	☐
• Do you lose your physical balance because of dizziness or do you ever lose consciousness?	☐	☐
• Is your doctor currently prescribing drugs for your blood pressure or heart condition?	☐	☐
• Do you know of any other reasons why you should not undergo physical activity? This might include severe asthma, diabetes, a recent sports injury, or serious illness.	☐	☐
• Do you have bone or joint problem that could be made worse by a change in your physical activity?	☐	☐
• Have you ever had any muscle problems in the hand/wrist /arm/shoulder?	☐	☐

- If you have answered NO honestly to all questions then you can be reasonably sure that you can take part in the physical activity requirement of the test procedure

....declare that the above information is correct at the time of əleting this questionnaire. Date......./........./200..

Test Data Sheet - Best-fit Workbench

Subject		Hand -	Date

	Time Mins.- 3	Depth/time	Depth/time	Depth/time	Depth/time
	Plugtop Assy.	**Metal Sawing**	**Wood Sawing**	**Planing**	**Metal Filing**
Exist. - 800					
E - 100					
E - 150					
E - 200					
E - 250					
E - 300					

ENDURANCE	Hours Estimate			
Exist. - 800			**Endurance Range**	
E - 100			**1 - More than 8**	
E - 150			**2 - 6 to 8 hours**	
E - 200			**3 - 4 to 6 hours**	
E - 250			**4 - 2 to 4 hours**	
E - 300			**5 - Less than 2 hrs.**	

Anthropometric Data

Stature			
Stan. Elbo			

See also BPD Scales

Test Data Sheet - Best-fit Workbench

Subject		Hand -	Date

	Time Mins.- 3	Depth/time	Depth/time	Depth/time	Depth/time
	Plugtop Assy.	**Metal Sawing**	**Wood Sawing**	**Planing**	**Metal Filing**
Exist. - 800					
E - 100					
E - 150					
E - 200					
E - 250					
E - 300					

ENDURANCE	Hours Estimate			
Exist. - 800			**Endurance Range**	
E - 100			**1 - More than 8**	
E - 150			**2 - 6 to 8 hours**	
E - 200			**3 - 4 to 6 hours**	
E - 250			**4 - 2 to 4 hours**	
E - 300			**5 - Less than 2 hrs.**	

Anthropometric Data

Stature			
Stan. Elbo			

See also BPD Scales

Subject:

Subjective Height Evaluation General and Specific

	Too Low	Satisfactory	Too High
E - 100			
E - 150			
E - 200			
E - 250			
E - 300			
Existing			

Height Evaluation Specific

Please tick your height satisfaction levels on the line scales below

Subject
Date
Comments

Bench Height
E - 100

Lo OK Hi — **Planing**
Lo OK Hi — **Metalsawing**
Lo OK Hi — **Woodsawing**
Lo OK Hi — **Filing**
Lo OK Hi — **Plug Assembly**

Bench Height
E - 150

Lo OK Hi — **Planing**
Lo OK Hi — **Metalsawing**
Lo OK Hi — **Woodsawing**
Lo OK Hi — **Filing**
Lo OK Hi — **Plug Assembly**

Bench Height
E - 200

Lo OK Hi — **Planing**
Lo OK Hi — **Metalsawing**
Lo OK Hi — **Woodsawing**
Lo OK Hi — **Filing**
Lo OK Hi — **Plug Assembly**

Bench Height
E - 250

Lo OK Hi — **Planing**
Lo OK Hi — **Metalsawing**
Lo OK Hi — **Woodsawing**
Lo OK Hi — **Filing**
Lo OK Hi — **Plug Assembly**

Bench Height
E - 300

Lo OK Hi — **Planing**
Lo OK Hi — **Metalsawing**
Lo OK Hi — **Woodsawing**
Lo OK Hi — **Filing**
Lo OK Hi — **Plug Assembly**

Bench Height
Existing

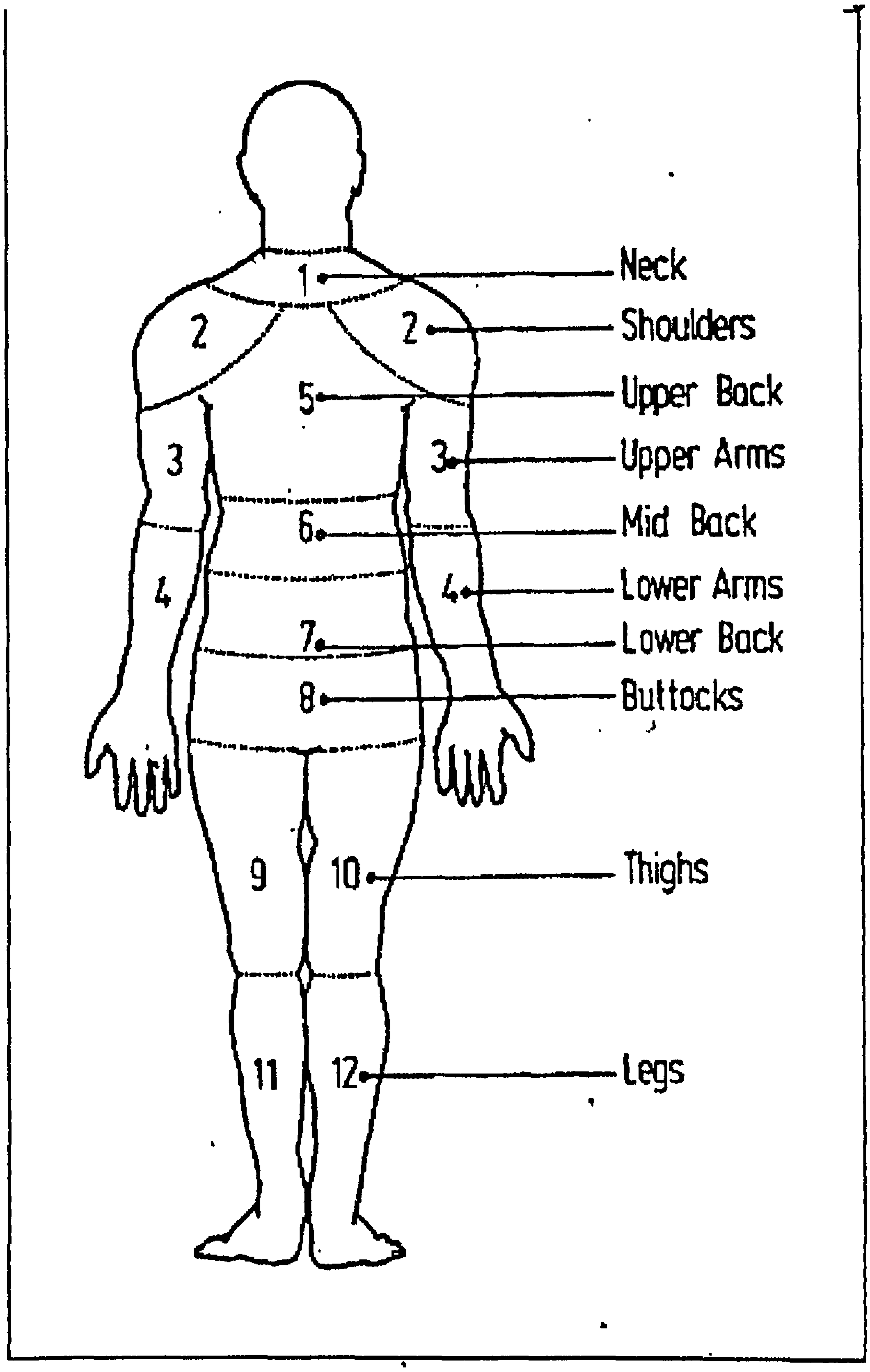
Lo OK Hi — **Planing**
Lo OK Hi — **Metalsawing**
Lo OK Hi — **Woodsawing**
Lo OK Hi — **Filing**
Lo OK Hi — **Plug Assembly**

BG Spec.

9.2 Appendix B

9.2.1 Test material used by others

The BPD zones of Corlett and Bishop, 1976

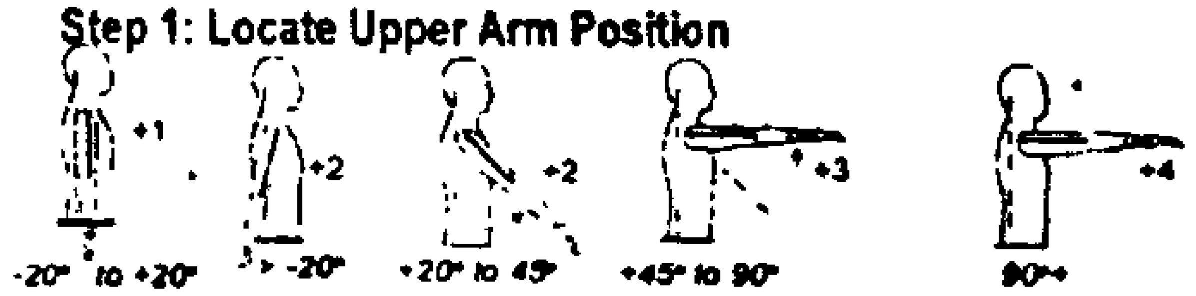


RULA Employee Assessment Worksheet

Complete this worksheet following the step-by-step procedure below. Keep a copy in the employee's personnel folder for future reference.

A. Arm & Wrist Analysis

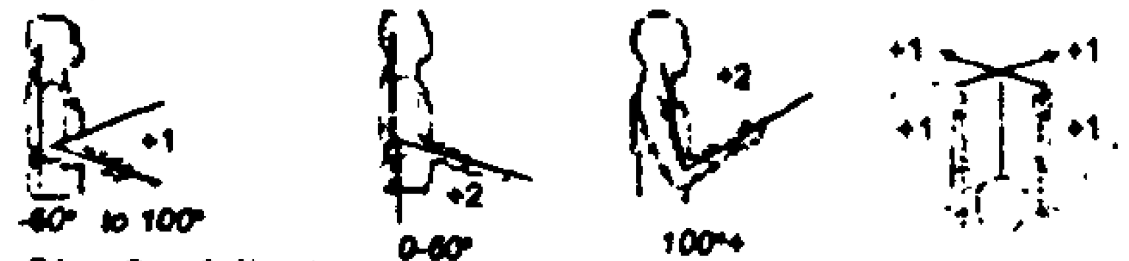
Step 1: Locate Upper Arm Position



Step 1a: Adjust...
If shoulder is raised: +1;
If upper arm is abducted: +1;
If arm is supported or person is leaning: -1

Final Upper Arm Score =

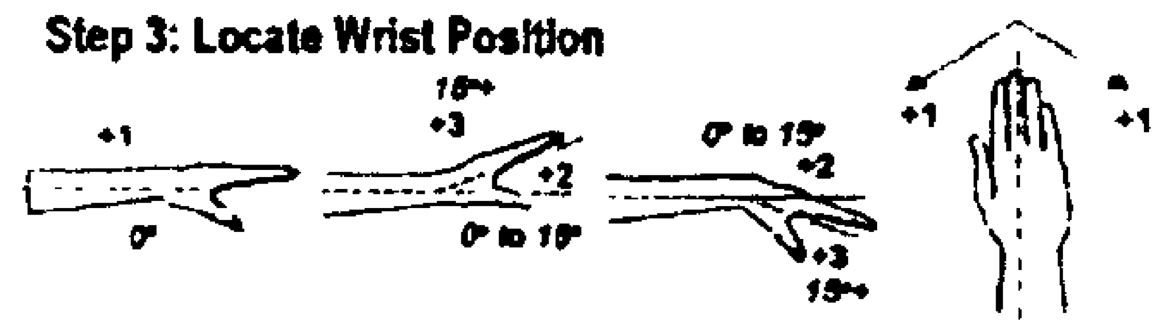
Step 2: Locate LowerArm Position



Step 2a: Adjust...
If arm is working across midline of the body: +1;
If arm out to side of body: +1

Final Lower Arm Score =

Step 3: Locate Wrist Position



Step 3a: Adjust...
If wrist is bent from the midline: +1

Final Wrist Score =

Step 4: Wrist Twist
If wrist is twisted mainly in mid-range =1;
If twist at or near end of twisting range = 2

Wrist Twist Score =

Step 5: Look-up Posture Score in Table A
Use values from steps 1,2,3 & 4 to locate Posture Score in table A

Posture Score A =

+

Step 6: Add Muscle Use Score
If posture mainly static (i.e. held for longer than 1 minute) or;
If action repeatedly occurs 4 times per minute or more: +1

Muscle Use Score =

+

Step 7: Add Force/load Score
If load less than 2 kg (intermittent): +0;
If 2 kg to 10 kg (intermittent): +1;
If 2 kg to 10 kg (static or repeated): +2;
If more than 10 kg load or repeated or shocks: +3

Force/load Score =

=

Step 8: Find Row in Table C
The completed score from the Arm/wrist analysis is used to find the row on Table C

Final Wrist & Arm Score =

SCORES

Table A

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

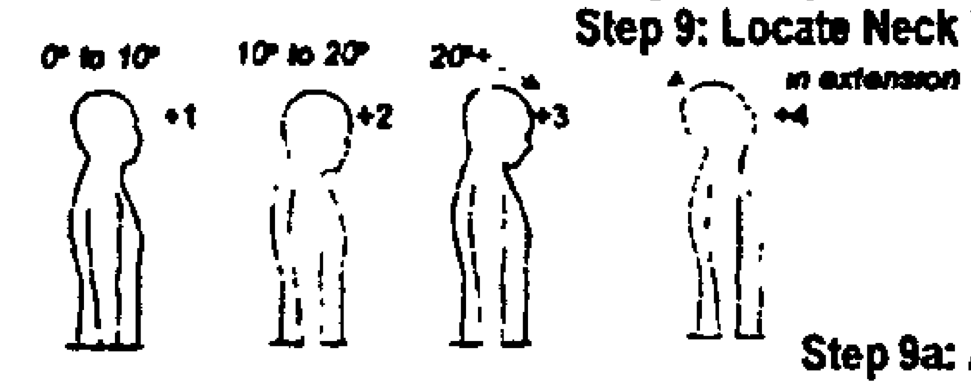
Table C

	1	2	3	4	5	6	7+
1	1	2	3	3	4	5	5
2	2	2	3	4	4	5	5
3	3	3	3	4	4	5	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	7	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

Final Score=

B. Neck, Trunk & Leg Analysis

Step 9: Locate Neck Position

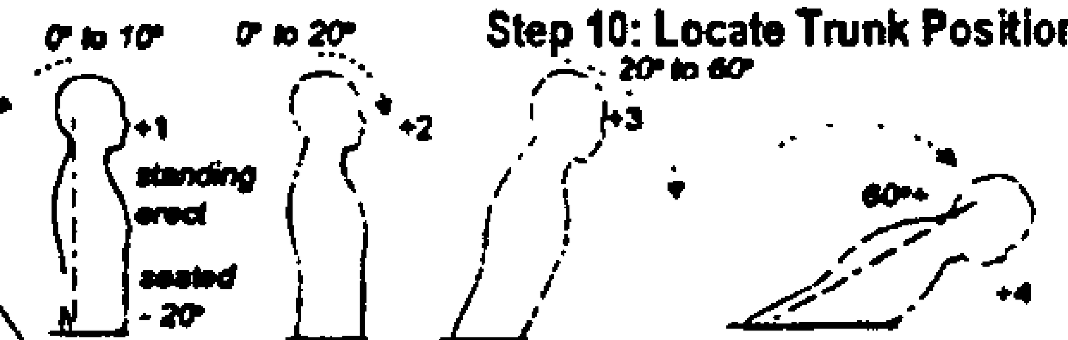


=Final Neck Score

Step 9a: Adjust...
If neck is twisted: +1; If neck is side-bending: +1

Step 10: Locate Trunk Position

1 also if trunk is well supported while seated
2 if not



Step 10a: Adjust...
If trunk is twisted: +1; If trunk is side-bending: +1

= Final Trunk Score

Step 11: Legs
If legs & feet supported and balanced: +1;
If not: +2

= Final LegScore

Table B

Trunk Posture Score

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

Step 12: Look-up Posture Score in Table B
Use values from steps 8,9,& 10 to locate Posture Score in Table B

= Posture B Score

+

Step 13: Add Muscle Use Score
If posture mainly static or;
If action 4/minute or more: +1

= Muscle Use Score

+

Step 14: Add Force/load Score
If load less than 2 kg (intermittent): +0;
If 2 kg to 10 kg (intermittent): +1;
If 2 kg to 10 kg (static or repeated): +2;
If more than 10 kg load or repeated or shocks: +3

= Force/load Score

=

Step 15: Find Column in Table C
The completed score from the Neck/Trunk & Leg analysis is used to find the column on Chart C

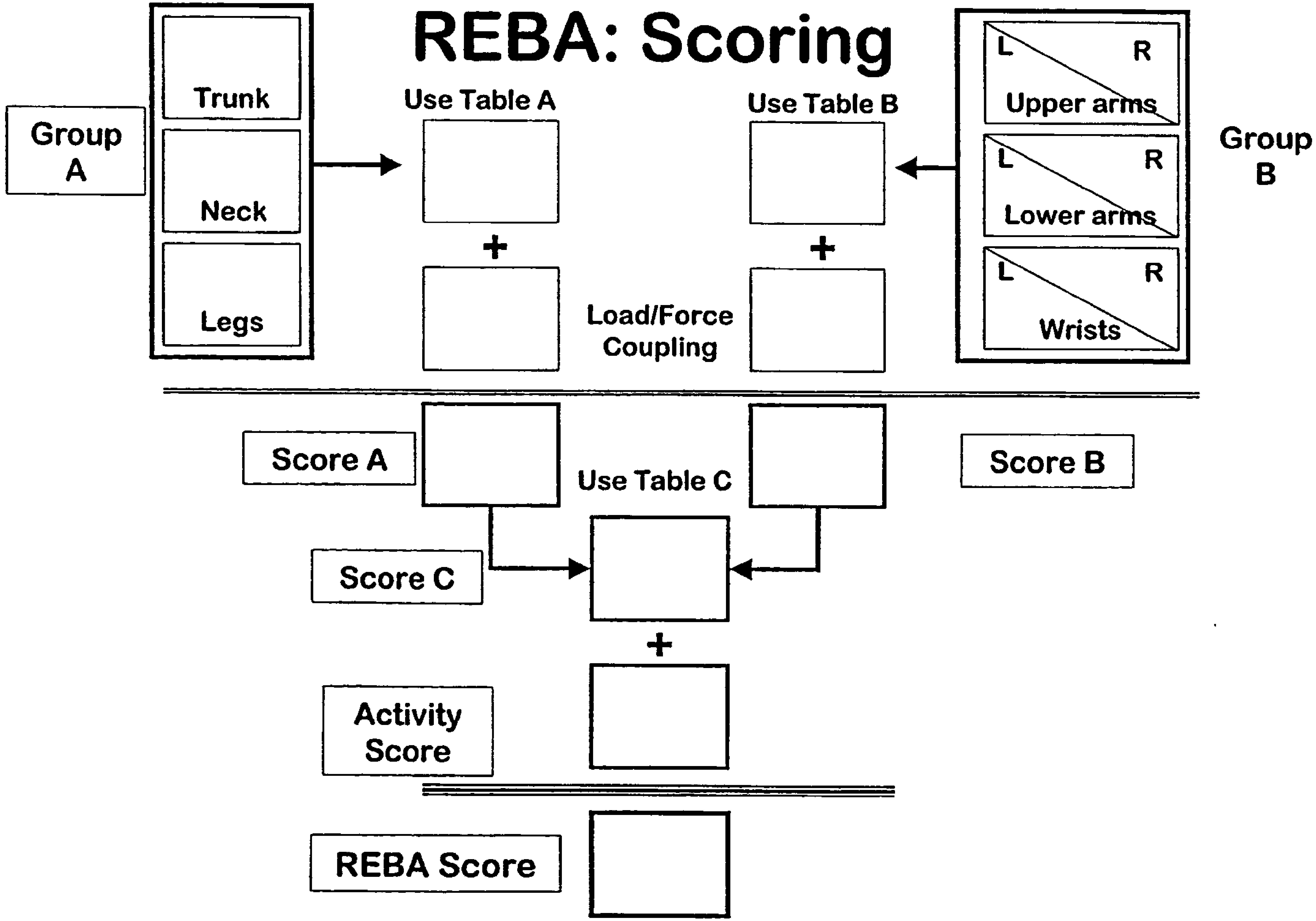
= Final Neck, Trunk & Leg Score

Subject: ______________________ Date: _ / _ / _
Company: ______________________ Department: ______________________ Scorer: ______________________

FINAL SCORE: 1 or 2 = Acceptable; 3 or 4 investigate further; 5 or 6 investigate further and change soon; 7 investigate and change immediately

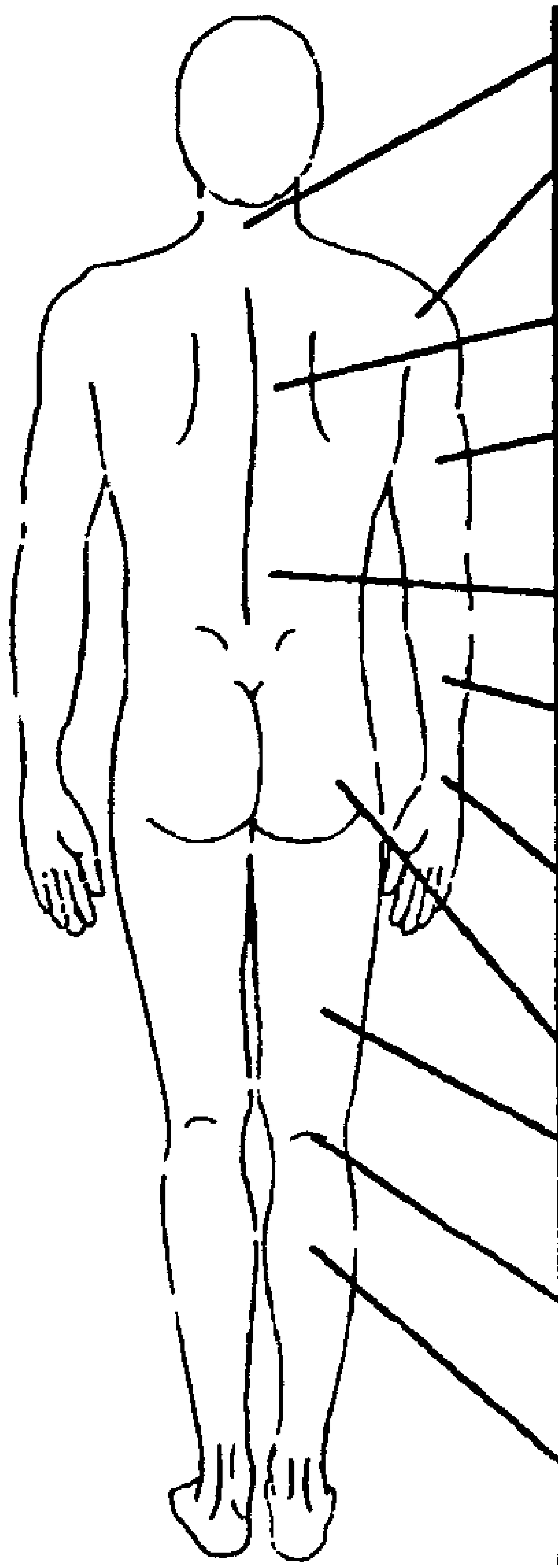
Source: McAtamney L & Corlett, E.N (1993) RULA a survey method for the investigation of work-related upper limb disorders, Applied Ergonomics, 24(2) 91-99.

REBA: Scoring



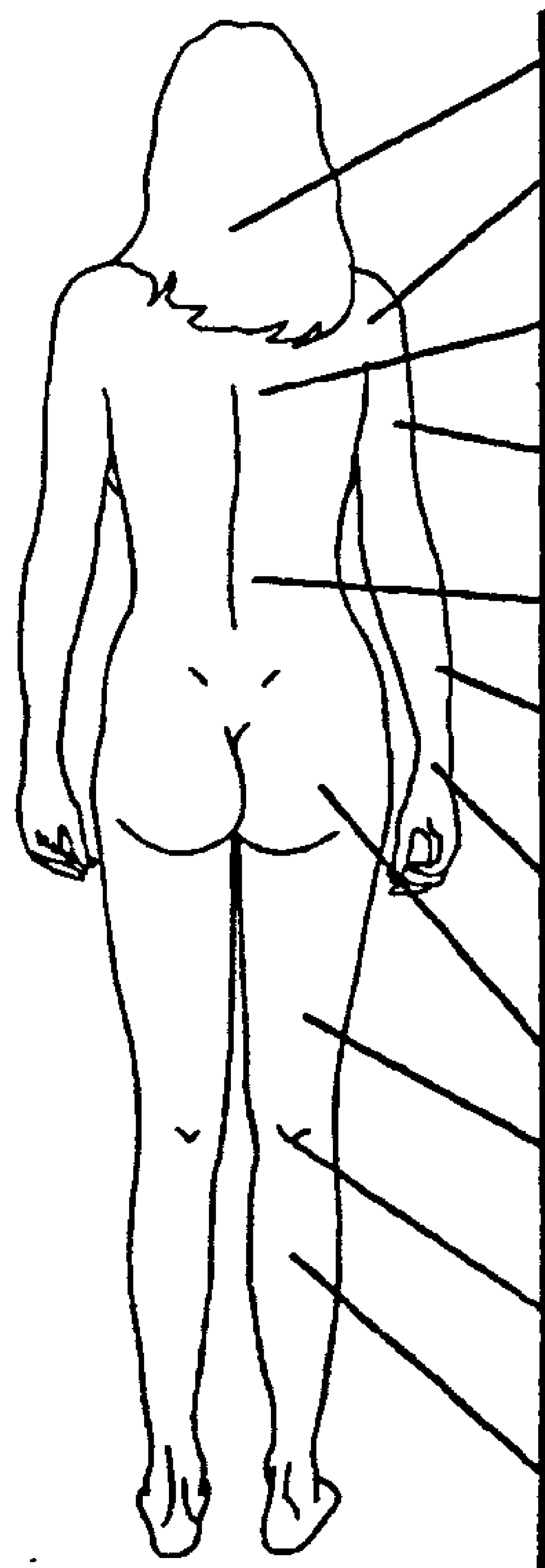
Source: Hignett, S., McAtamney, L. (2000) Applied Ergonomics, 31, 201-5.

The diagram below shows the approximate position of the body parts referred to in the questionnaire. Please answer by marking the appropriate box.



		During the last work <u>week</u> how often did you experience ache, pain, discomfort in:					If you experienced ache, pain, discomfort, how uncomfortable was this?			If you experienced ache, pain, discomfort, did this interfere with your ability to work?		
		Never	1-2 times last week	3-4 times last week	Once every day	Several times every day	Slightly uncomfortable	Moderately uncomfortable	Very uncomfortable	Not at all	Slightly interfered	Substantially interfered
Neck		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Shoulder	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Upper Back		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Upper Arm	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lower Back		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Forearm	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Wrist	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Hip/Buttocks		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Thigh	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Knee	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lower Leg	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

The diagram below shows the approximate position of the body parts referred to in the questionnaire. Please answer by marking the appropriate box.



Body part	Side	During the last work <u>week</u> how often did you experience ache, pain, discomfort in: Never	1-2 times last week	3-4 times last week	Once every day	Several times every day	If you experienced ache, pain, discomfort, how uncomfortable was this? Slightly uncomfortable	Moderately uncomfortable	Very uncomfortable	If you experienced ache, pain, discomfort, did this interfere with your ability to work? Not at all	Slightly interfered	Substantially interfered
Neck		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Shoulder	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Upper Back		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Upper Arm	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lower Back		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Forearm	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Wrist	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Hip/Buttocks		☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Thigh	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Knee	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Lower Leg	(Right)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
	(Left)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Musculoskeletal Injury (MSI) Prevention/Risk Evaluation

Purpose: To reduce risk and discomfort related to MSI(s) through identification of risk factors and implementation of appropriate risk controls. The goal is to prevent injuries!

Instructions: Complete the attached checklist for each high-risk task. A high-risk task is one causing discomfort to the worker. Focus the control measures on the risk factors that are present on the checklist.

Employee: ______________________________ **Job Title:** ________________________________

Location: ______________________________ **Date:** ___________________________________

Report completed by: ____________________ **Incident No:** ___________________________

Subjective (what you were told): What did the employee say regarding their concerns, discomfort, or signs and symptoms of MSIs?

____
____
____
____

Objective (what you observed): Use the attached checklist to identify risk factors that may be the cause of discomfort.

____
____
____
____

Is it an operational issue where changes can be made at the unit to improve work place design, location of materials, and organization of tasks? If so, the supervisor or manager should correct the problem or concern at the unit, where possible. **Yes______ / No ______**

Does this task require assistance and/or further investigation from the Safety Co-ordinator or University Resources?
Yes _____/ No_____ Contacted Who: _____________________________________ **Date:** _____________

Recommended Corrective Action:

____
____
____

Person(s) Responsible for Action: ____

Date action to be implemented: ____

Follow Up: (Date and by whom)

____
____
____
____
____
____

UBC Ergonomic Behaviour Checklist

TASK: ____

In **Section I. Physical Demands**, mark "Yes" or "No" if the Risk Factor is present. If "Yes", then check which body part is affected.

I. Physical Demands	**Yes/ No**	**Neck**	**Back**	**Shoulder**	**Wrist/ Hand**	**Knee**	**Ankle/ feet**
A. Force and Working Distance							
Do employees push, pull, lift, lower, or carry objects							
- that are too heavy or require too much force?							
- away from the centre of the body?							
- in a jerky or twisting manner?							
B. Work Postures							
Do employees work using non-neutral joint positions where the							
- back is curved too much or in a stooped position?							
- back is twisted during movements?							
- neck is bent or twisted?							
- reaching?							
- arms are away from the body?							
- wrists are in flexed, extended or pinched positions?							
- are objects too big or too small for the hand?							
- knees are in a locked position when standing?							
C. Repetitive Use of Similar Muscles							
Do employees perform movements over and over in the same way? (Specify)							
Repetitive Motion:							
Repetitive Motion:							
D. Static Muscle Use							
Do employees...							
- hold any of the above work postures for > 20 sec.?							
- stand for long periods with their knees locked?							
- stand in one position without moving or stretching?							
- over-grip controls or hand tools and/or not let go to rest?							
E. Contact Stress							
Do employees put localized pressure on any part of their body?							

II. Work Space

Are there working heights, reaches in workspace, equipment, tool design, storage conditions, etc., that cause or contribute to employees experiencing any of the physical demands risk factors?	**Comments:**

III. Organization of Work

Are there work processes, monotonous job tasks, machine paced tasks or peak activity demands that cause or contribute to rushing, frustration, fatigue or other visible signs of stress?	**Comments:**

IV. Environmental Conditions

Are employees exposed to:	**Comments:**
- poor lighting? vibration	
- cold air/wind/water? Hot air/wind/water	

THINGS TO LOOK OUT FOR:

FORCEFUL EXERTIONS (LIFTING):

- Is the load heavy? Test the load before lifting. Always best to ask for assistance!
- Is the load bulky? Are the contents of the load likely to shift?
- Are there handling points on the load?
- Are workers using proper lifting techniques: lifting with the knees bent and back in neutral S-curve position; pivoting with your feet, not twisting the back?
- Is the load being carried close to the body?
- How far is the load being carried? Should a transport device be used instead? Is the path clear of obstacles?
- Is the load being pushed rather than pulled? Has the equipment been properly maintained?

AWKWARD POSTURES:

- Stooping is the equivalent of lifting a 30 kg weight with knees bent. However, there is no muscular support in this position. So, if you must stoop, bend forward from your hips (BUTT OUT) and try to place a hand on a table or your thigh.
- Reaching and holding arms away from the body.
- Standing for long periods of time, particularly on hard surfaces, will place pressure on the back. This may result in lower back pain. Use anti-fatigue matting, supportive shoes and alternate feet on a step.
- Awkward wrist positions; any wrist position that is not straight. Example: flexing, extending, bending wrist toward little finger, bending the wrist toward the thumb or pinching.

REPETITION:

- How long is the worker repeating the same motion for? Remember the longer the exposure the greater the risk.
- Are they building in pauses or breaks into the work cycle which allow the muscles time to recover?
- Are they changing tasks on a regular basis to avoid prolonged repetition?

ENVIRONMENT:

- Is appropriate clothing used when working in cold?
- Are space constraints an issue?
- Floor/ground surfaces: Do they pose a risk? Are they slippery or uneven? Use non-slip supportive footwear.
- Is the lighting adequate?
- Vibration?
- Noise?

SAFESTART:

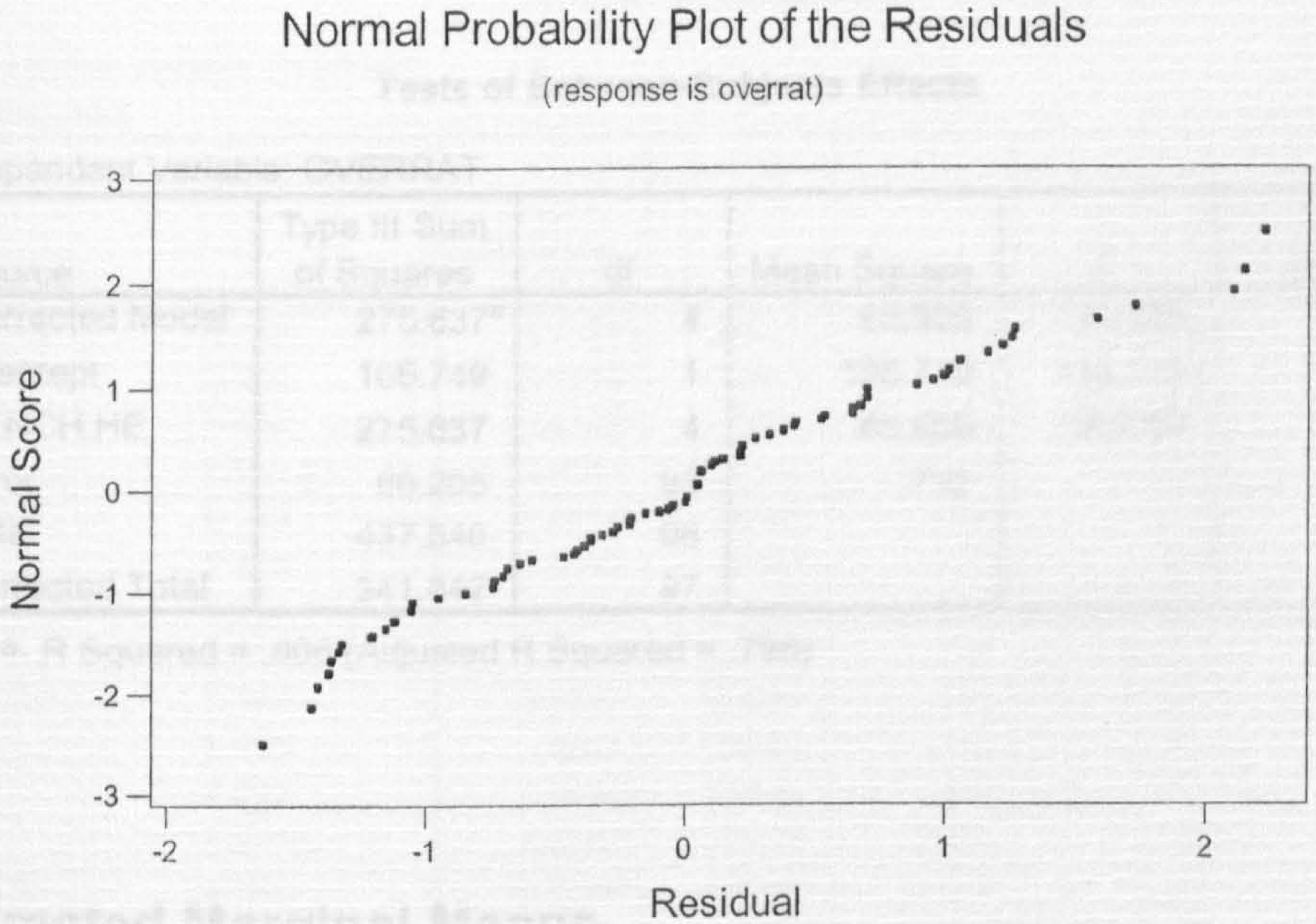
- ❑ Rushing
- ❑ Frustration
- ❑ Fatigue
- ❑ Complacency
- ❑ Eyes not on task
- ❑ Mind not on task
- ❑ Line-of-fire
- ❑ Balance/traction/grip

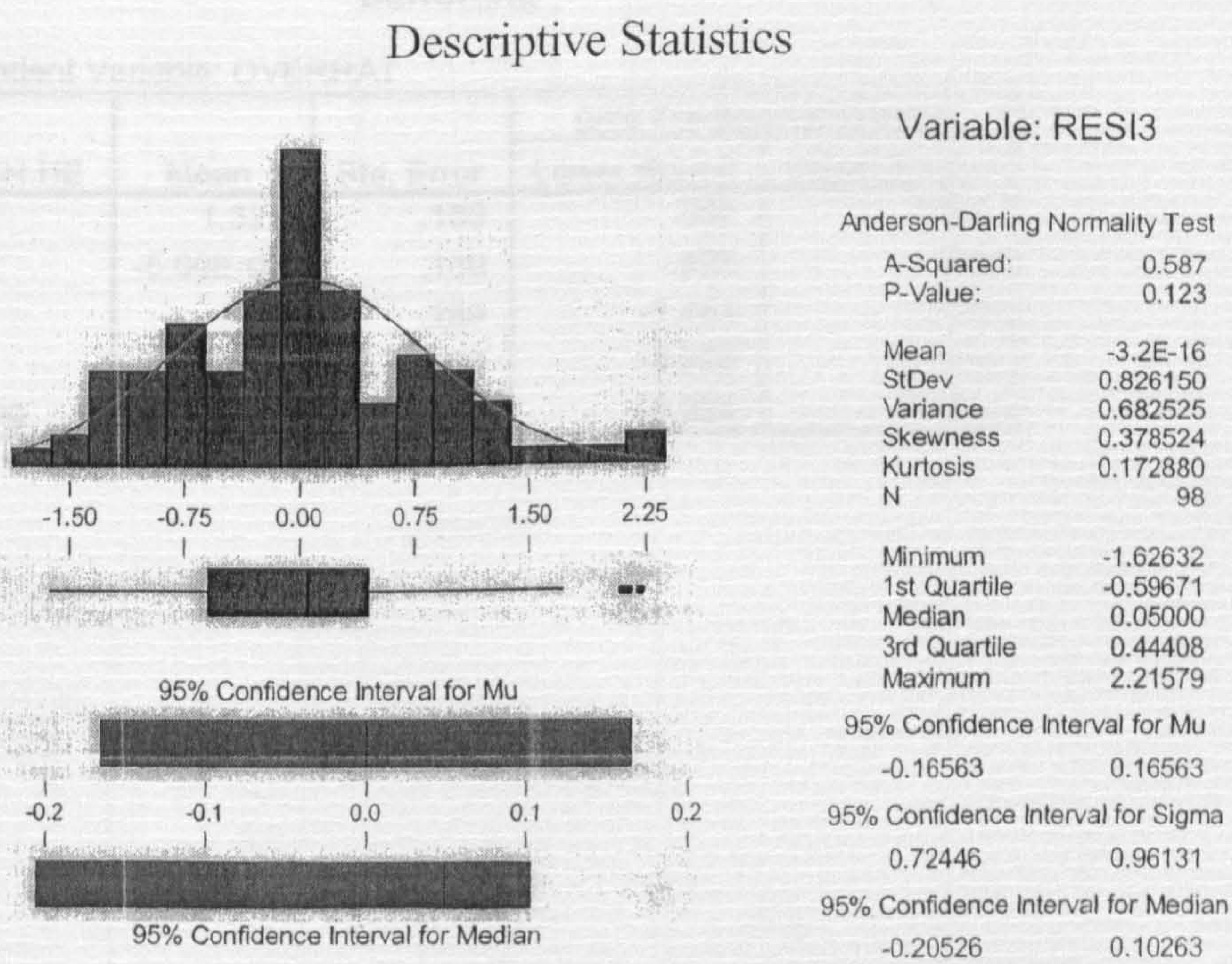
9.3 Appendix C

9.3.1 Analysis of data additional material

Overall Subjective Height Ratings - SENIORS

ANOVA





ANOVA was run using overall subjective height and bench height was the only result found to be significant. The following results were obtained from SPSS:

SPSS Printout – Height evaluations

Tests of Between-Subjects Effects

Dependent Variable: OVERRAT

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	275.637[a]	4	68.909	96.799	.000
Intercept	105.749	1	105.749	148.549	.000
BENCH.HE	275.637	4	68.909	96.799	.000
Error	66.205	93	.712		
Total	437.540	98			
Corrected Total	341.842	97			

a. R Squared = .806 (Adjusted R Squared = .798)

Estimated Marginal Means

BENCH.HE

Dependent Variable: OVERRAT

			95% Confidence Interval	
BENCH.HE	Mean	Std. Error	Lower Bound	Upper Bound
E-100	1.321	.189	.946	1.696
E-150	-5.00E-02	.189	-.425	.325
E-200	-.689	.189	-1.064	-.315
E-250	-2.216	.189	-2.590	-1.841
Existing	-3.564	.199	-3.959	-3.169

Tukey's Multiple Comparisons:

Multiple Comparisons

Dependent Variable: OVERRAT
Tukey HSD

(I) BENCH.HE	(J) BENCH.HE	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
E-100	E-150	1.3711*	.26681	.000	.6288	2.1133
	E-200	2.0105*	.26681	.000	1.2683	2.7528
	E-250	3.5368*	.26681	.000	2.7946	4.2791
	Existing	4.8854*	.27412	.000	4.1228	5.6480
E-150	E-100	-1.3711*	.26681	.000	-2.1133	-.6288
	E-200	.6395	.26681	.125	-.1028	1.3817
	E-250	2.1658*	.26681	.000	1.4235	2.9081
	Existing	3.5143*	.27412	.000	2.7517	4.2769
E-200	E-100	-2.0105*	.26681	.000	-2.7528	-1.2683
	E-150	-.6395	.26681	.125	-1.3817	.1028
	E-250	1.5263*	.26681	.000	.7840	2.2686
	Existing	2.8749*	.27412	.000	2.1122	3.6375
E-250	E-100	-3.5368*	.26681	.000	-4.2791	-2.7946
	E-150	-2.1658*	.26681	.000	-2.9081	-1.4235
	E-200	-1.5263*	.26681	.000	-2.2686	-.7840
	Existing	1.3485*	.27412	.000	.5859	2.1112
Existing	E-100	-4.8854*	.27412	.000	-5.6480	-4.1228
	E-150	-3.5143*	.27412	.000	-4.2769	-2.7517
	E-200	-2.8749*	.27412	.000	-3.6375	-2.1122
	E-250	-1.3485*	.27412	.000	-2.1112	-.5859

Based on observed means.

*. The mean difference is significant at the .05 level.

Homogeneous Subsets

OVERRAT

Tukey HSD[a,b,c]

BENCH.HE	N	Subset			
		1	2	3	4
Existing	18	-3.5643			
E-250	20		-2.2158		
E-200	20			-.6895	
E-150	20			-.0500	
E-100	20				1.3211
Sig.		1.000	1.000	.133	1.000

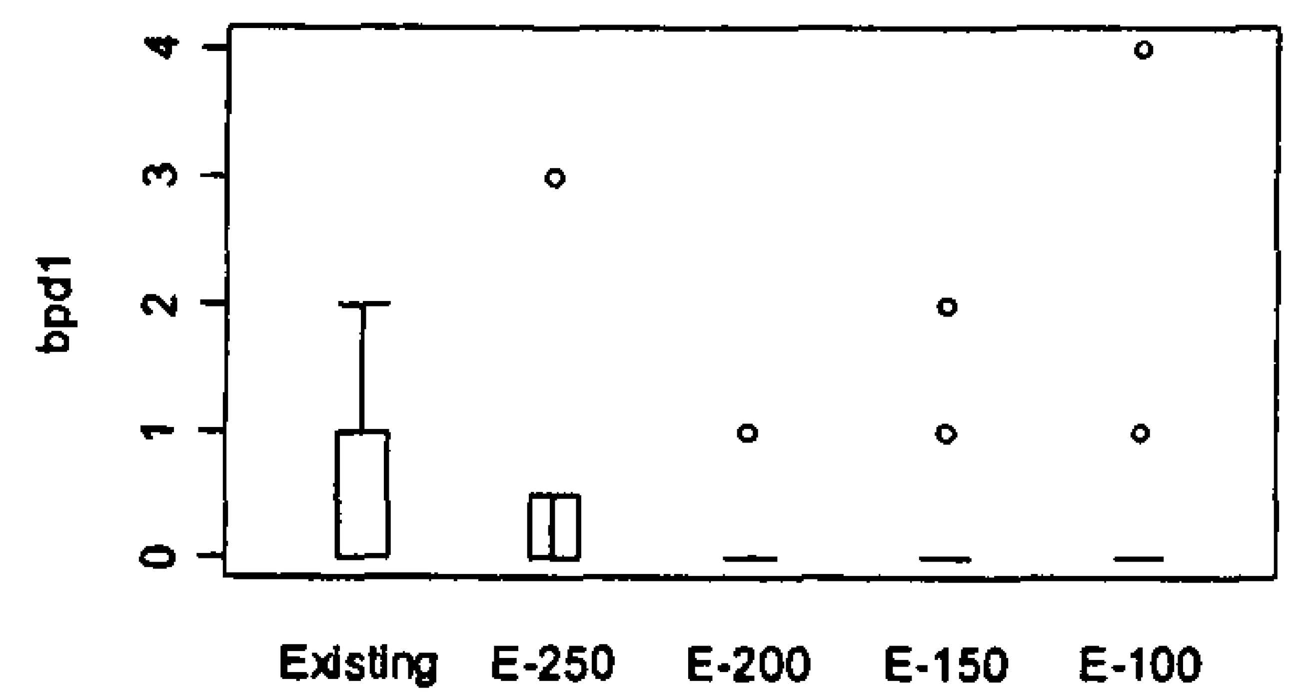
Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = .712.

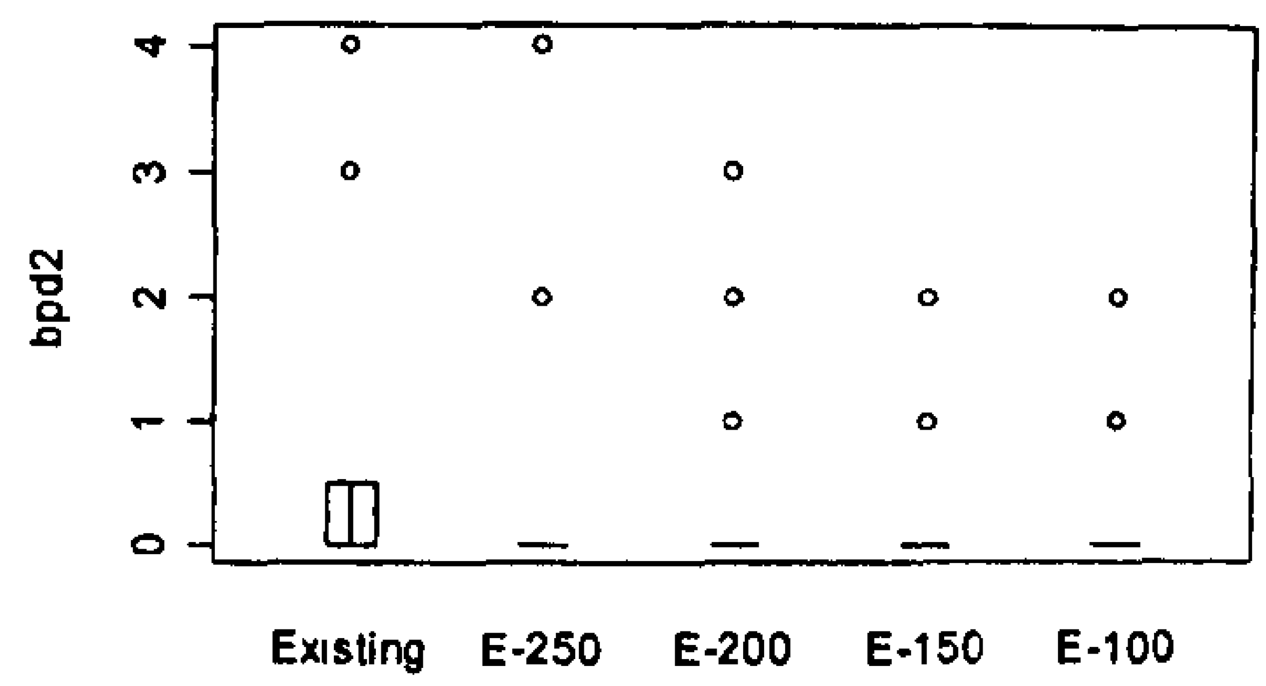
a. Uses Harmonic Mean Sample Size = 19.565.

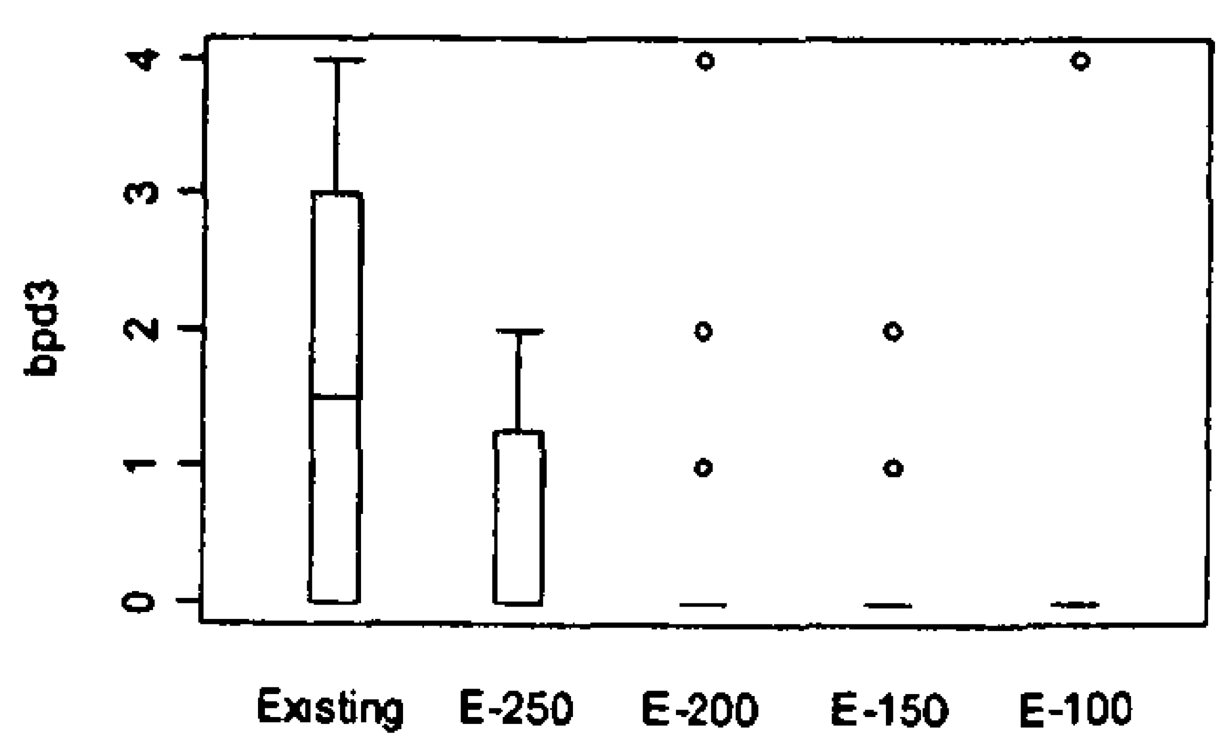
b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

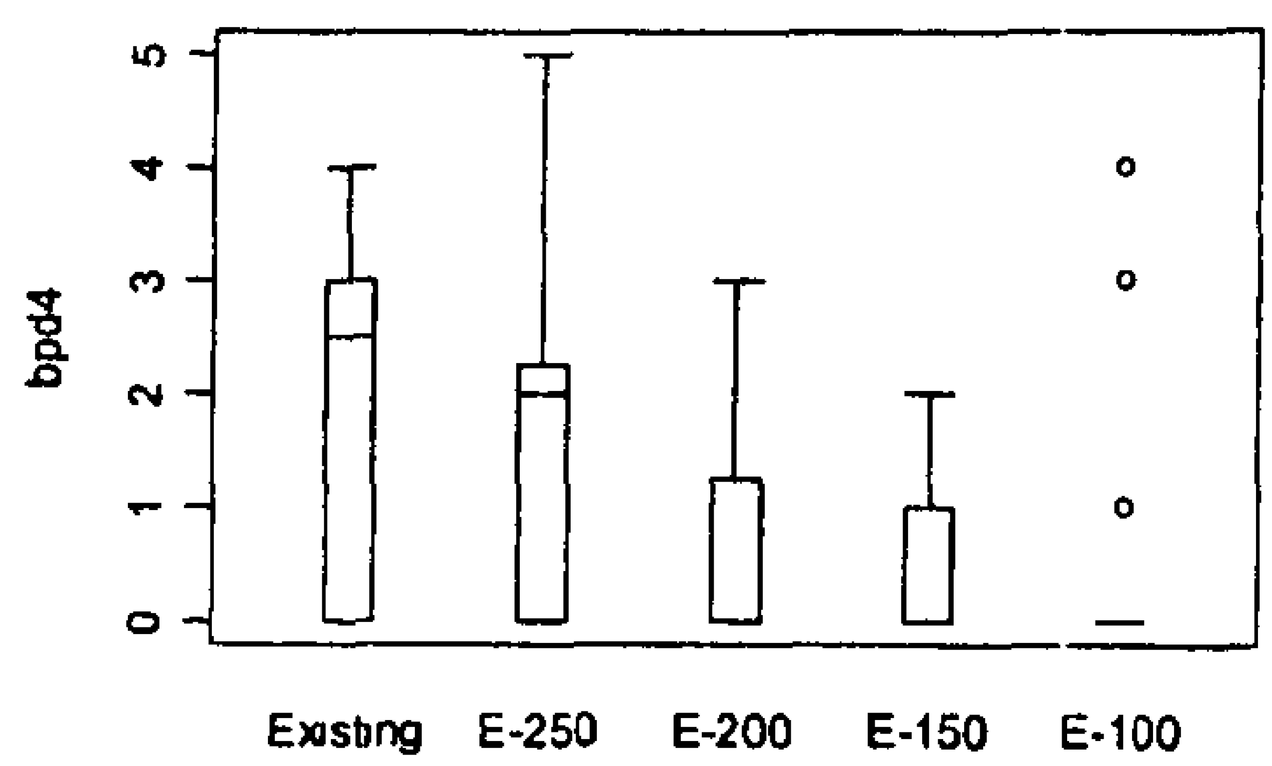
c. Alpha = .05.

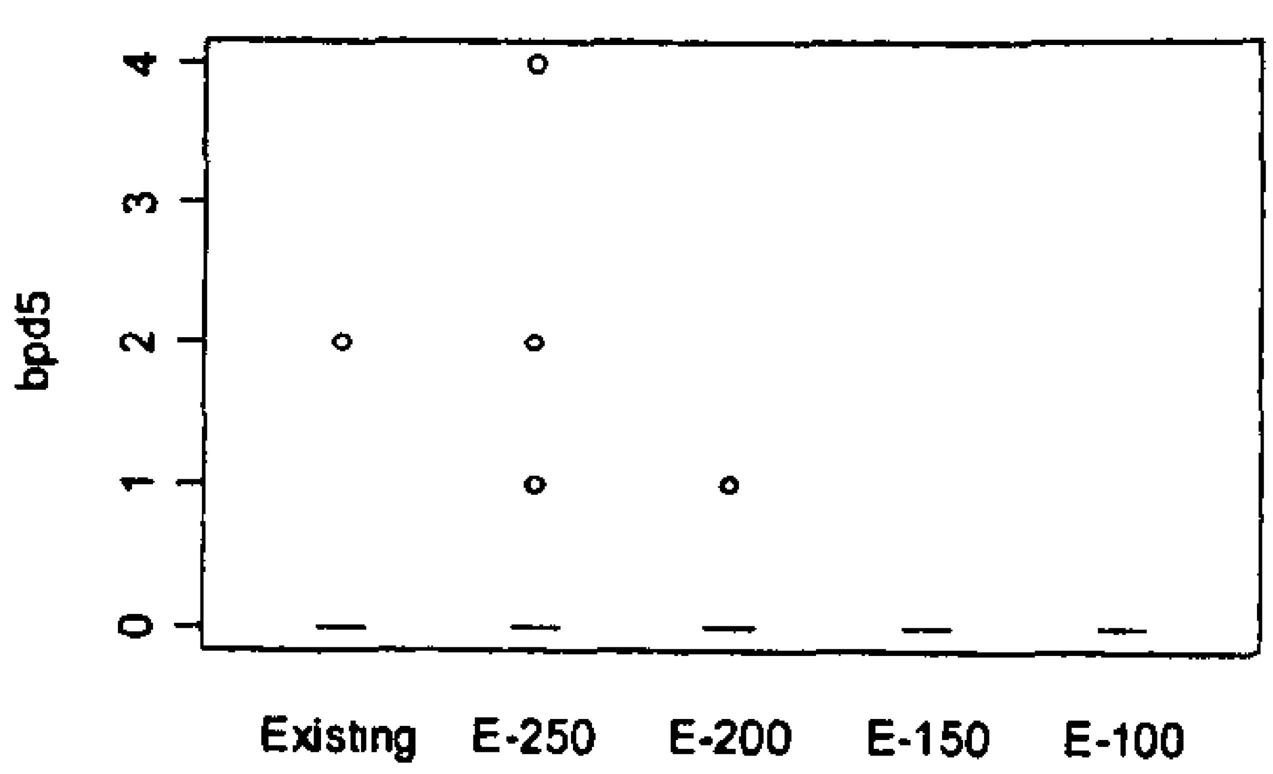
Box-plots Adults BPD

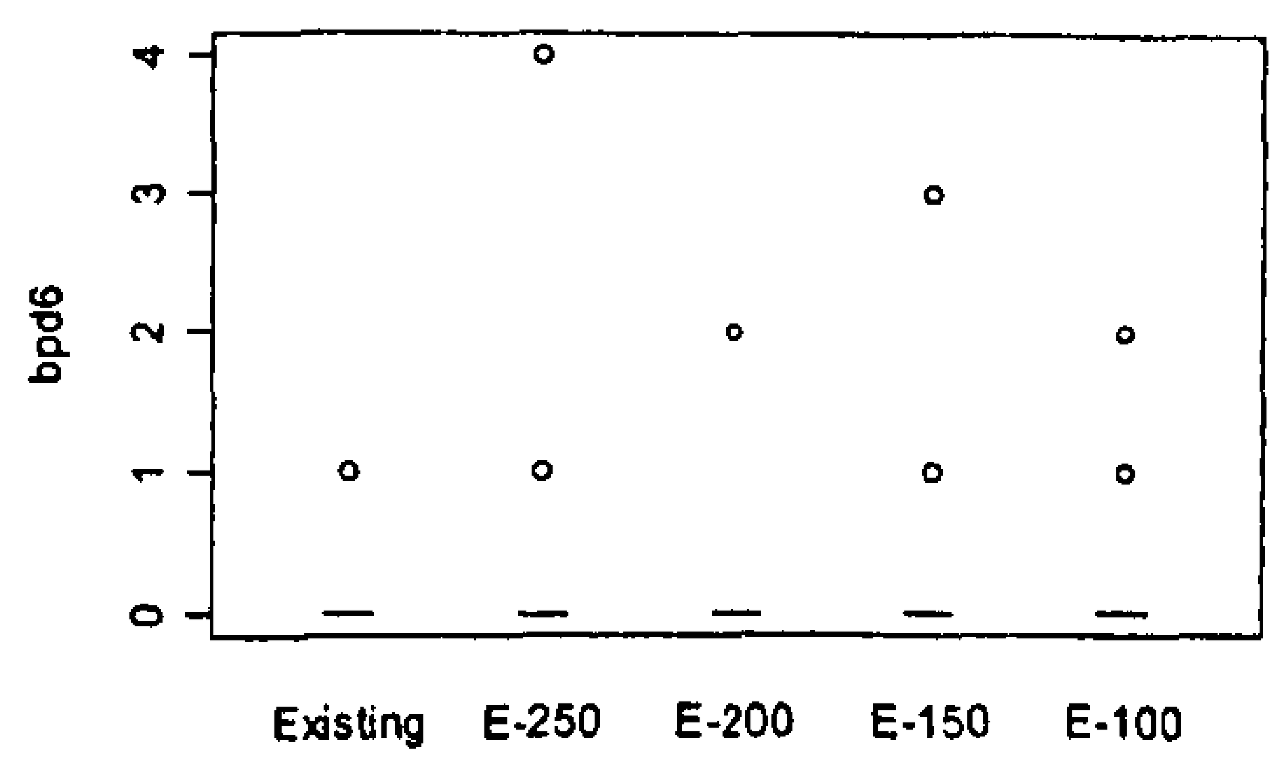


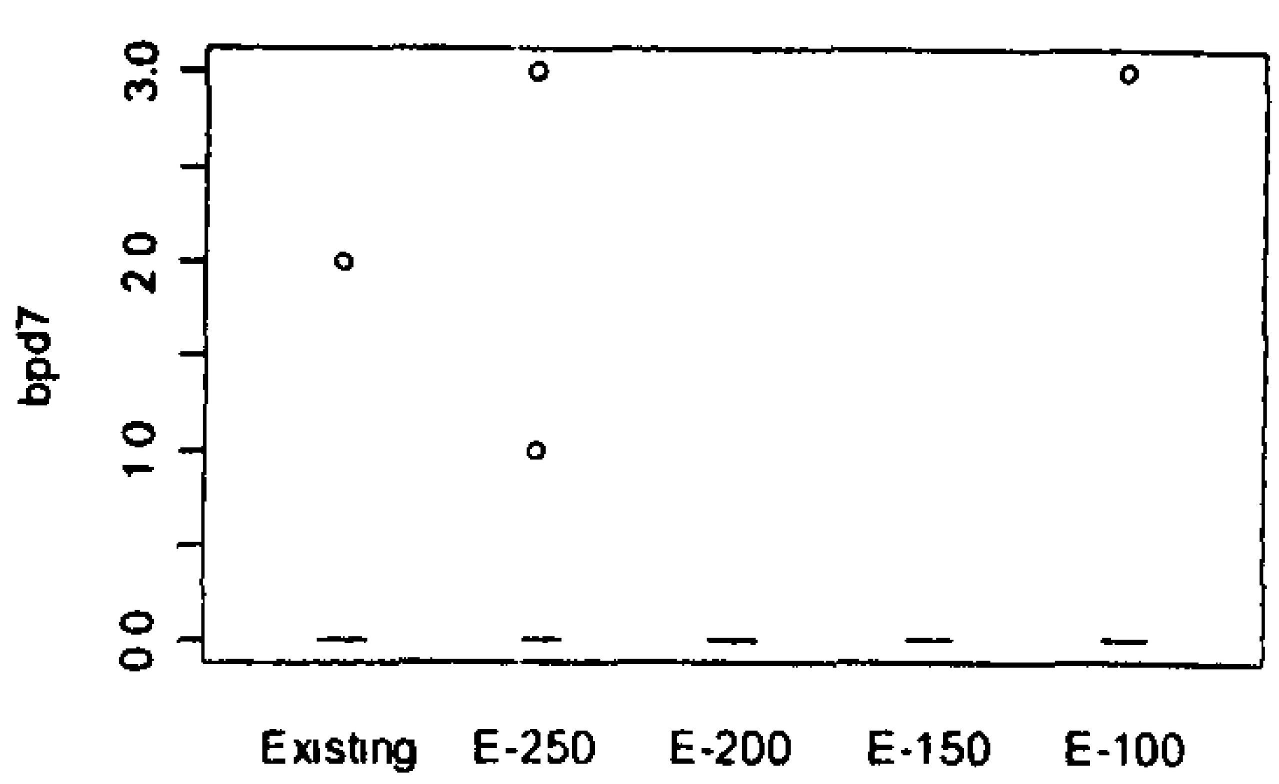


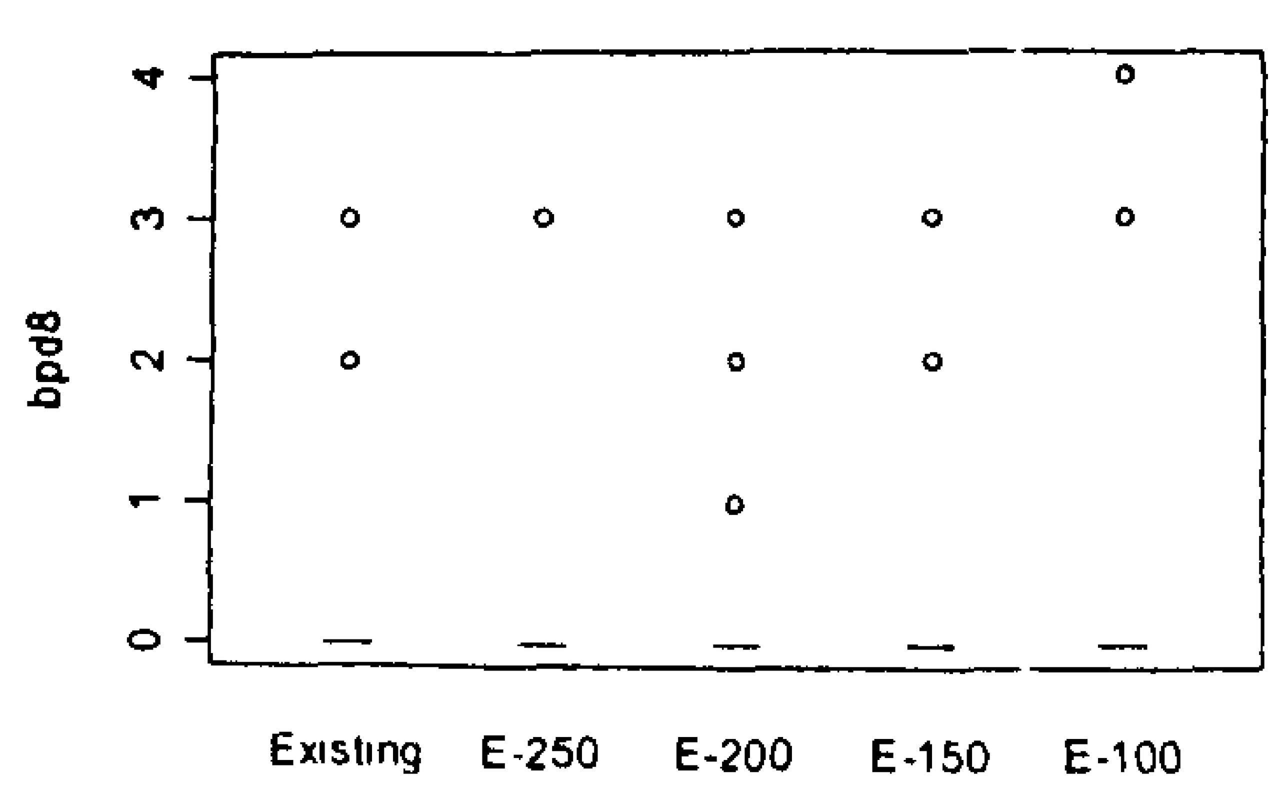


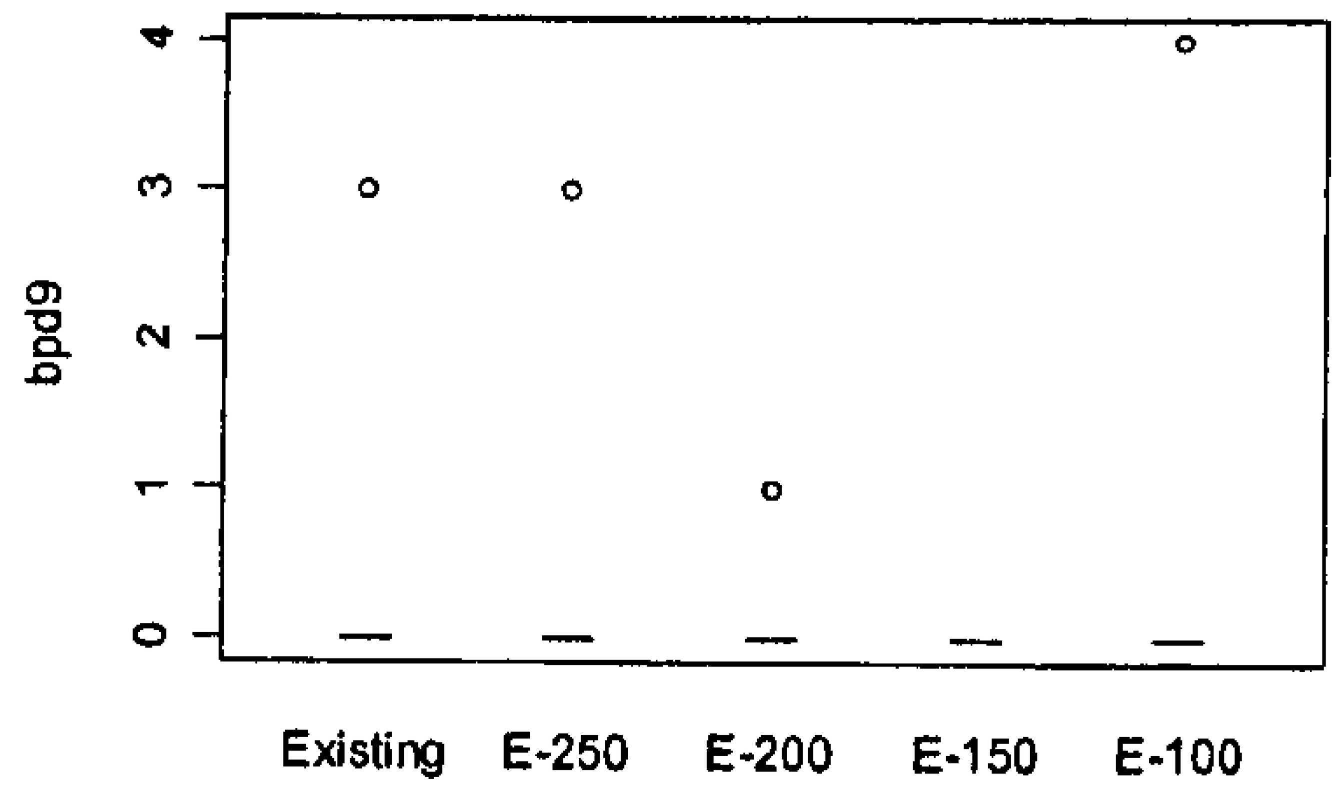


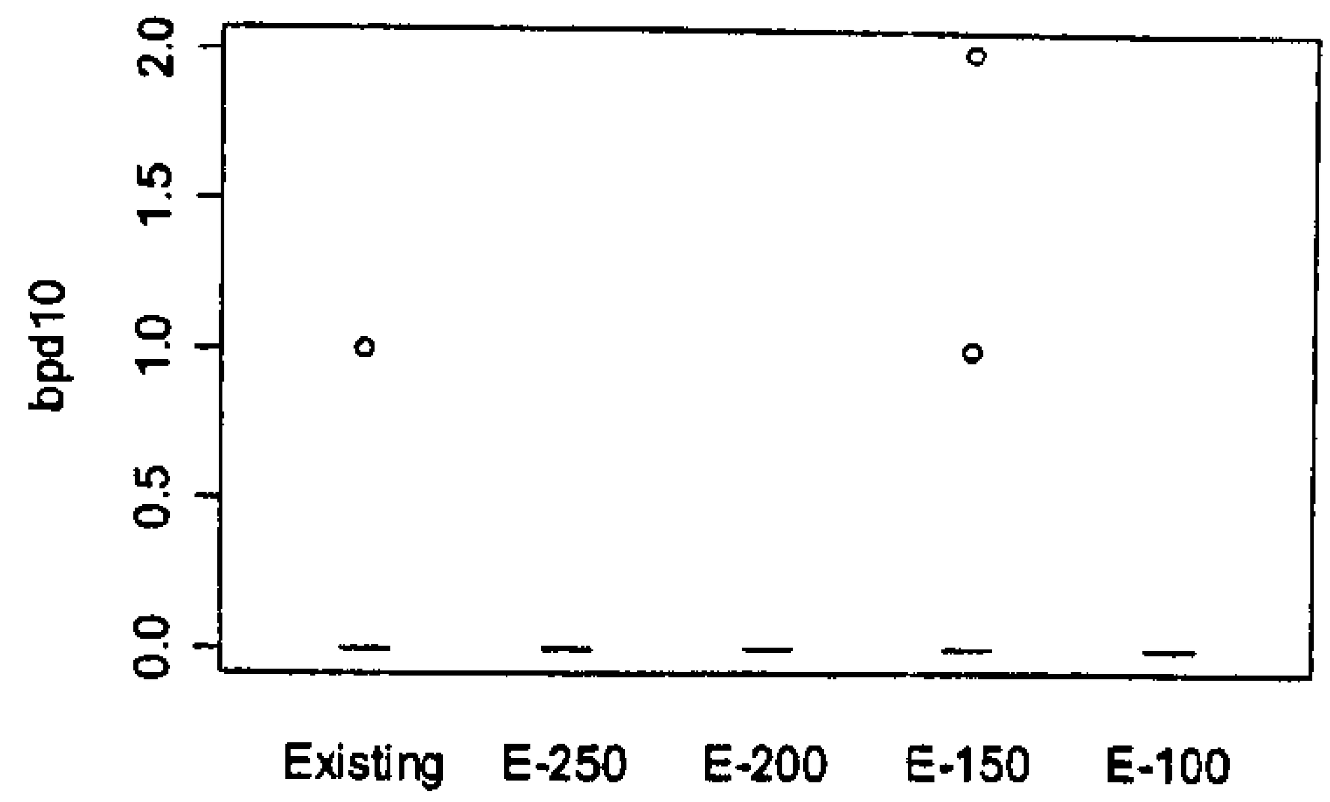


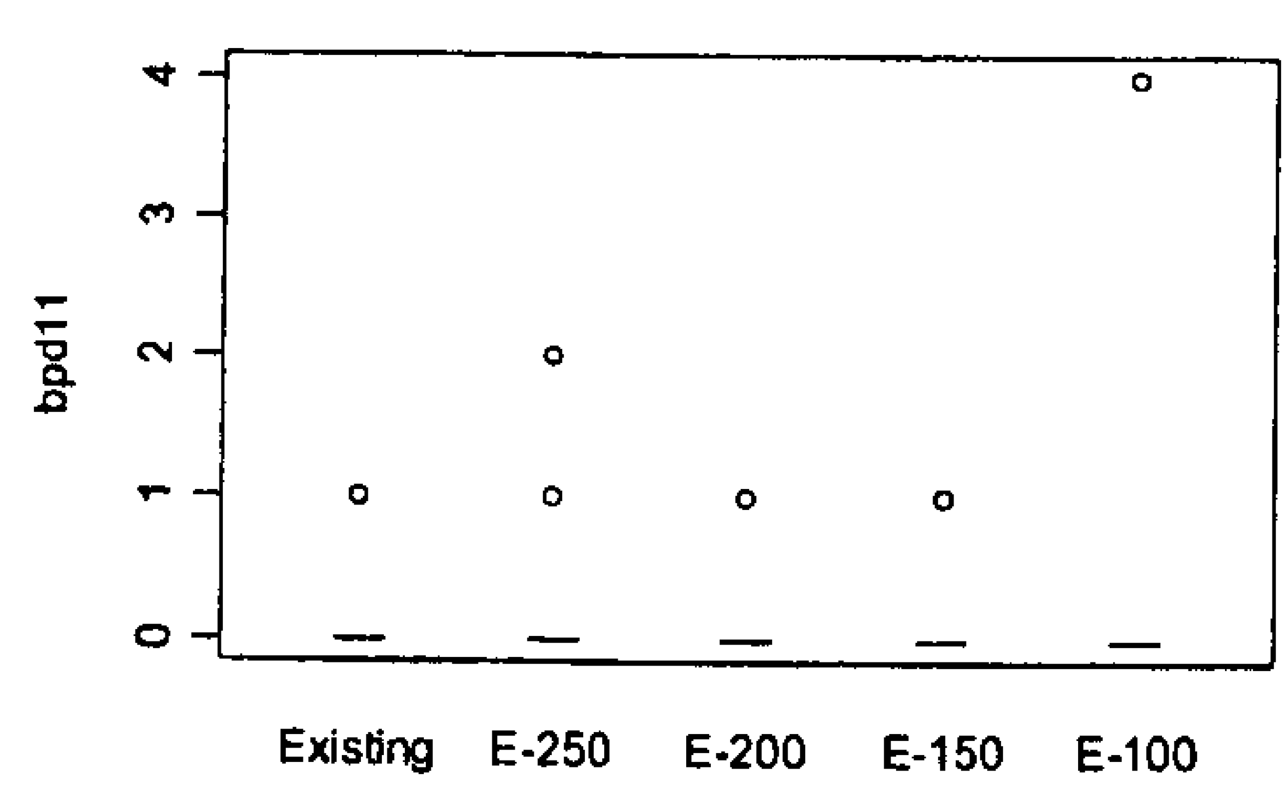


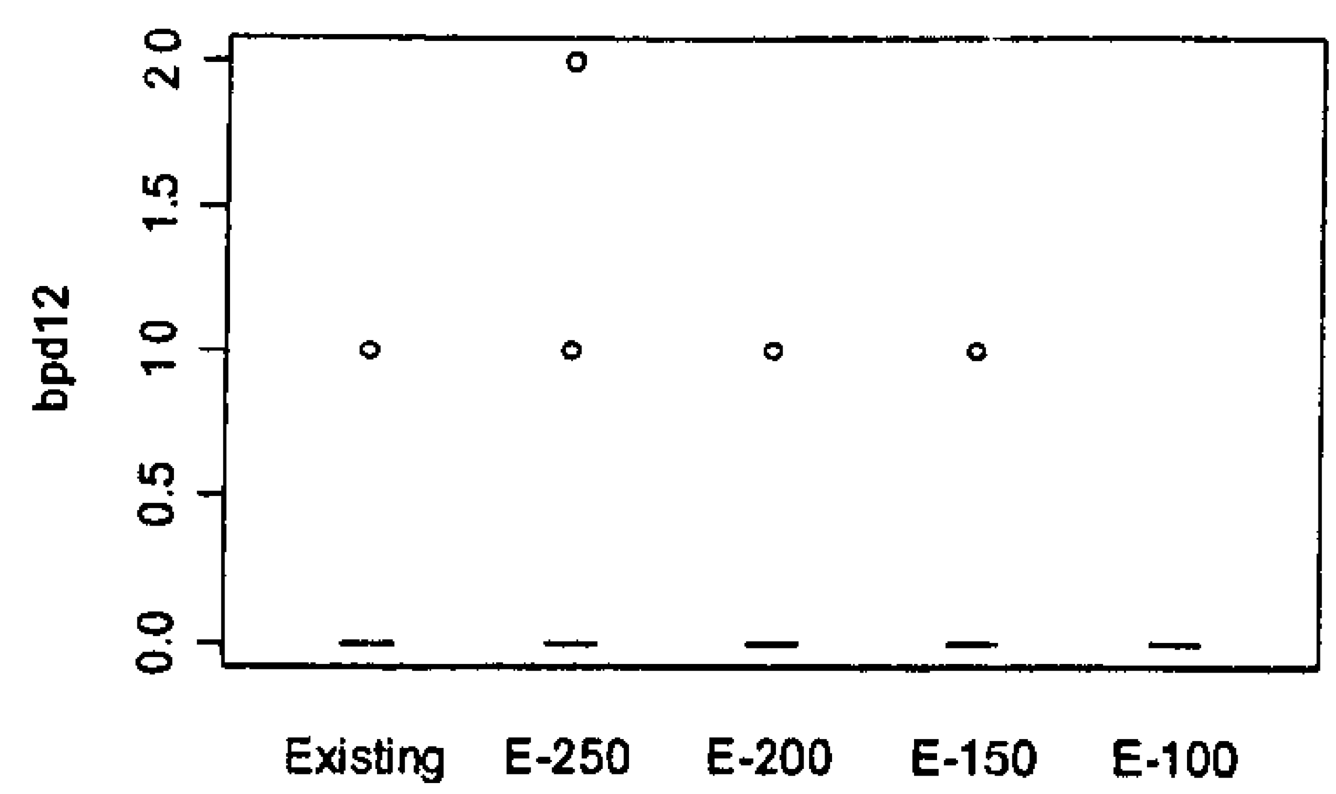


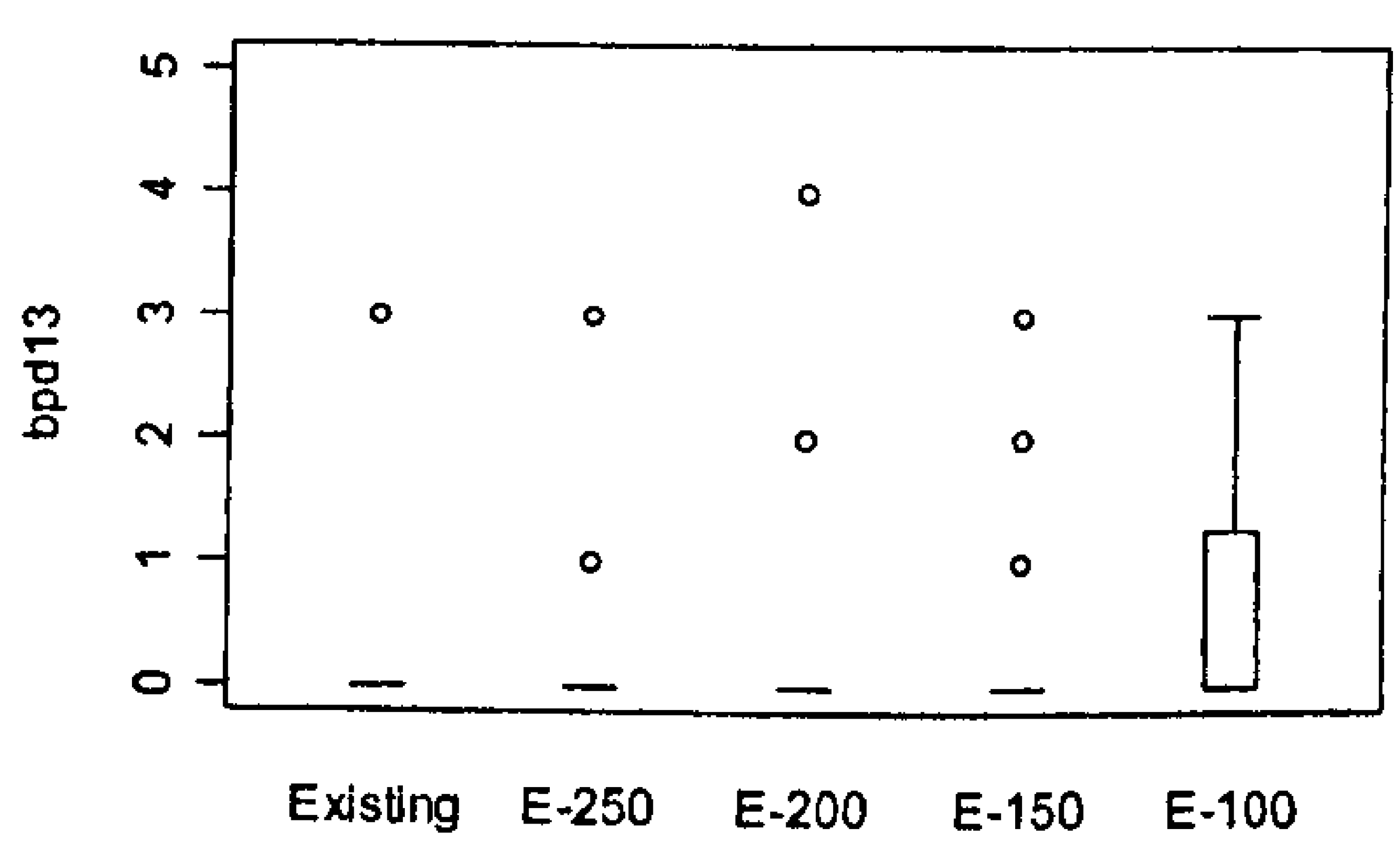


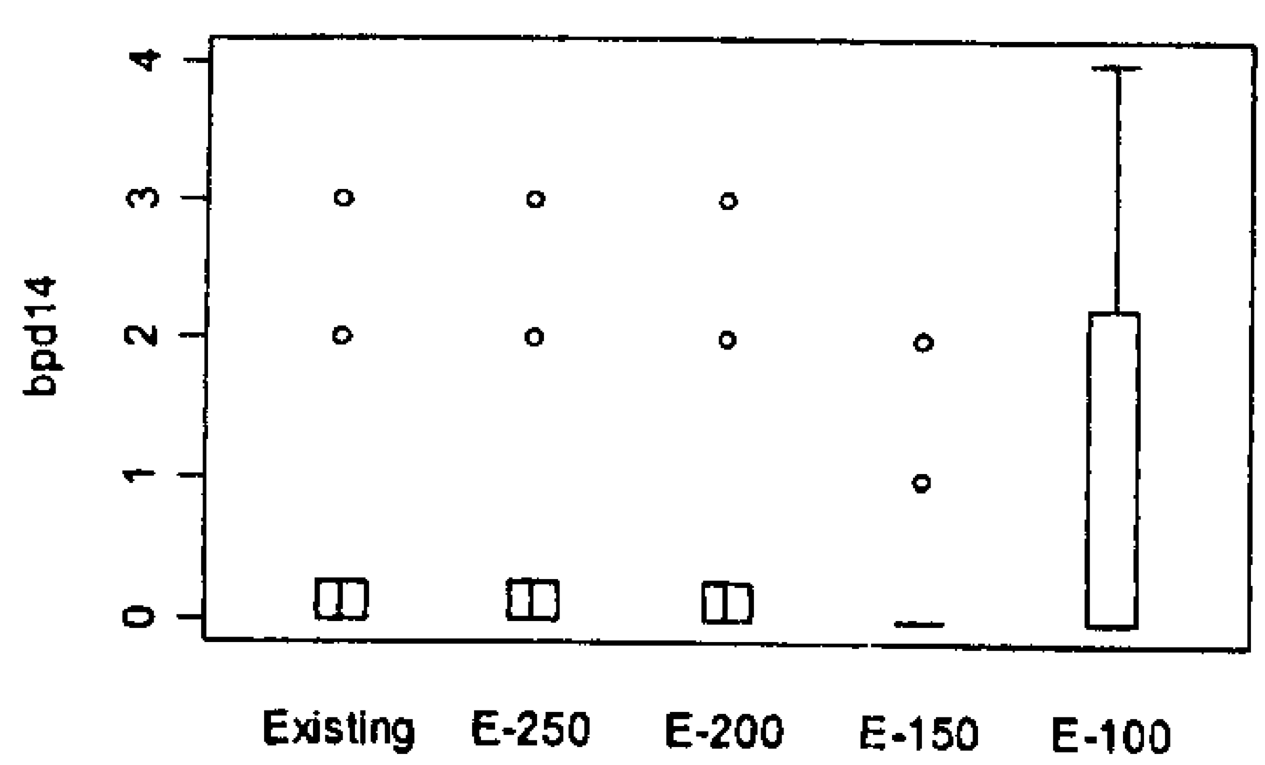

bpd9
0
1
2
3
4
Existing
E-250
E-200
E-150
E-100

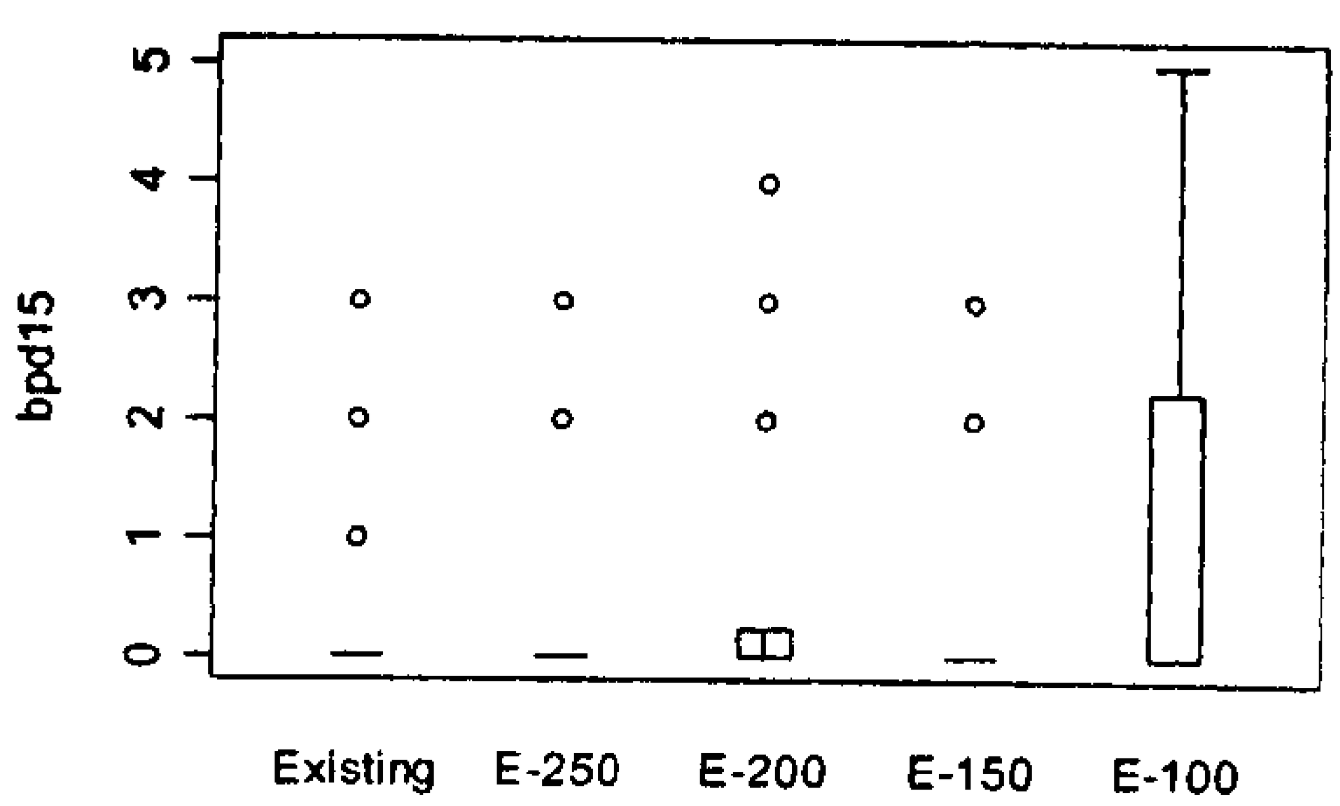

bpd10
0.0
0.5
1.0
1.5
2.0
Existing
E-250
E-200
E-150
E-100

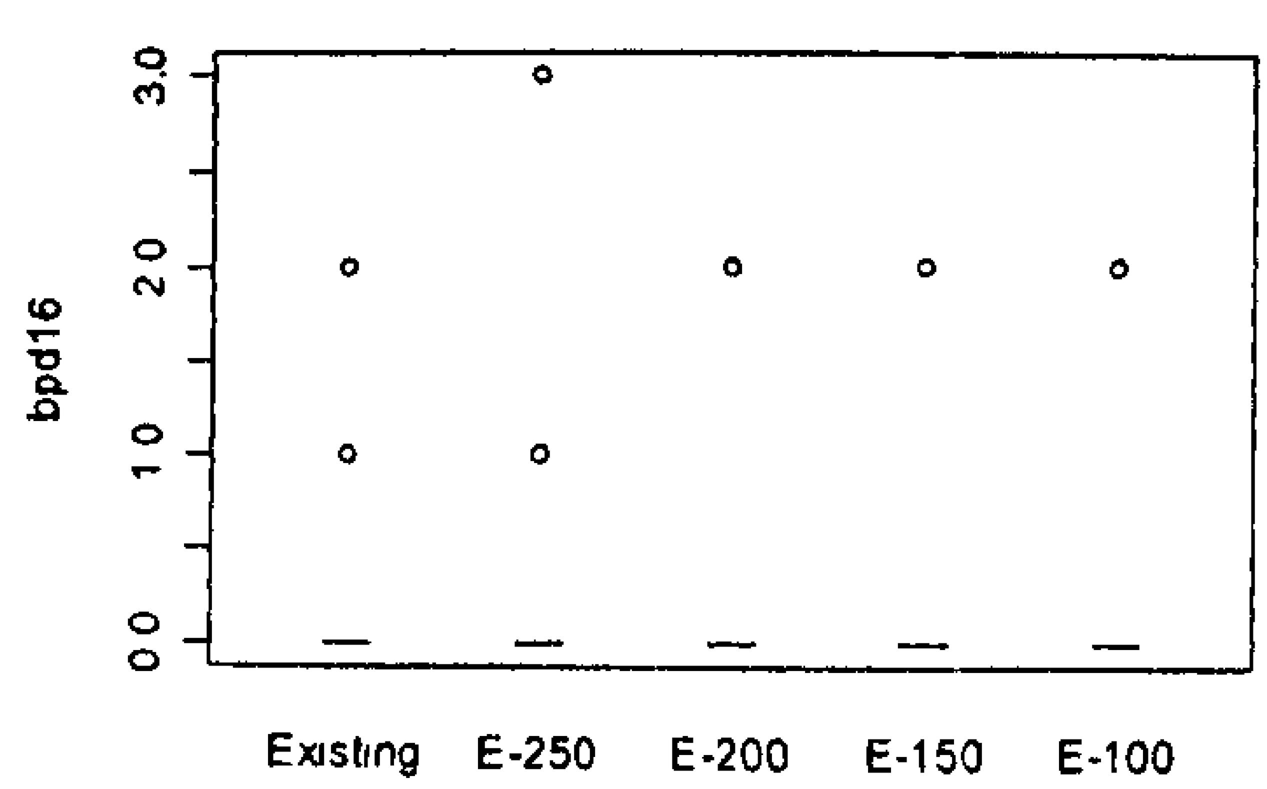

bpd11
0
1
2
3
4
Existing
E-250
E-200
E-150
E-100

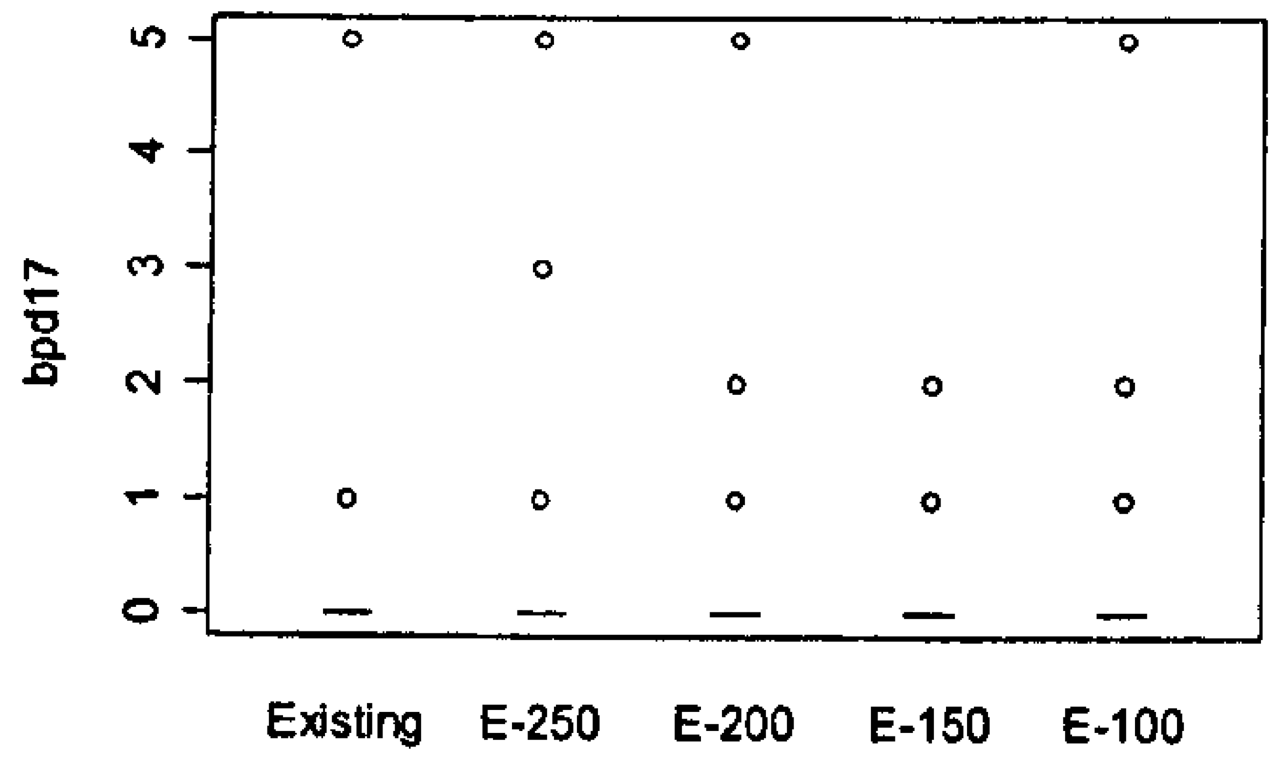

bpd12
0.0
0.5
1.0
1.5
2.0
Existing
E-250
E-200
E-150
E-100

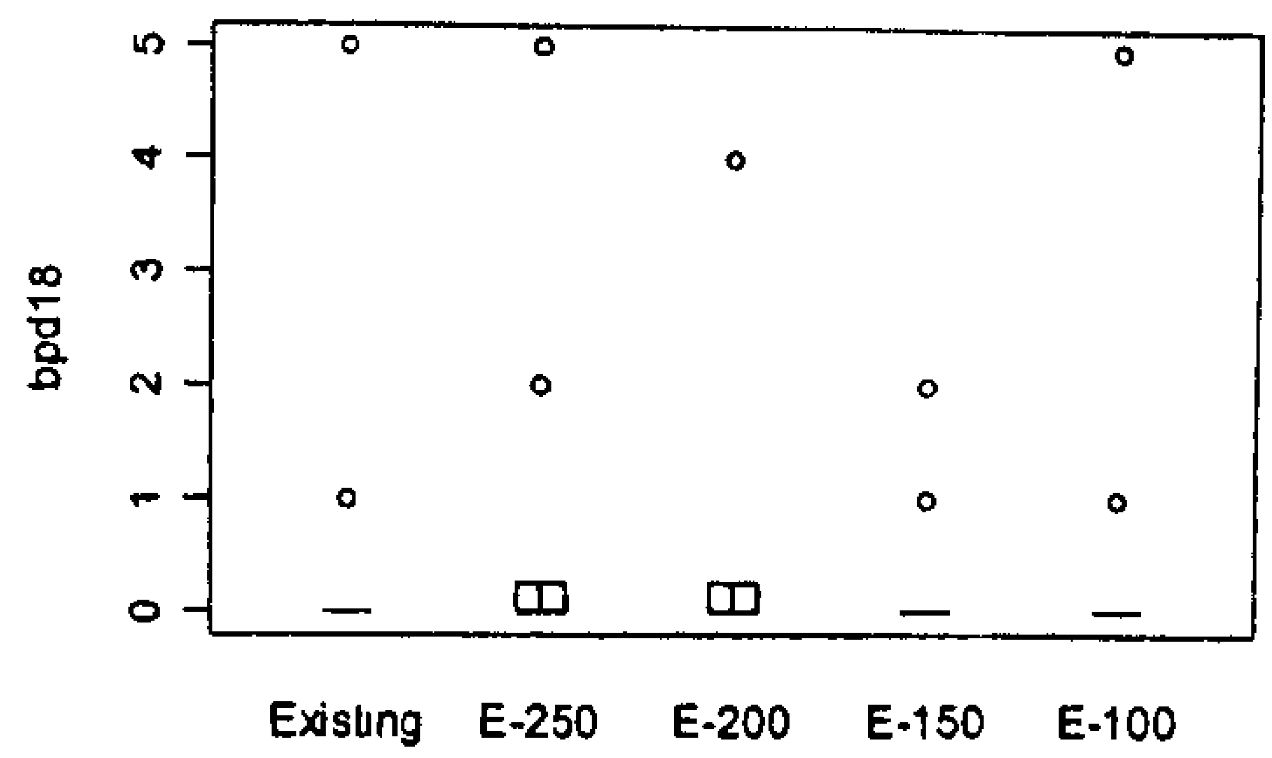

bpd13
0
1
2
3
4
5
Existing
E-250
E-200
E-150
E-100

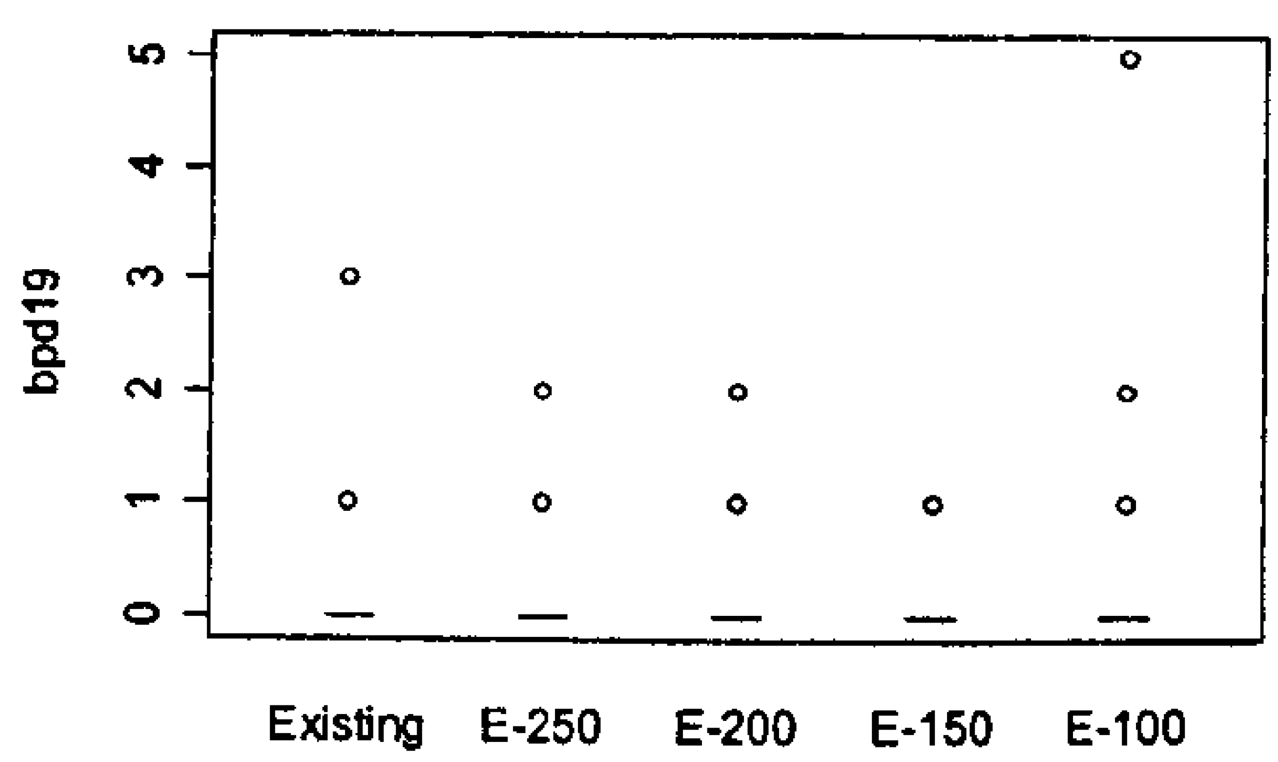

bpd14
0
1
2
3
4
Existing
E-250
E-200
E-150
E-100

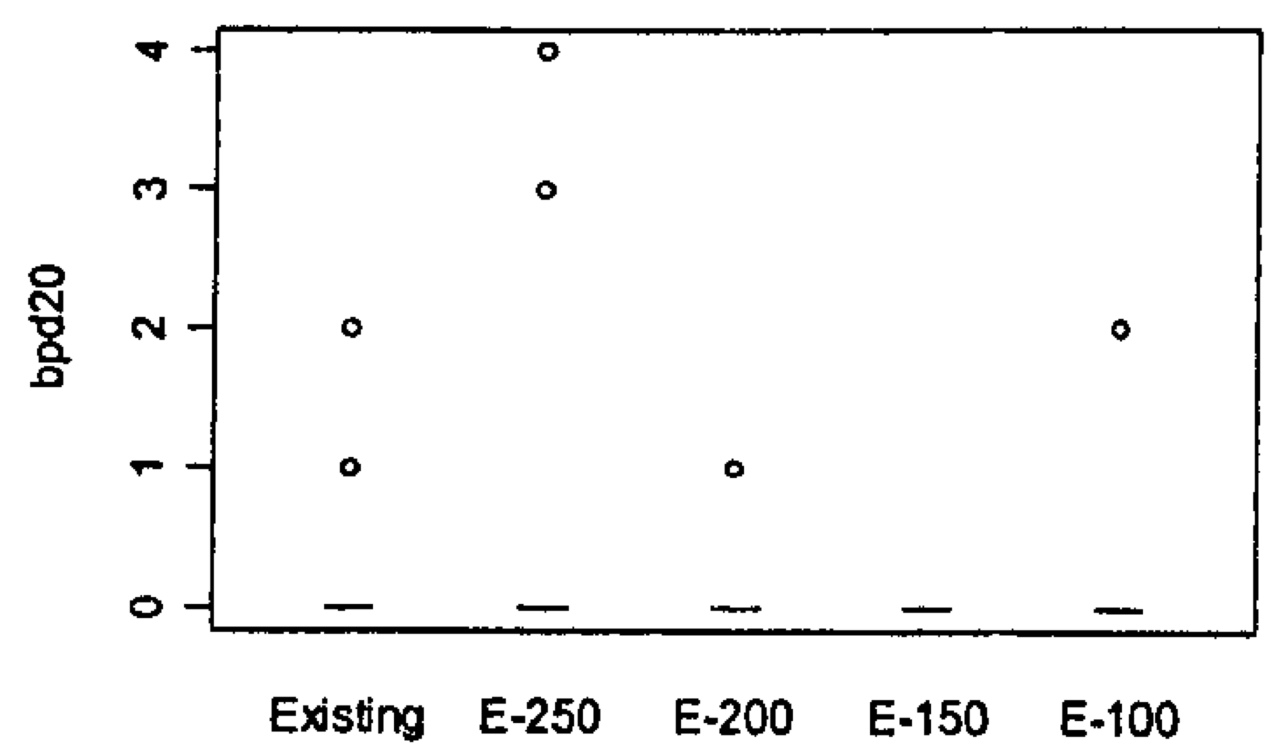

bpd15
0
1
2
3
4
5
Existing
E-250
E-200
E-150
E-100

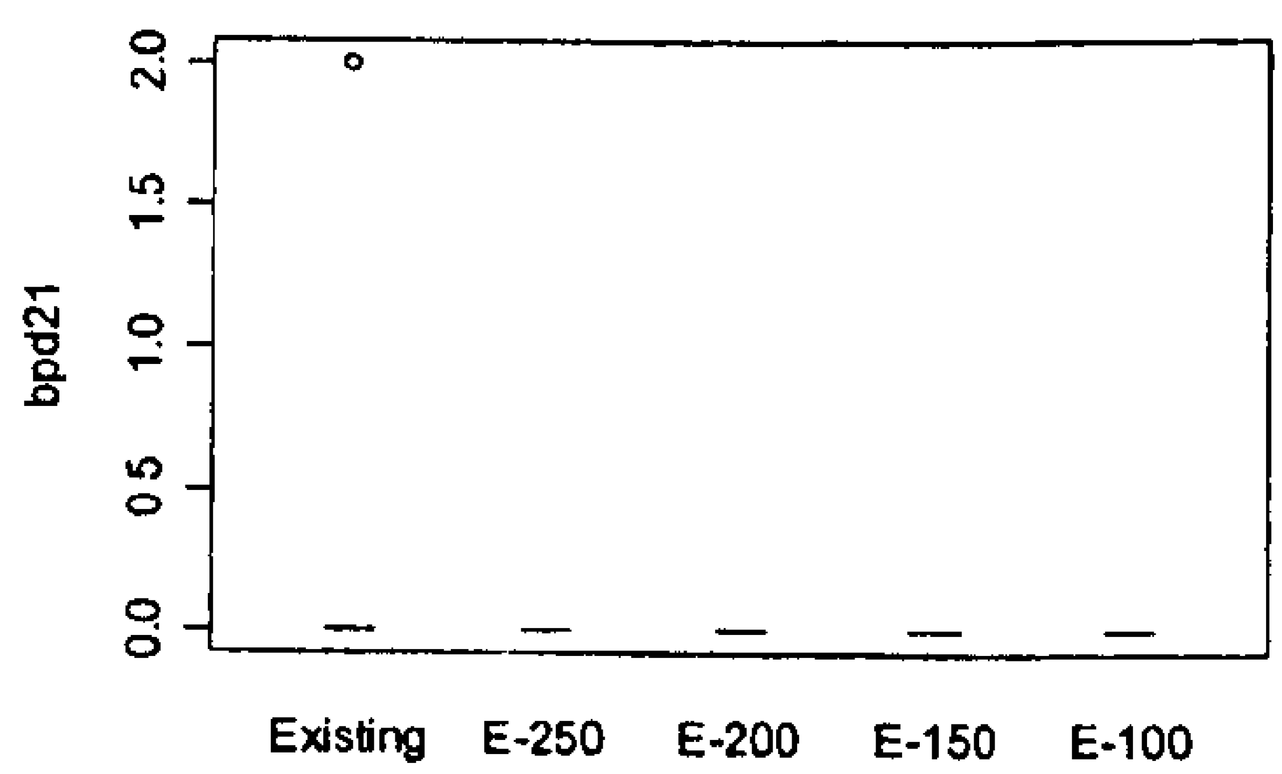

bpd16
0.0
1.0
2.0
3.0
Existing
E-250
E-200
E-150
E-100

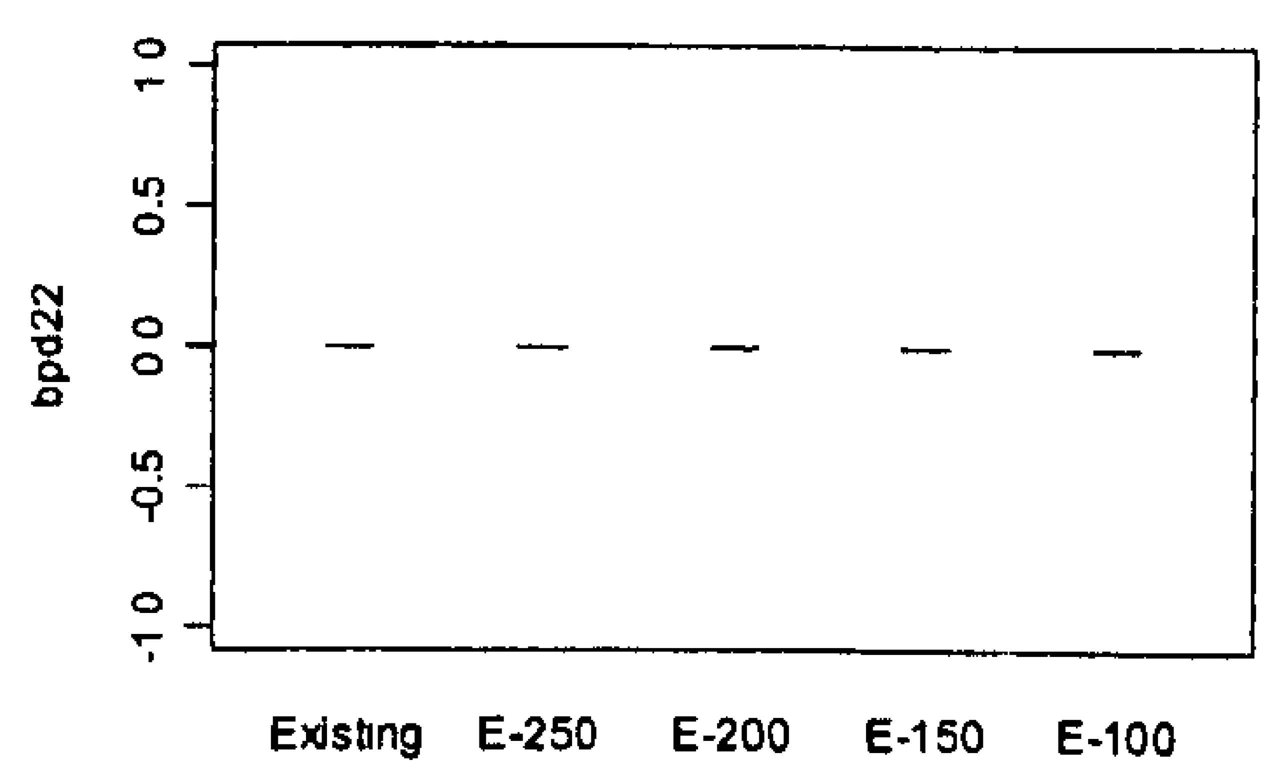

bpd17
0 1 2 3 4 5
Existing E-250 E-200 E-150 E-100

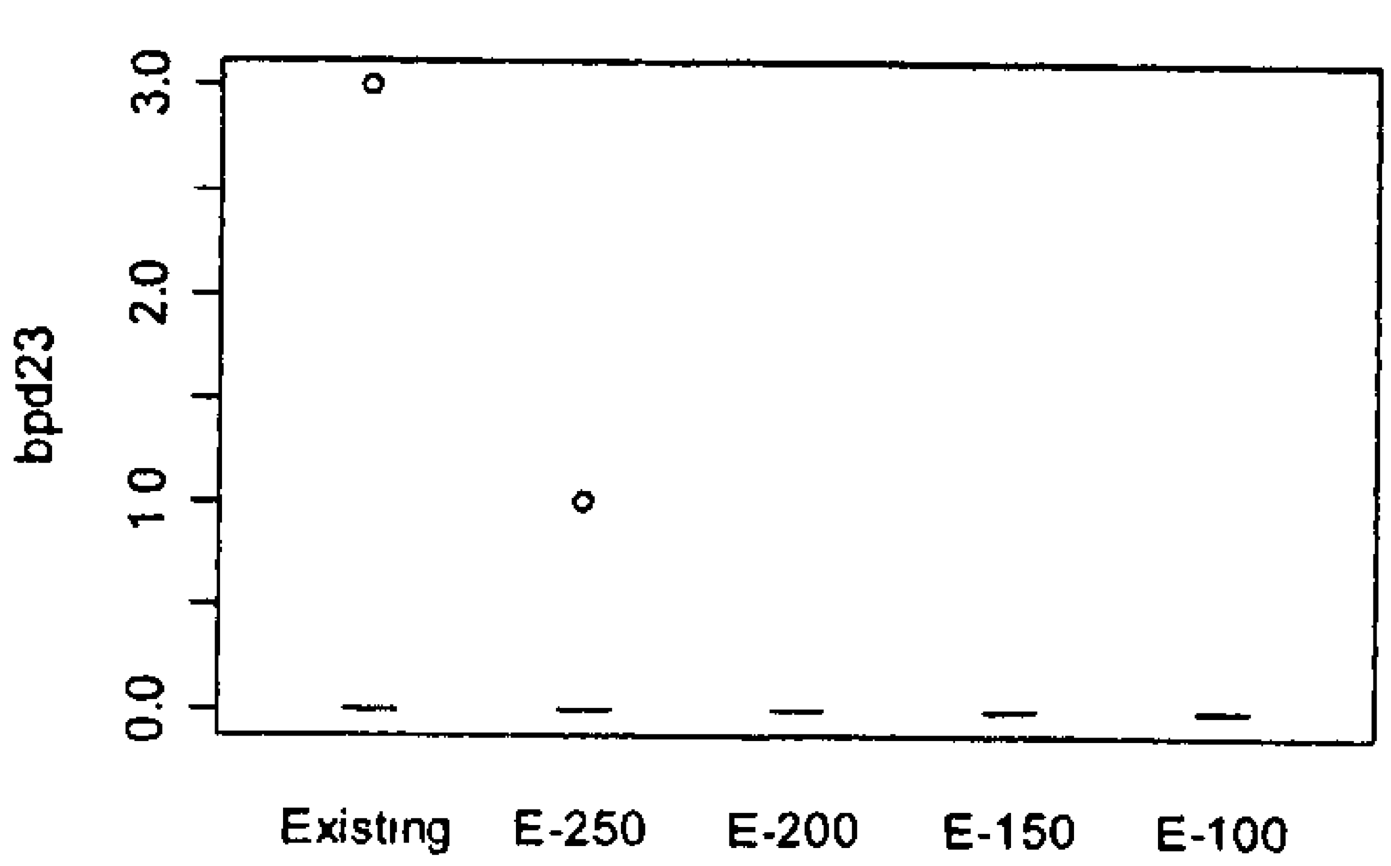

bpd18
0 1 2 3 4 5
Existing E-250 E-200 E-150 E-100

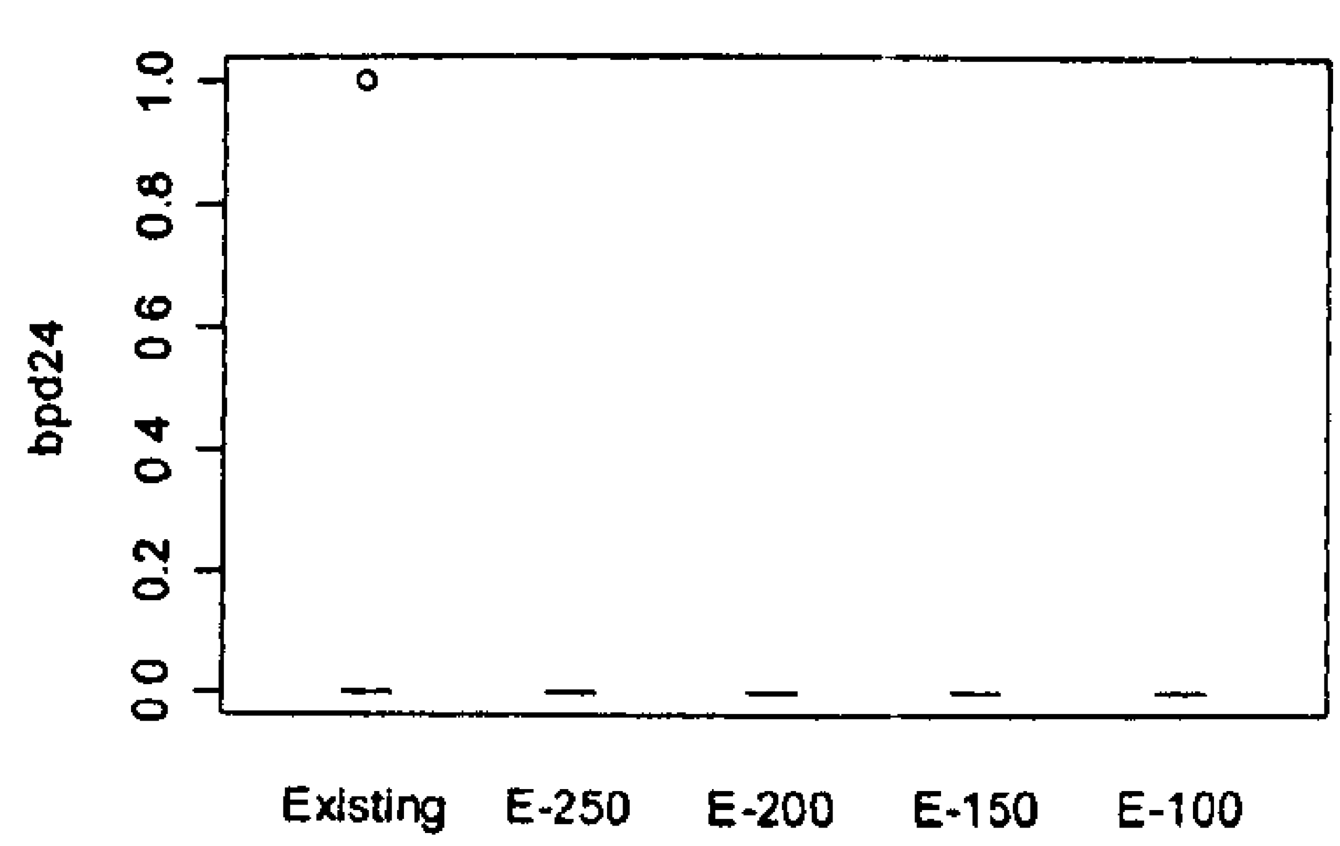

bpd19
0 1 2 3 4 5
Existing E-250 E-200 E-150 E-100

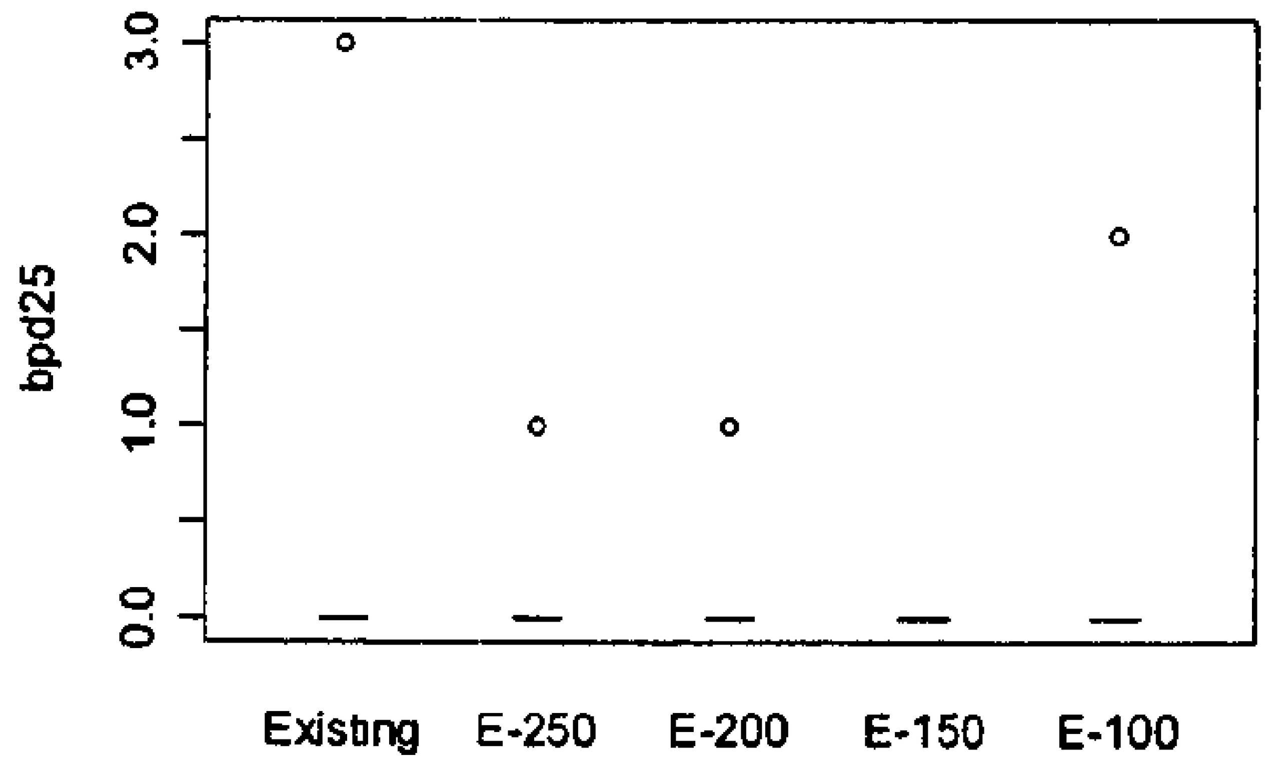

bpd20
0 1 2 3 4
Existing E-250 E-200 E-150 E-100

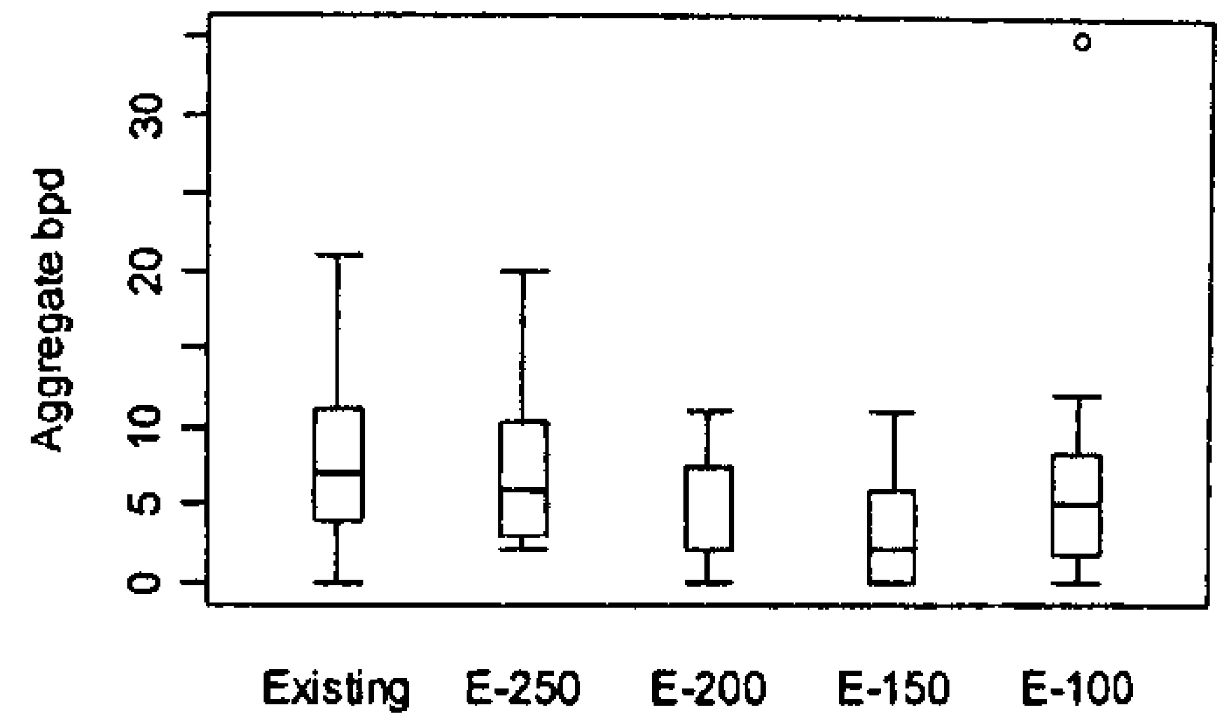

bpd21
0.0 0.5 1.0 1.5 2.0
Existing E-250 E-200 E-150 E-100

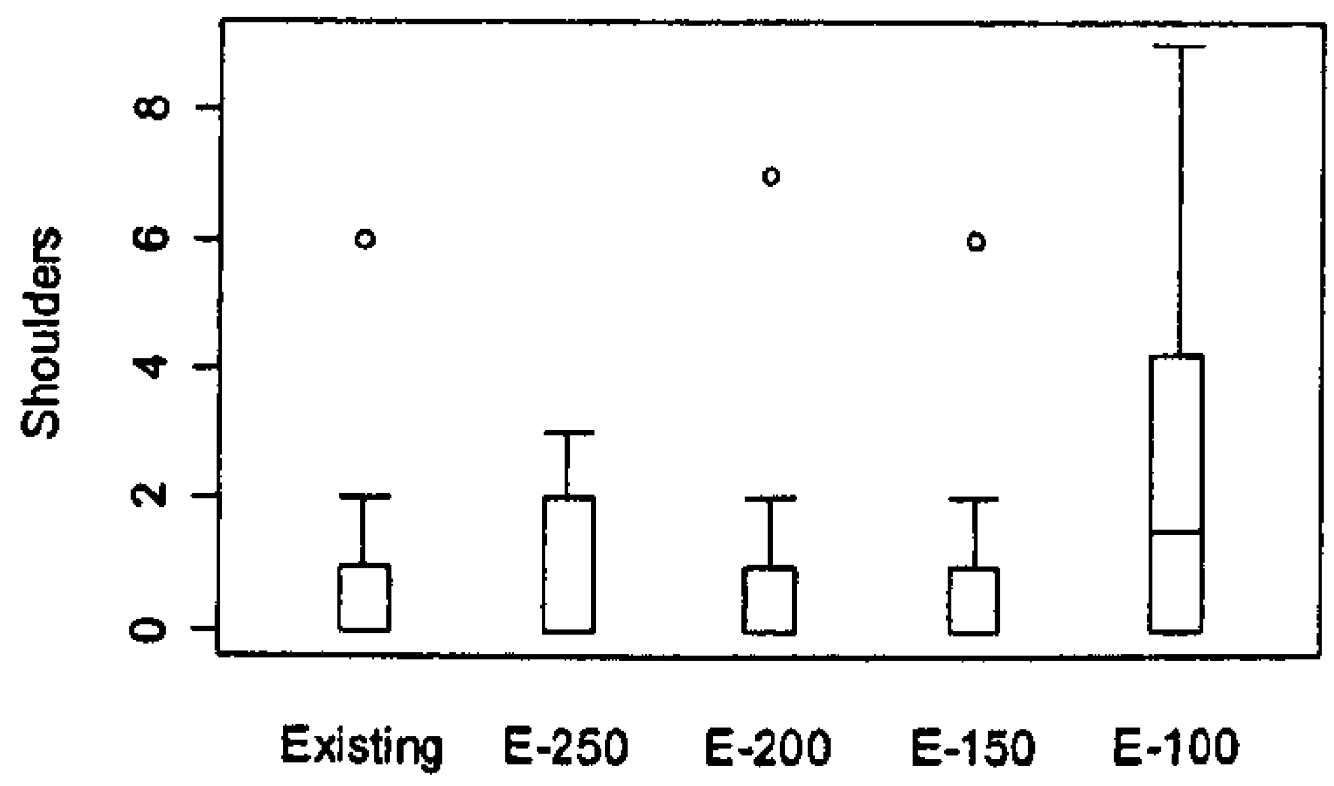

bpd22
-1.0 -0.5 0.0 0.5 1.0
Existing E-250 E-200 E-150 E-100

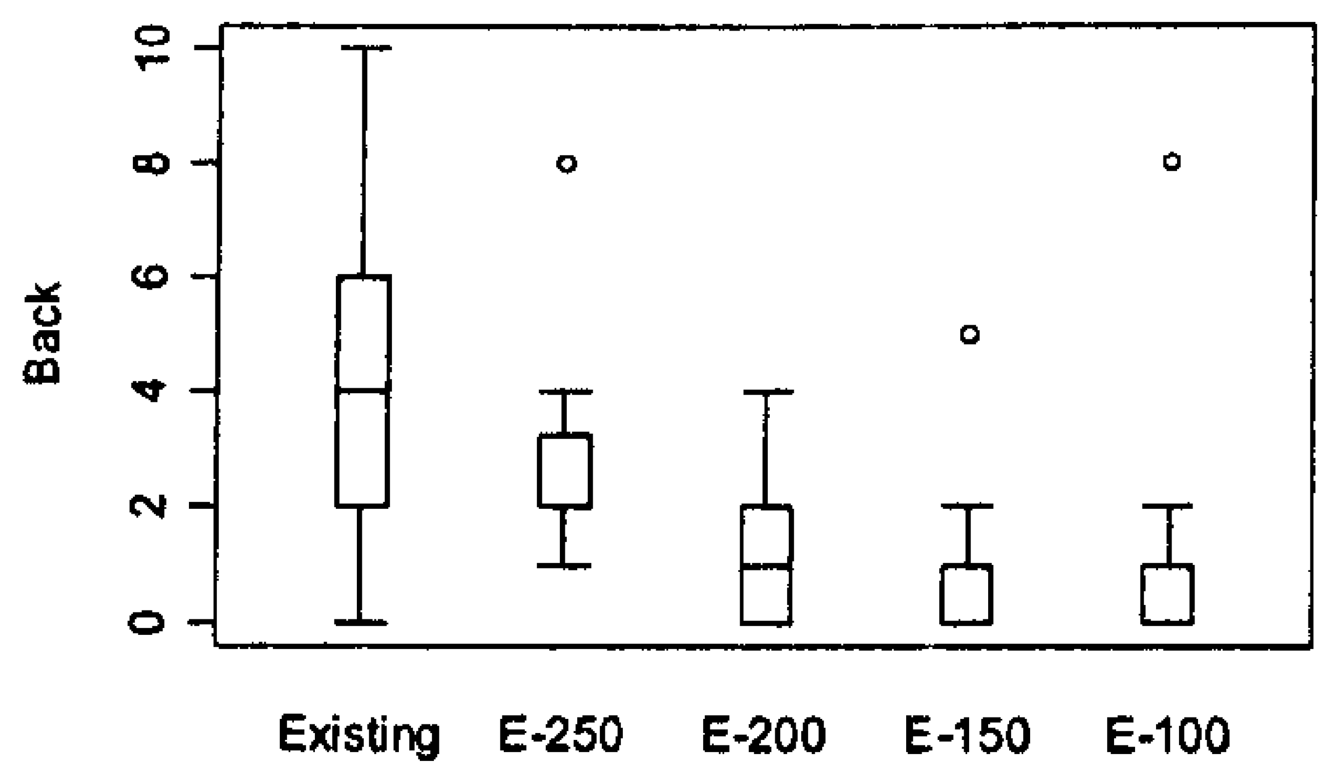

bpd23
0.0 1.0 2.0 3.0
Existing E-250 E-200 E-150 E-100

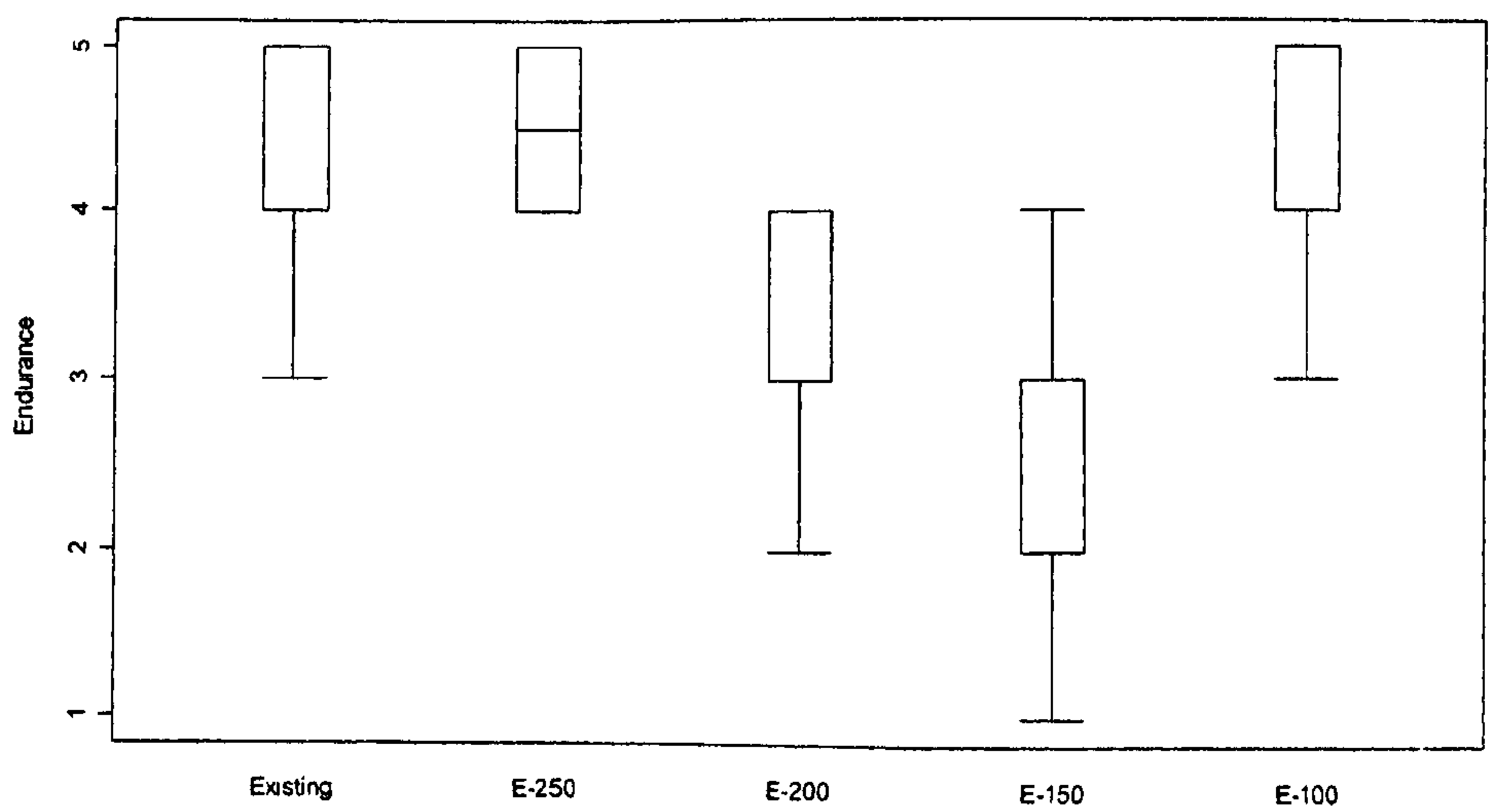

bpd24
0.0 0.2 0.4 0.6 0.8 1.0
Existing E-250 E-200 E-150 E-100


bpd25
0.0
1.0
2.0
3.0
Existing
E-250
E-200
E-150
E-100

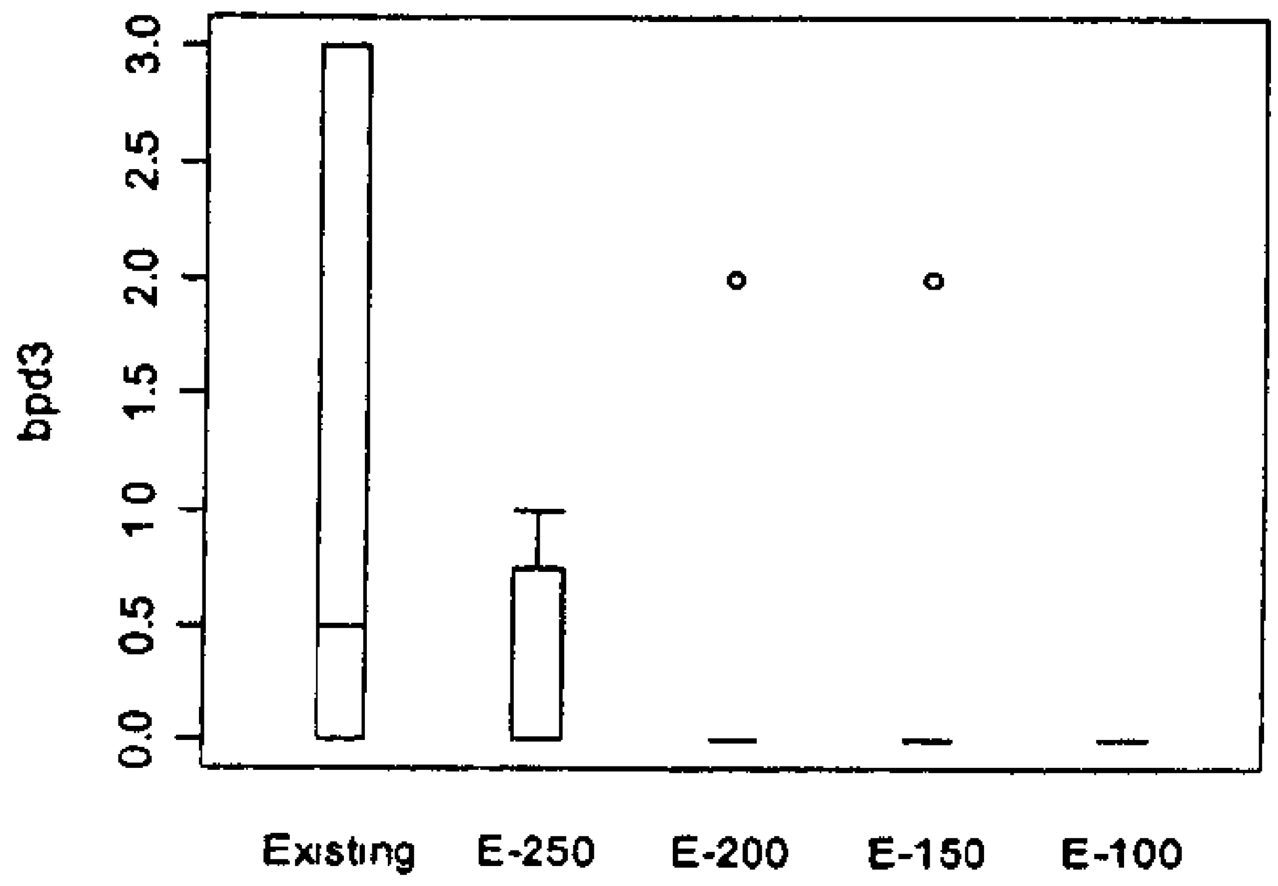

Aggregate bpd
0
5
10
20
30
Existing
E-250
E-200
E-150
E-100

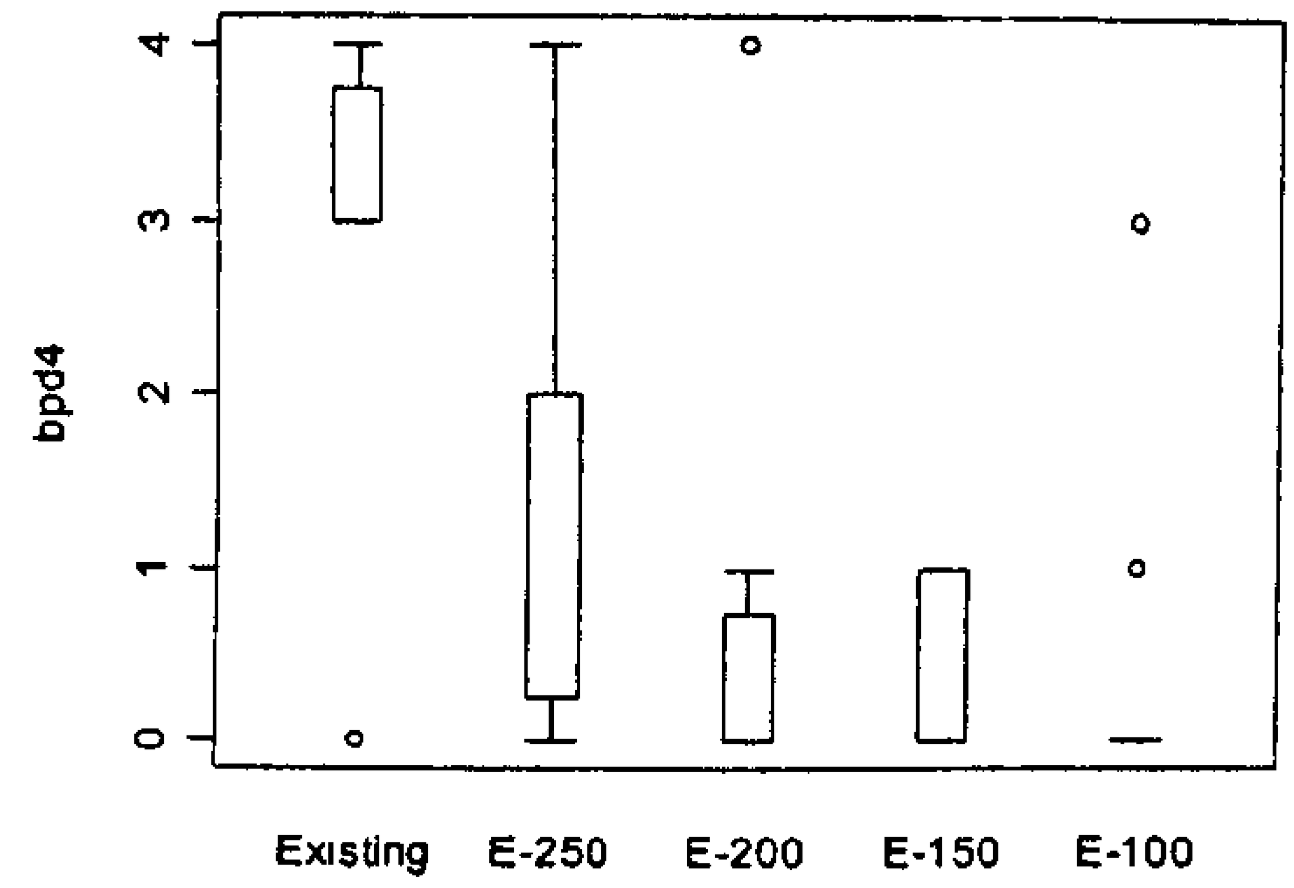

Shoulders
0
2
4
6
8
Existing
E-250
E-200
E-150
E-100

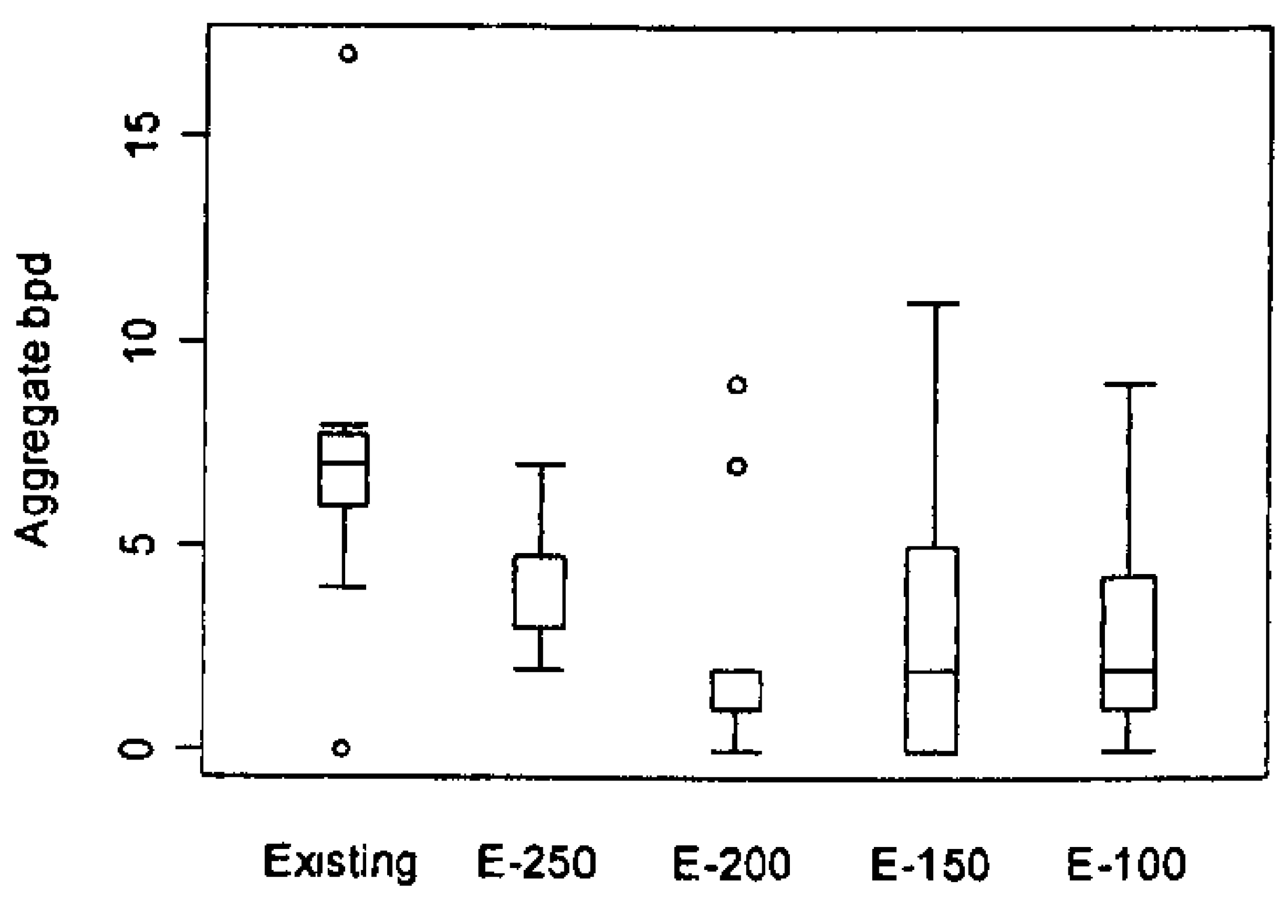

Back
0
2
4
6
8
10
Existing
E-250
E-200
E-150
E-100

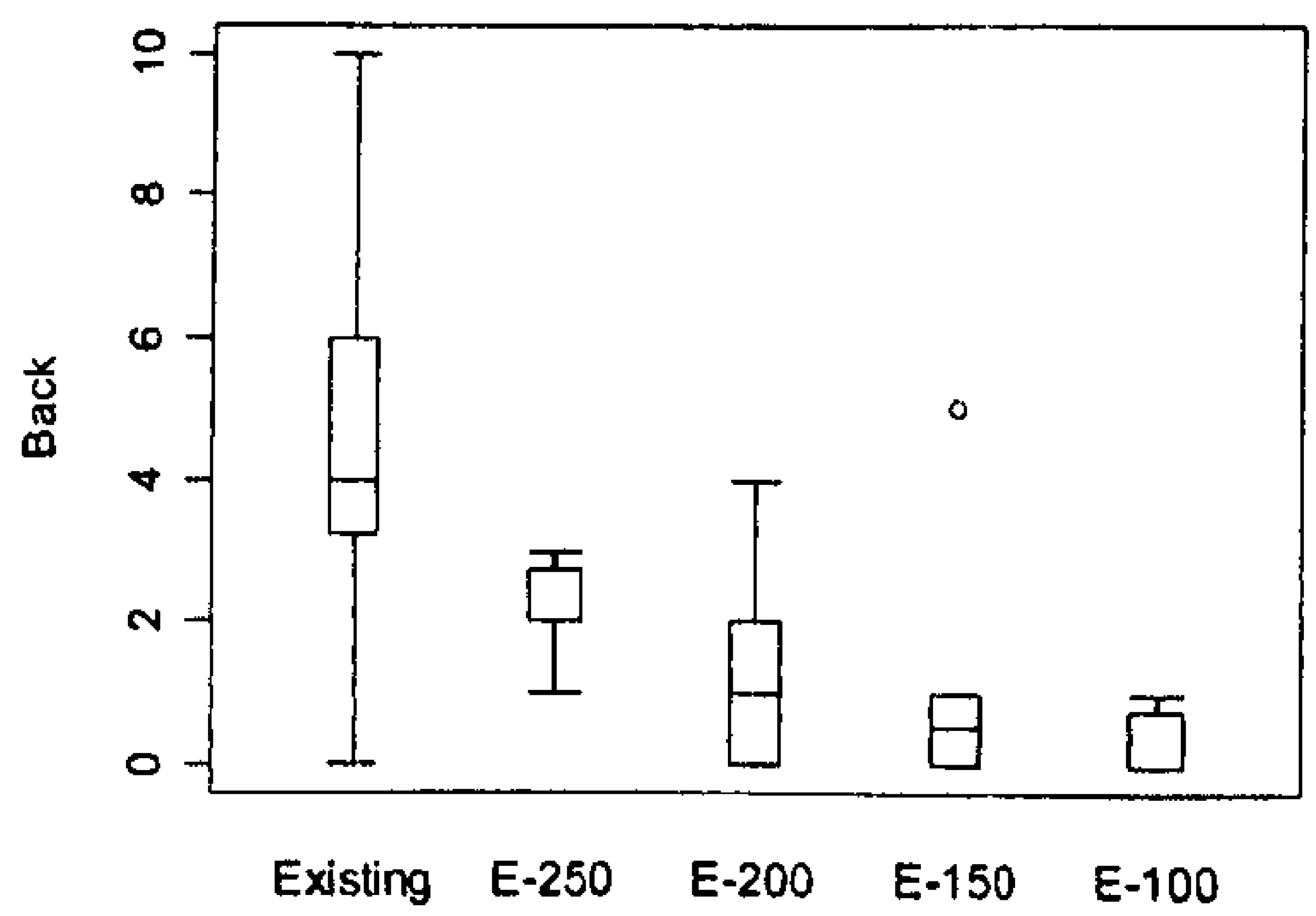

Endurance
1
2
3
4
5
Existing
E-250
E-200
E-150
E-100

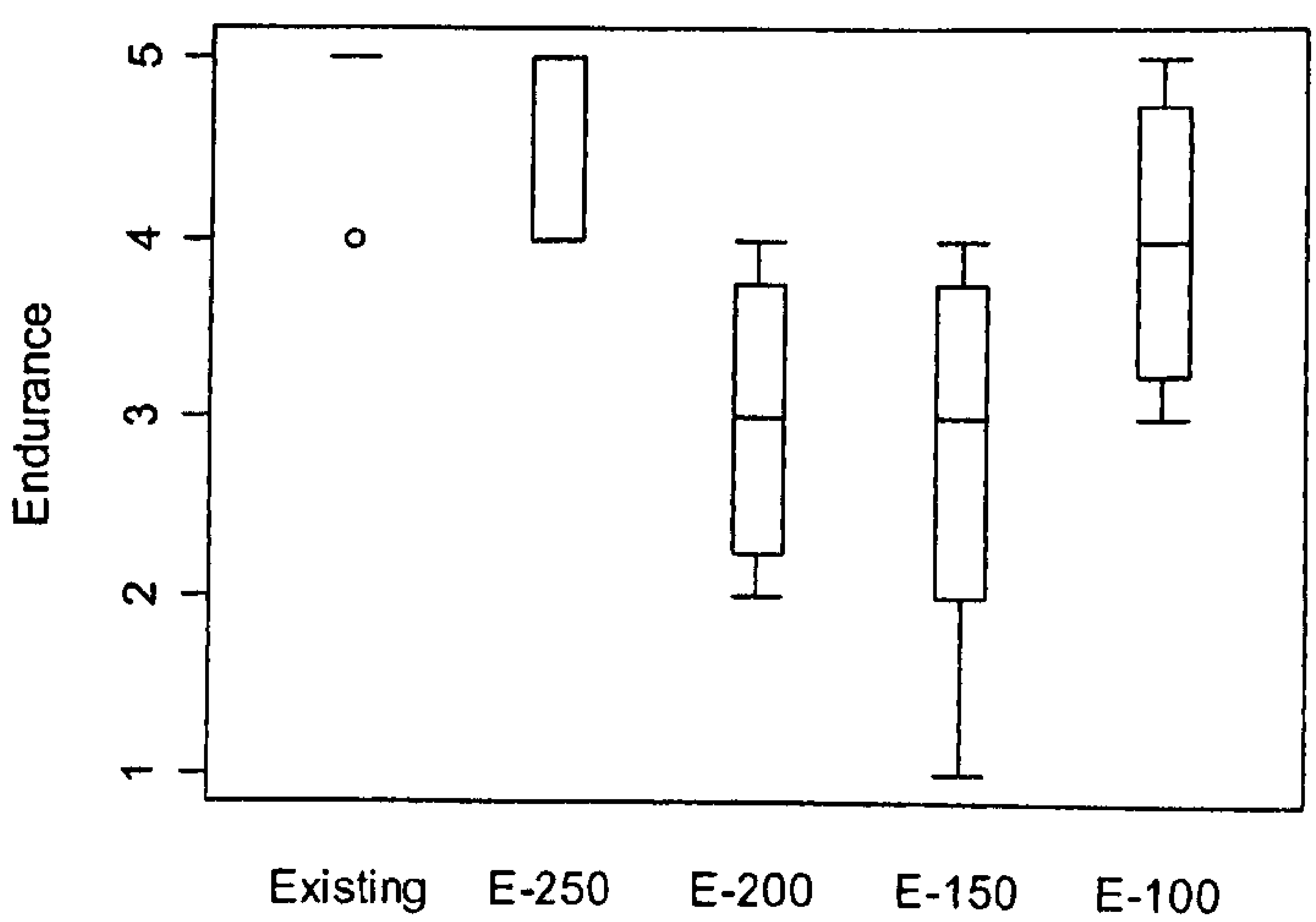
Male Adult BPD – Most effected body parts



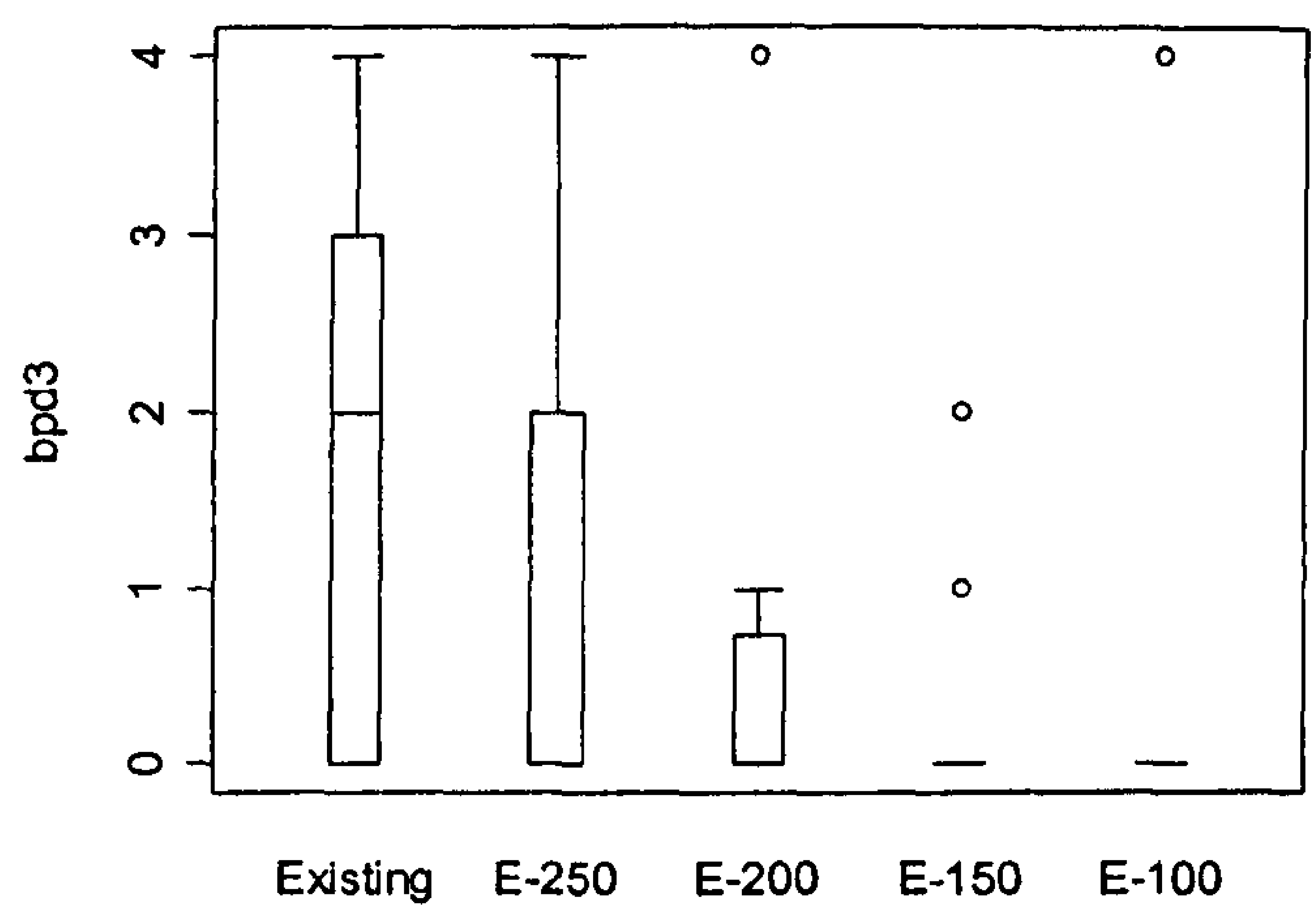


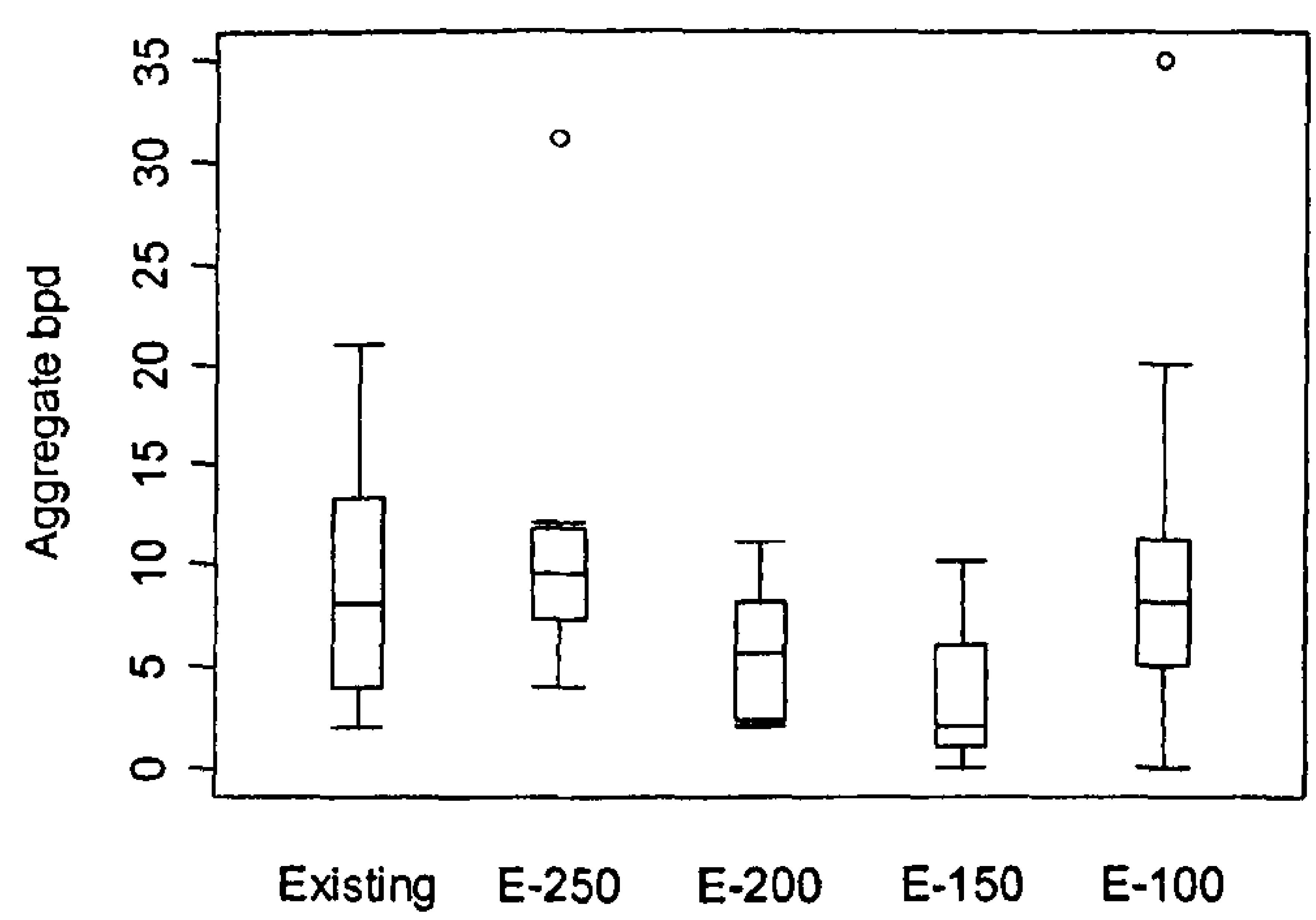


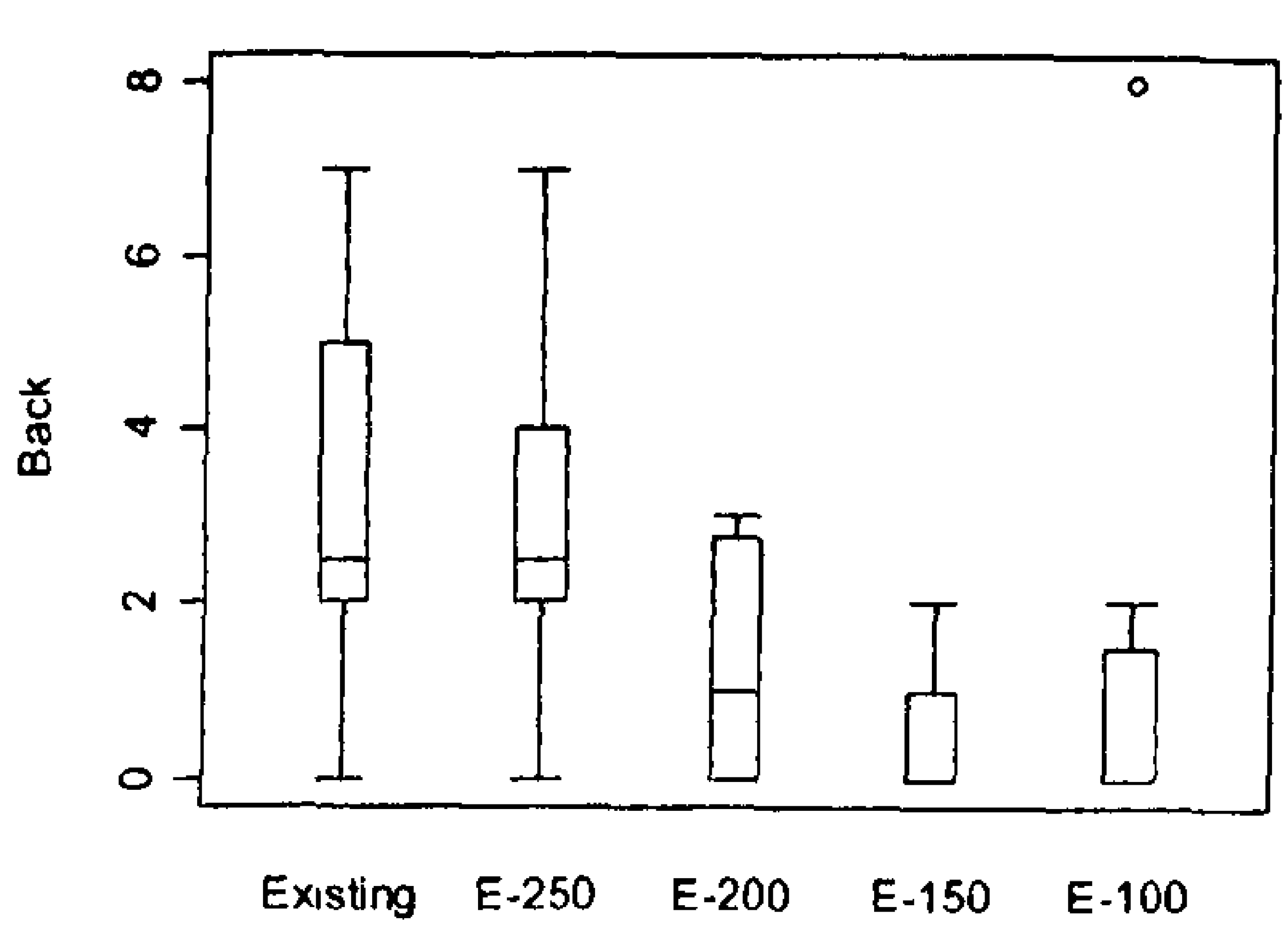


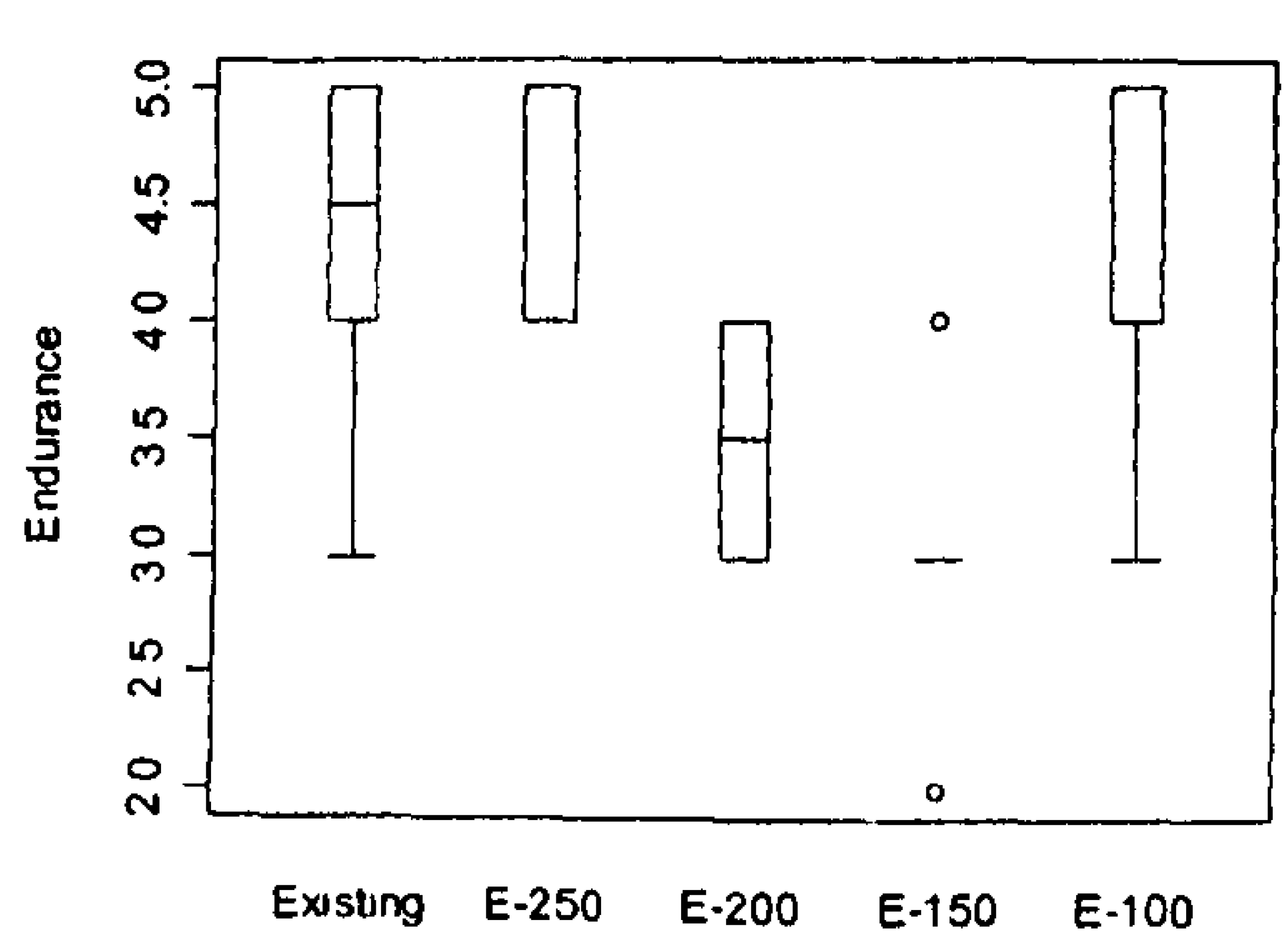


Female Adult BPD – most effected parts









NPar Tests - Compared heights

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00006 - VAR00001	Negative Ranks	4[a]	3.75	15.00
	Positive Ranks	2[b]	3.00	6.00
	Ties	5[c]		
	Total	11		
VAR00006 - VAR00003	Negative Ranks	11[d]	6.00	66.00
	Positive Ranks	0[e]	.00	.00
	Ties	0[f]		
	Total	11		
VAR00005 - VAR00003	Negative Ranks	10[g]	5.50	55.00
	Positive Ranks	0[h]	.00	.00
	Ties	1[i]		
	Total	11		
VAR00003 - VAR00001	Negative Ranks	0[j]	.00	.00
	Positive Ranks	10[k]	5.50	55.00
	Ties	1[l]		
	Total	11		

a. VAR00006 < VAR00001

b. VAR00006 > VAR00001

c. VAR00001 = VAR00006

d. VAR00006 < VAR00003

e. VAR00006 > VAR00003

f. VAR00003 = VAR00006

g. VAR00005 < VAR00003

h. VAR00005 > VAR00003

i. VAR00003 = VAR00005

j. VAR00003 < VAR00001

k. VAR00003 > VAR00001

l. VAR00001 = VAR00003

Test Statistics[c]

	Existing - KH+00	Existing - KH+100	KH+200 - KH+100	KH+100 - KH+00
Z	-1.000[a]	-3.071[a]	-2.836[a]	-2.842[b]
Asymp. Sig. (2-tailed)	.317	.002	.005	.004

a. Based on positive ranks.

b. Based on negative ranks.

c. Wilcoxon Signed Ranks Test

NPar Tests Existing v KH+100

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	8[a]	4.50	36.00
	Positive Ranks	0[b]	.00	.00
	Ties	3[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-2.549[a]
Asymp. Sig. (2-tailed)	.011

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	6[a]	3.50	21.00
	Positive Ranks	0[b]	.00	.00
	Ties	5[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-2.232[a]
Asymp. Sig. (2-tailed)	.026

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	0[a]	.00	.00
	Positive Ranks	0[b]	.00	.00
	Ties	11[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	.000[a]
Asymp. Sig. (2-tailed)	1.000

a. The sum of negative ranks equals the sum of positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	7[a]	5.86	41.00
	Positive Ranks	2[b]	2.00	4.00
	Ties	2[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-2.209[a]
Asymp. Sig. (2-tailed)	.027

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	8[a]	5.31	42.50
	Positive Ranks	1[b]	2.50	2.50
	Ties	2[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-2.395[a]
Asymp. Sig. (2-tailed)	.017

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	8[a]	4.50	36.00
	Positive Ranks	0[b]	.00	.00
	Ties	3[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-2.636[a]
Asymp. Sig. (2-tailed)	.008

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	5[a]	3.90	19.50
	Positive Ranks	1[b]	1.50	1.50
	Ties	5[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-1.897[a]
Asymp. Sig. (2-tailed)	.058

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	4[a]	2.50	10.00
	Positive Ranks	0[b]	.00	.00
	Ties	7[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-1.841[a]
Asymp. Sig. (2-tailed)	.066

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	4[a]	3.38	13.50
	Positive Ranks	1[b]	1.50	1.50
	Ties	6[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-1.633[a]
Asymp. Sig. (2-tailed)	.102

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	4[a]	2.50	10.00
	Positive Ranks	0[b]	.00	.00
	Ties	7[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-1.890[a]
Asymp. Sig. (2-tailed)	.059

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	3[a]	2.00	6.00
	Positive Ranks	0[b]	.00	.00
	Ties	8[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-1.633[a]
Asymp. Sig. (2-tailed)	.102

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	7[a]	4.86	34.00
	Positive Ranks	1[b]	2.00	2.00
	Ties	3[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-2.266[a]
Asymp. Sig. (2-tailed)	.023

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	4[a]	2.50	10.00
	Positive Ranks	0[b]	.00	.00
	Ties	7[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-1.826[a]
Asymp. Sig. (2-tailed)	.068

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	4[a]	3.38	13.50
	Positive Ranks	1[b]	1.50	1.50
	Ties	6[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-1.633[a]
Asymp. Sig. (2-tailed)	.102

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	3[a]	2.00	6.00
	Positive Ranks	0[b]	.00	.00
	Ties	8[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-1.604[a]
Asymp. Sig. (2-tailed)	.109

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	3[a]	2.67	8.00
	Positive Ranks	1[b]	2.00	2.00
	Ties	6[c]		
	Total	10		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-1.134[a]
Asymp. Sig. (2-tailed)	.257

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	4[a]	2.50	10.00
	Positive Ranks	0[b]	.00	.00
	Ties	7[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-1.890[a]
Asymp. Sig. (2-tailed)	.059

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
VAR00002 - VAR00001	Negative Ranks	4[a]	2.50	10.00
	Positive Ranks	0[b]	.00	.00
	Ties	7[c]		
	Total	11		

a. VAR00002 < VAR00001

b. VAR00002 > VAR00001

c. VAR00001 = VAR00002

Test Statistics[b]

	VAR00002 - VAR00001
Z	-1.890[a]
Asymp. Sig. (2-tailed)	.059

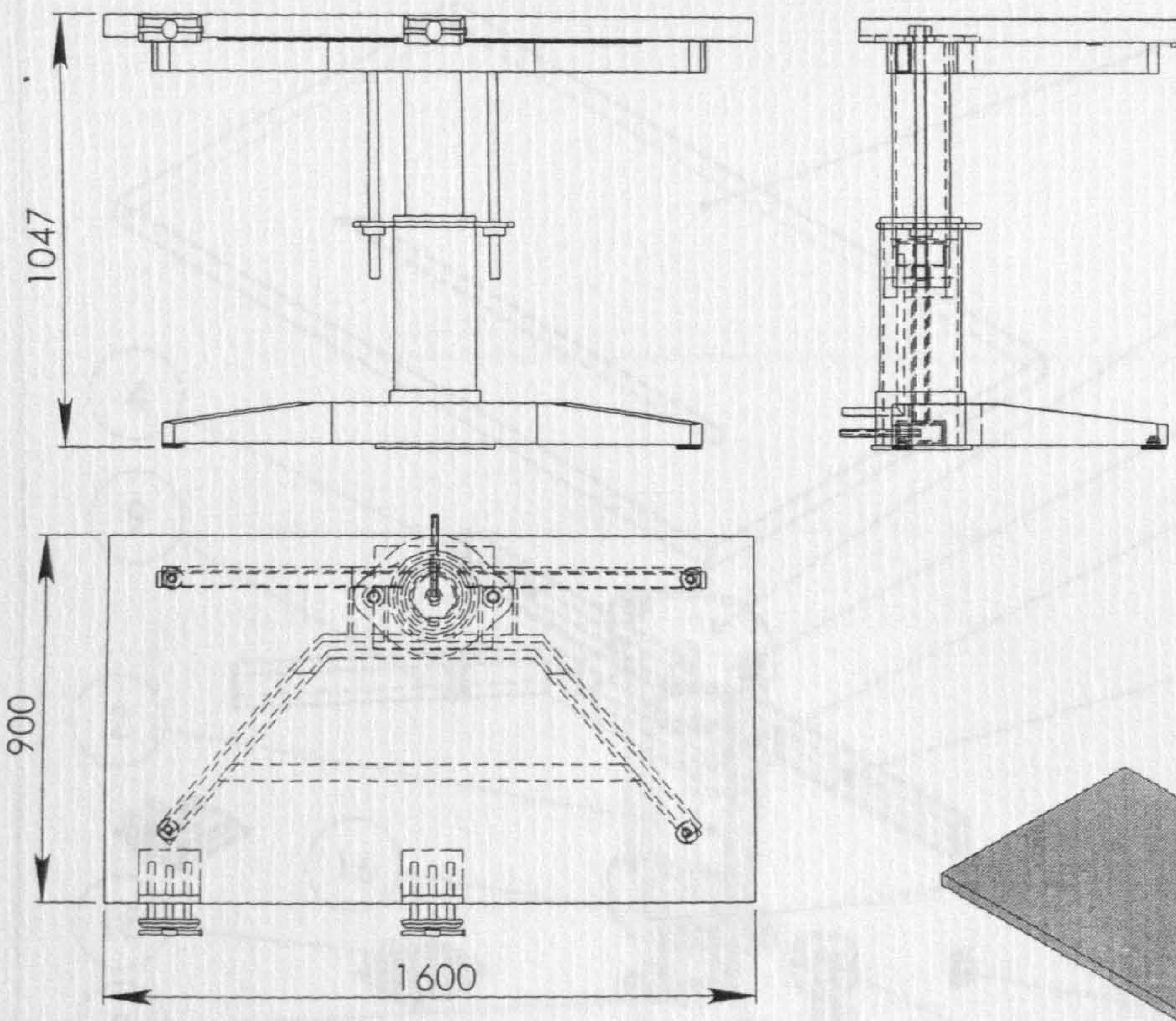
a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

9.4 Appendix D

9.4.1 Prototype drawings and finite element analysis plots

WORKBENCH FULLY EXTENDED



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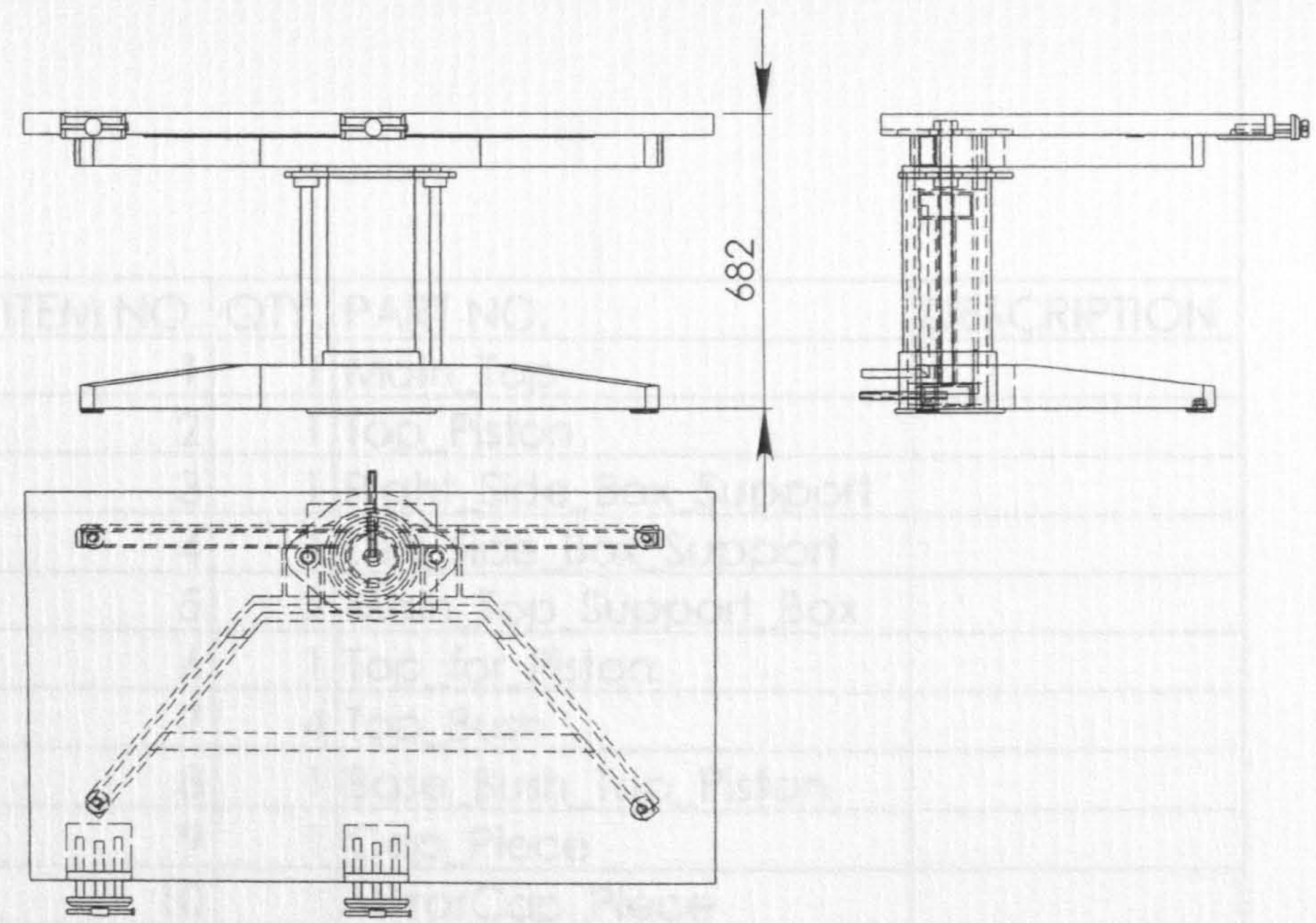

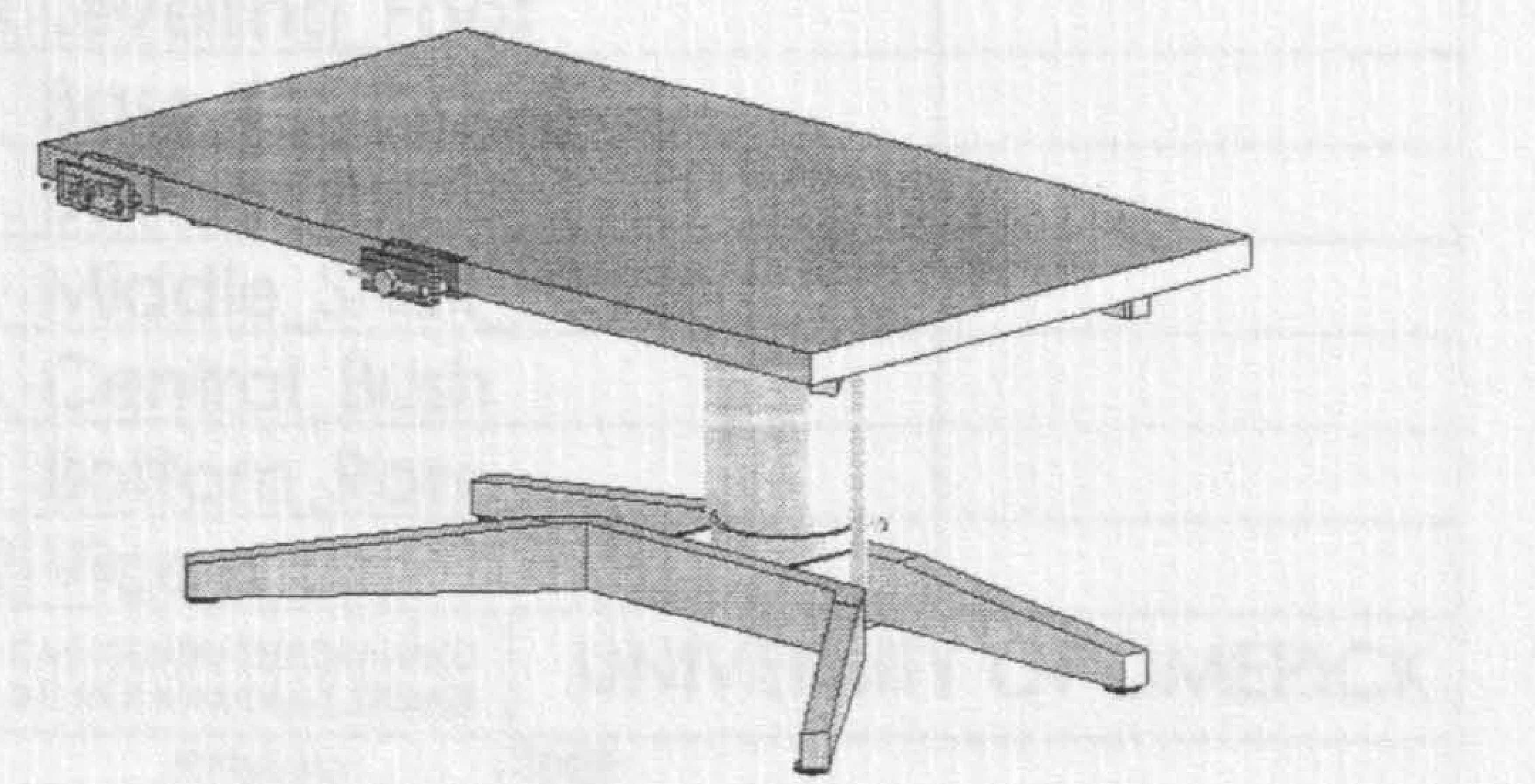

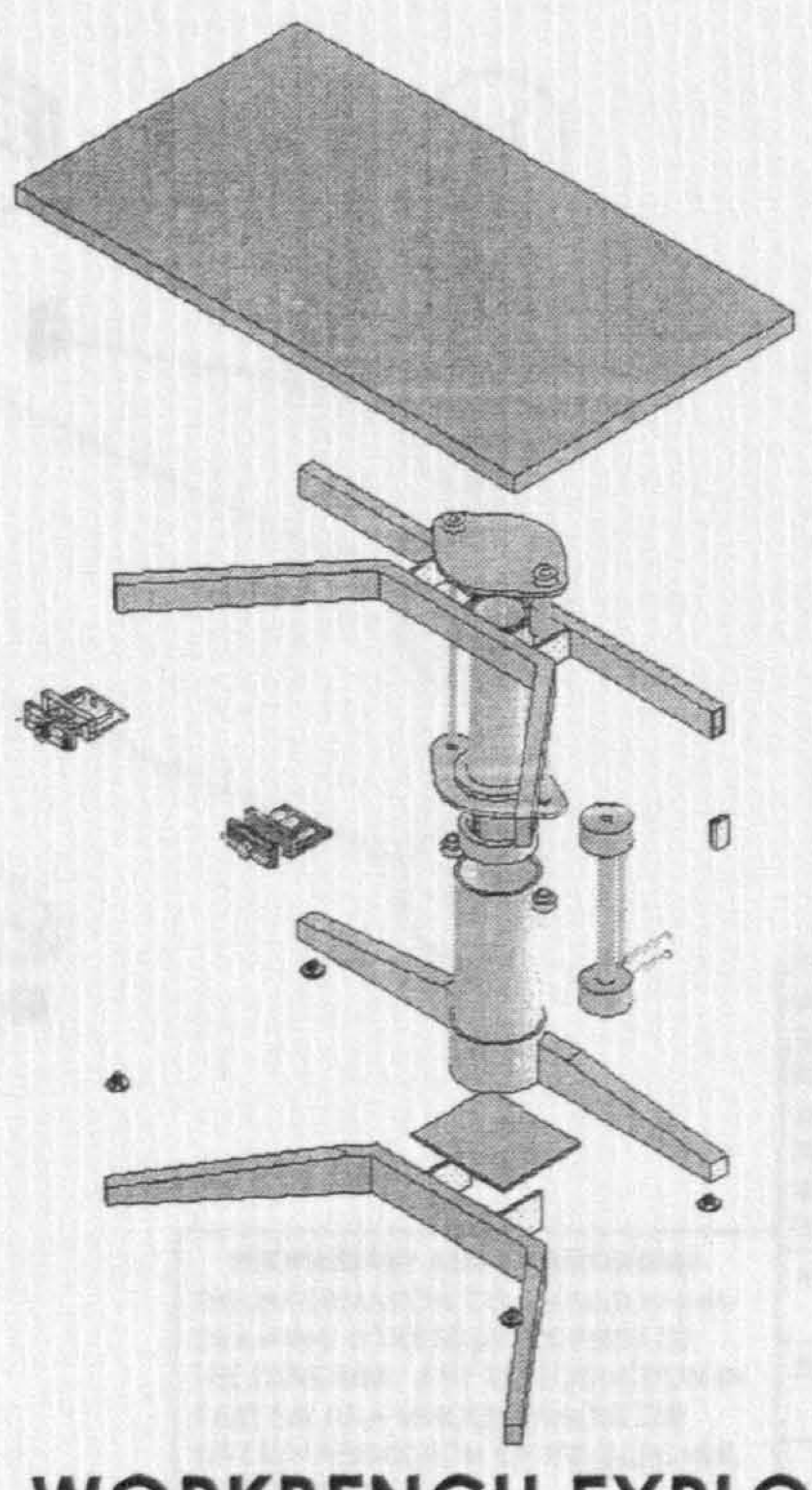

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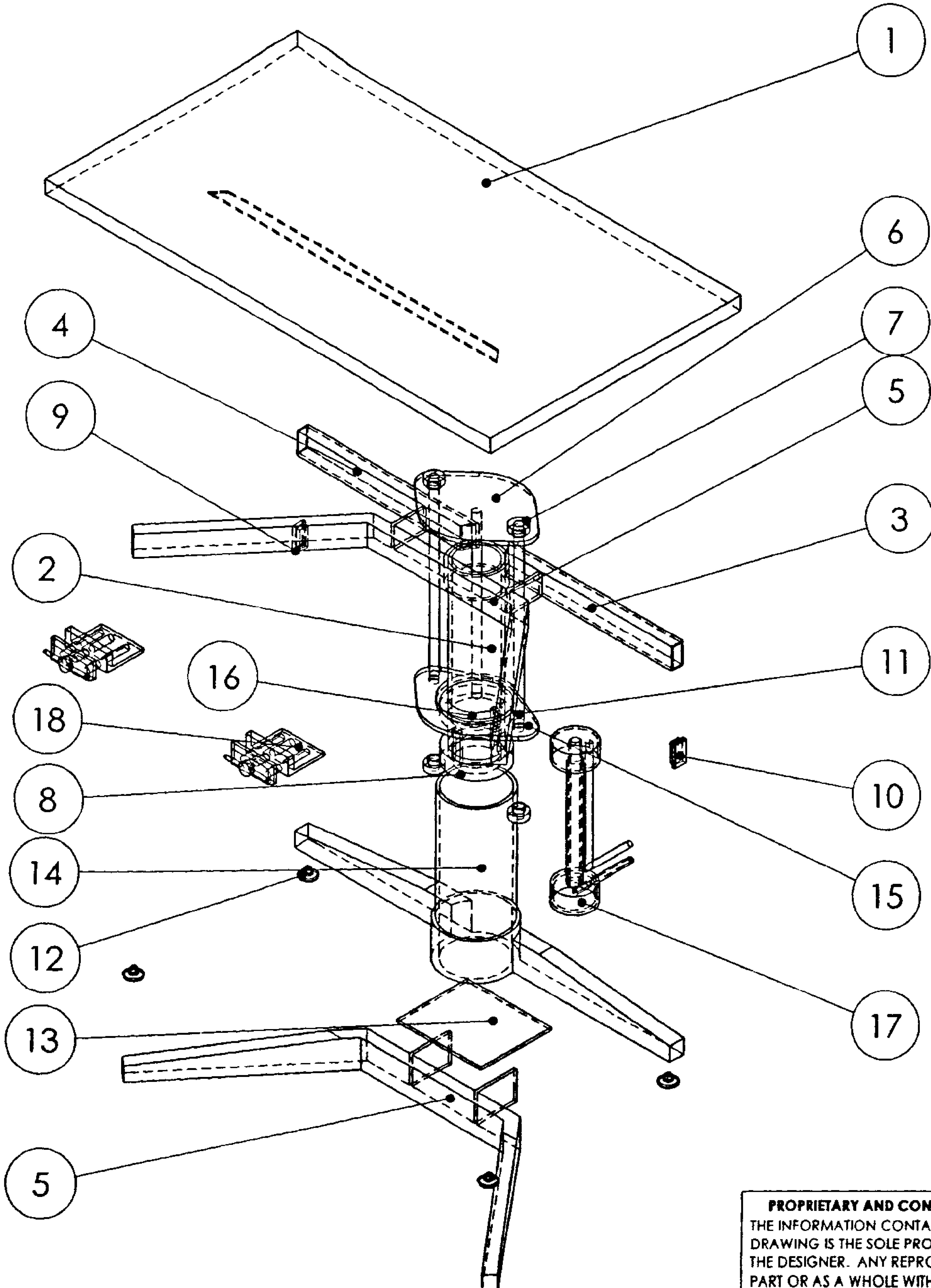

ITEM NO.	QTY.	PART NO.	DESCRIPTION
1	1	Main_Top	
2	1	Top_Piston	
3	1	Right_Side_Box_Support	
4	1	Left_Side_Box_Support	
5	2	Main_Top_Support_Box	
6	1	Top_for_Piston	
7	4	Top_Bush	
8	1	Base_Bush_Top_Piston	
9	1	Cap_Piece	
10	1	MirrorCap_Piece	
11	2	Guide_Bar	
12	4	Levelling_Foot	
13	1	Base_for_Piston	
14	1	Bottom_Piston	
15	1	Middle_Shelf_Piston	
16	1	Central_Bush	
17	1	Bottom_Ram	
18	2	Vice	

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DIMENSIONS ARE IN MILLIMETERS
TOLERANCES ARE:
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XX.X (1 PLS) ±0.1MM
X XX (2 PLS) ±0.03MM
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MATERIAL

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TITLE:
Labelled_View

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DIRECTORY C \Documents and Settings\Administrator\Desktop\Bill\
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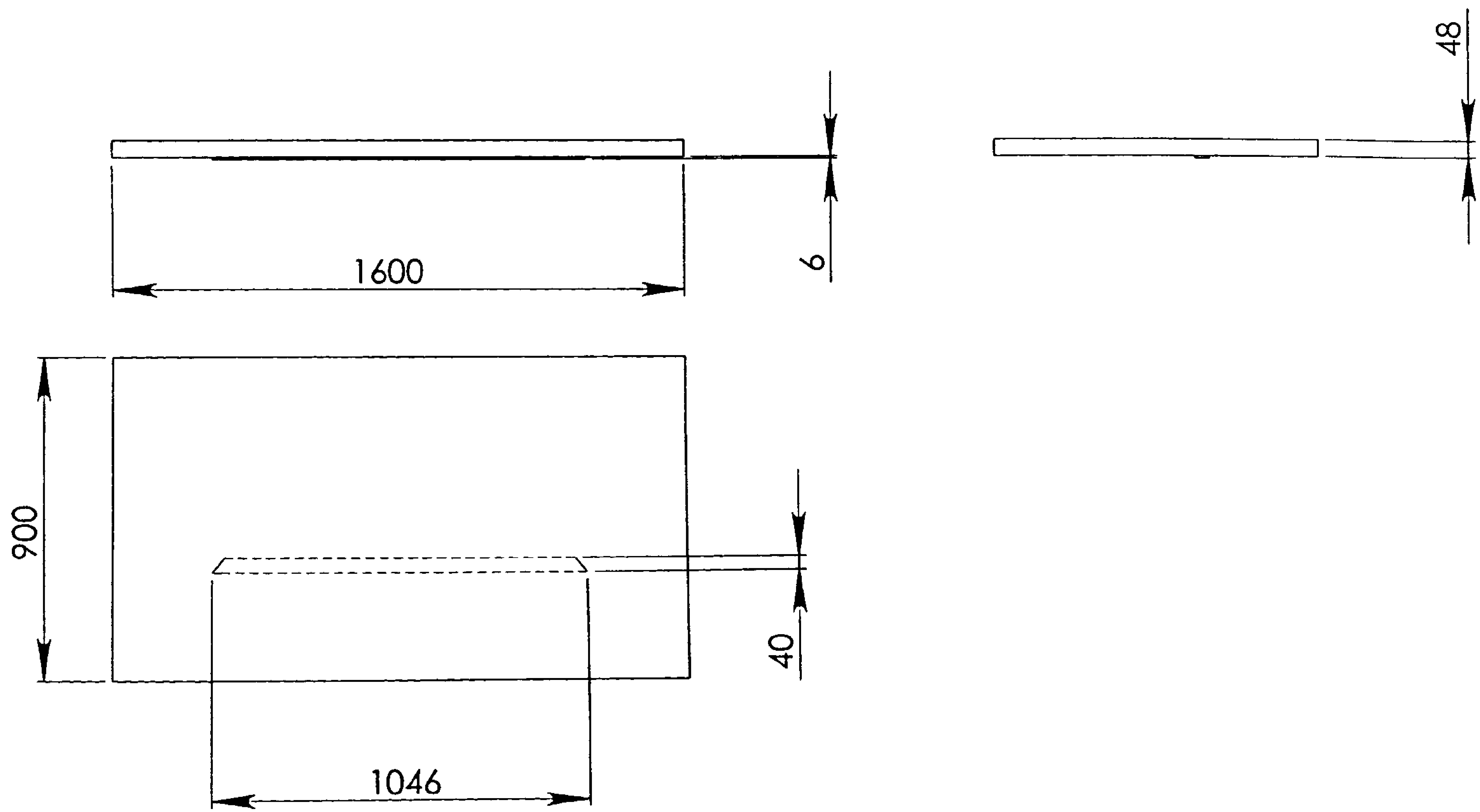

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X XX (2 PLS) ±0.03MM
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MATERIAL -----

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DESIGNER.
APPROVED:
DATE: 10/05/2004

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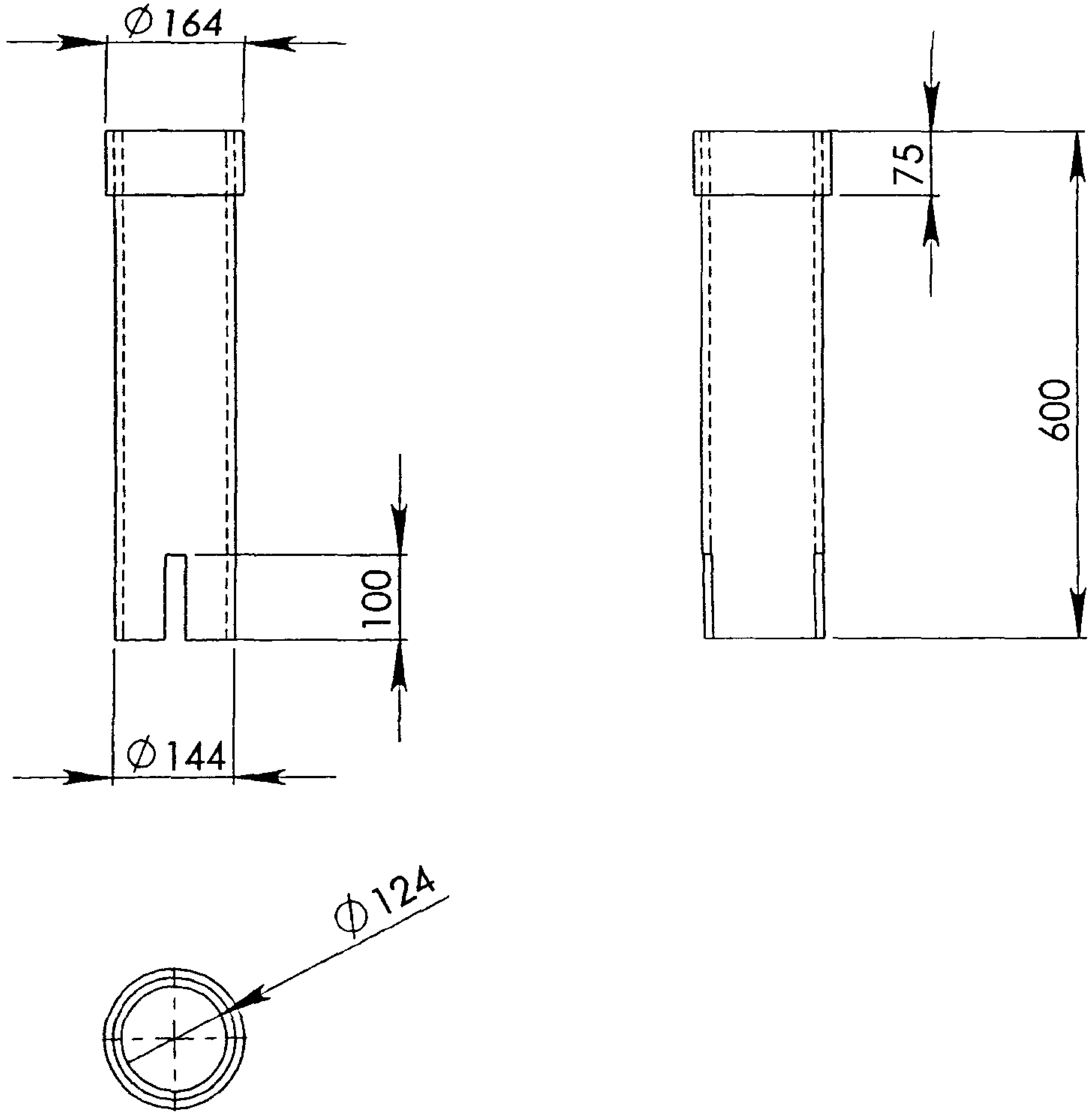
TITLE:
Main_Top

FILE NAME:
Main_WorkBench

DIRECTORY
C \Documents and Settings\Administrator\Desktop\Bill\

SIZE A4 | DWG NO :3 | REV. 1

SCALE 1.20 | SIGNATURE: | SHEET 3 OF 20



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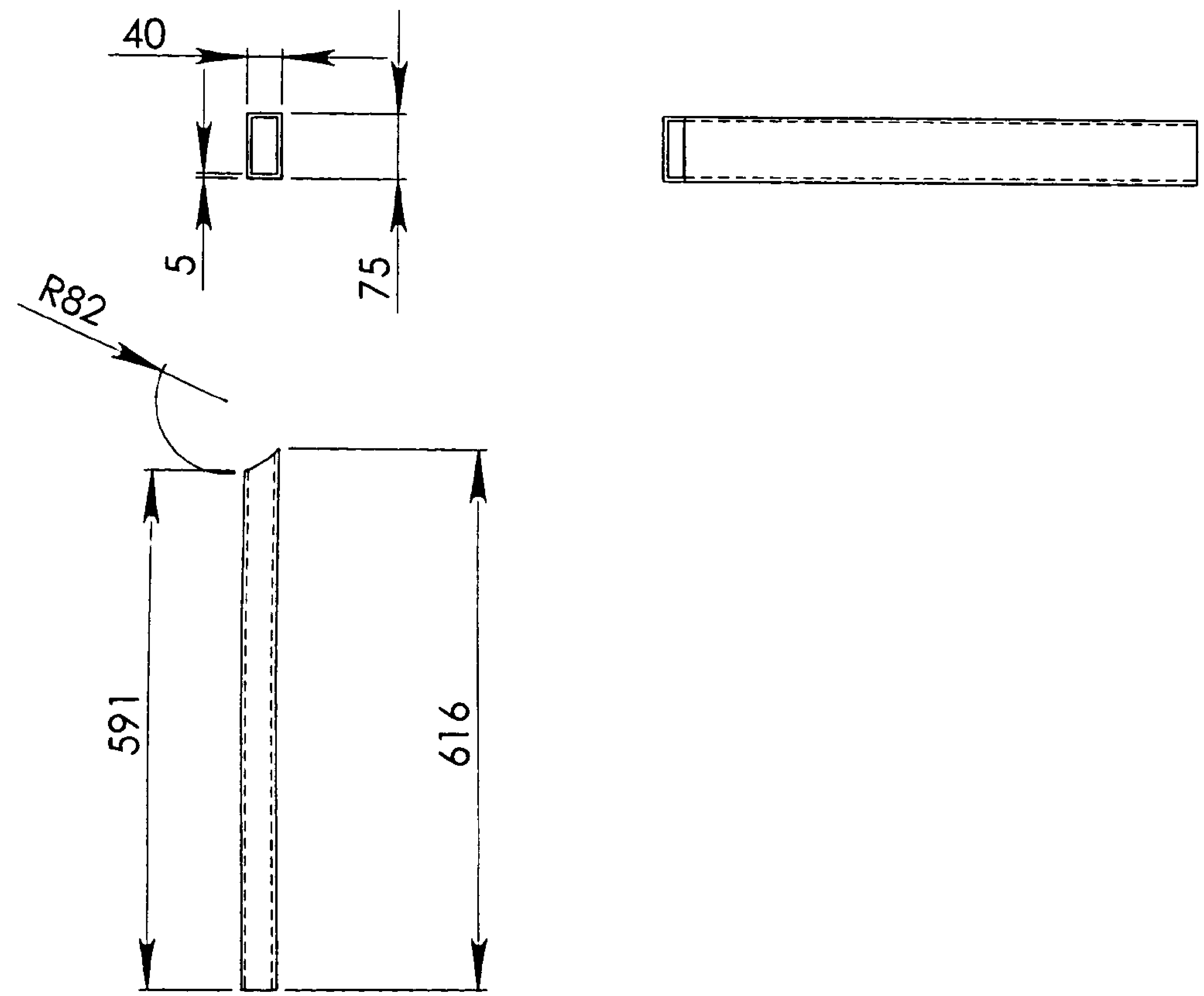

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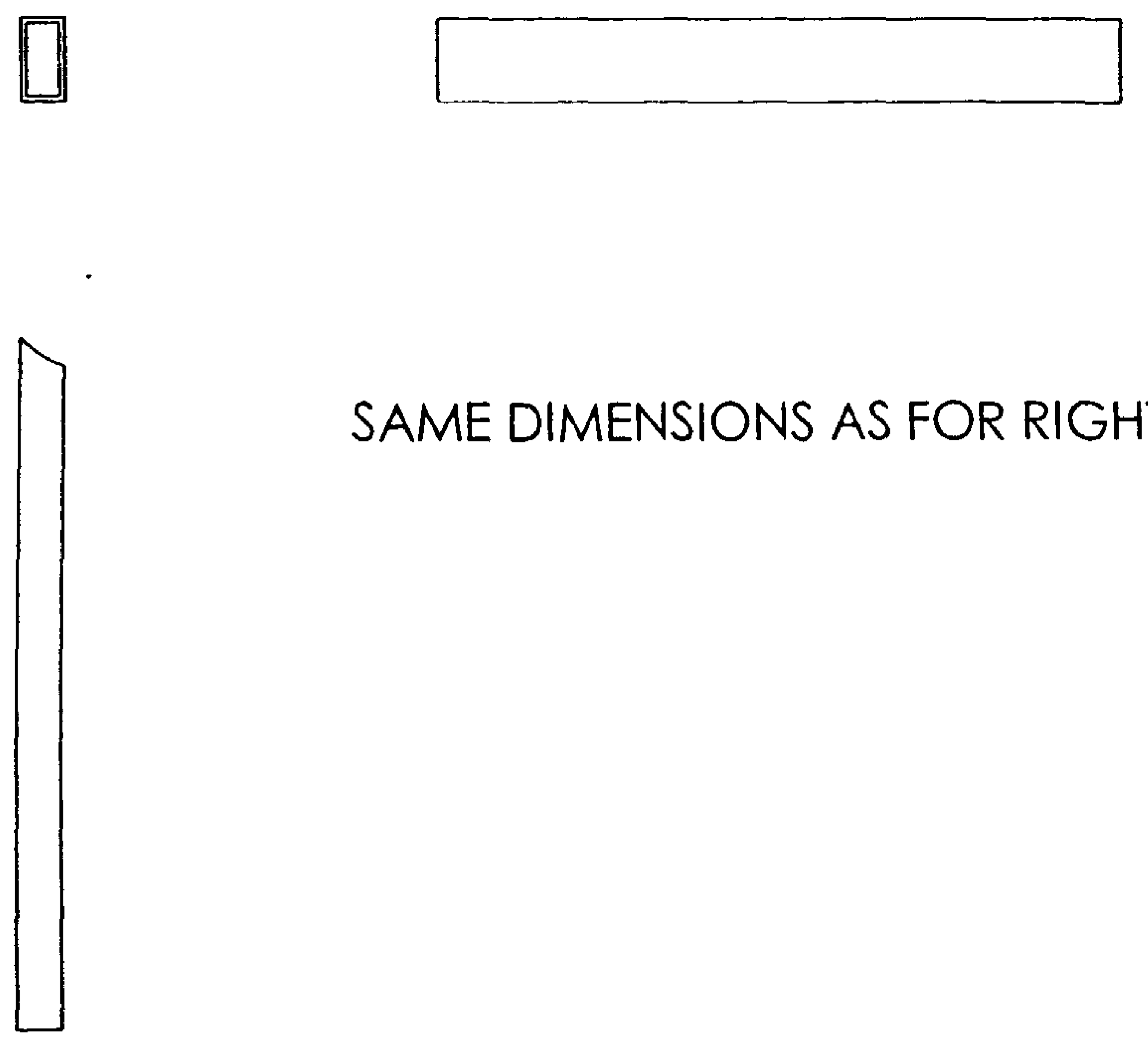

SAME DIMENSIONS AS FOR RIGHT BOX TOP SUPPORT

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XX.X (1 PLS) ±0.1MM
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MATERIAL ------

FINISH: BREAK ALL SHARP EDGES R0.13 MAX

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APPROVED:
DATE 10/05/2004

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TITLE: Left_Box_Top_Support

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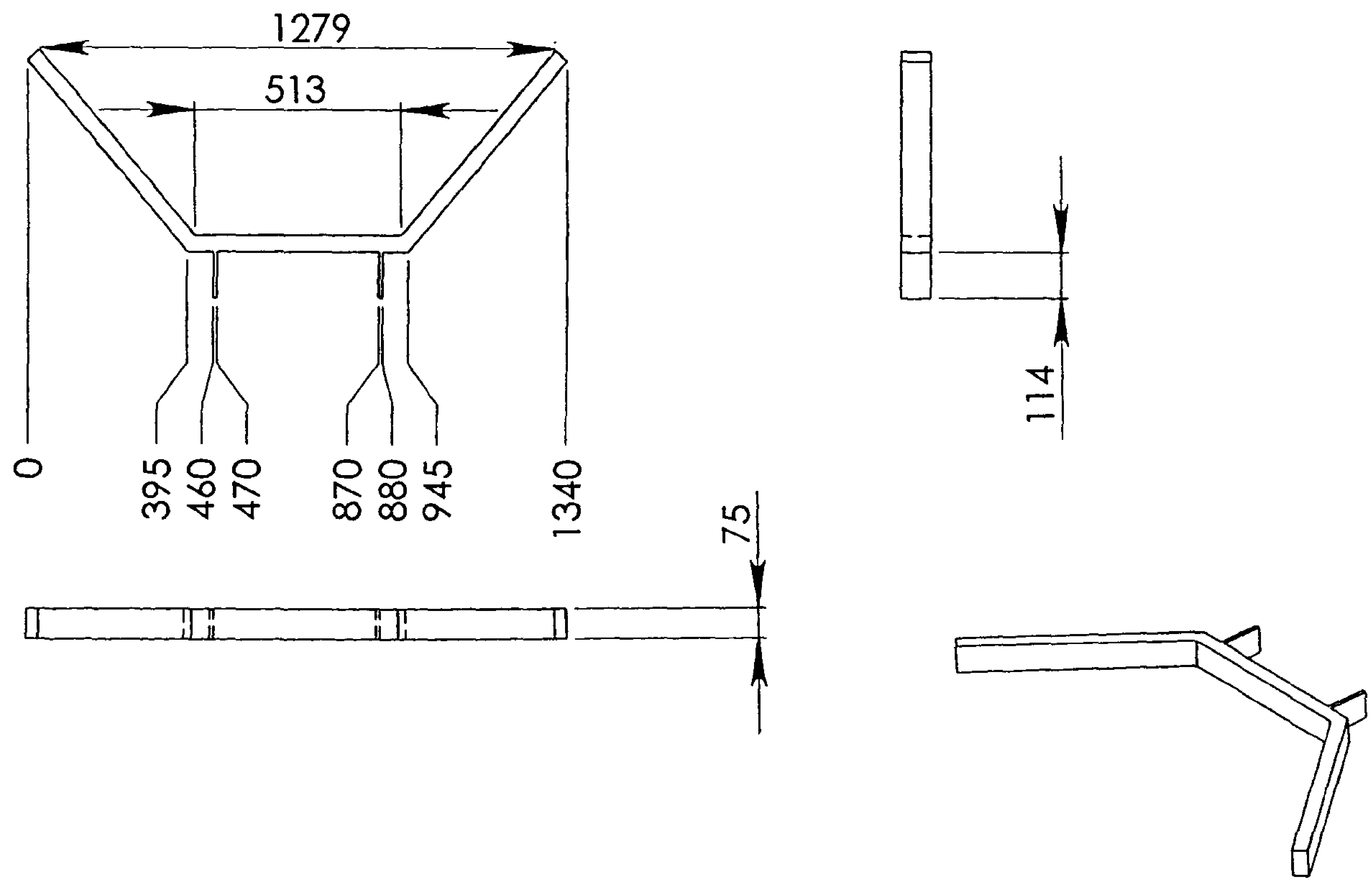

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R0.13 MAX

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DATE: 10/05/2004

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TITLE:
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FILE NAME:
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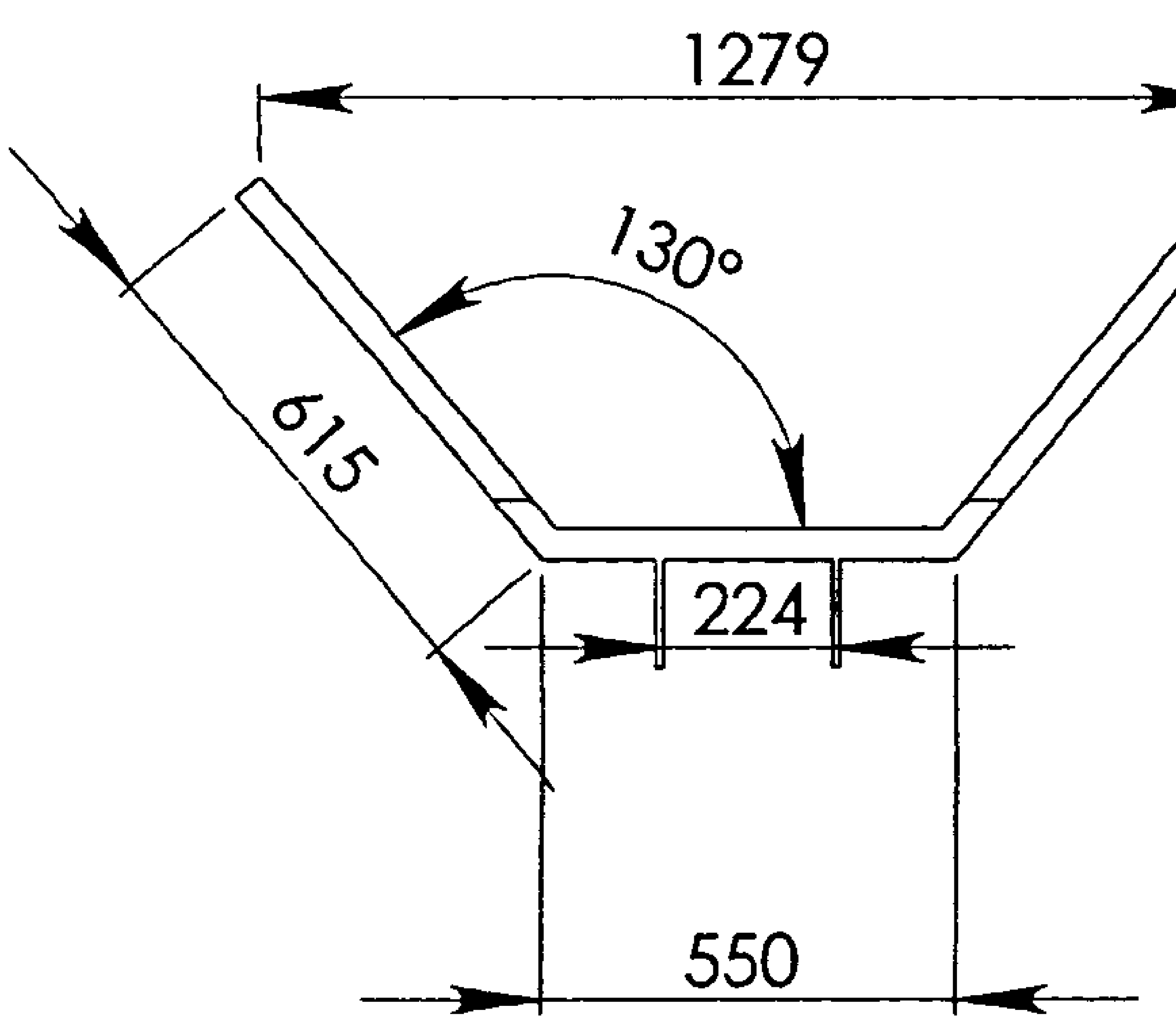

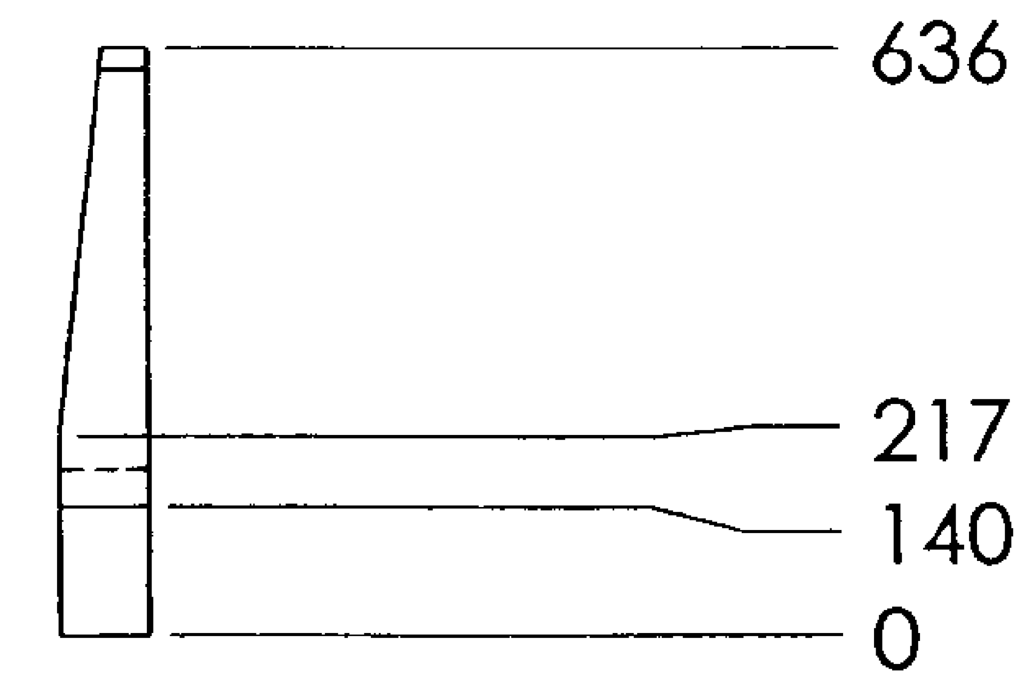

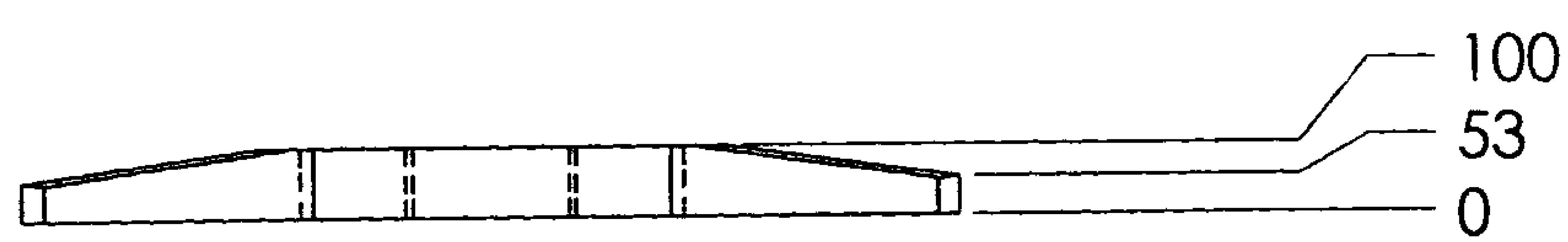

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UNLESS OTHERWISE NOTED

MATERIAL

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DESIGNER:
APPROVED:
DATE: 13/05/2004

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TITLE:
Main_Top_Support_Box_Ver.2

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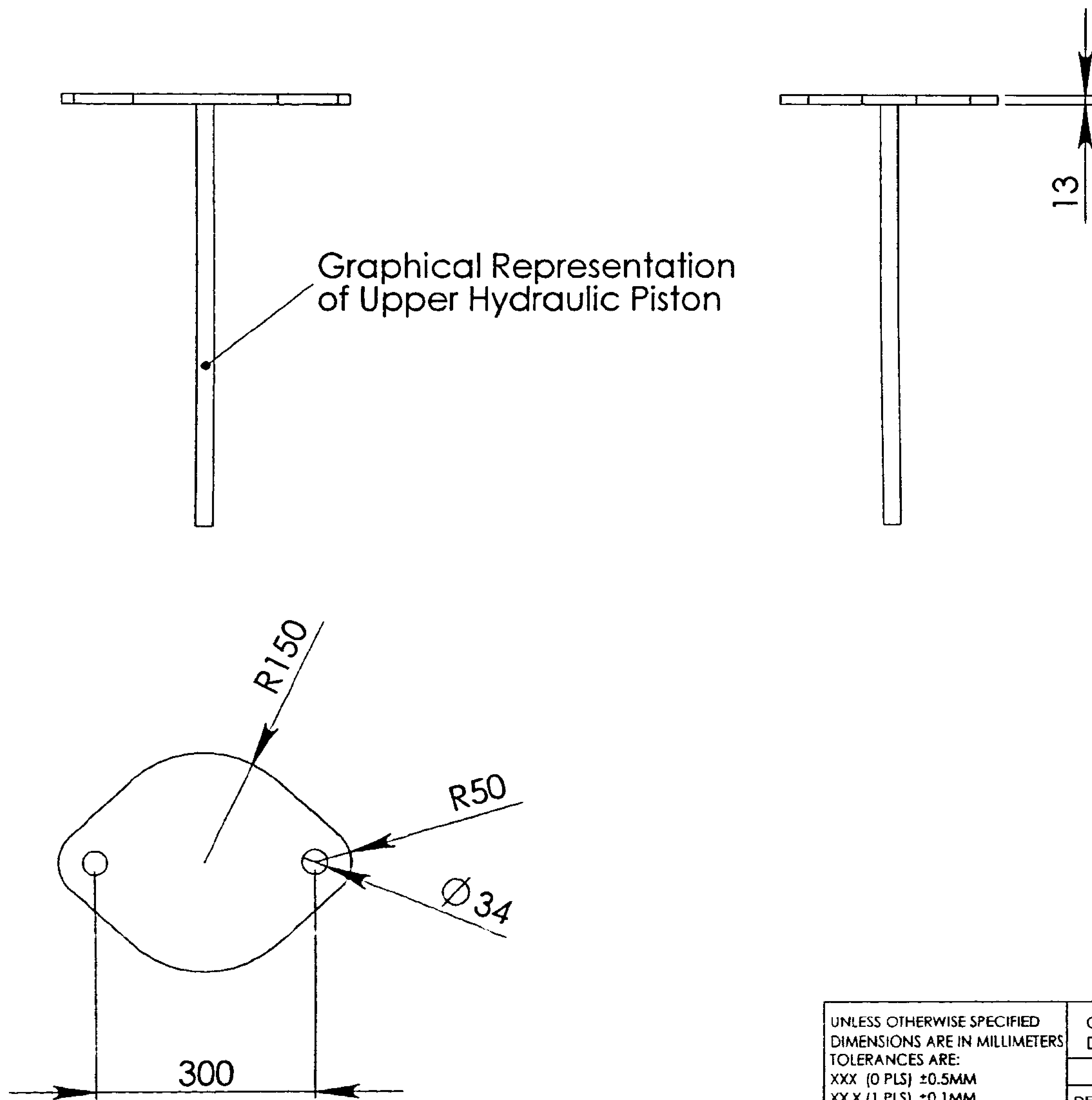
SHEET 8 OF 20



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MATERIAL

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R0 13 MAX

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TITLE:
Top_for_Piston

FILE NAME:
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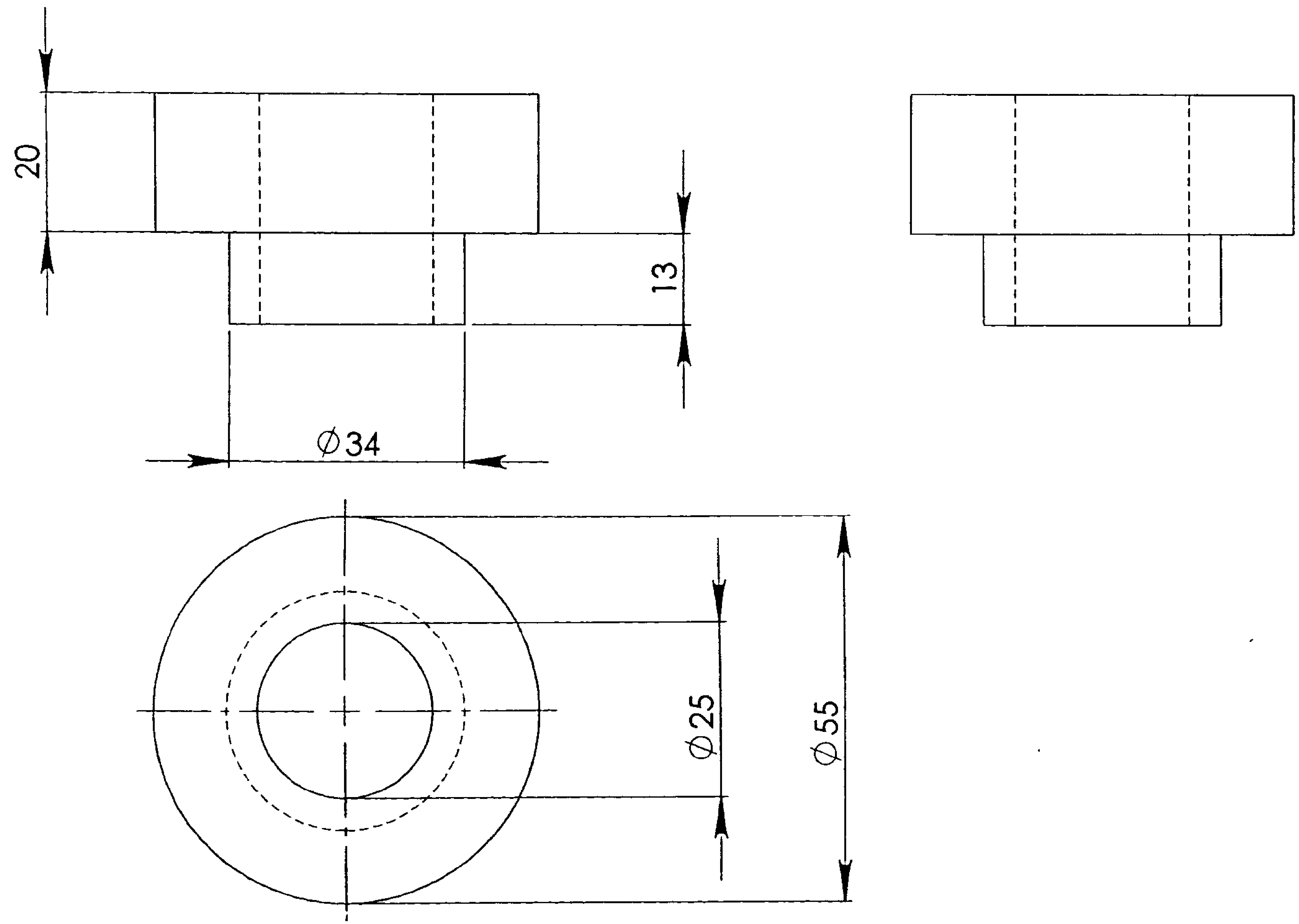

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DATE: 10/05/2004

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TITLE:
Top_Bush

FILE NAME:
Main_WorkBench

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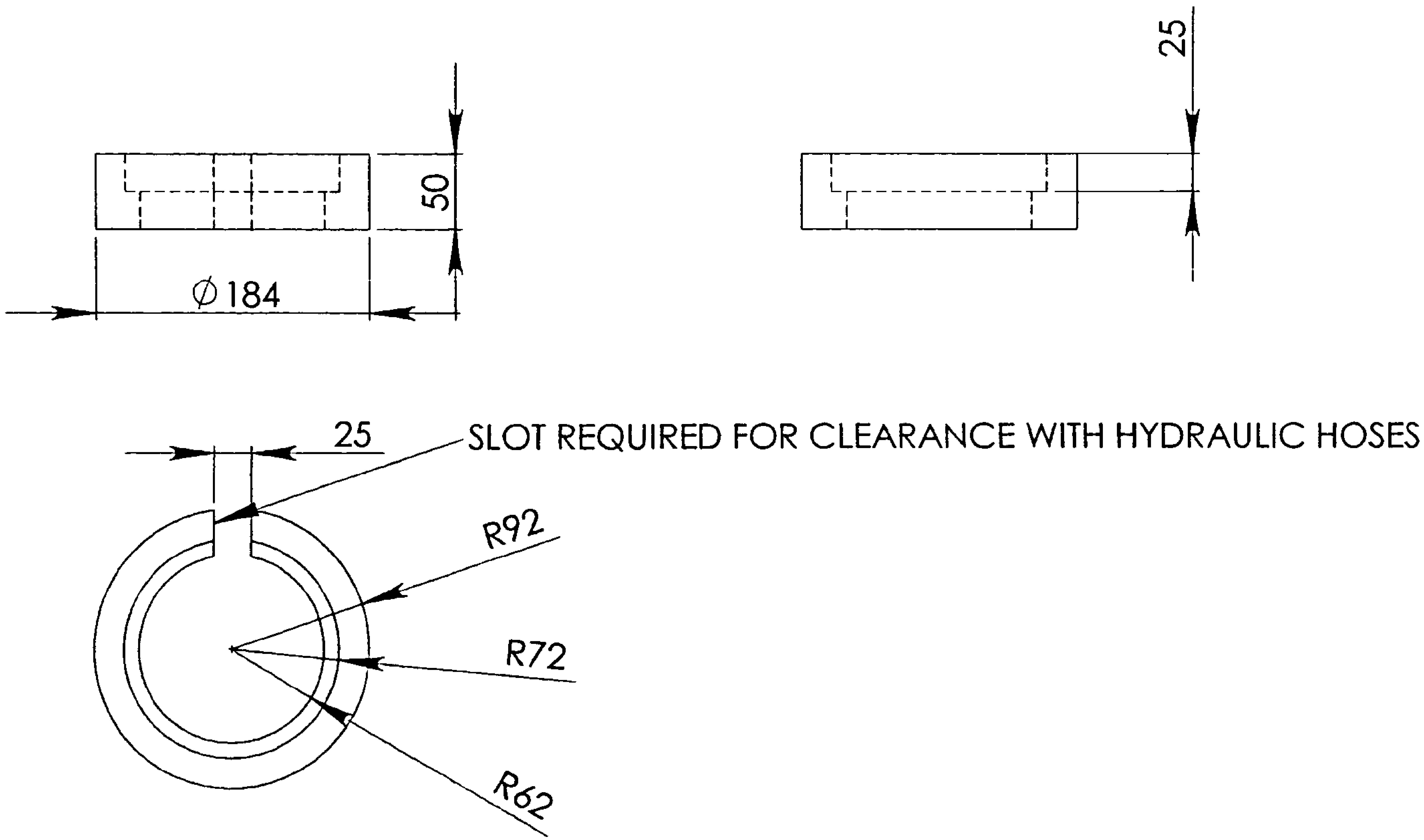

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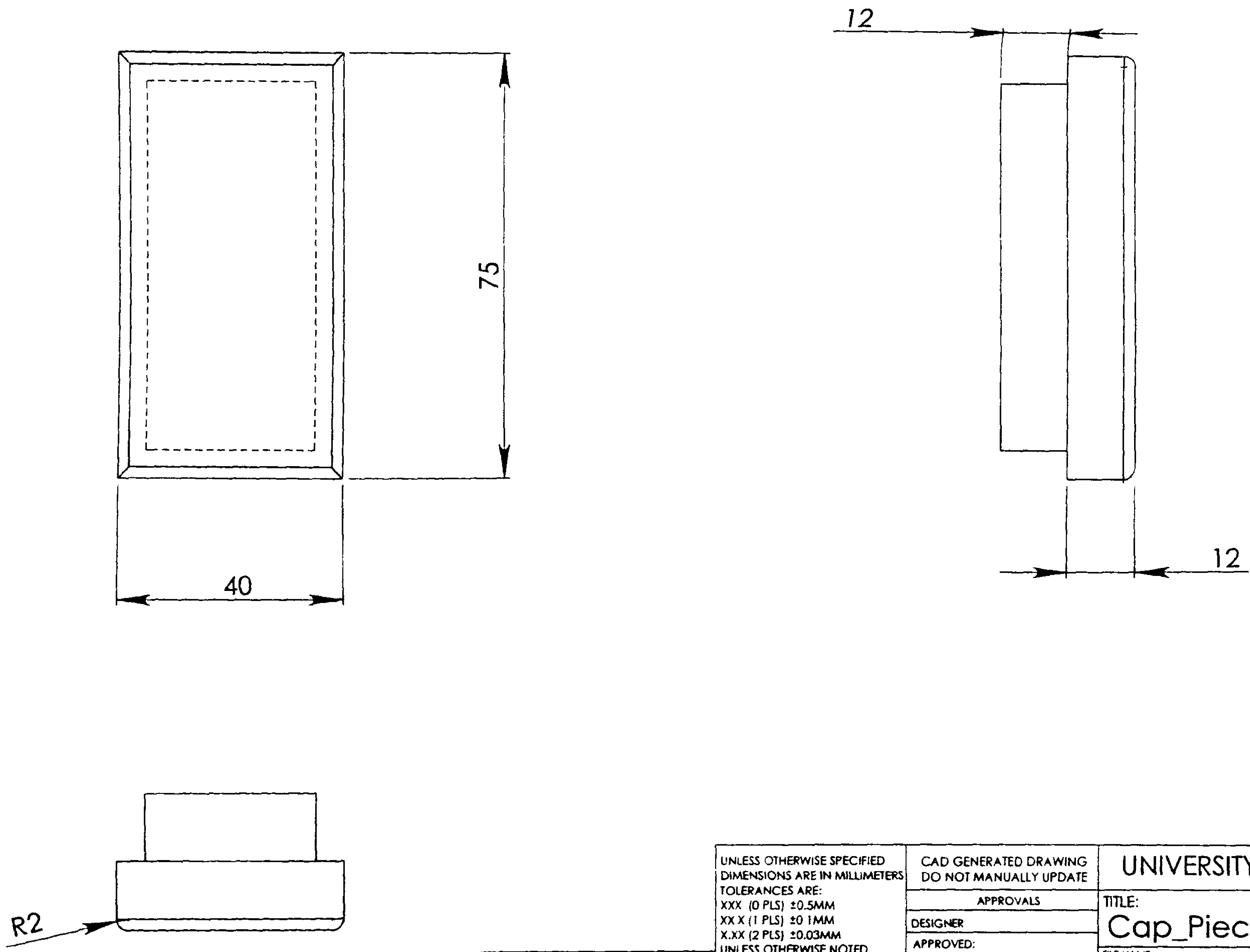
DO NOT SCALE DRAWING		SCALE 1:5 SIGNATURE SHEET 11 OF 20



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MATERIAL -----	APPROVALS
FINISH: BREAK ALL SHARP EDGES R0.13 MAX	DESIGNER
DO NOT SCALE DRAWING	APPROVED:
	DATE 10/05/2004

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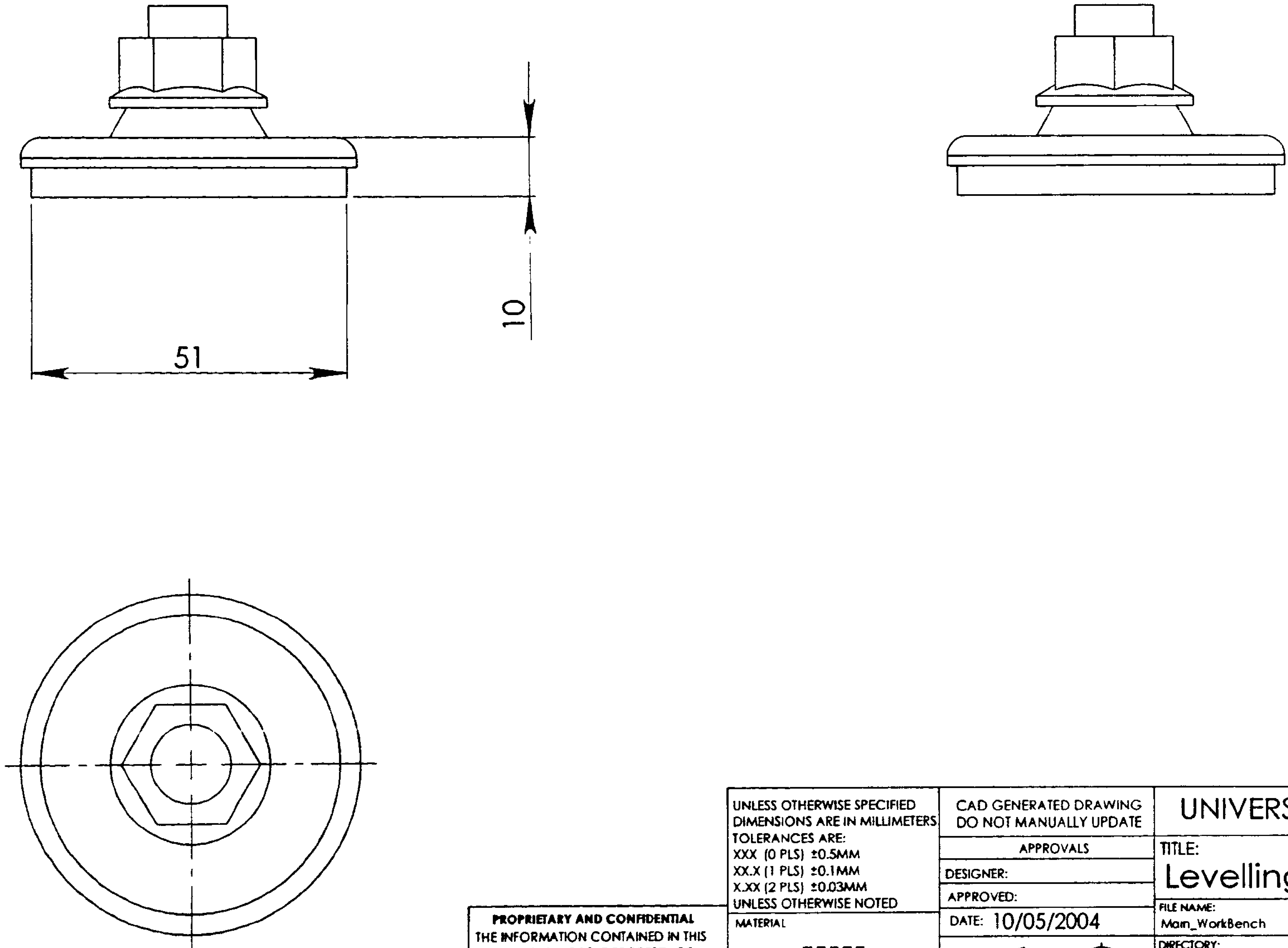
TITLE: Cap_Piece

FILE NAME: Main_WorkBench

DIRECTORY C \Documents and Settings\Administrator\Desktop\bill\

SIZE A4 | DWG NO :12 | REV 1

SCALE:1.1 | SIGNATURE: | SHEET 12 OF 20



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MATERIAL

FINISH: BREAK ALL SHARP EDGES R0.13 MAX

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DESIGNER:
APPROVED:
DATE: 10/05/2004

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TITLE:
Levelling_Foot

FILE NAME:
Main_WorkBench

DIRECTORY:
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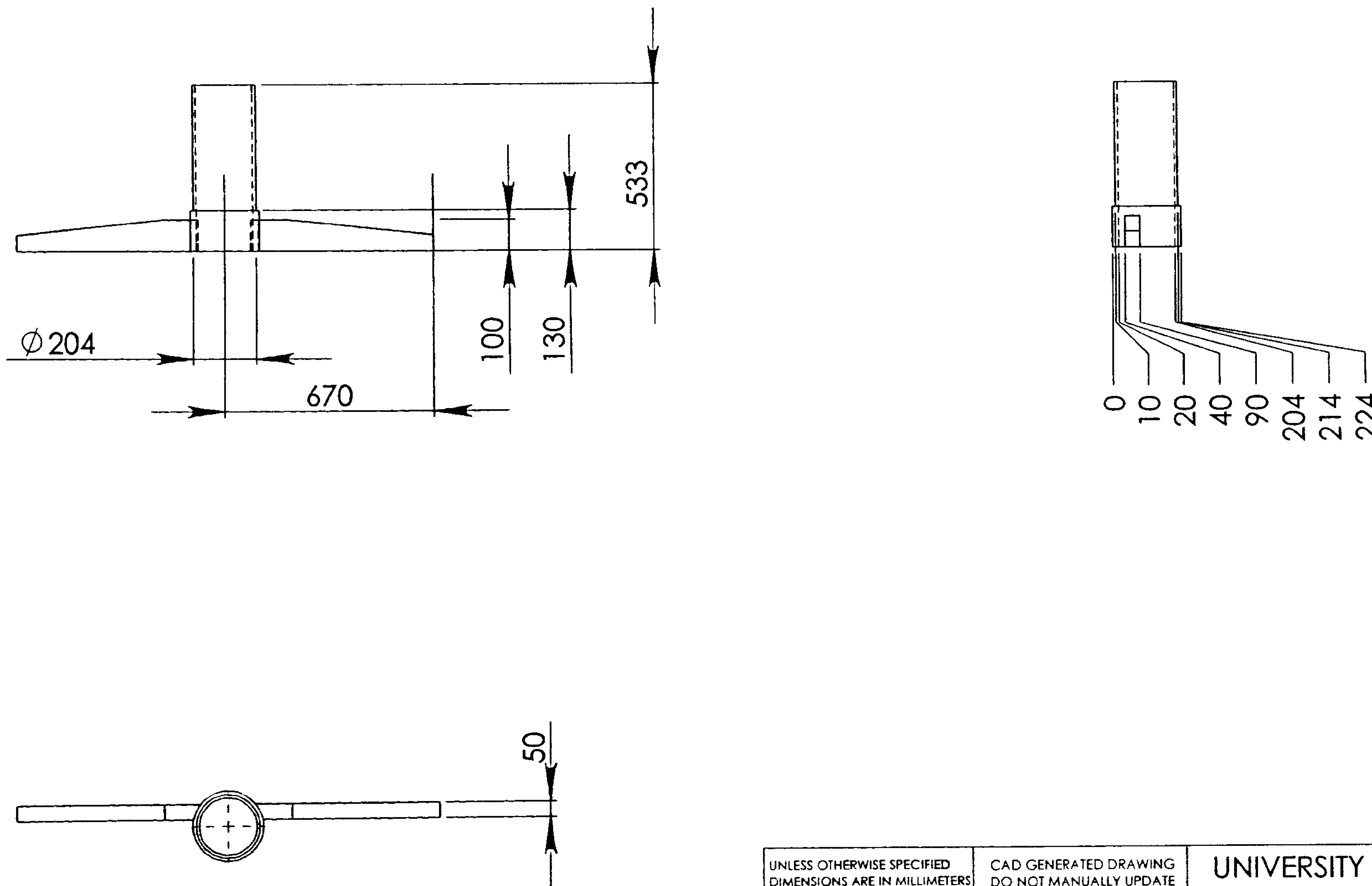

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TITLE:
Bottom_Piston

FILE NAME:
Main_WorkBench

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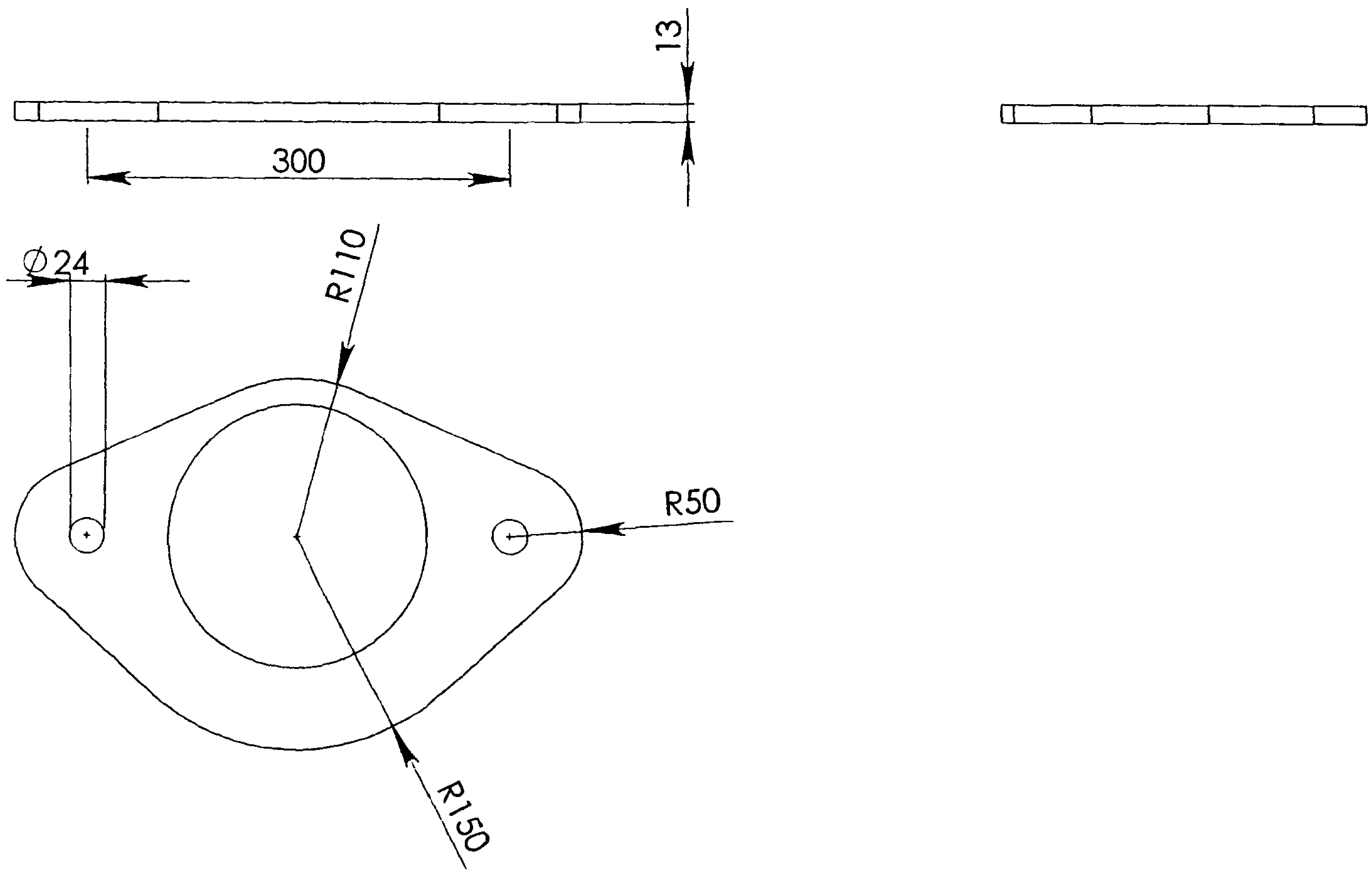

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MATERIAL -----

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DATE: 10/05/2004

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TITLE:
Middle_Shelf_Piston

FILE NAME:
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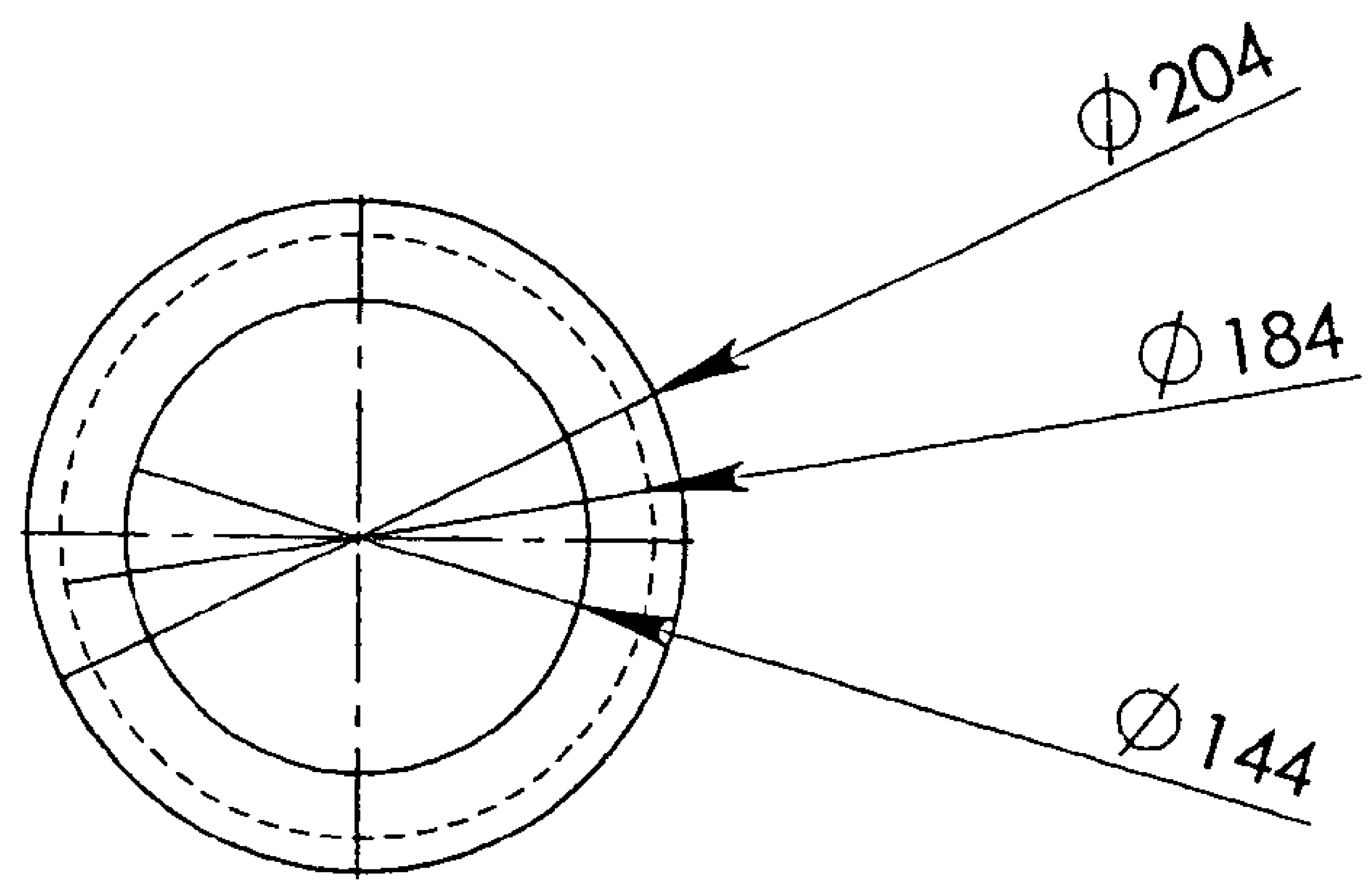

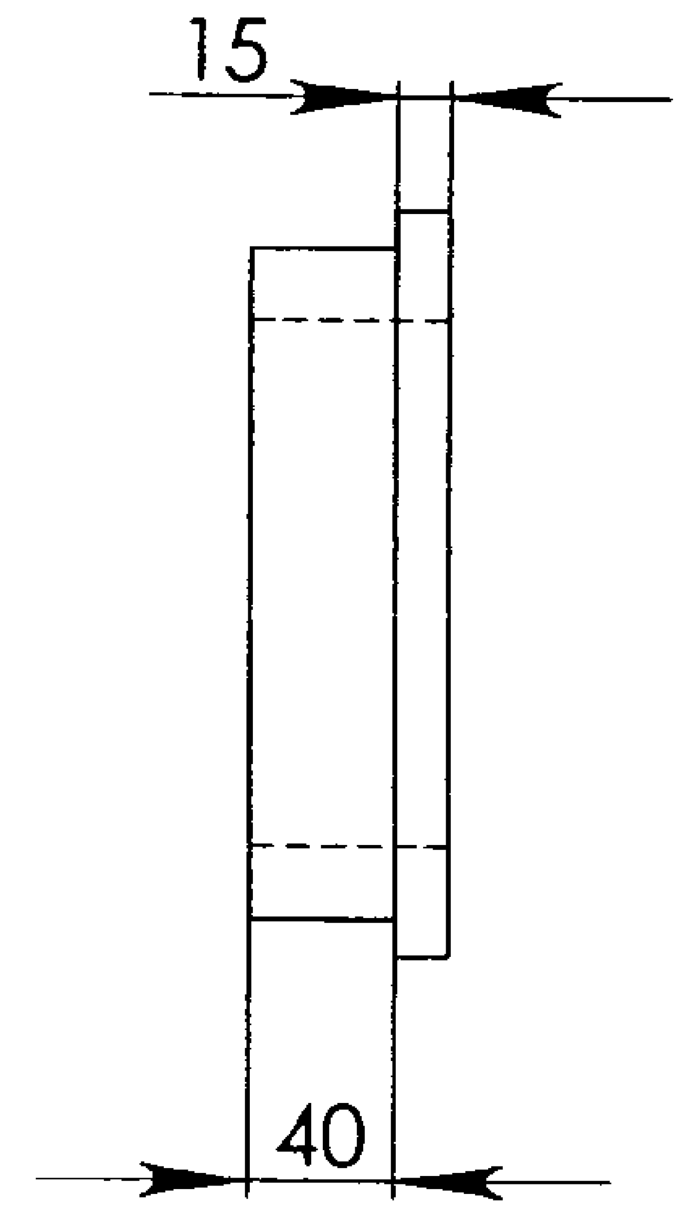

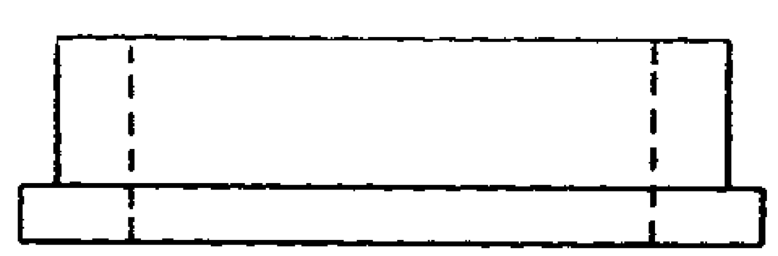

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UNLESS OTHERWISE NOTED

MATERIAL

FINISH BREAK ALL SHARP EDGES
R0.13 MAX

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TITLE:
Central_Bush

FILE NAME:
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DIRECTORY:
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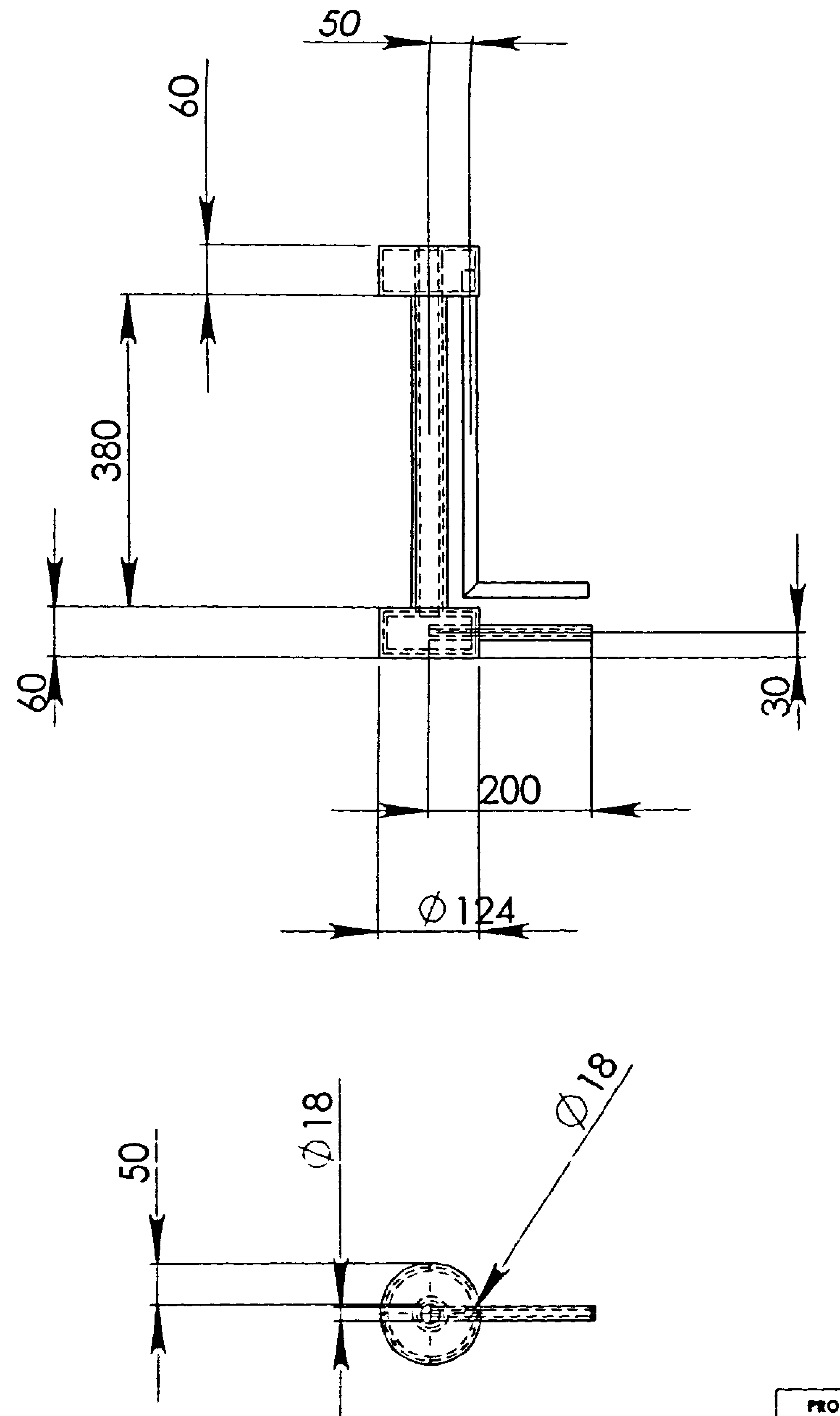
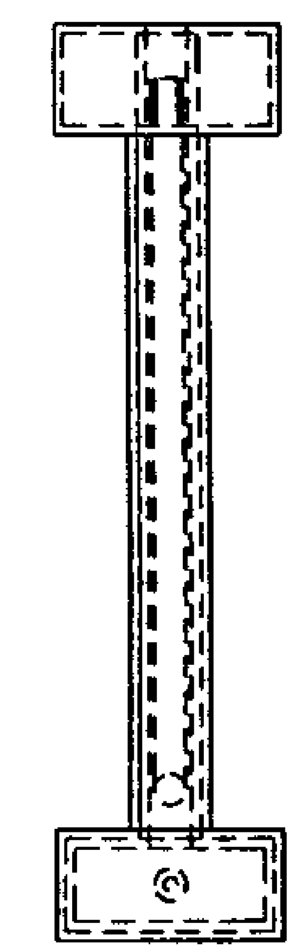
SIZE A4 | DWG NO :18 | REV 1

SCALE:1:5 | SIGNATURE: | SHEET 18 OF 20





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UNLESS OTHERWISE NOTED

MATERIAL
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TITLE:
Bottom_Ram

FILE NAME.
Main_WorkBench

DIRECTORY:
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SIZE A4 | DWG NO. :19 | REV 1

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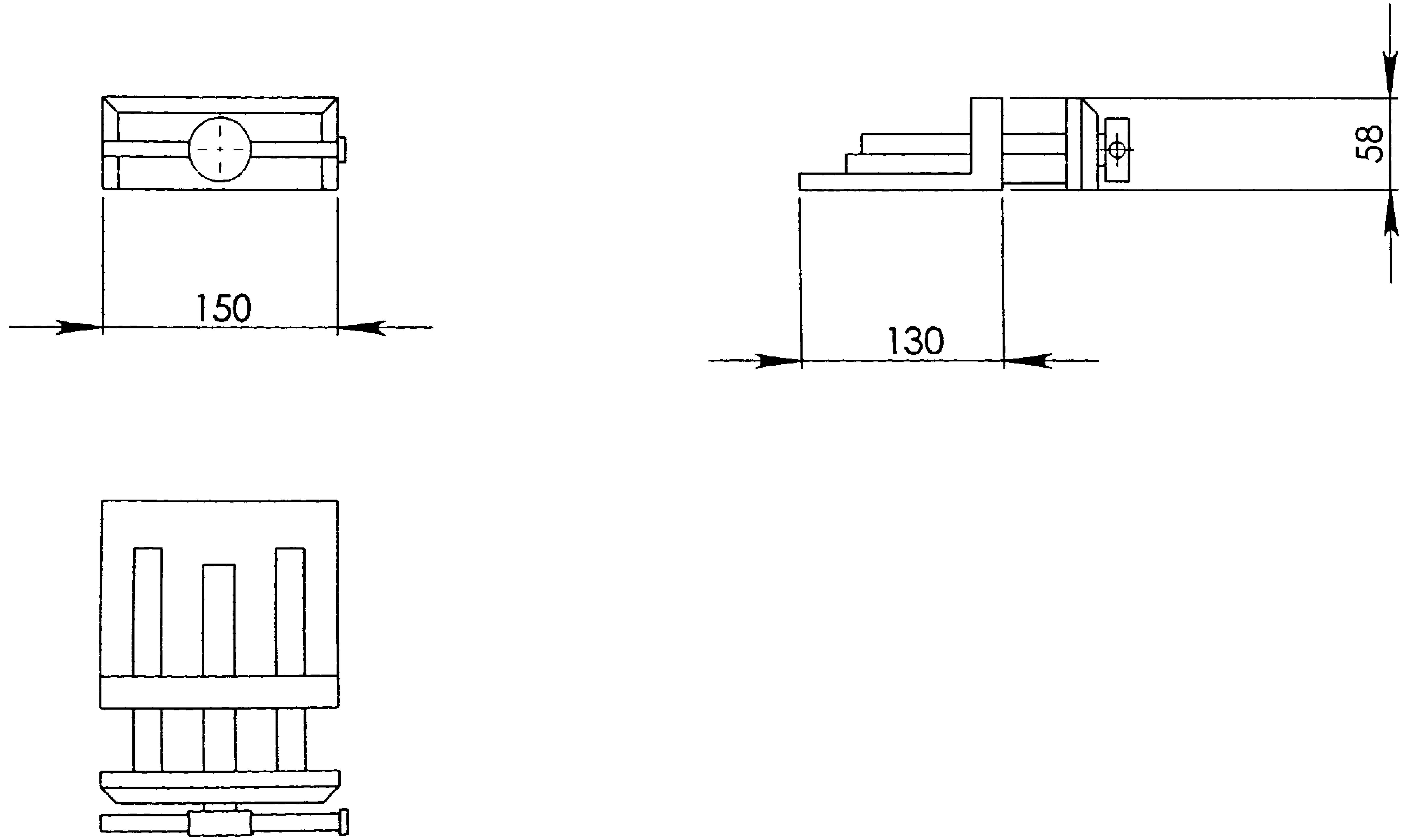

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UNLESS OTHERWISE NOTED

MATERIAL

FINISH BREAK ALL SHARP EDGES R0 13 MAX

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APPROVALS
DESIGNER:
APPROVED:
DATE. 10/05/2004

UNIVERSITY OF LIMERICK

TITLE:
Vice

FILE NAME:
Main_WorkBench

DIRECTORY:
C \Documents and Settings\Administrator\Desktop\Bill\

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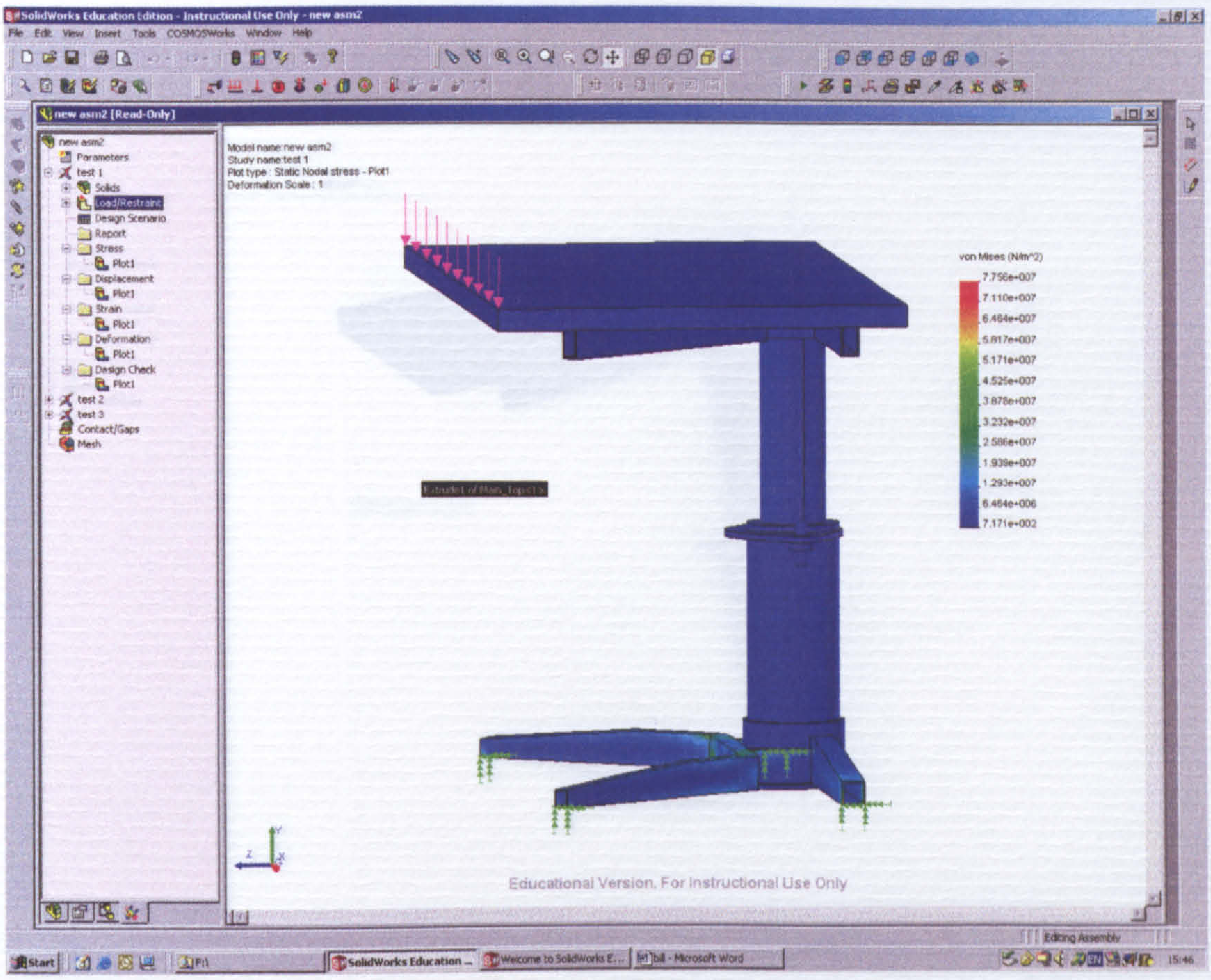
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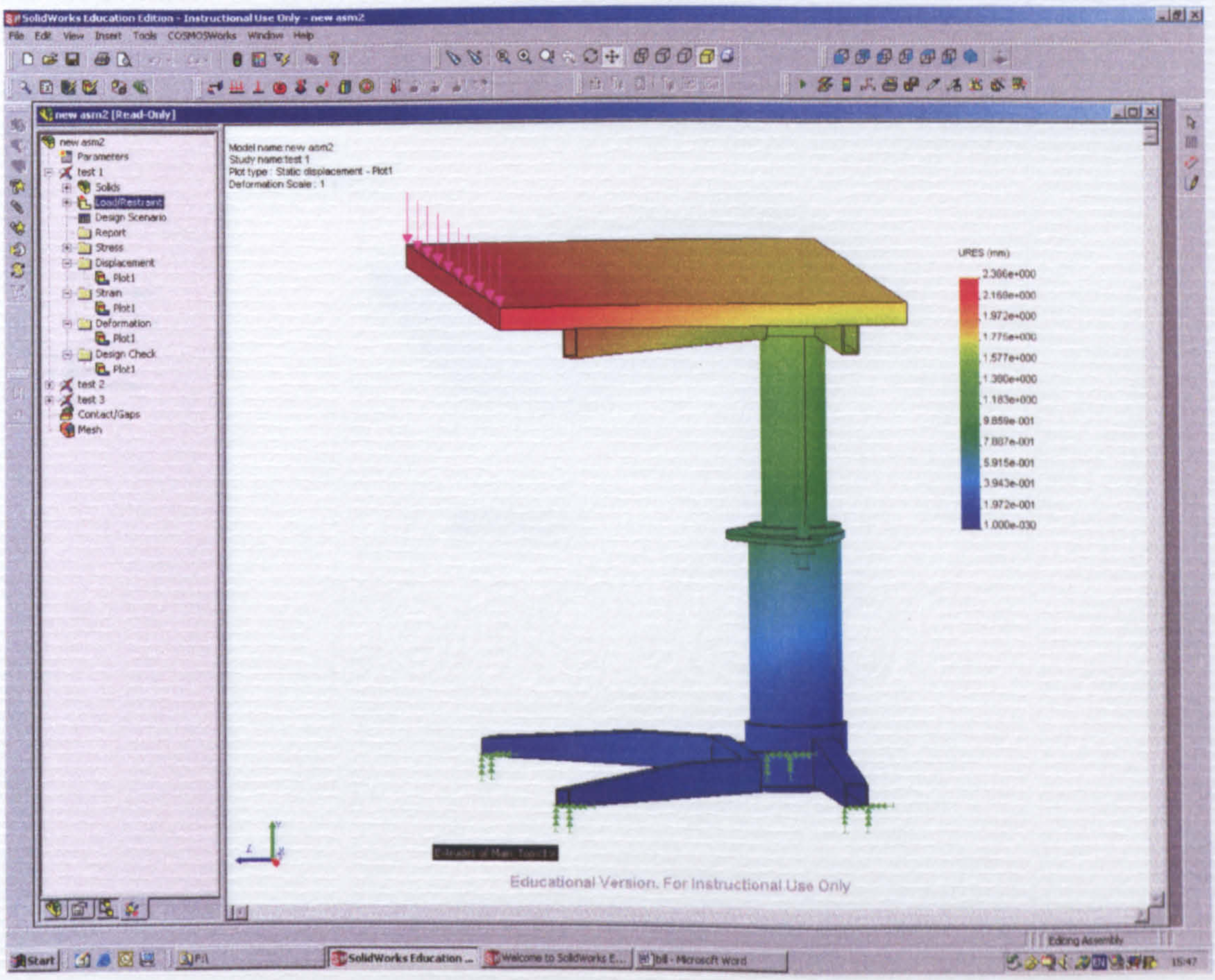
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Deformation Scale : 1
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1.577e+000
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1.183e+000
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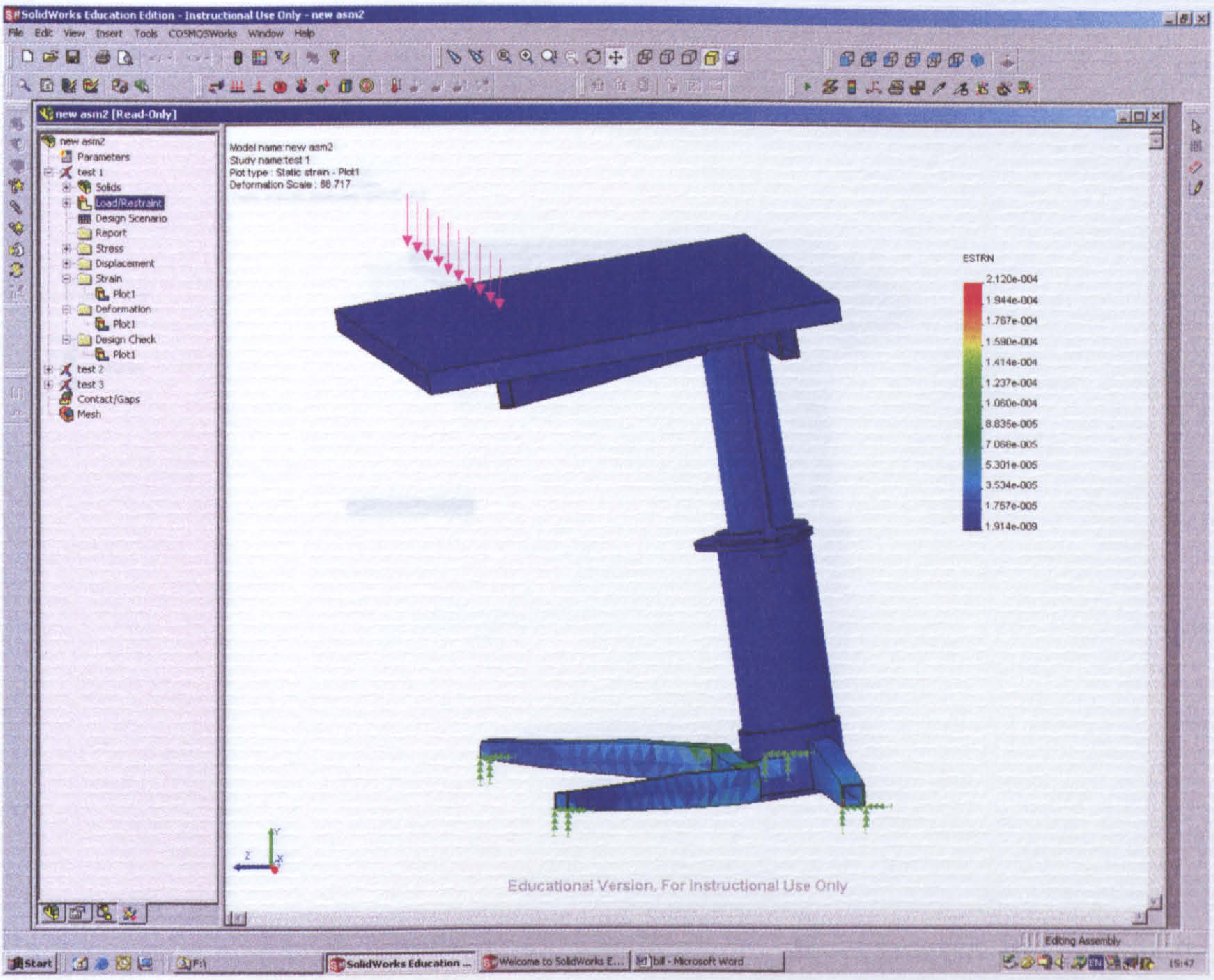
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Displacement
Strain
Plot1
Deformation
Plot1
Design Check
Plot1
test 2
test 3
Contact/Gaps
Mesh
Model name:new asm2
Study name:test 1
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Deformation Scale : 88.717
ESTRN
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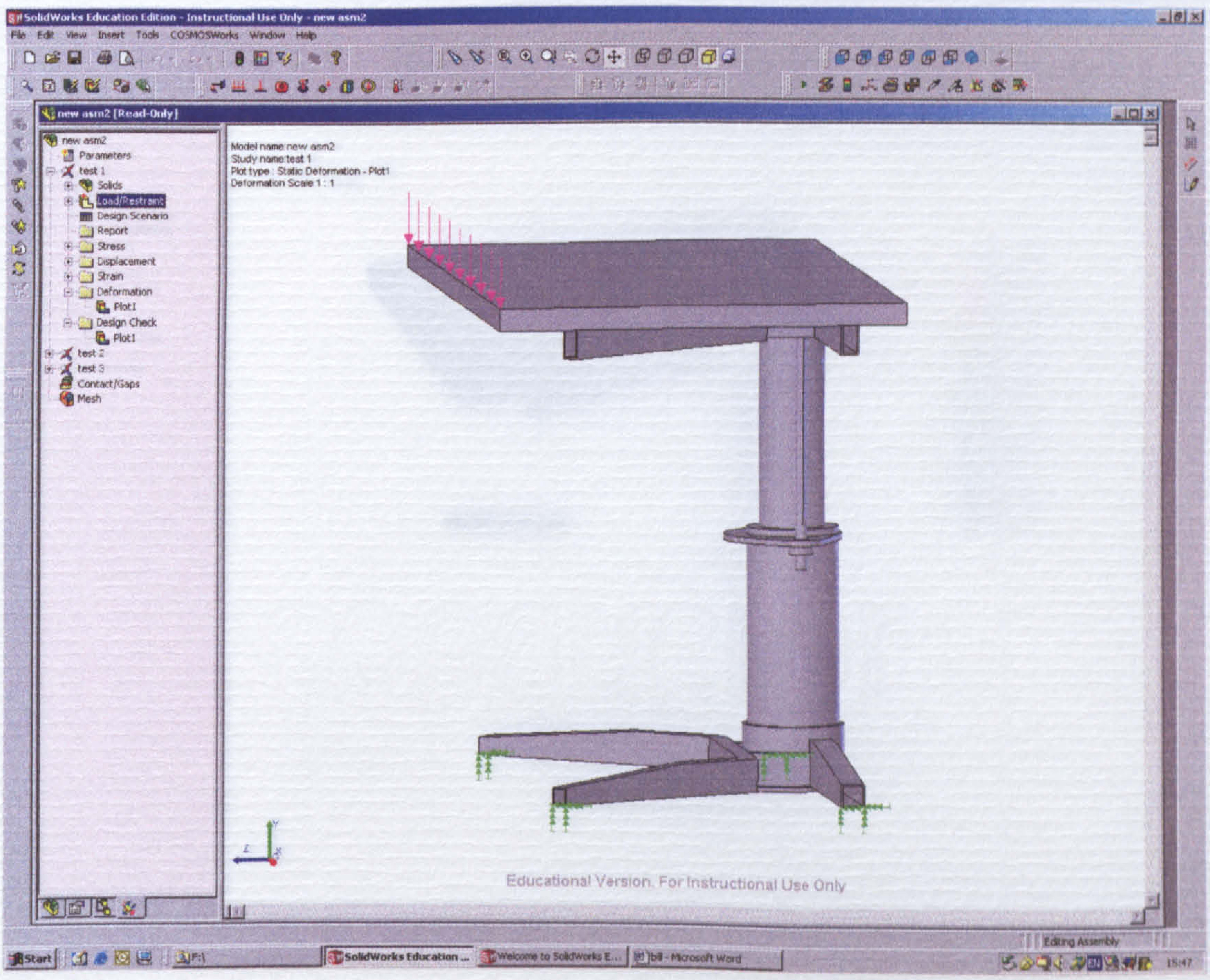
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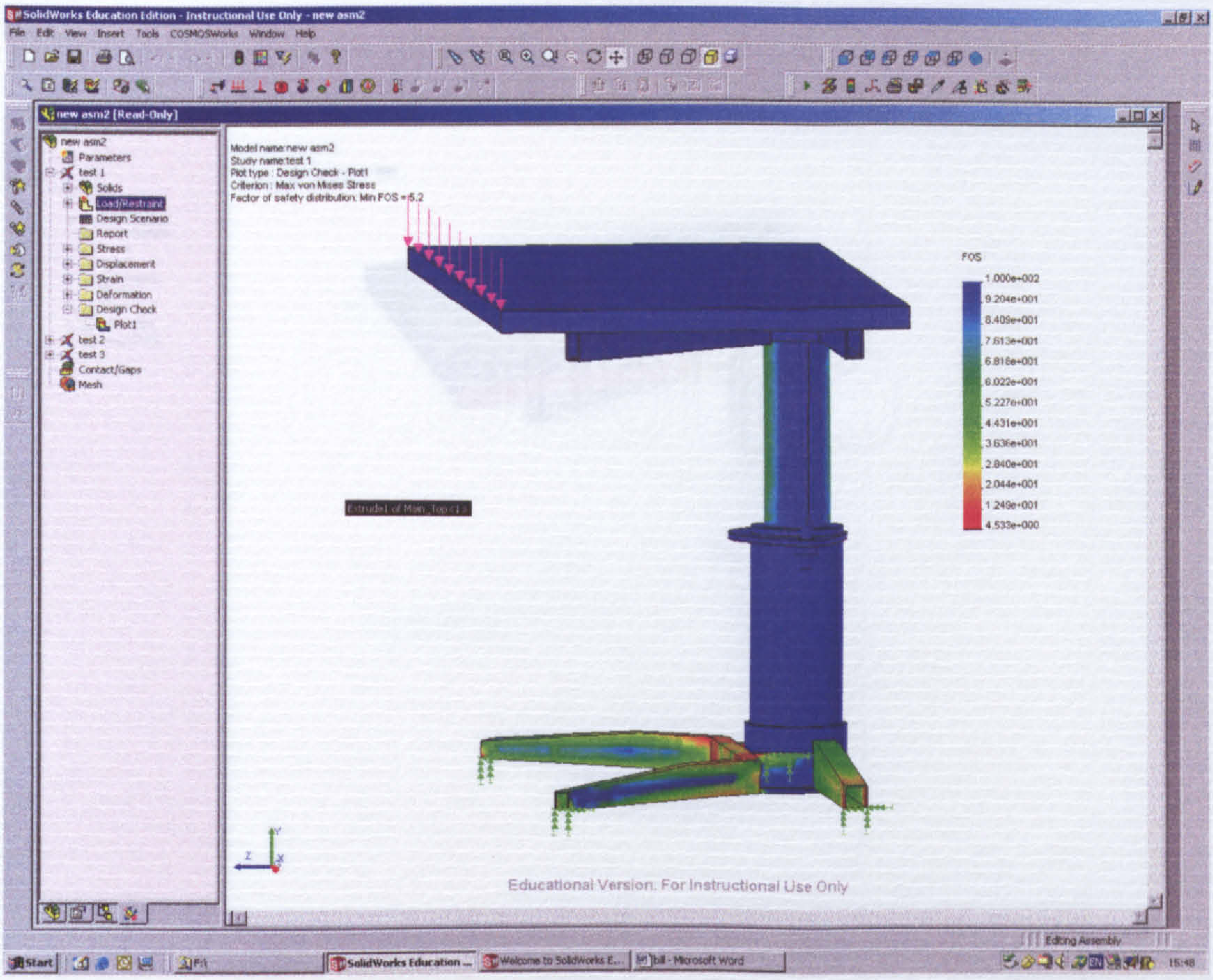
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8.409e+001
7.613e+001
6.818e+001
6.022e+001
5.227e+001
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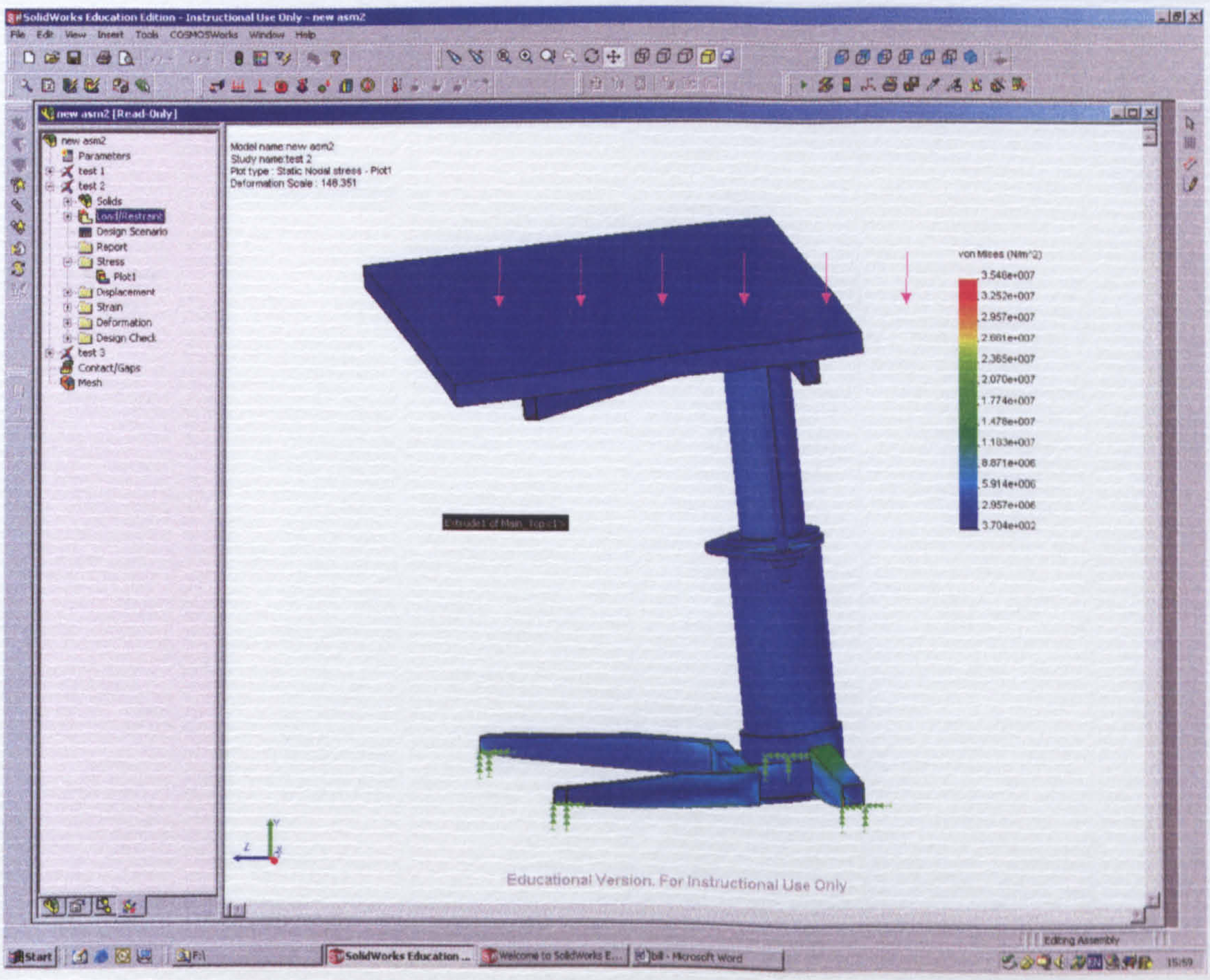
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2.070e+007
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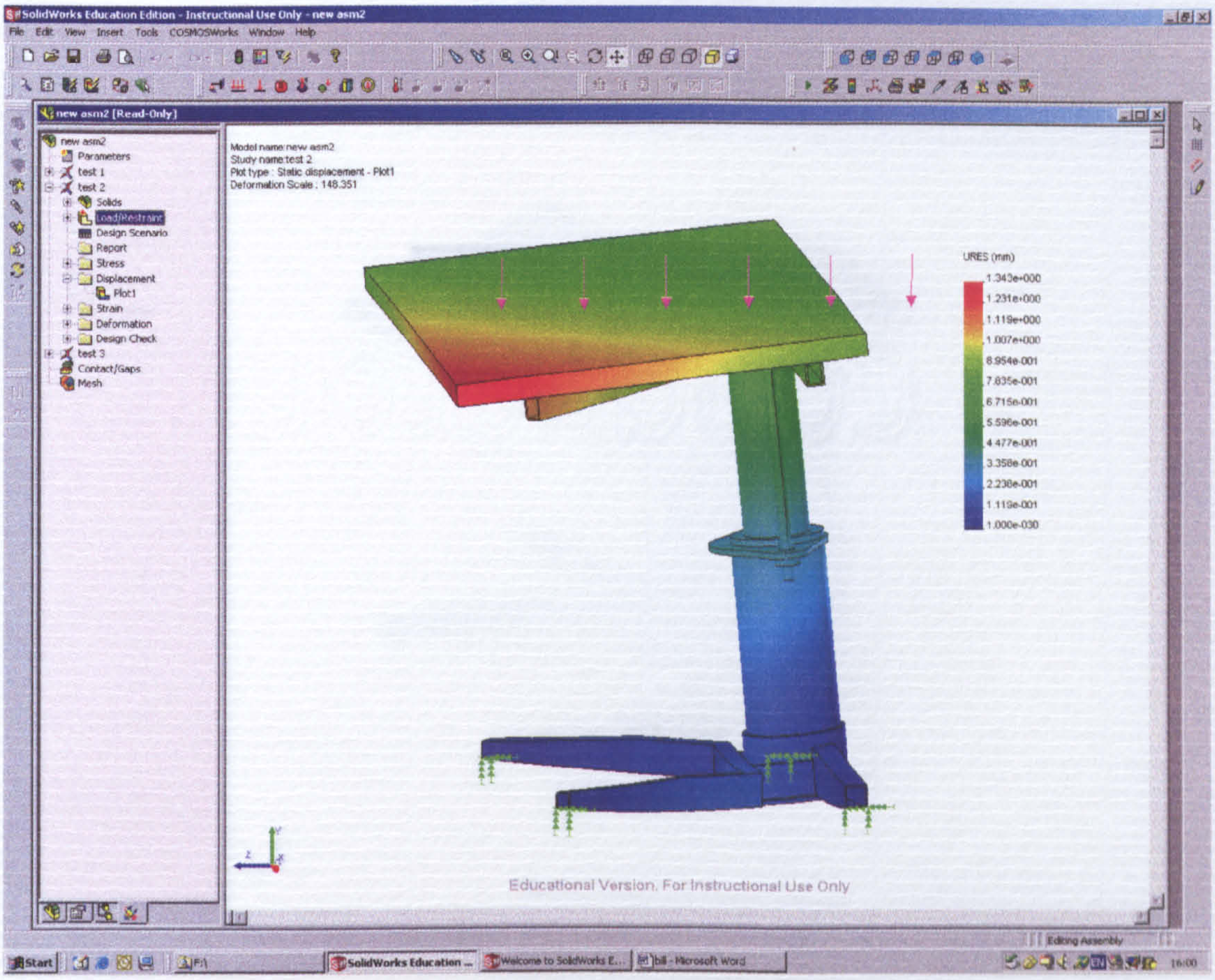
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test 3
Contact/Gaps
Mesh
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Study name:test 2
Plot type : Static displacement - Plot1
Deformation Scale : 148.351
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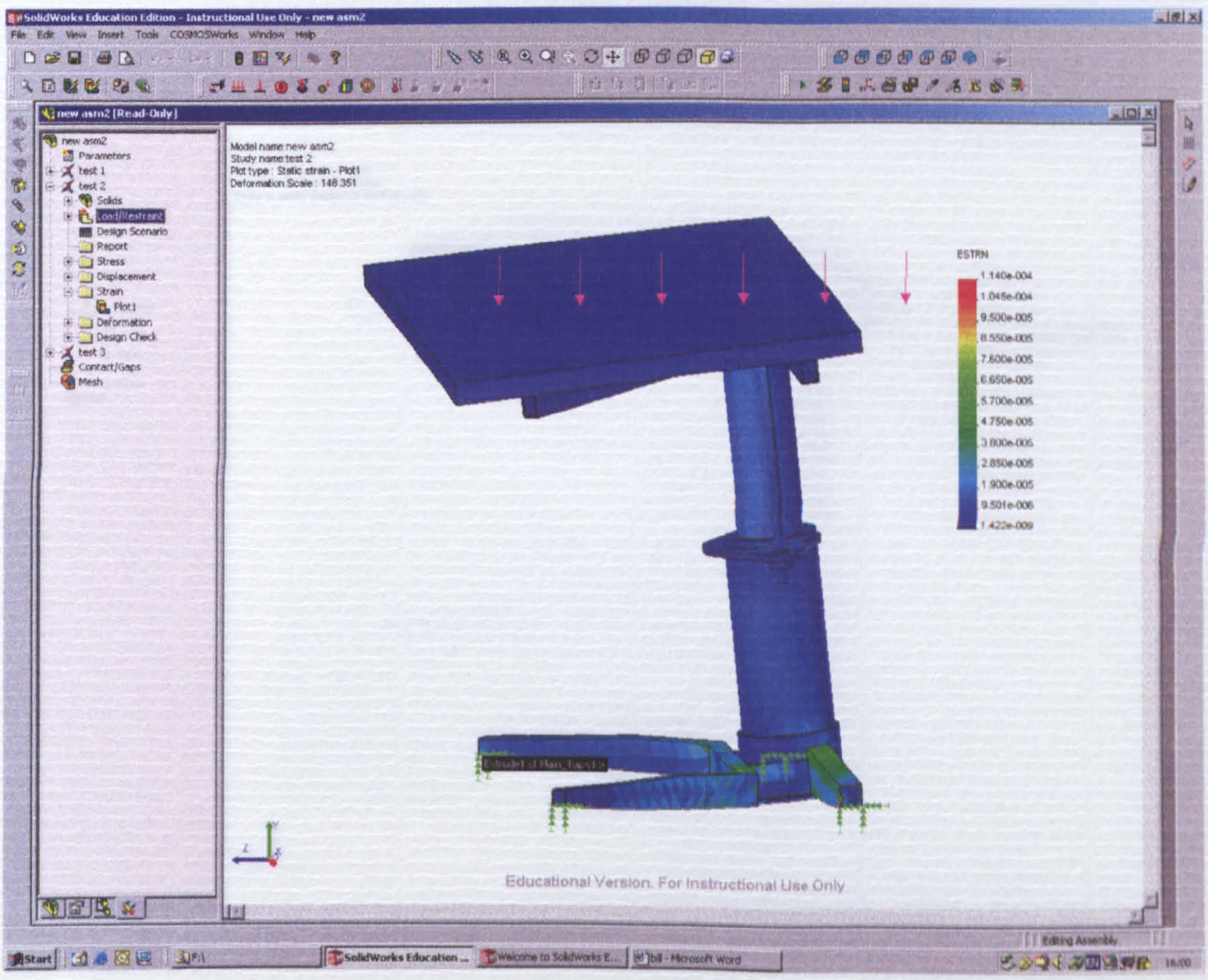
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Contact/Gaps
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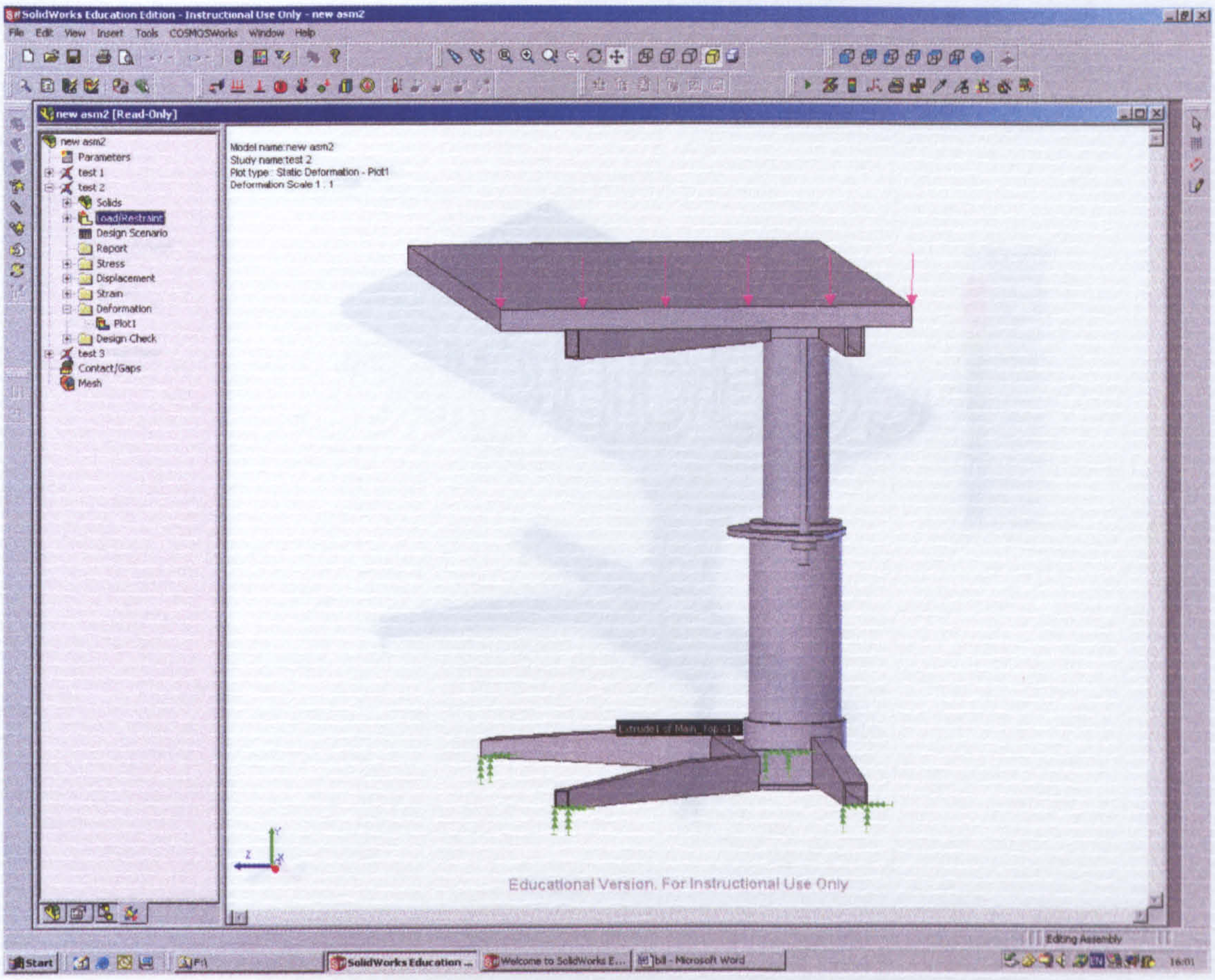
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test 3
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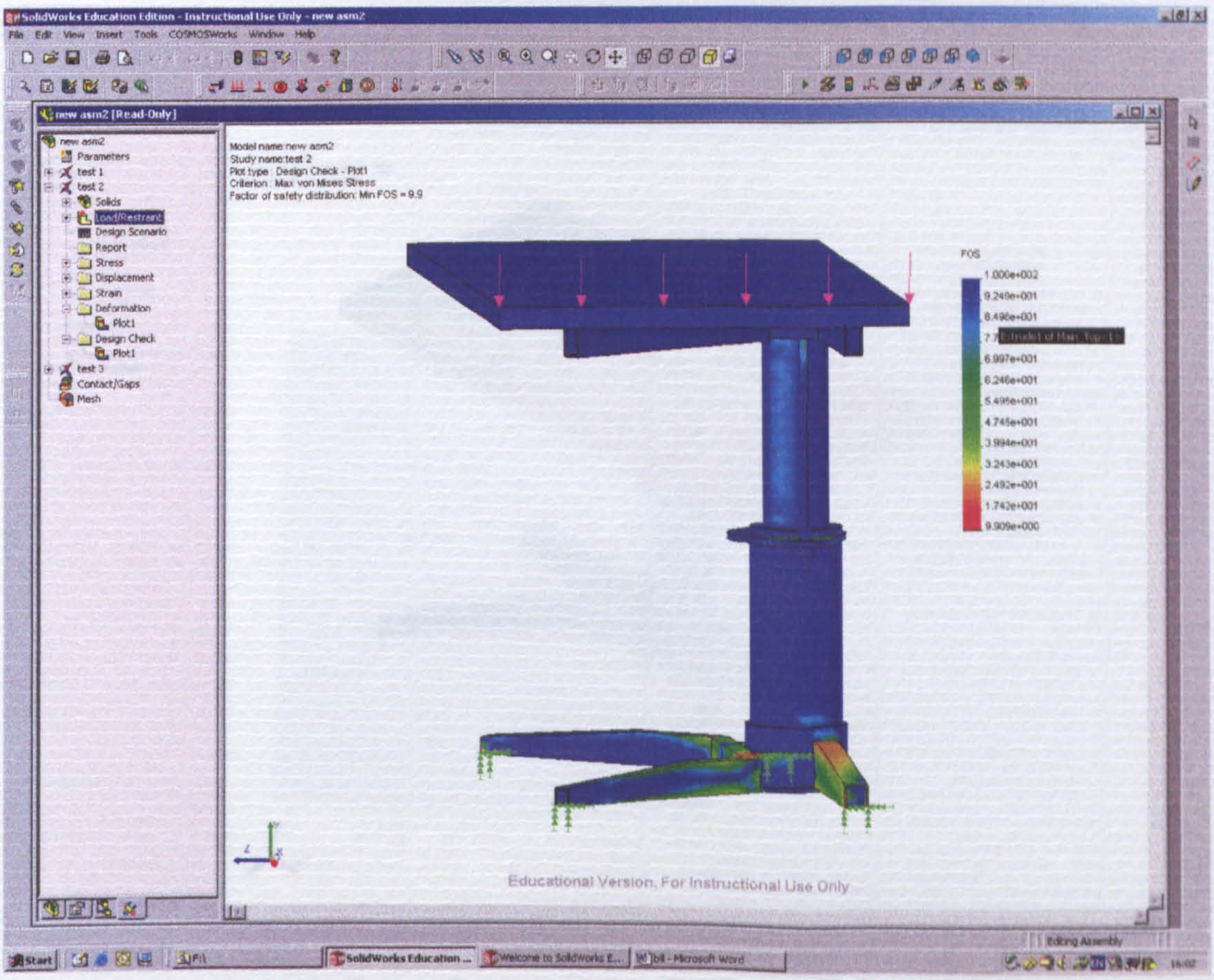
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Plot1
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Contact/Gaps
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6.246e+001
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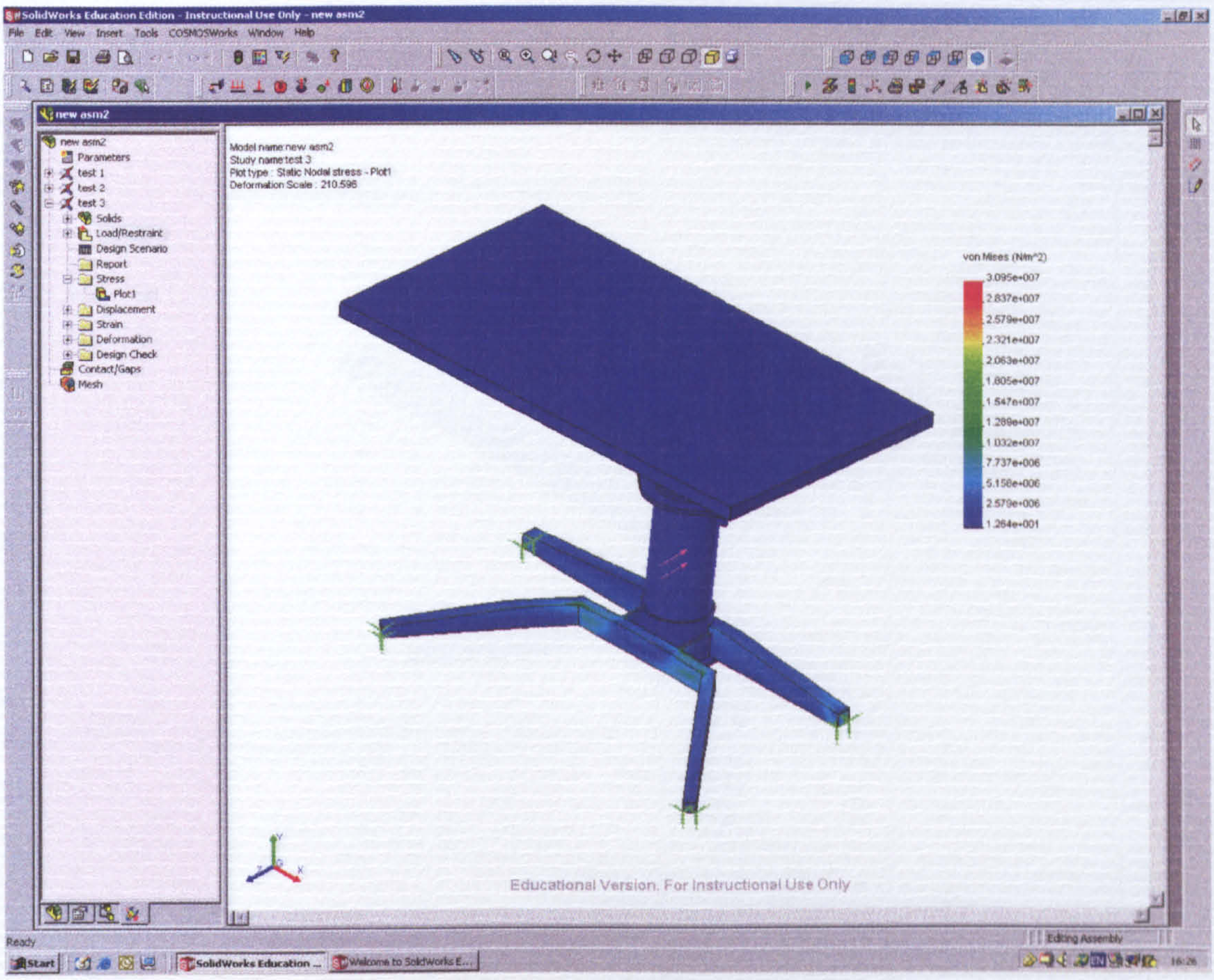
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Design Check
Contact/Gaps
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Plot type : Static Nodal stress - Plot1
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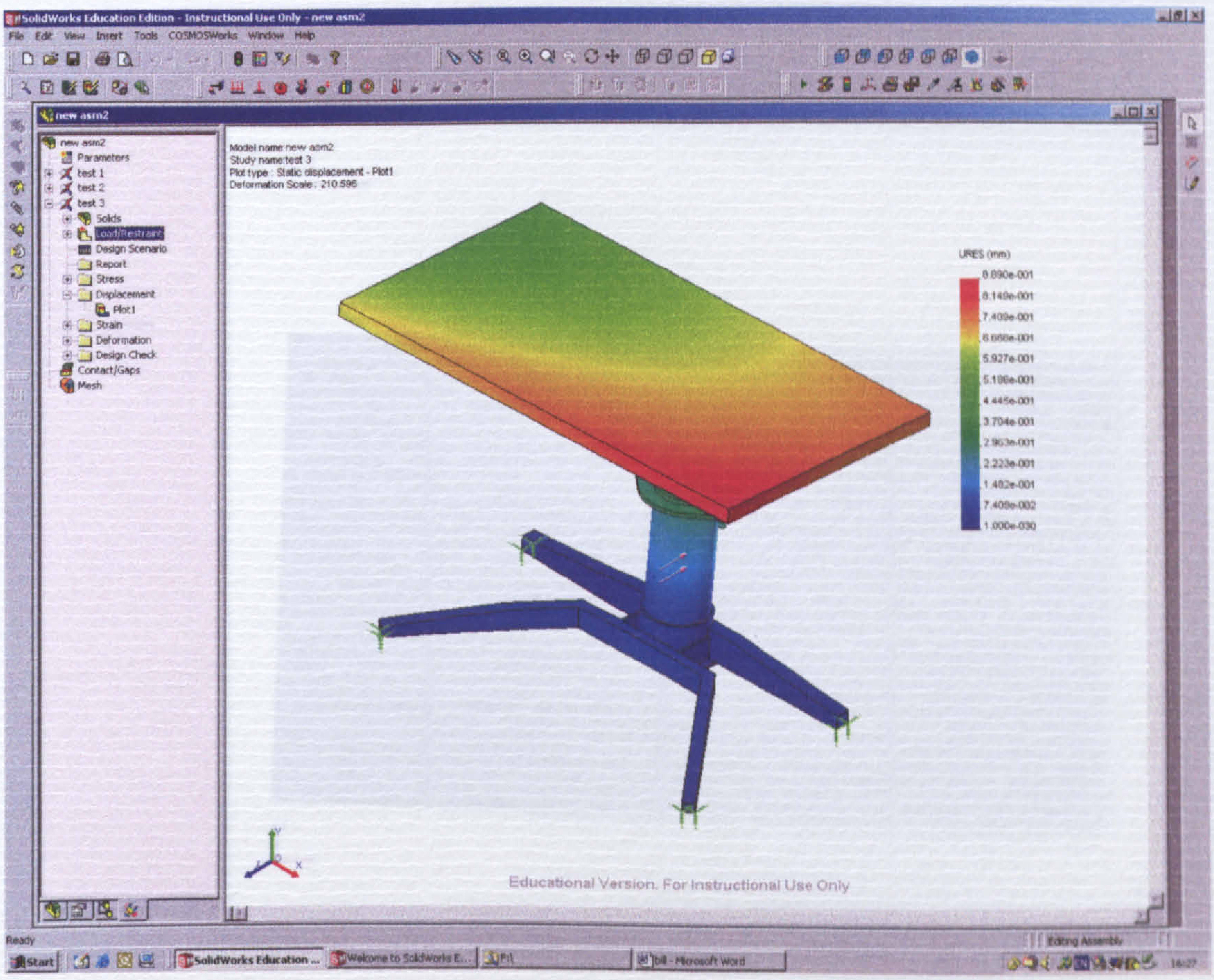
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Plot1
Strain
Deformation
Design Check
Contact/Gaps
Mesh
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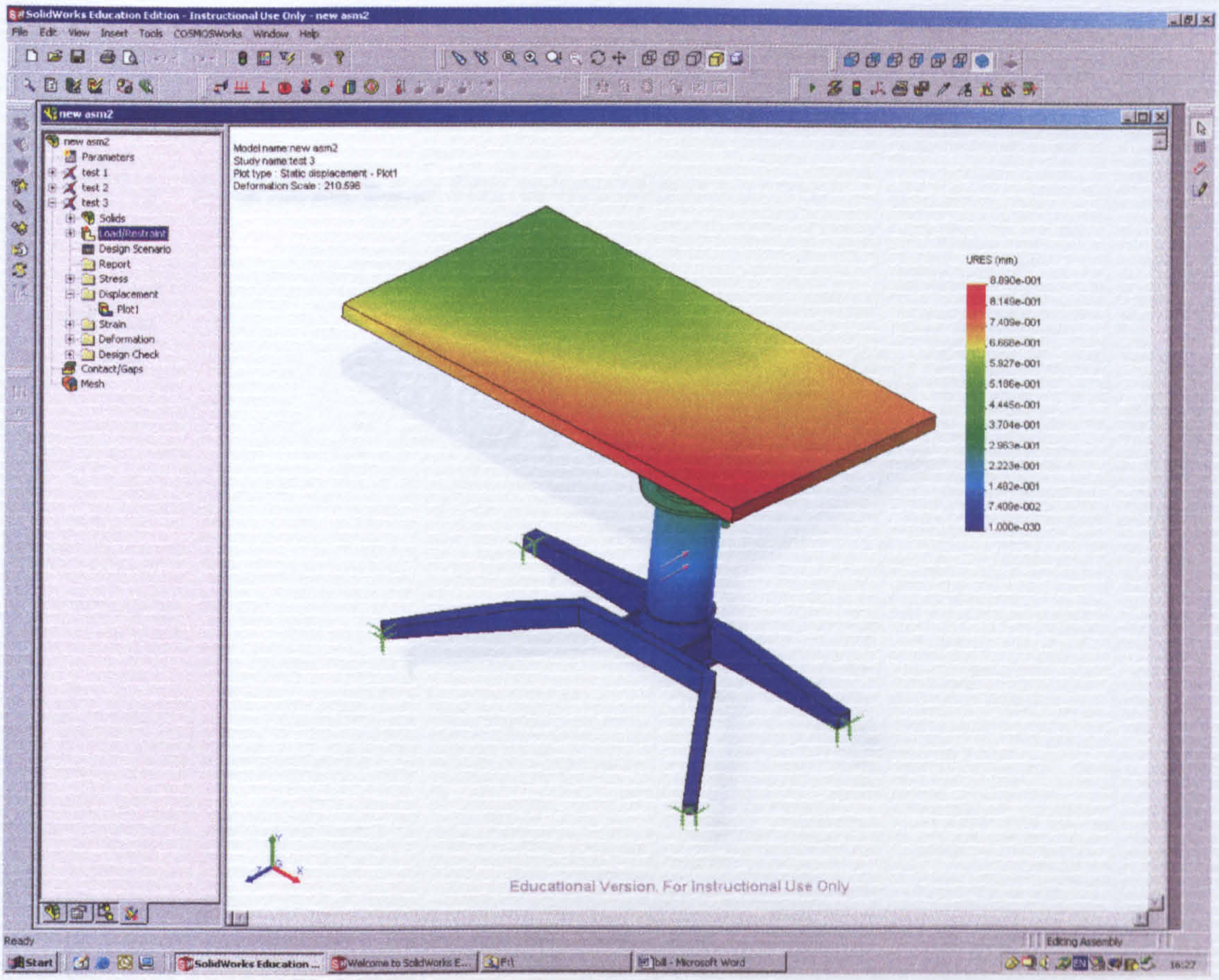
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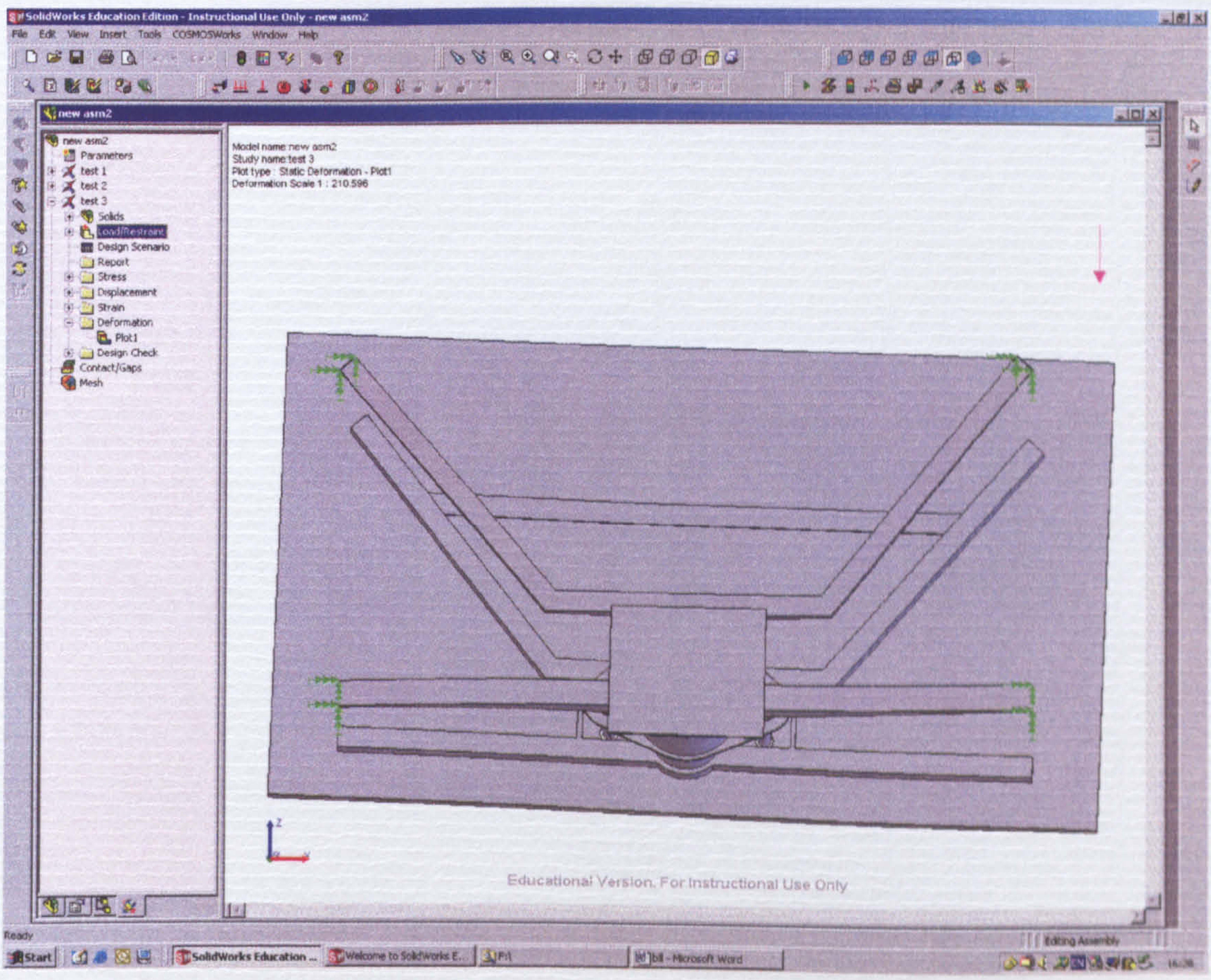
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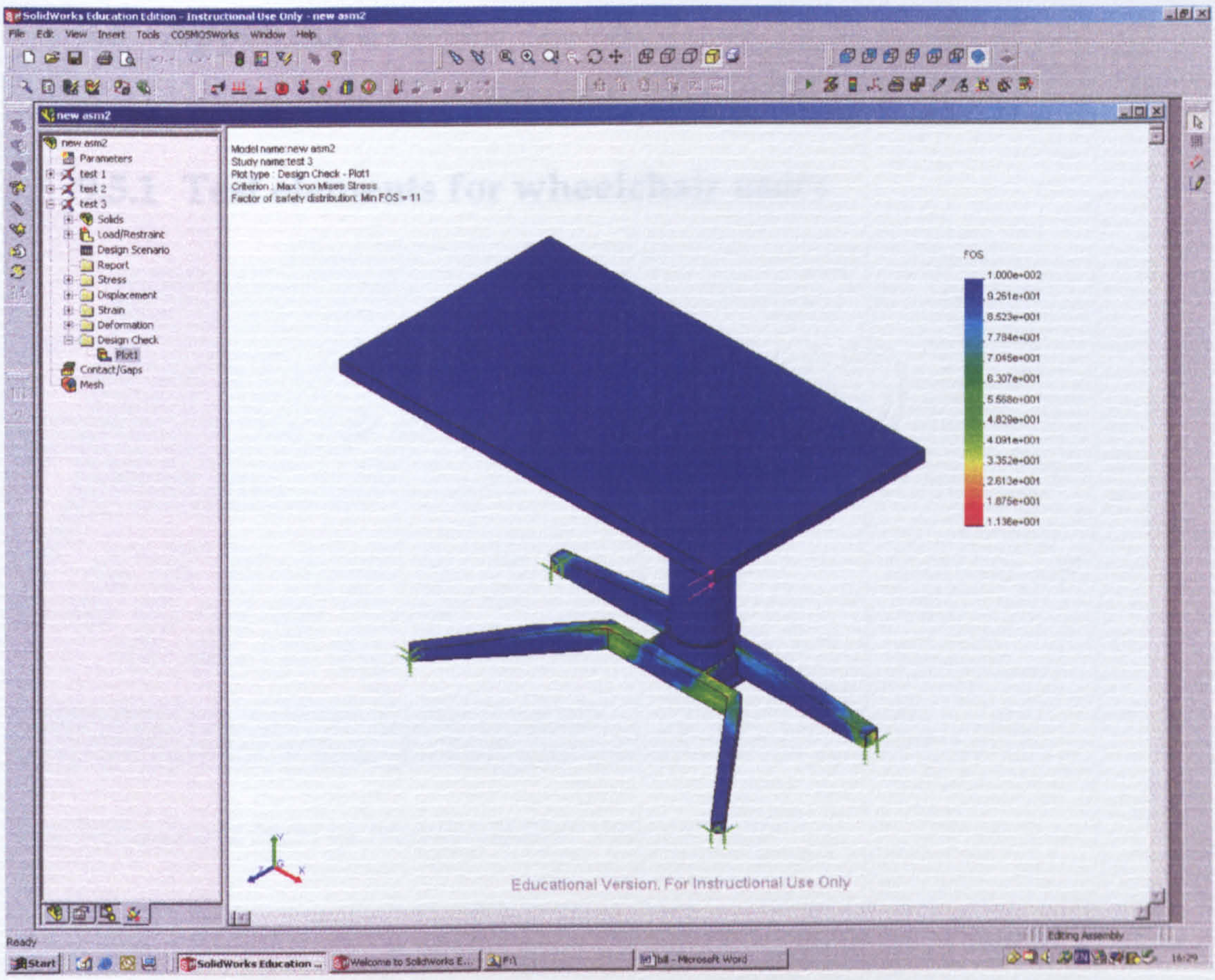
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Design Scenario
Report
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Displacement
Strain
Deformation
Design Check
Plot1
Contact/Gaps
Mesh
Model name:new asm2
Study name:test 3
Plot type : Design Check - Plot1
Criterion : Max von Mises Stress
Factor of safety distribution: Min FOS = 11
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7.045e+001
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3.352e+001
2.613e+001
1.875e+001
1.136e+001
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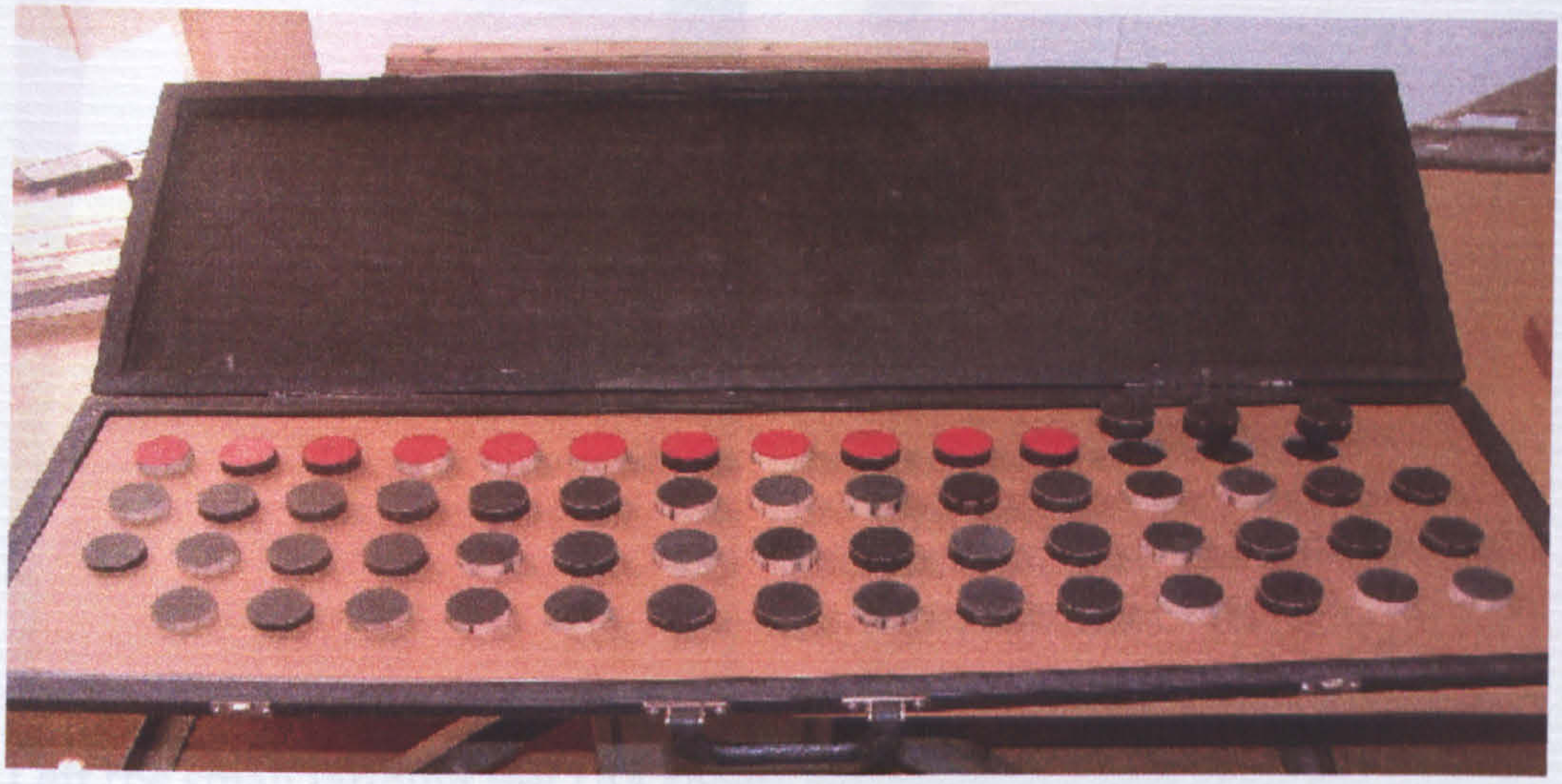
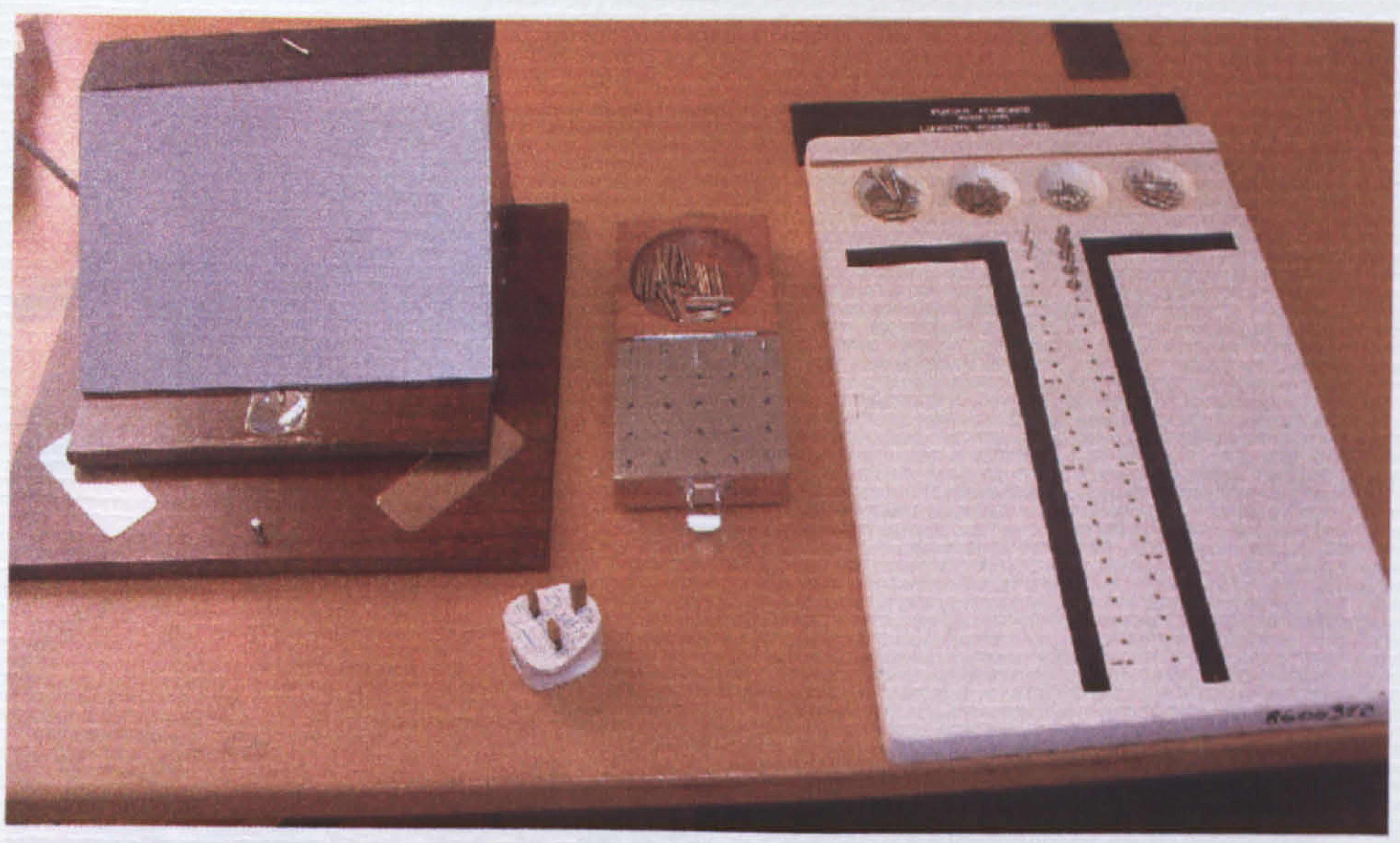
9.5 Appendix E

9.5.1 Test elements for wheelchair users

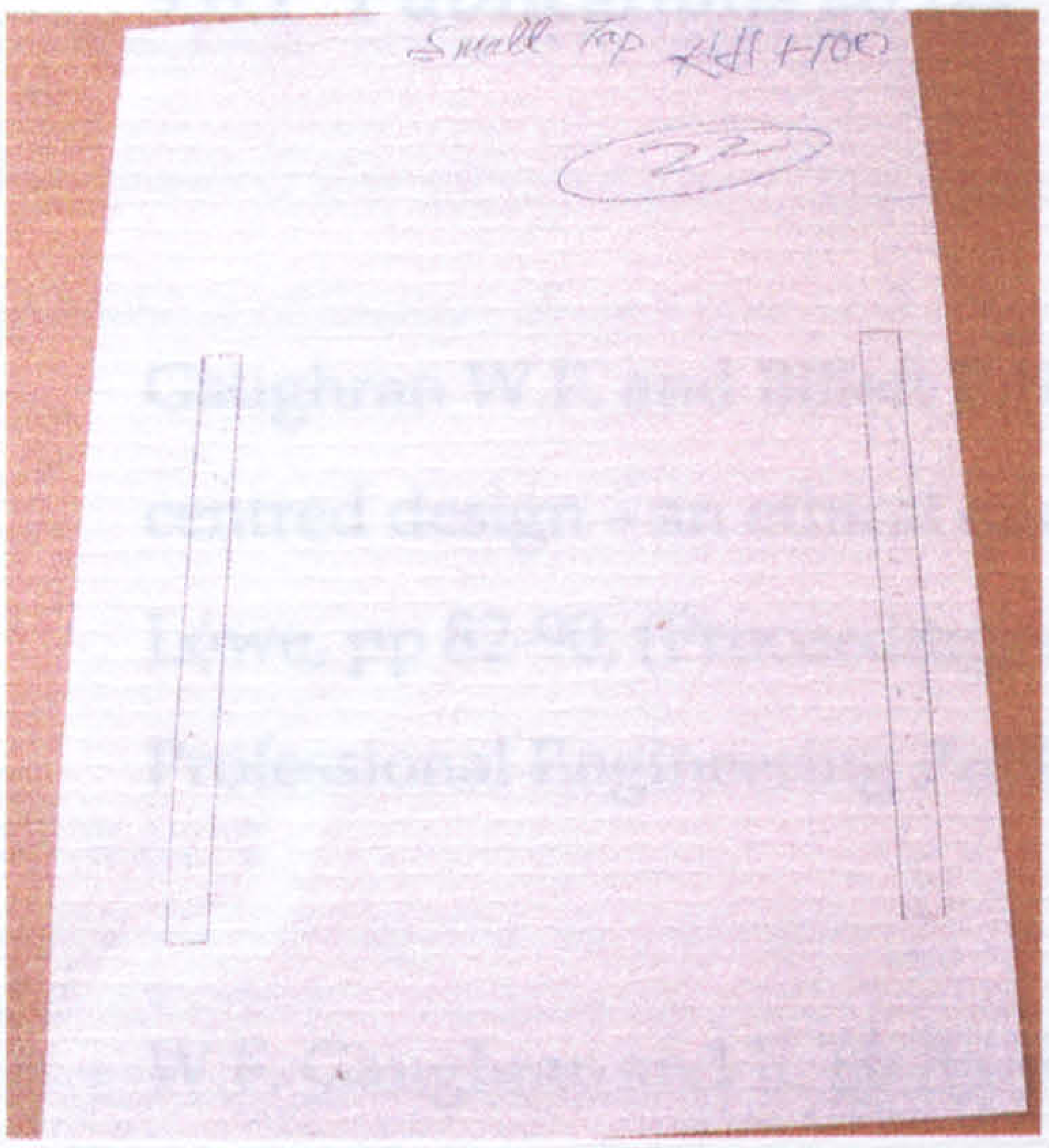
The test bank elements used for the wheelchair users and surrogates

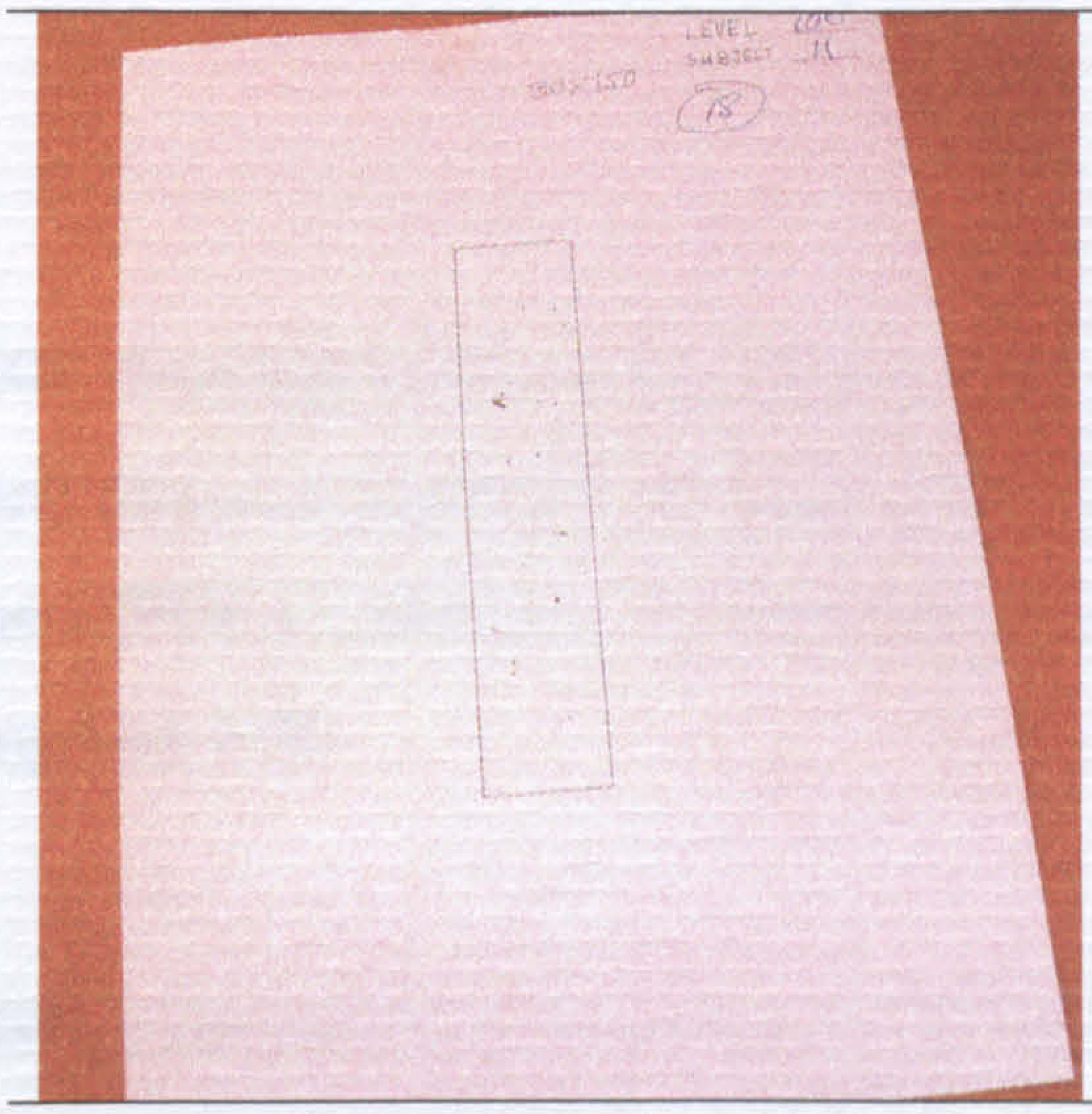


The Minnesota Rate of Manipulation Test (MRMT)



Left to right – the one-hole test, the grooved pegboard and the Purdue pegboard.





Left the small tapping test (A4 sheet) and right the large tapping test, the rectangle is 30 mm by 150mm and a second is locates 1 m away and located centrally in front of the subject. These measure the simple ballistic movement, and gross motor movement, respectively.

The arrangement for the plug-top assembly

9.6 Appendix F

9.6.1 Publications so far

Gaughran W.F. and Billett E.H., 2003, 'Surrogate wheelchair users in user-centred design - an ethical question? *Ethics in Engineering Design,* Editor J.R. Lowe, pp 82-90, (Proceedings of the ICPDE Conference, Bournemouth, Sept.) Professional Engineering Publishing Ltd. U.K.

W.F. Gaughran and E. H. Billett, 2003, Comparative Analysis of Wheelchair Users and Surrogates in Workbench Design, *International Conference on Production Research,* Blacksburg, Virginia.

W.F. Gaughran and E. H. Billett, 2004, Inclusive Design Ergonomics for Workbenches, *Flexible Automation and Intelligent Manufacturing - International Conference,* Toronto, Canada, July 2004 - accepted for publication.

Copies of these papers follow.

Surrogate Wheelchair Users in User- Centered Design An Ethical Question

W.F. Gaughran[1] and E. H. Billett[2]

[1] Department of Manufacturing and Operations Engineering, University of Limerick, Ireland

[2] Department of Design, Brunel University, England

ABSTRACT

The use of surrogates in user-based design, for wheelchair users (WUs) may raise some ethical questions. Goldsmith (2000) suggests that it is quite appropriate to use surrogate wheelchair users in establishing anthropometric and ergonomic data. Is the data gathered by such means valid? Is it ethical to use able-bodied people sitting in wheelchairs and say that the data gathered is applicable in designing for wheelchair users? At the University of Limerick, a number of WUs have been evaluated, and a like cohort of surrogate wheelchair users (SWUs), in establishing design ergonomics related to workbench design, with particular reference to best-fit working heights. Both groups were tested and comparatively analysed to ascertain factors-of-difference and to test the legitimacy of using such subjects in future design research. Optimum work heights, relating to comfort and efficiency have been established and the feasibility of using SWUs in determining best-fit ergonomics is discussed.

Key words/phrases: *Wheelchair/ Surrogate Wheelchair user ergonomics, Optimum working-heights, Inclusivity.*

1. INTRODUCTION

Ethics relating to design can have many facets, amongst which are, designer/client trust, materials selection, ecological and safety issues. However, there are issues of an ethical nature which impact at a more fundamental level. The establishing of data relating to design ergonomics may be one such area. As part of a research project at the University of Limerick, it has been necessary to develop ergonomic data relating to best-fit workbenches. As the project was for universal application, it was deemed necessary to include wheelchair users (WUs). WUs with normal upper body strength would be the most likely to use industrial workbenches, and such subjects can be difficult to locate. Goldsmith[1] says that it is appropriate to use surrogates in establishing ergonomic data, but there is no evidence that this is appropriate for industrial bench tasks. This element of the research project therefore makes a comparative analysis of a cohort of WUs and a like cohort of surrogate wheelchair users (SWUs), and is primarily concerned with best-fit bench ergonomics, with particular reference to optimum working heights.

1.1 The Test Cohorts

While the research concerns itself with trial fittings in a 'design-for-all' context, this part of the study sets out to determine best-fit work-heights for wheelchair users, at the workbench. The study was undertaken in three parts, (i) a cohort of paraplegic wheelchair users with 'normal' upper body strength. The criterion for suitability was that they should be capable of propelling themselves in the wheelchair. i.e. without the use of a motorised model; (ii) the same test bank for a similar cohort of surrogate wheelchair users; (iii) a comparative analysis of the findings for both cohorts.

2. EXPERIMENTAL PROCEDURE

2.1 The Test-bench Rig

In order to accommodate the individual requirements of the user and to determine a preferred height, efficiency rates, and estimated endurance, it was necessary to design a rig, which would cater for a range of heights. Pilot anthropometric data collected, determined that the lowest knee clearance required would be 570mm and a range of heights up to 200mm above Knee Height (KH) would be required. An electronically controlled, rack and pinion operated, telescopic lifting column was used to support the bench-top. To accommodate the depth requirement for knee clearance, the bench-top was cantilevered, and as the minimum column height was 610mm, a cranked support bracket was designed to allow for the lower levels. The work surface dimensions were deemed to be sufficient at 1200mm x 650mm. The finished test-rig had a height range of 570mm to 1100mm.

2.2 The Test Bank

A range of standard manipulative tests was chosen as well as a typical electric plug-top assembly. The tests and their associated values were as follows: Three Pin Plug Assembly (Total time to assemble three plug-tops); One Hole Test (The largest throughput in three trials in one minute); Small Tapping Task (Number of pairs of taps within the targets after 30 seconds); Purdue Pegboard (Total number of pins for left hand, right hand, both hands, and assembly); Grooved Pegboard (Total time to complete Pegboard); MRMT (Time to complete four trials); Large Tapping Task (Number of pairs of taps on the targets after 30 seconds).

Observation and WU interviews revealed that the most restrictive factor at traditional workstations was an inability to accommodate the user's legs underneath. This meant that the user could not work close to the bench in a comfortable working posture. The second element, which created significant difficulty, was the height of the working surface. Normally, the work-height for ambulant users is associated with elbow height. However as the usual difficulty for WUs was associated with knee clearance, it was decided that their knee-height would be used as the datum level. For the purpose of analysis, several anthropometric measurements were taken. These were: sitting stature, knee height, shoulder height and elbow height. The test-rig was relative to the subject's knee height but analysis of elbow height would were also made. The test-rig represented the traditional bench and five other heights, ranging from knee height to knee height plus 200mm, see Table 1 for heights range.

Table 1 – Test Heights

Height Number	Height Level
H 1	Knee Height (KH) - inaccessible
H2	KH + 50
H3	KH + 100
H4	KH + 150
H5	KH + 200
H6 (800mm)	Existing – inaccessible bench

2.3 The Test Subjects

Twelve wheelchair users were identified for the tests, but one was later eliminated because of insufficient hand-dexterity. The age range was from 19 years to 55 years. The period of time the test cohort were using wheelchairs ranged between 1.5 years and 37 years. Their disabilities resulted from stroke, spina bifida, and accident. The gender mix was seven males and four females. A similar test group of SWUs were selected.

2.4 The Test Method

2.4.1 Wheelchair Users Tests

All the subjects were briefed on the test objectives and completed a questionnaire. The duration of the test bank was approximately three hours. The Latin Square Order was used to randomise the test elements and the sequence of the bench heights. Each WU test-subject used their personal wheelchair. The anthropometric data was collected prior to testing and all heights were set in relation to the knee height of the subject, with the exception of the traditional engineering test-rig, which was fixed at 800 mm high. It was determined that there was no significant Body Part Discomfort (BPD) beforehand.

All tests were stopwatch timed, measuring either the completion times for the prescribed tasks or the quantum of task for a given time. The tasks measured hand manipulative tasks, hand ballistic task, pick and place and industrial assembly tasks. All tasks were recognised standard psychomotor tasks except the electric plug-top task, which was developed at the Ergonomics Research Centre at UL.

At the end of each test bank at the prescribed height the subjects filled in a BPD form, adapted from the Corlett and Bishop, 1976[3] models. The outline divided the upper body into eighteen zones, and the BPD for each zone was rated by the subjects on a scale of 0 to 5. With 0 representing no discomfort and a rating of 5 for high/severe discomfort. The diagram represented the body view from the back and eighteen parts were identified, from waist up.

2.4.1 Surrogate Wheelchair User Tests

The Surrogate Wheelchair Users (SWUs) were chosen to approximately match the Wheelchair user cohort. The ages ranged from nineteen to fifty-eight. There were six males and five females. All subjects used the same wheelchair but the footrests were adjusted to suit leg length, so that the subjects seated position was best-fit for the individual. None used armrests. In addition to the anthropometric data gathered from the WUs, the standing stature and standing elbow height of the SWUs was taken. Otherwise the procedure was the same as for the WUs.

3. ANALYSIS OF THE TEST DATA

The test results were analysed in three ways:

- Best-fit, performance and BPD for the WU cohort
- Best-fit, performance and BPD for the SWU cohort
- The comparative analysis of the resulting data for the two cohorts, to determine whether a factors-of-difference existed

3.1 Ergonomic evaluation and comparative analysis of working heights

This section determined the effects of working height on BPD, estimated endurance time, height rating and completion times. Each variable was tested at five levels on the auto-adjustable workbench. The objective of the test was to identify an optimum working height, relative to the user's knee height (KH).

3.2 The effects of working height on BPD

BPD was measured in eighteen body part regions for wheelchair users, after they had completed all seven tasks at each level of working height. Analysis of the test data revealed that KH+100 was identified as resulting in least discomfort among subjects, while KH+0 resulted the greatest discomfort. It also shows that, as the working height deviates upward or downward from KH+100, that BPD increases. A Friedman Test (a non parametric alternative to a within–subject analysis of variance) was used to analyse whether the working height had a significant effect on individual body parts. The results of this significance test for each of the eighteen body parts measured (see Figure 1) are shown in Table 2. The statistically significant parts (<0.05) are underlined.

Table 2. Friedman test results on the effects of working height on BPD – WUs.

Part	Chi square	Sig.	Part	Chi square	Sig.
1	12.233	0.016	10	11.688	0.020
2	6.452	0.168	11	7.789	0.100
3	17.972	0.001	12	10.094	0.069
4	20.058	0.000	13	10.359	0.035
5	19.789	0.001	14	9.521	0.049
6	12.134	0.016	15	8.500	0.075
7	14.261	0.007	16	4.388	0.356
8	12.989	0.011	17	7.273	0.122
9	12.092	0.017	18	11.347	0.023

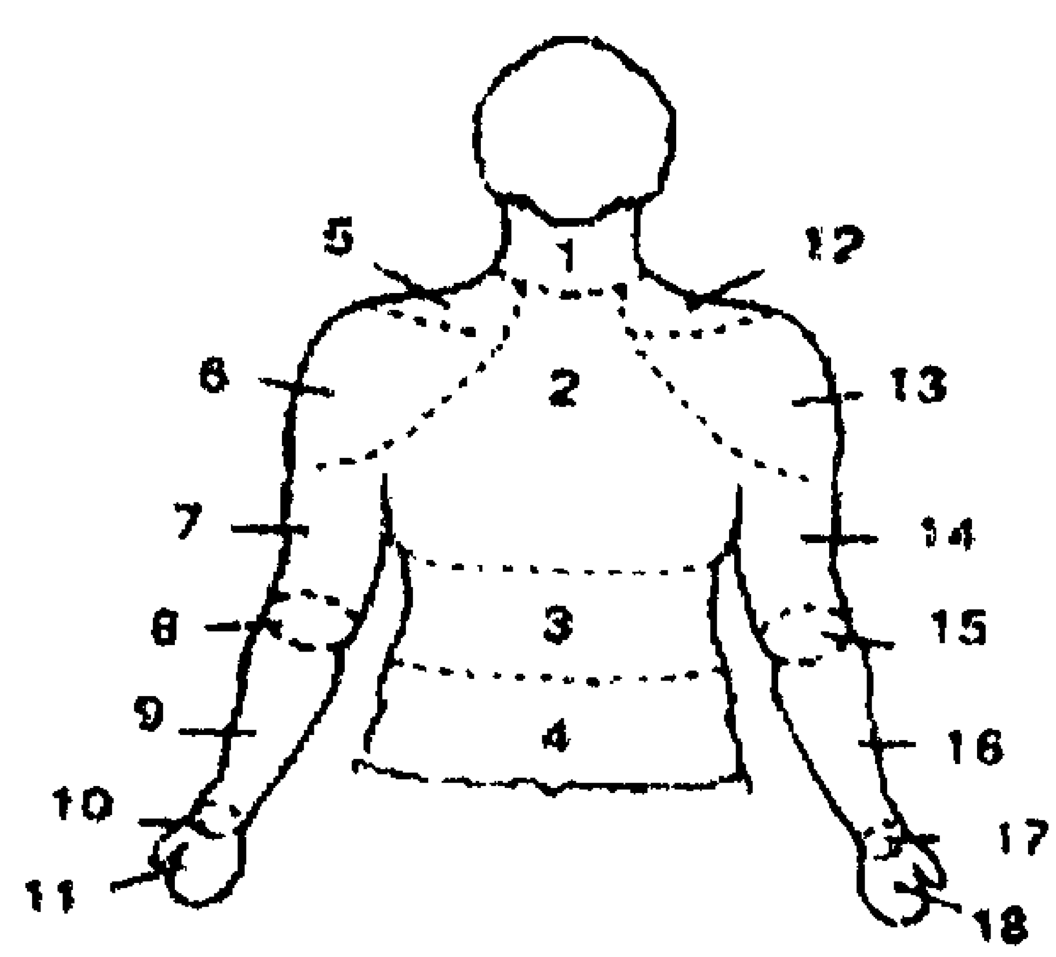


Figure 1 – BPD areas

The results in Table 2 indicate that the working height had a significant effect on twelve of the body parts tested, confirming the importance of best-fit working heights in order to reduce discomfort, and as a result reduce the likelihood of injury, in the long term. Body parts 3, 4 and 5, the waist, lower back and left shoulder were highly significant statistically for WUs.

Table 3. Friedman test results on the effects of working height on BPD – SWUs

Part	Chi square	Sig.	Part	Chi square	Sig.
1	12.672	0.013	10	5.644	0.227
2	17.824	0.001	11	2.813	0.590
3	21.161	0.000	12	13.271	0.010
4	20.275	0.000	13	9.932	0.042
5	14.521	0.006	14	6.852	0.144
6	9.096	0.590	15	1.114	0.892
7	9.442	0.510	16	1.429	0.839
8	5.134	0.274	17	4.247	0.374
9	1.778	0777	18	6.540	0.162

For the SWUs, parts 2, 3, 4 and 5, upper back, waist, lower back and left shoulder had greatest statistical significance. Parts 3, 4, and 5 were common to both groups.

3.3 BPD comparisons of existing workbench to best-fit workbench height

The mean BPD data for working at the existing workbench and working at KH+100mm on new design are contained in Figure 2 below. Discomfort was measured on a zero to five scale on the Y-axis, where zero indicated **'no discomfort'** and five indicated **'severe discomfort'.**

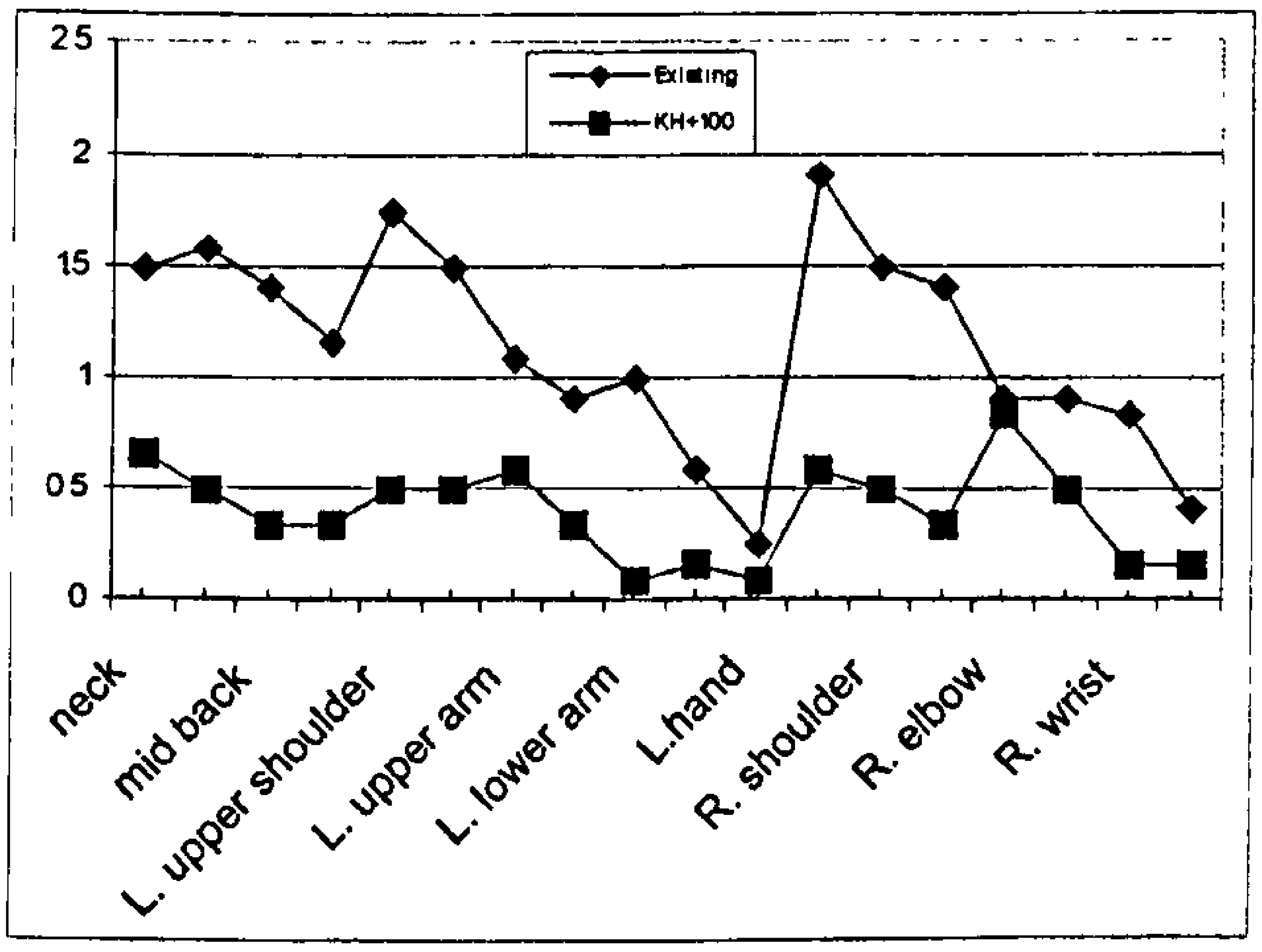


Figure 2. Mean BPD scores for existing workbench and preferred height (KH+100) on test workbench for WU group

The BPD line graphs for the WU and SWU (Figure 3) groups are similar and when subjected to comparative statistical analysis show no significant difference. The preferred height graph is very similar for both groups indicating a highly significant value for the SWU group of, p <0.001 and for the WU group a value of p <0.001. Therefore for both groups the identified, preferred working height of KH+100 significantly contributes to the reduction of BPD.
The visual inspection of both graphs, Figures 2 and 3 reinforce this.

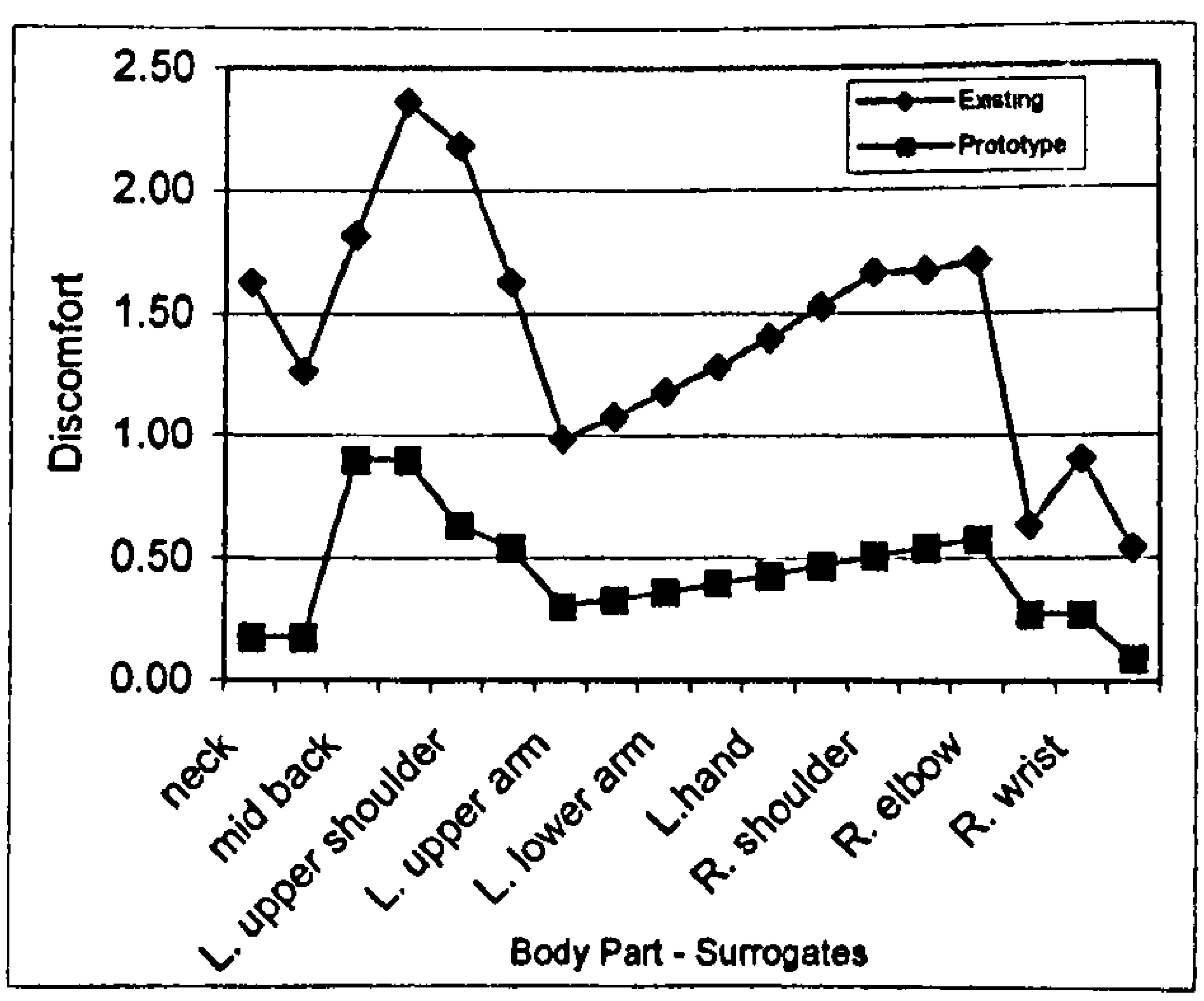


Figure 3. Mean BPD scores for existing workbench and preferred height (KH+100) on test workbench for the SWU group

The results show that there was a significant effect on eight of the body parts tested, most notably all back regions and the shoulders, for the WU group and there were six body parts showing significant discomfort for the SWU group.

Five of the affected body parts are common to both groups. The neck did present a problem for the surrogates, but did not for the WU group. Body part 13 and 14 registered significant discomfort for the WU group but did not for the SWU group. The general discomfort for the total cohort is registered in the shoulders and back. Therefore the preferred height of KH+100 contributes to neutralising body posture for seated workers whether WUs or SWUs.

3.4 The effects of working height on estimated endurance times

Figures 4 and 5 below, indicates the mean estimated endurance times for both groups, while operating at various working heights. On the Y axis below 1 indicates **'less than two hours'**, 2 is **'two to four hours'**, 3 indicates **'four to six hours'** and 4 indicates **'six to eight hours.**

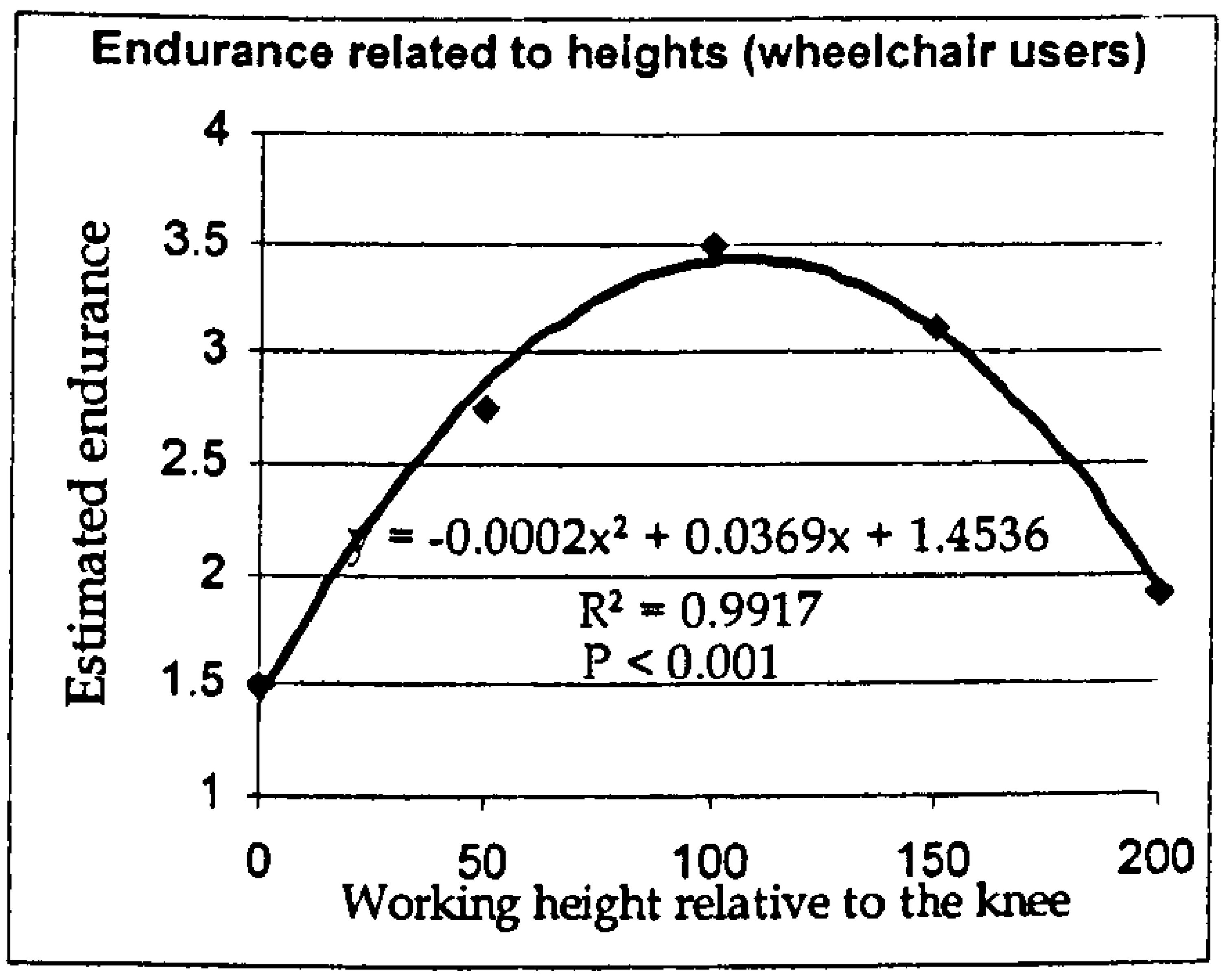


Figure 4. The relationship between bench working-heights and endurance for WUs.

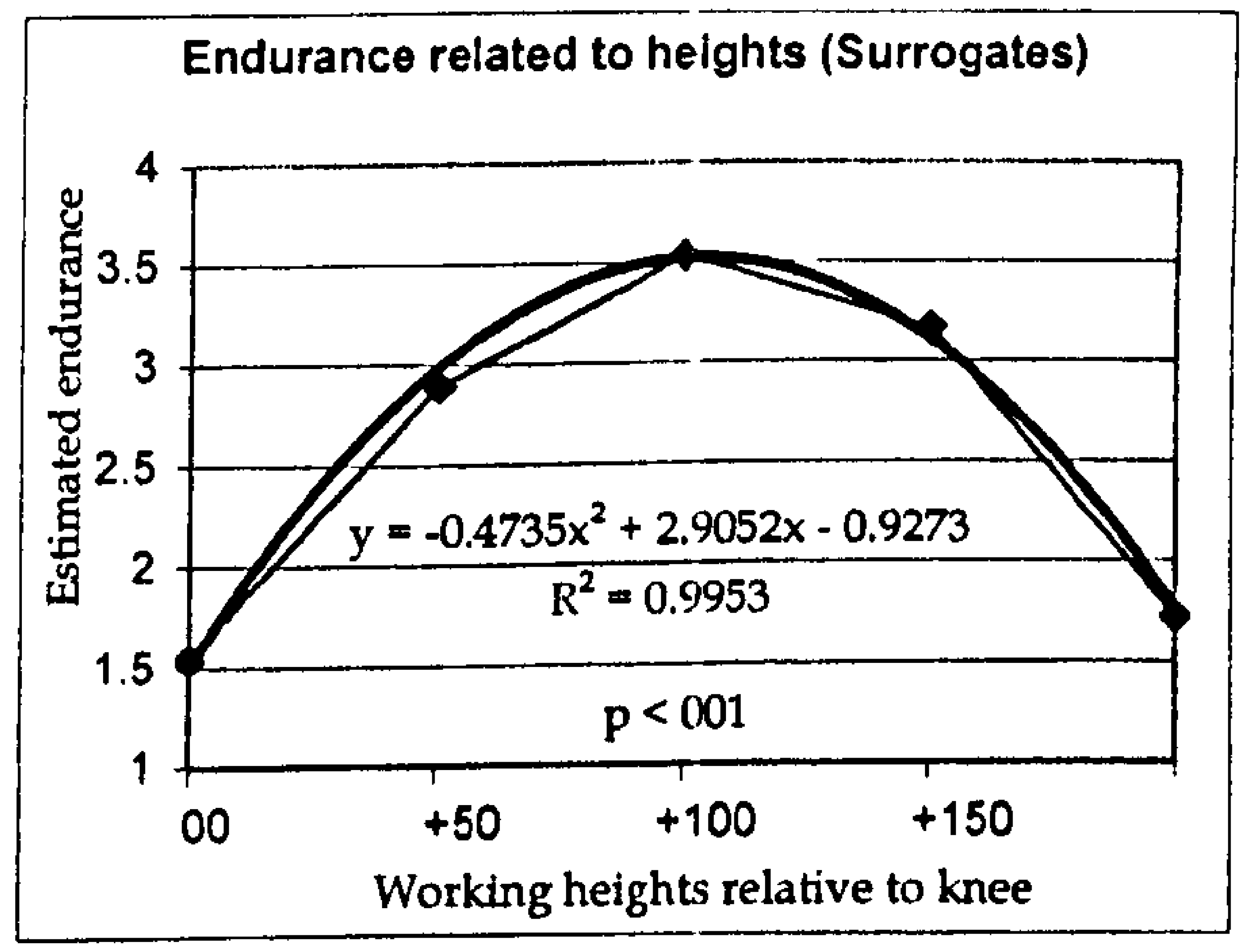


Figure 5. The relationship between bench working-heights and endurance for SWUs

The quadratic equation added to the graphs, may be used to predict estimated endurance times relative to working height above the KH of the wheelchair user, as well as for surrogates. As there was found to be no statistical significance between the endurance for both groups ($p > 0.05$), then it is appropriate to use surrogates to determine endurance. However differences in BPD may need to be considered as this might have a significant affect during prolonged activities. The data collected was based on the test-subjects estimated time that they felt they could spend doing the type of activity associated with the test bank. *A comparative analysis of the curves and their values show that there is no significant factor-of –difference between WUs and SWUs associated with endurance.*

3.5 The effects of working height on completion time

The data revealed that working height does not have a significant effect on completion time for tasks with the exception of the one hole test. There is however a significant improvement on completion times for both the WU and the SWU groups when comparing the existing bench rig with the KH+100 rig. Analysis of WU group data using Friedman test, produced a significance value of $p = 0.010$, and for the SWU group $p = 0.002$. There is therefore a significant improvement in performance for both groups at the preferred bench height, and again the application of any factor-of-difference between the groups was seen as unnecessary.

3.6 Subjective rating of the working heights

Subjects rated the working height upon completion of all seven tasks, at each level. Figure 6 below shows the mean results of these ratings, for the WU group, using error bars with a confidence limit of 95%. Zero on the Y-axis indicates a working height of **'too low'** 5 is **'adequate'** and 10 is **'too high'**.

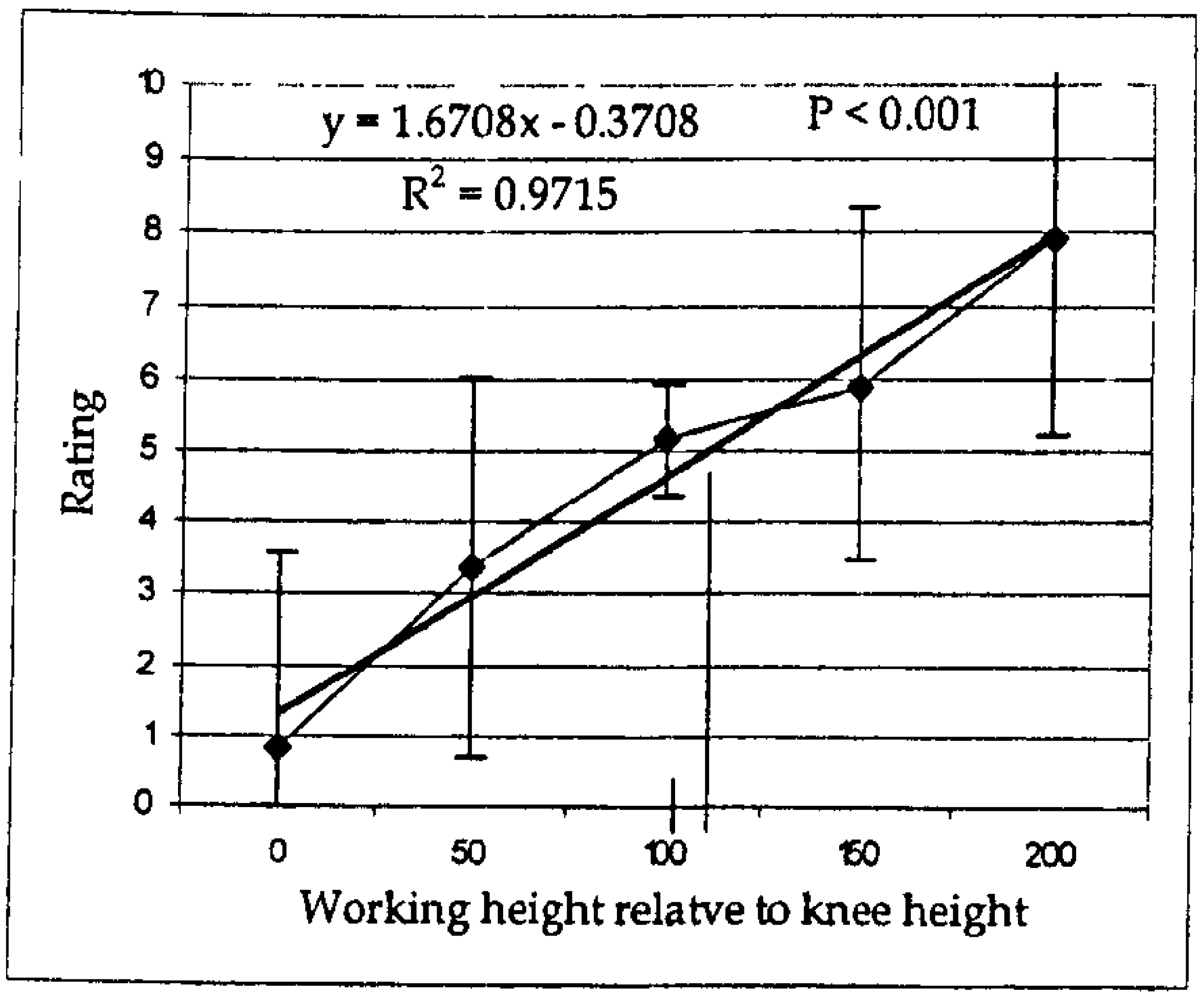


Figure 6. Work heights rating - WU group.

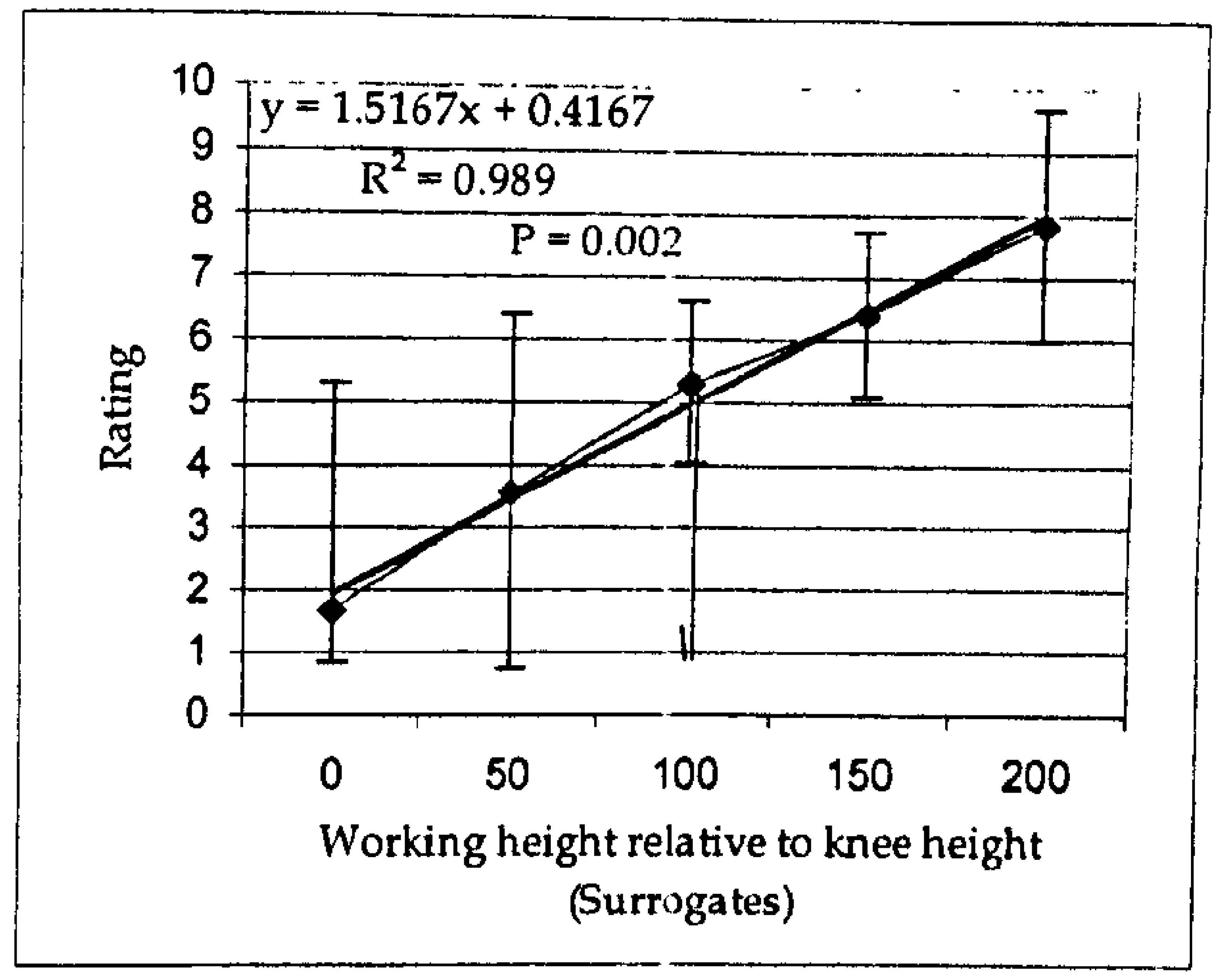


Figure 7. Work heights rating - SWU group.

These results indicated that the working height had a significant effect on the subject's rating ($p<0.001$) for both groups, as seen in Figures 6 and 7. However, there was a significant difference between all others. The results suggest that there is a near perfect correlation between working height, and rating as r = 0.97 and 0.99, a positive linear relationship exists. Overall, there is no necessity to apply a factor-of difference for working heights, between the two groups, as the subjective rating was almost identical for both.

4. Existing workbench design vs. preferred working height on test workbench

As an optimum height was identified (KH+100), it was now possible to compare this height with the existing workbench, in order to analyse the effects of workbench design on BPD, completion times and estimated endurance time.

4.1 Estimated endurance times for existing workbench vs. preferred workbench height

The results of the mean estimated endurance time indicate that subjects will work on average two hours (1.75) on the existing workbench, while they will work six hours (3.5) on the new accessible height (100mm above knee level). A Wilcoxon non-parametric test was used to identify whether the populations had the same means. The results ($p=0.002$), indicates that there was a positive increase in endurance, resulting from working at KH+100.

4.2 Productivity comparisons for existing workbench and preferred height workbench

Comparisons were made for the 'existing workbench' scores and the 'best-fit' workbench scores, in order to determine the effects of workbench design on productivity. The results indicated that productivity has increased in all tasks with the largest increase being for the three-pin plug assembly. The results of all tests show that there was a significant difference for all completion times, with the exception of the grooved pegboard, as a result of working on different workbenches for WUs. A similar increase in productivity was established for the SWU group at the KH+100 bench height. The improved productivity for the three pin electric plug was highly significant for both groups.

5. DISCUSSION

The research set out to establish a best-fit datum for working heights for wheelchair users at industrial tasks and to determine if surrogate wheelchair users may also be used in establishing the data. The following conclusions were seen as significant.

- The most appropriate height for wheelchair users (including surrogate wheelchair users) was found to be at Knee Height plus 100 millimetres, i.e. KH+100.
- Working at this height improved productivity and reduced body part discomfort.
- Endurance curves and equations have been devised which will allow the calculation of estimated endurance for a range of heights.
- Moving from the identified optimum in either direction will result in reduced endurance times and increased body part discomfort.
- The comparisons between working at the existing/traditional engineering bench, and the best-fit KH+100 bench produces highly significant statistical evidence of reduced body part discomfort, and improved productivity and work endurance times.
- There was a distinct correlation between the WU group and the SWU group in nearly all facets of the test results, with the exception of some elements of BPD. There was however, a very good match, in the BPD analysis of back and shoulders for both groups.
- There appears to be no ethical reason why surrogate wheelchair users may not be used as test subjects in research relating to bench design to accommodate wheelchair users at industrial tasks. The research also suggests that it is appropriate to mix test groups.

The combined group of WUs and SWUs have not been analysed as a whole. However the findings show that they can be. This will increase the test cohort for the overall research. It will also allow easier access to suitable test subjects. This element of the research has significantly extended ergonomic test methodology and data for wheelchair users at workbenches. In answer to the ethical question of the legitimacy of using surrogate wheelchair users to establish such ergonomic data, the test results speak for themselves – yes, it is ethical.

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Comparative Analysis of Wheelchair Users and Surrogates in Workbench Design

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ABSTRACT
Industrial environments are generally seen as unsuitable and unsafe for wheelchair users (Wus). In a recent survey of over 120 engineering industries in Ireland, it was revealed that no wheelchair-using operatives worked in the engineering workshops. Research at the University of Limerick has identified several areas which, if properly addressed would make the work environment safer and more efficient for (WUs). User-based workbench design is seen as a key element in the inclusion of WUs as equal team members and in improved safety and efficiency for all users. Little anthropometric and ergonomic data exists in this area and one of the research aims is to extend this. The data has been compiled and analysed using an auto-adjustable-height test-rig. While a range of 'ambulant' WUs have undertaken an extensive test-bank, there is always some difficulty in acquiring sufficient numbers who live reasonably close to the test lab. To overcome this difficulty, an equal number of surrogate wheelchair users (SWUs) are tested and comparatively analysed to ascertain factors-of-difference and to test the legitimacy of using such subjects in future design research. Optimum work heights, relating to comfort and efficiency have been established and the feasibility of using SWUs in industrial design research is discussed.

Key words/phrases:
Design ergonomics, Wheelchair user ergonomics, Best-fit bench design, Surrogate wheelchair users.

1. INTRODUCTION

For centuries workbenches have been at the core of manufacturing and production. The development of the workbench has produced a variety of models for a broad range of activities. Various trades in many cultures have established 'standard' workbenches for 'non-standard' users. If for instance we consider that a normal engineering workbench height is 800mm (32') and may be used by individuals who range in stature (according to a sample survey of young adults) from 1500mm (5') to 2030mm (6'-8"), then there is a serious best-fit ergonomic problem. Add to this the possibility of a seated operative, such as a wheelchair user and the design ergonomics present a real problem. This paper is concerned with best-fit bench ergonomics for wheelchair users, with particular reference to optimum working heights.

As part of a recent research project, at the University of Limerick, on workshop accessibility for wheelchair users (WUs), a survey of over 120 engineering workshops was undertaken. One of the objectives of the survey was to determine whether there were any WUs employed by these companies and particularly if any were operating on the shop floor. There was a response rate of thirty percent, which might be an indication that none of the non-respondents had any WUs in employment. Three of the thirty-seven respondents employed people with disabilities, however:

- None of the companies has any WUs on the shop floor.
- Twenty percent of the workshop managers indicated that they would not be comfortable having WUs on the shop floor.
- They also felt that the workshop was not a safe environment for WUs
- Much of the work would be too heavy for WUs.

In examining the safety aspects of the workshops it was found that, in improving safety for wheelchair users we increase safety for all. Ingress and egress were seen as problematic but could be overcome without too much difficulty. Machines and workbenches were for the most part inaccessible to WUs. The implications are clear, (a) WUs cannot operate as equal team members in engineering workshops, as they are currently designed, (b) a valuable asset is being lost to engineering, (c) wheelchair users are not reaching their full working potential, and sometimes see many of these professions as outside their capabilities.

1.1 Bench Design

Of the workbenches examined, none were truly accessible to Wus, and while many excellent workbenches are available on the market these too are inaccessible. See Figure 1. The bench illustrated would have some accessibility at both ends, but the height would likely be problematic.

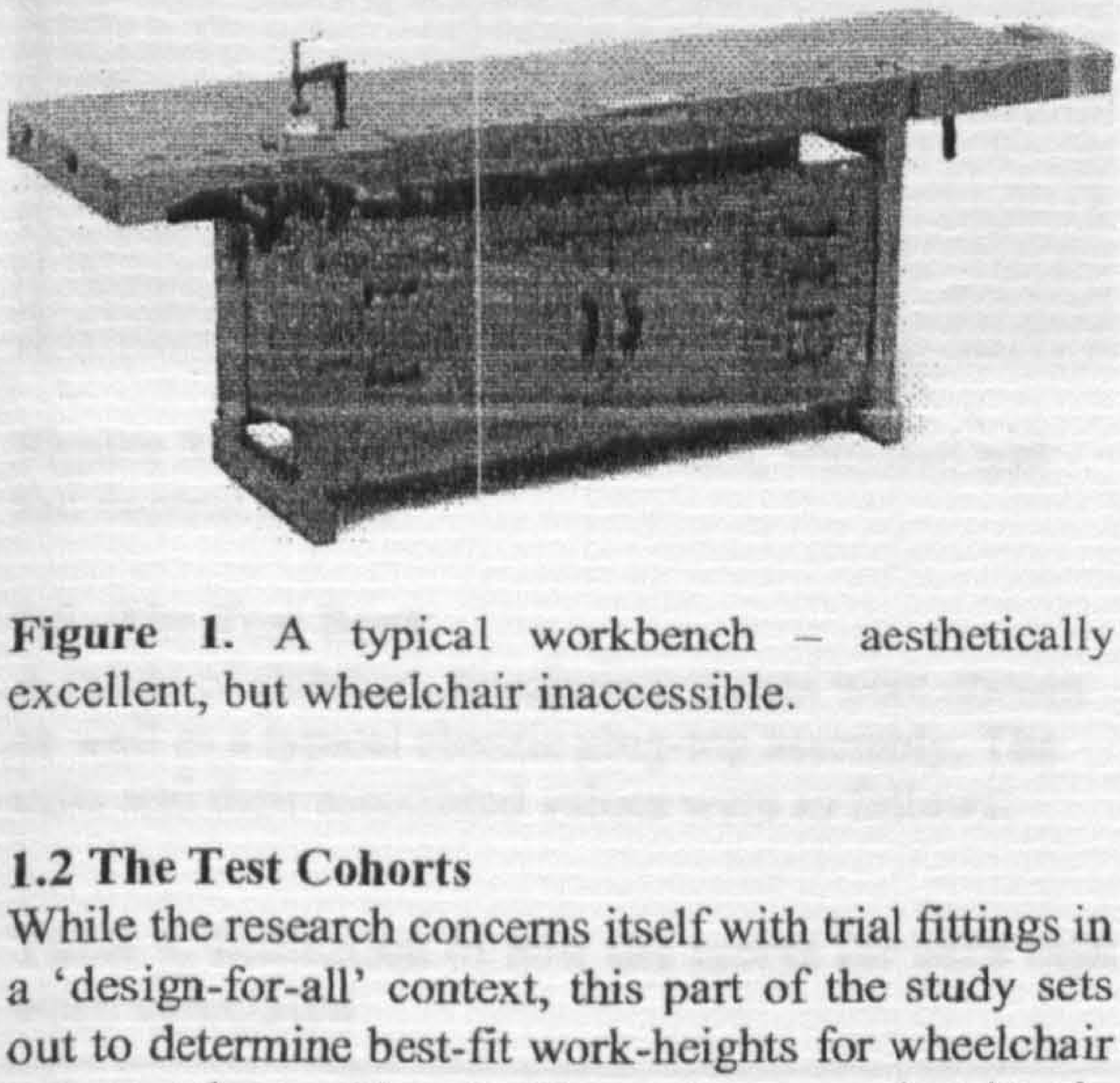

Figure 1. A typical workbench – aesthetically excellent, but wheelchair inaccessible.

1.2 The Test Cohorts

While the research concerns itself with trial fittings in a 'design-for-all' context, this part of the study sets out to determine best-fit work-heights for wheelchair users, at the workbench. The study was undertaken in three parts, (i) a cohort of paraplegic wheelchair users with 'normal' upper body strength. The criterion for suitability was that they should be capable of propelling themselves in the wheelchair, i.e. without the use of a motorised model, (ii) a similar cohort of surrogate wheelchair users. This is because WUs can be difficult to recruit for such testing, but Goldsmith (2000) maintains, that it is acceptable to use surrogates to establish ergonomic data. However Goldsmith's testing did not include the range of psychomotor exercises, which would normally be encountered at a workbench, (iii) a comparative analysis of the findings for both cohorts.

2. Experimental Procedure

2.1 The Test-bench Rig

In order to accommodate the individual requirements of the user and to determine a preferred height, efficiency rates and estimated endurance, it was necessary to design a rig, which would cater for a range of heights. Pilot anthropometric data determined that the lowest knee clearance required would be 570mm and a range of heights up to 200mm above Knee Height (KH) would be required. An electronically controlled, rack and pinion operated, telescopic lifting column was used to support the bench-top.

In addition to vertical knee clearance, a depth clearance of 650 mm would be required. Figure 2 gives the standard for a wheelchair user at a reception desk.

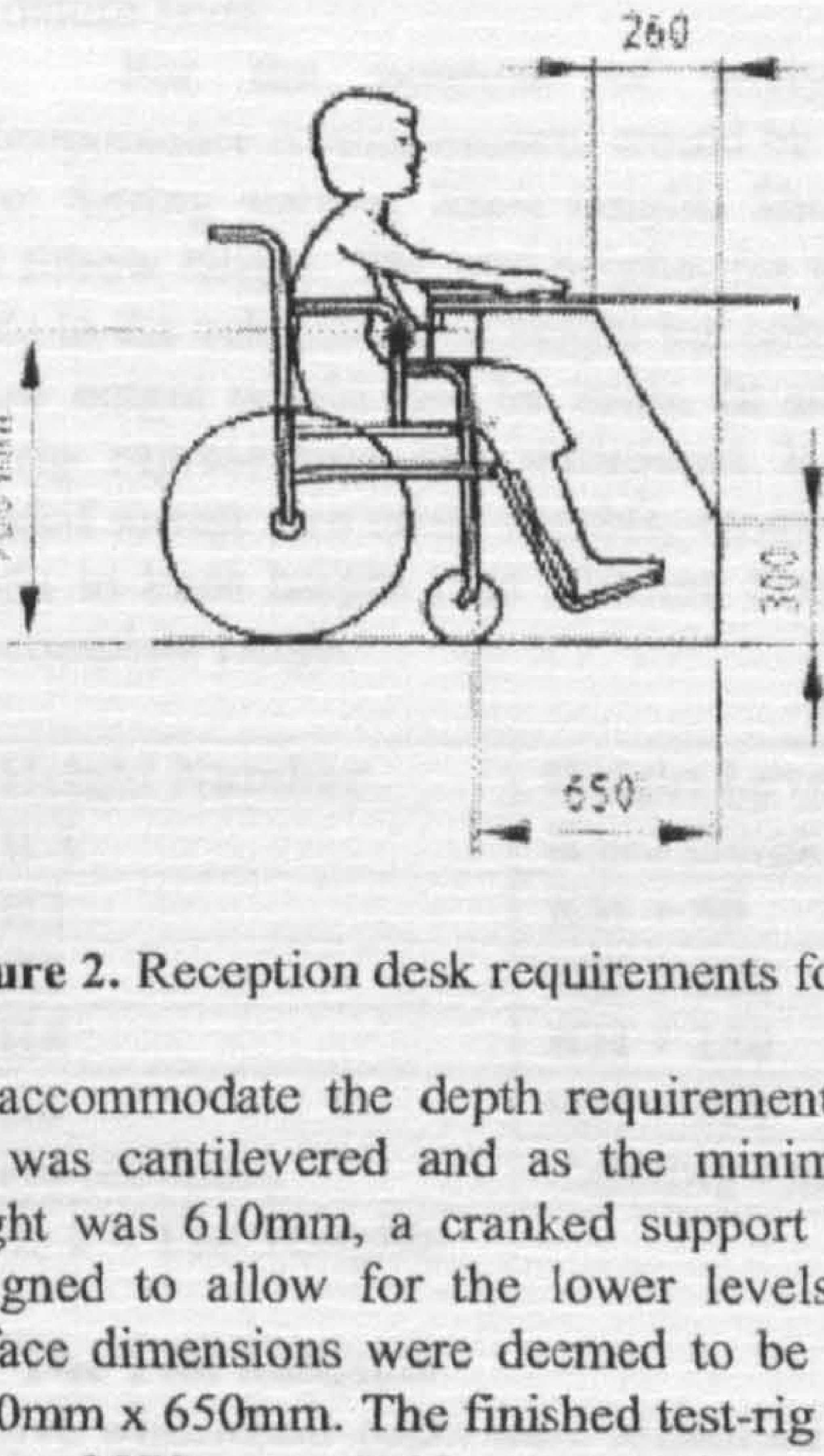

Figure 2. Reception desk requirements for WUs

To accommodate the depth requirement the bench-top was cantilevered and as the minimum column height was 610mm, a cranked support bracket was designed to allow for the lower levels. The work surface dimensions were deemed to be sufficient at 1200mm x 650mm. The finished test-rig had a height range of 570mm to 1100mm. See Figures 3, 4 and 5.

The electronic lifting column used in the auto-height adjustable rig. Lifting capacity 2000N and the column is telescopic. It is height adjustable from 610mm to 1100mm.

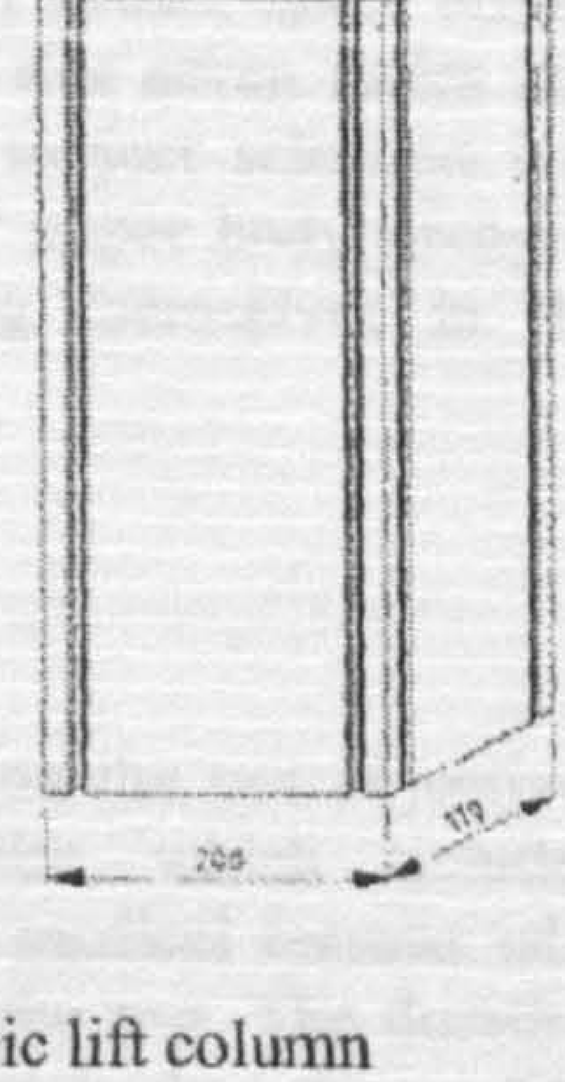

Figure 3. The telescopic lift column

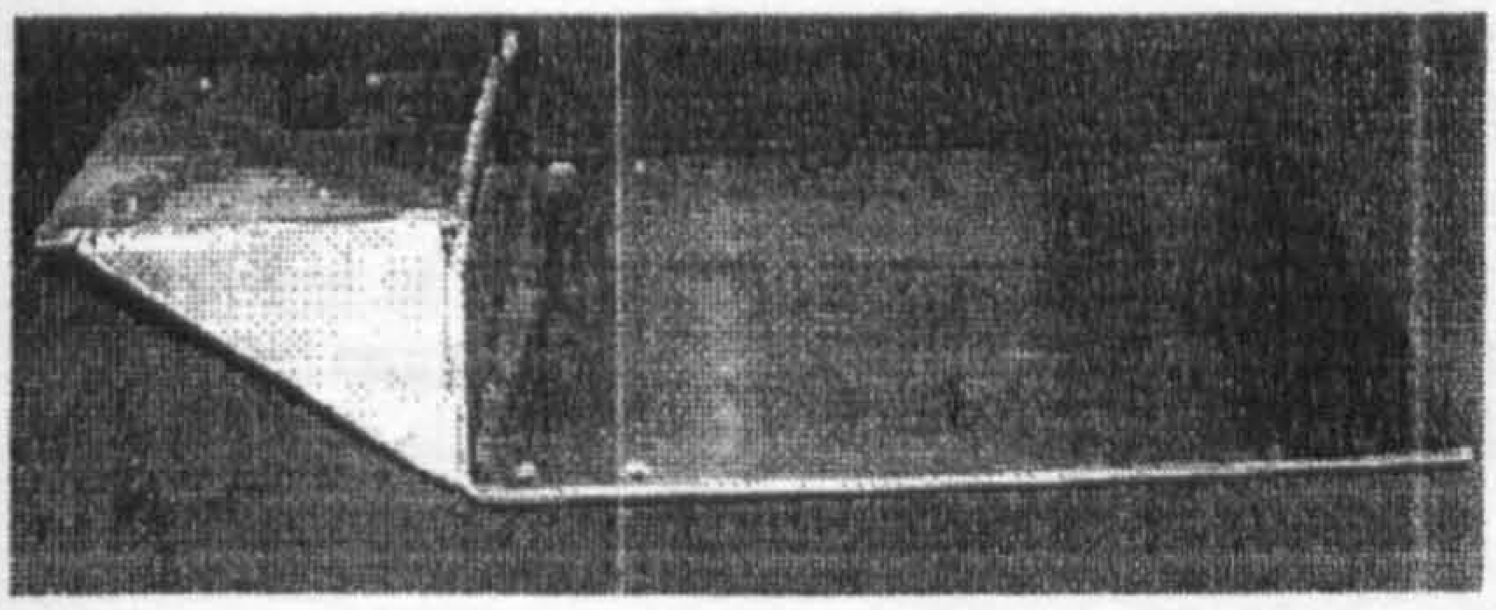

Figure 4. The cranked support bracket (see Fig. 5)

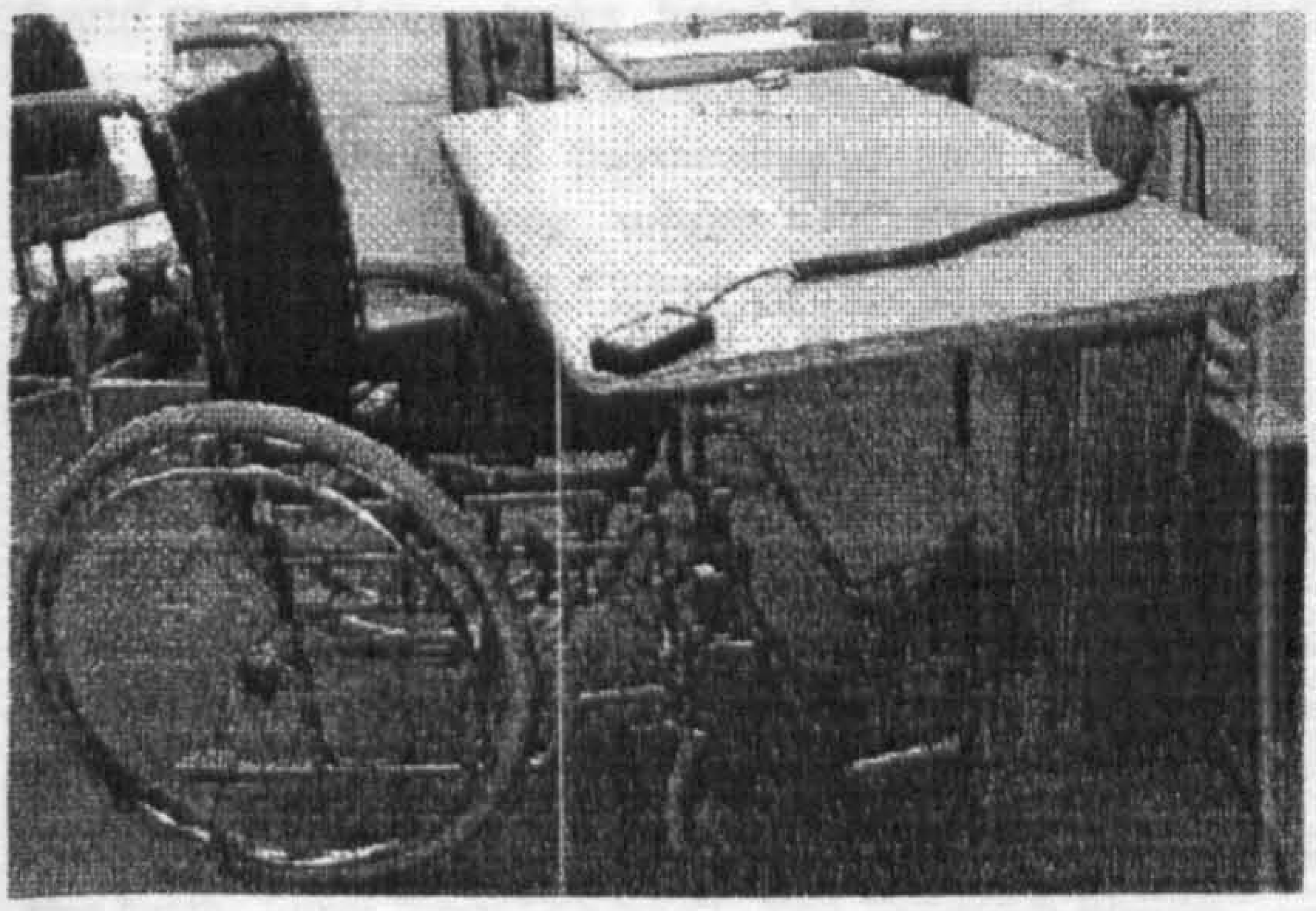

Figure 5. The assembled test-bench, with rise and fall control switch

2.2 The Test Bank

A range of standard, manipulative tests were chosen as well as a typical electric plug-top assembly. The tests and their associated values were as follows:

Table 1. Indication of how the scores for each task were calculated

Test	Test Name	Value
1	Three Pin Plug Assembly	Total time (s) to assemble three plugtops.
2	One Hole Test	The largest throughput in three trials (Trials one minute).
3	Small Tapping Task	Number of pairs of taps within the targets after 30 seconds.
4	Purdue Pegboard	Total no. of pins for left + right + both (30s) and total for assembly (60s).
5	Grooved Pegboard	Total time to complete Pegboard (s).
6	MRMT	Time (s) to complete four trials
7	Large Tapping Task	Number of pairs of taps within the targets after 30 seconds.

Observation and WU interviews revealed that the most restrictive factor at traditional workstations was, that the benches were normally inaccessible, in that the user could not work close to the bench because there was no leg-room. The very fine bench for ambulant users in Figure 1 is an example of this. The second element, which created significant difficulty, was the height of the working surface. Normally, the work-height for ambulant users is associated with elbow height. However as the usual difficulty for WUs was associated with knee clearance, it was decided that the their knee-height would be used as the datum level.

For the purpose of analysis, several anthropometric measurements would be taken. These were: Sitting stature, Knee height, Shoulder height and Elbow height. The test heights for the rig would relate to the subjects knee height but comparison with elbow height would also be made. In addition to the test-rig representing the traditional bench, it was decided to test five other heights, ranging from knee height to knee height plus 200mm. See Table 1 for the complete range.

Height Number	**Height Level**
H 1	**Knee Height (KH)**
H2	**KH + 50**
H3	**KH + 100**
H4	**KH + 150**
H5	**KH + 200**
H6 (800mm)	**Existing - inaccessible**

Table 2 – Test Heights

2.3 The Test Subjects

Twelve wheelchair users were identified for the tests, but one was later eliminated because of insufficient hand-dexterity.

The age range was from 19 years to 55 years. The period of time the test cohort were using wheelchairs ranged from 1.5 years and 37 years. Their disabilities resulted from stroke, spina bifida, and accident. The gender mix was seven males and four females. A criterion for subject selection was that they should have 'normal' upper body strength, e.g. be capable of propelling themselves in the wheelchair.

2.4 The Test Method

2.4.1 Wheelchair Users Tests

All the subjects were briefed on the test objectives and completed a questionnaire, which included requiring a declaration of any medical reasons why subjects should not undertake the test. The duration of the test bank was approximately three hours. The Latin Square Order was used to randomise the test elements and the sequence of the bench heights. Each test-subject would use their own wheelchair. The Anthropometric data would be collected prior to testing and all heights would be set in relation to the knee height of the subject, with the exception of the traditional engineering test-rig. It was determined that there was no significant Body Part Discomfort (BPD) beforehand.

All tests were stop-watch timed, measuring either the completion times for the prescribed tasks or the quantum of task for a given time. The tasks measured hand manipulative tasks, hand ballistic task, pick and place and industrial assembly tasks. All tasks were recognised standard psychomotor tasks except the electric plug-top task, which was developed at the Ergonomics Research Centre at UL.

At the end of each test bank at the prescribed height the subjects filled in a BPD form, adapted from the Corlett and Bishop, 1976 model. The outline divided the upper body into eighteen zones, and the BPD for each zone was rated by the subjects on a scale of 0 to 5. With 0 representing no discomfort and a rating of 5 for high/severe discomfort. The diagram represented the body view from the back. See Figure 6 below.

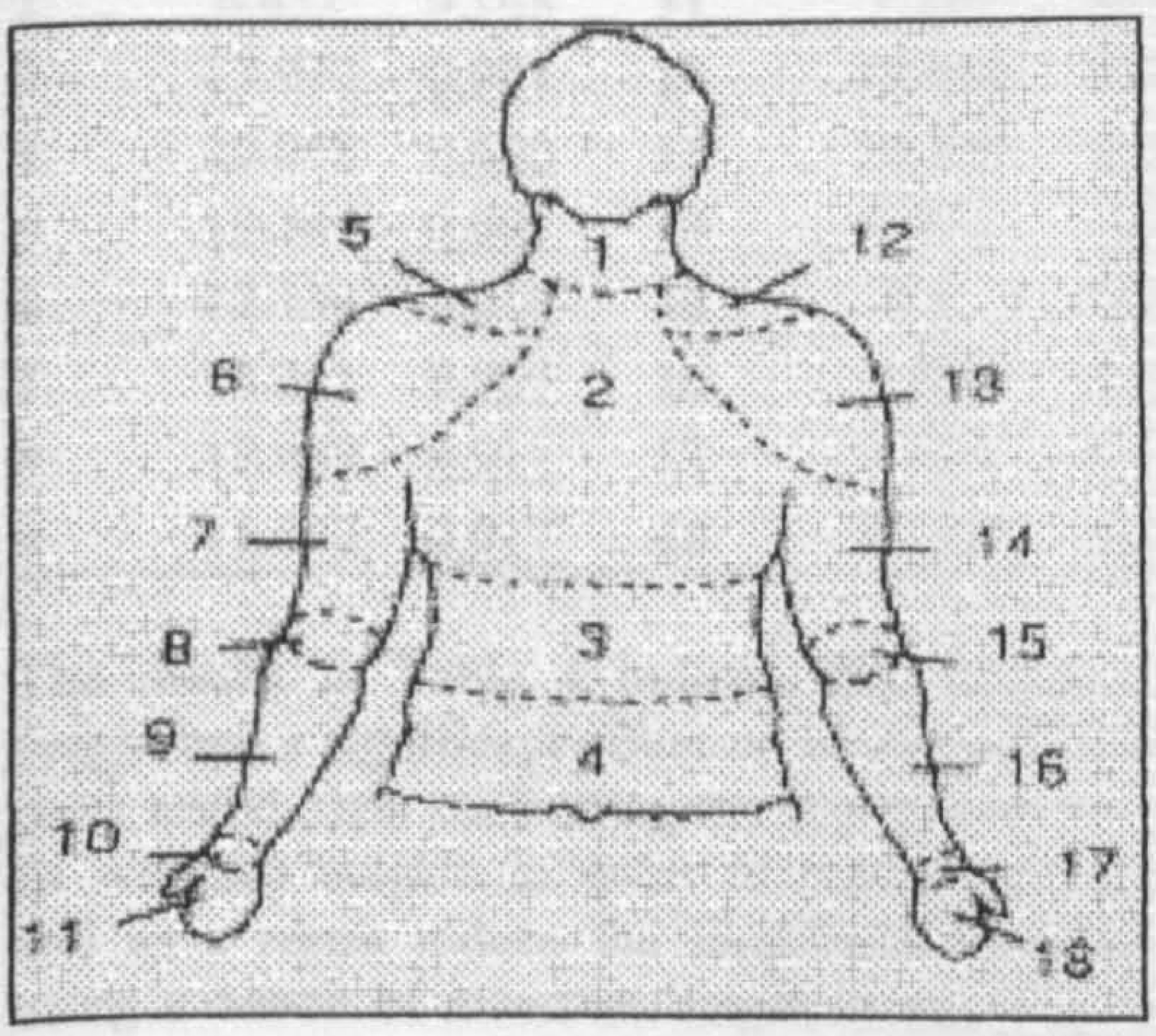

Figure 6. Body Part Discomfort (BPD) zones - evaluation sheet based on Corlett and Bishop's figure.

2.4.2 Surrogate Wheelchair User Tests

The Surrogate Wheelchair Users (SWUs) were chosen to approximately match the Wheelchair user cohort. The ages ranged from nineteen to fifty-eight. There were six males and five females. All subjects used the same wheelchair but the footrests were adjusted to suit leg length, so that the subjects seated position was best-fit for the individual. None used armrests.

In addition to the anthropometric data gathered from the WUs, the standing stature and standing elbow height of the SWUs was taken. Otherwise the procedure was the same as for the WUs.

3. The Outcomes

The test results were analysed in three ways:

- Best-fit, performance and BPD for Wheelchair Users
- Best-fit, performance and BPD for Surrogate Wheelchair Users
- The comparative analysis of the two cohorts to determine factors-of-difference, if any

3.1 Wheelchair Users

3.3.1 Personal Details

The experiment was conducted with eight male (-1), and four female participants. The subjects were aged between twenty and fifty-five, the age range of the target working population (Mean 32.5, SD 15.03). Eight right handed and three left-handed subjects participated in the study. Of the eleven that participated, six were university students, three were working (sales representative, office clerk and an assembly operator). The remaining two subjects were recently retired (a teacher and a craftsman). The subjects were all WUs and suffered from a range of disabilities. The majority of the subjects (8) had been WUs for more than a decade. Only one subject was using a wheelchair for less than two years. Two of the subjects had armrests on their wheelchairs. None of the subjects knew a WU who was working in an engineering environment or a manufacturing shop-floor.

3.3.2 Anthropometric data

Anthropometric characteristics of all wheelchair users in the sitting position in their wheelchairs are given in Table 3.

Table 3. Subjects Anthropometric Data

Percentile	Stature	Shoulder	Elbow	Knee
5^{th}	1093.01	823.69	583.51	583.86
50^{th}	1240.75	960.42	672.25	630.25
95^{th}	1388.49	1097.14	760.99	676.64

3.3.3 Ergonomic evaluation and comparative analysis of working heights

This section determined the effects of working height on BPD, estimated endurance time, height rating and completion times. Each variable was tested at five levels on the adjustable workbench. The objective of the test was to identify an optimum working height, if such could be established, relative to the users knee height (KH).

3.3.4 The effects of working height on BPD

BPD was measured in eighteen body part regions for wheelchair users, after they had completed all seven tasks at each level of working height. Analysis of the tests showed that KH+100 was identified as causing the least discomfort among subjects, while KH+0 experienced the greatest discomfort. It also shows that as the working height deviates from KH+100 that the discomfort increases. The subjects identified this with estimated endurance at the various heights as discussed in the next section.
A Friedman Test (a non parametric alternative to a within–subject analysis of variance) was used to analyse whether the working height had a significant effect on individual body parts. The results of this significance test for each body part are shown in Table 4. The significant parts are underlined.

Table 4. Friedman test results on the effects of working height on BPD – WUs.

Part	Chi square	Sig.	Part	Chi square	Sig.
1	12.233	0.016	10	11.688	0.020
2	6.452	0.168	11	7.789	0.100
3	17.972	0.001	12	10.094	0.069
4	20.058	0.000	13	10.359	0.035
5	19.789	0.001	14	9.521	0.049
6	12.134	0.016	15	8.5	0.075
7	14.261	0.007	16	4.388	0.356
8	12.989	0.011	17	7.273	0.122
9	12.092	0.017	18	11.347	0.023

The results in Table 4 indicate that the working height had a significant effect on twelve of the body parts tested, thus confirming the importance of best-fit working heights in order to reduce discomfort, and as a result reduce the likelihood of injury, if using a bench of incorrect height in the long term. While the analysis of the BPD for surrogates (Table 5) show that there were six areas of significant body part discomfort (BPD), it is interesting to note the corresponding areas for both cohorts. Body parts 1 to 5 show significant correlation, with the exception of body part 2, the shoulder area for wheelchair users. However the waist, lower back and left shoulder indicate highly significant discomfort for both groups. BPD part 13, the right shoulder is also common to both groups.

Some of the significant discomfort for the WU group may be as a result of having to balance themselves with their non-dominant hand while completing a task with the dominant hand, at the lower levels.

Table 5. Friedman test results on the effects of working height on BPD – Surrogate WUs

Part	Chi square	Sig.	Part	Chi square	Sig.
1	12.672	0.013	10	5.644	0.227
2	17.824	0.001	11	2.813	0.590
3	21.161	0.000	12	13.271	0.010
4	20.275	0.000	13	9.932	0.042
5	14.521	0.006	14	6.852	0.144
6	9.096	0.590	15	1.114	0.892
7	9.442	0.510	16	1.429	0.839
8	5.134	0.274	17	4.247	0.374
9	1.778	0.777	18	6.540	0.162

3.3.5 BPD comparisons of existing workbench to best-fit workbench height

The mean BPD data for working at the existing workbench and working at KH+100mm on new design are contained in Figure 7 below. Discomfort was measured on a zero to five scale on the Y-axis, where zero indicated **'no discomfort'** and five indicated **'severe discomfort'**.

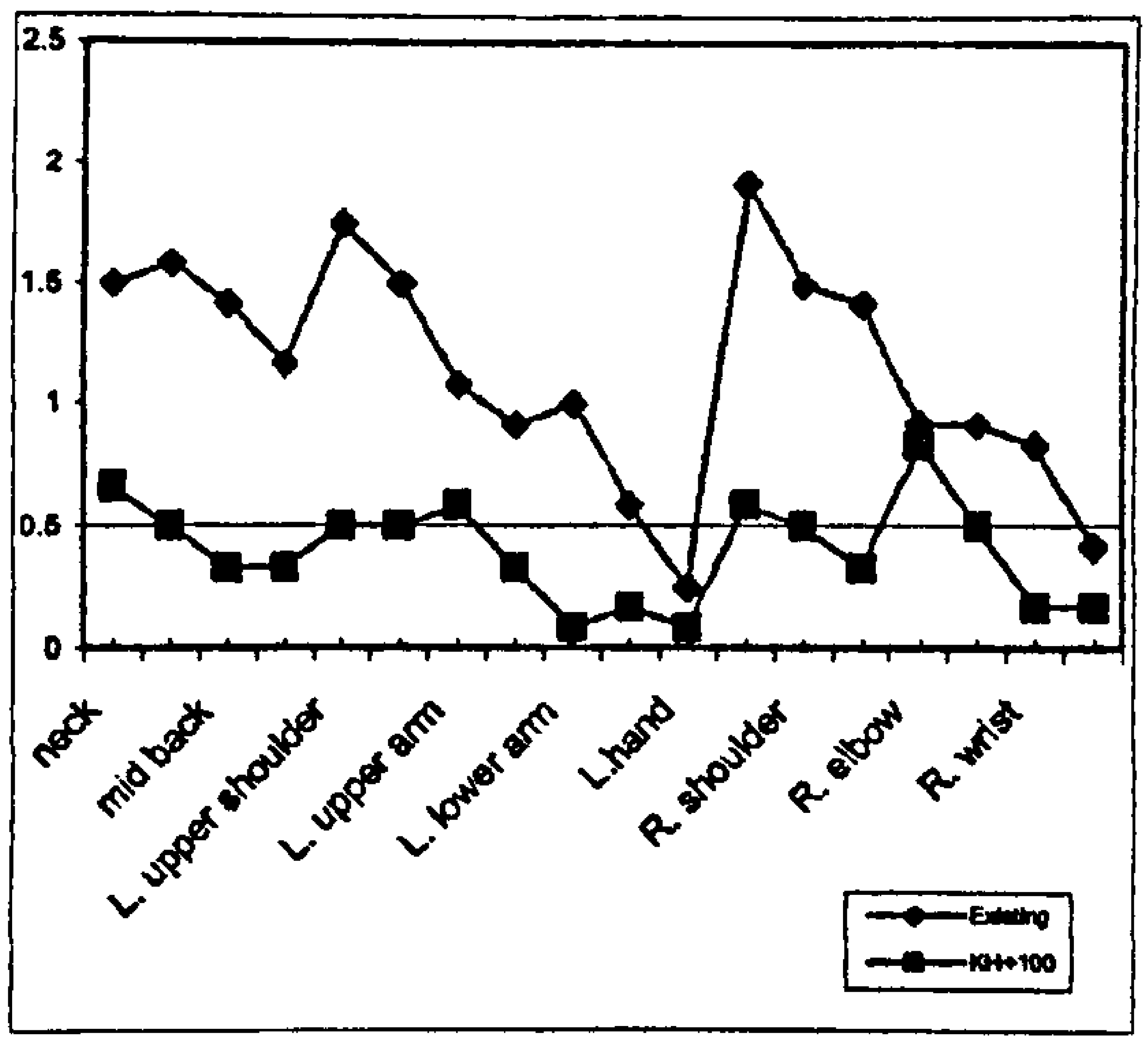

Figure 7. Mean BPD scores for existing workbench and preferred height (KH+100) on test workbench for wheel-chair users.

The BPD line graphs for the WU and SWU groups are similar and when subjected to comparative statistical analysis show no significant difference. The preferred height graph is very similar for both groups indicating a highly significant value for the SWU group of, $p < 0.001$ and for the WU group a value of $p < 0.001$. Therefore for both groups the identified, preferred working height of KH+100 significantly contributes to the reduction of BPD.

The visual inspection of both graphs, Figures 7 and 8 reinforce this.

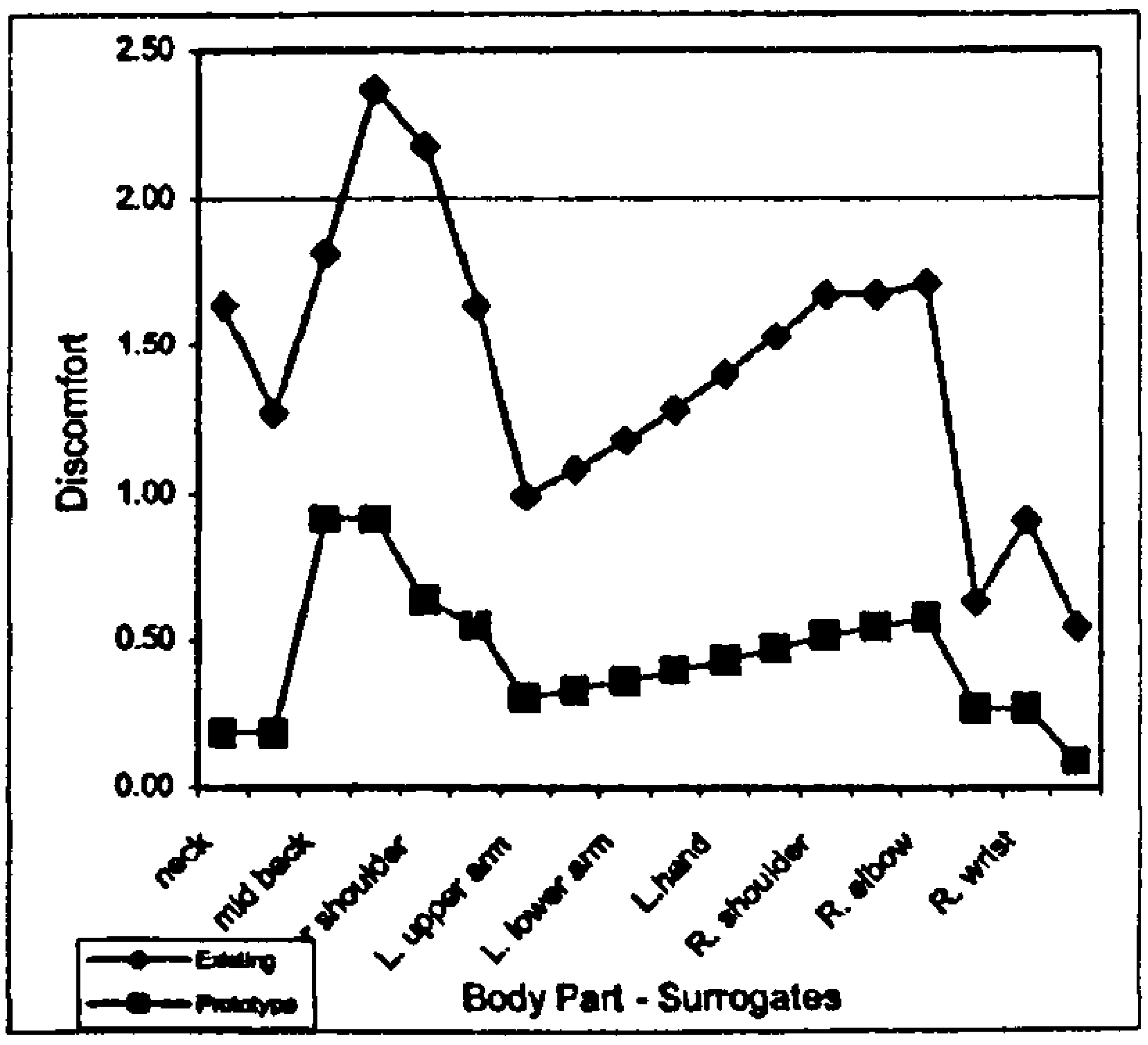

Figure 8. Mean BPD scores for existing workbench and preferred height (KH+100) on test workbench for the SWU group

The Wilcoxon test for both groups is shown below in Tables 6 (WU group) and 7 SWU group.

Table 6. Wilcoxon test results on the effects of workbench best-fit design on BPD – WU group

Body Part	Sig.	Body Part	Sig.
1	0.074	10	0.102
2	0.033	11	0.157
3	0.016	12	0.016
4	0.039	13	0.026
5	0.024	14	0.028
6	0.024	15	0.705
7	0.293	16	0.059
8	0.157	17	0.109
9	0.068	18	0.180

The results show that there was a significant effect on eight of the body parts tested, most notably all back regions and the shoulders, for the WU group and there were six body parts showing significant discomfort for the SWU group.

Five of the affected body parts are common to both groups, namely, 2,4,5,6 and 12. The neck did present a problem for the surrogates, but did not for the WU group. Parts 13 and 14 registered significant discomfort for the WU group but did not for the SWU group. The general discomfort for the total cohort is registered in the shoulders and back. Therefore the preferred height of KH+100 contributes to neutralising body posture for seated workers.

Table 7. Wilcoxon test results on the effects of workbench best-fit design on BPD – SWU group

Body Part	Sig.	Body Part	Sig.
1	0.011	10	0.059
2	0.026	11	0.102
3	1.000	12	0.023
4	0.027	13	0.068
5	0.017	14	0.102
6	0.008	15	0.109
7	0.058	16	0.257
8	0.066	17	0.059
9	0.102	18	0.059

3.3.5 The effects of working height on estimated endurance times

Figure 9 below indicates the mean estimated endurance times for the WU subjects while operating at various working heights. On the Y axis below 1 indicates **'less than two hours'**, 2 indicates **'two to four hours'**, 3 indicates **'four to six hours'** and 4 indicates **'six to eight** hours.

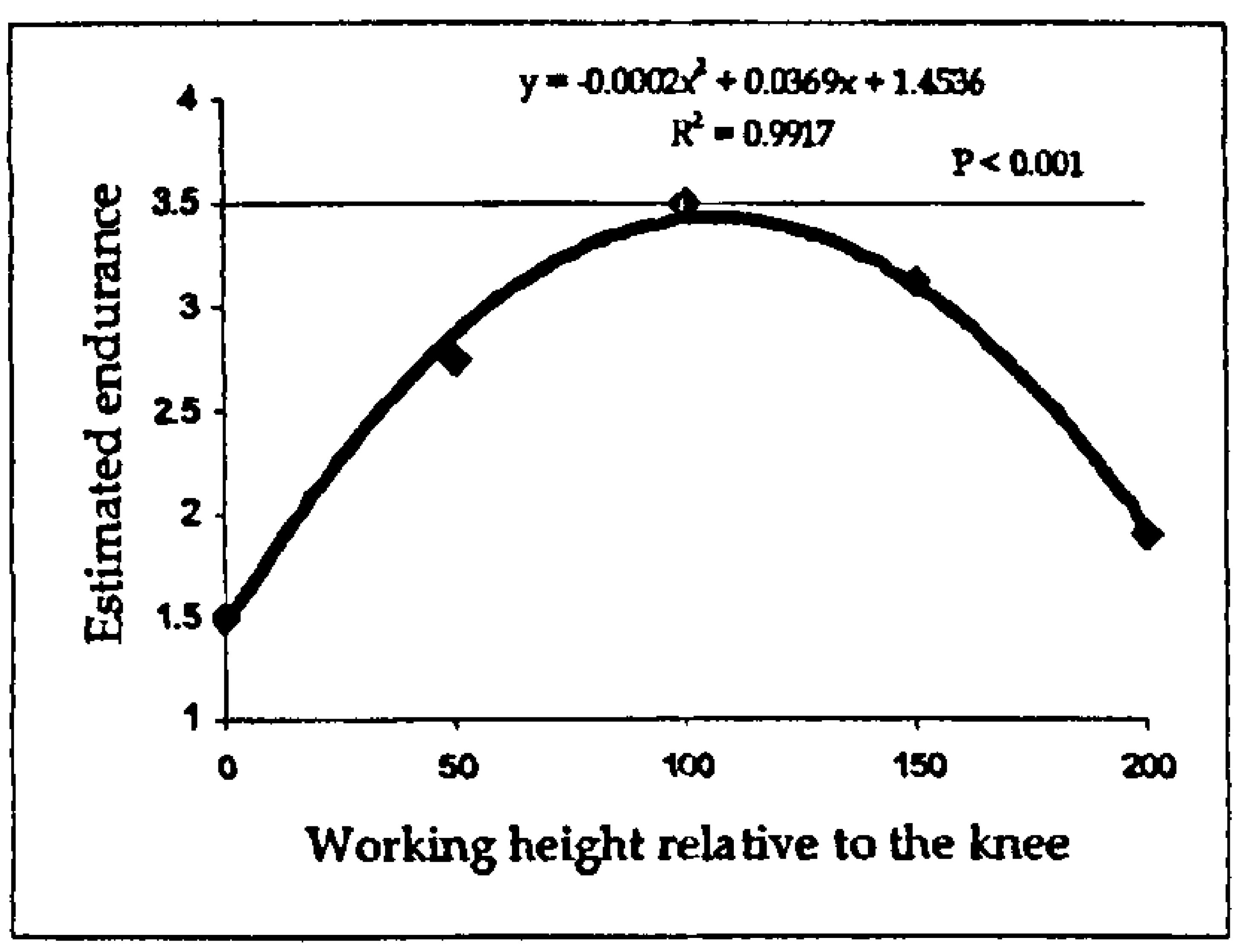

Figure 9. The relationship between bench working heights and endurance.

The quadratic equation added to the graphs, may be used to predict estimated endurance times relative to working height above the KH of the wheelchair user, as well as for surrogates. As there was found to be no statistical significance between the endurance for both groups (p >0.05), then it is appropriate to use surrogates to determine endurance. However differences in BPD may need to be considered as this might have a significant affect during prolonged activities. Apart from the statistical analysis (Non-parametric), a visual comparison of the endurance curves shows a very close similarity.

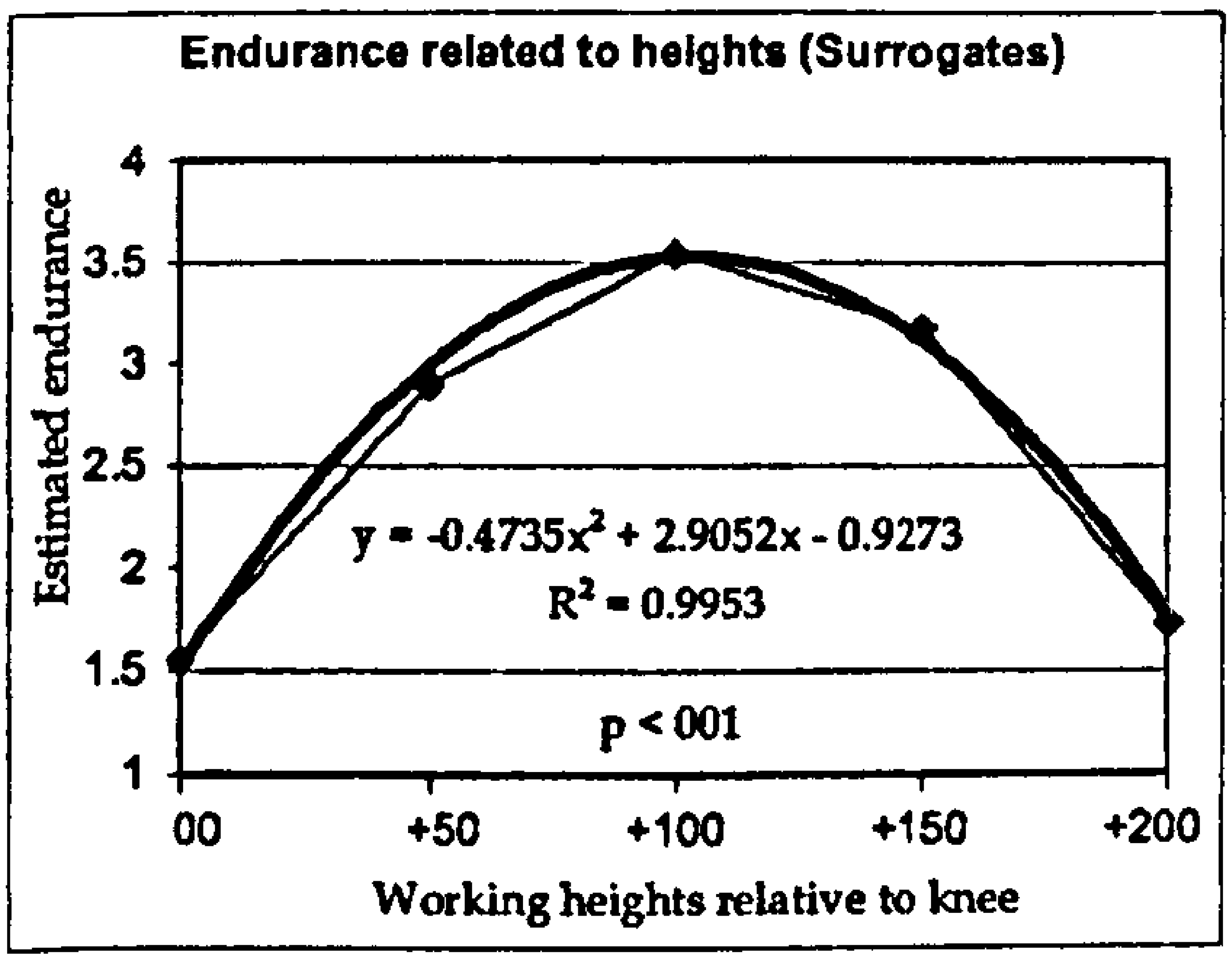

Figure 10. The relationship between bench working heights and endurance for SWUs

The data collected was based on the test-subjects estimated time, they felt they could spend doing the type of activity associated with the test bank. *A comparative analysis of the curves and their values show that there is no significant factor-of -difference between WUs and SWUs associated with endurance.*

Before analysing the data, it was tested for conformance to a normal distribution and equality of variance. As the results did not conform to a normal distribution, they were then tested using the Friedman test. These results showed that there was a highly significant difference between means ($p<0.001$). Figures 9 and 10 therefore suggests, that the further the height goes away from the optimum, the shorter the estimated endurance time.

A Wilcoxon test was carried out for individual pairs and showed that there was no significant difference between estimated endurance for KH+0 and KH+200(P=0.132), KH+100 and KH+150 (P=0.241) and KH+50 and KH+150(P=0.131). The results revealed that there was a significant difference between all other variables.

3.6 The effects of working height on completion time

Completion times were analysed to test if working height had a significant effect on performance. The assumption of normally distributed data was violated for all tests, except the Purdue pegboard (assembly). The large tapping task had to be normally tested using a natural log transformation, which confirmed normality. The Friedman Test was used to analyse the results for all tests and an ANOVA was used to analyse the Purdue Pegboard test and the large tapping scores. The results are shown in Table 8.

Table 8. Friedman test results of the effects of working height on completion time WU group

Test	Significance Value
Three Pin Plug Assembly (1 l)	0.062
One Hole Test	0.015
Small Tapping Task	0.062
Purdue Pegboard (D-H)	0.618
Purdue Pegboard (N-D)	0.513
Purdue Pegboard (both)	0.135

The data in Table 8 clearly illustrates that working height does not have a significant effect on completion time for tasks with the exception of the one hole test. There is however a significant improvement on completion times for both the WU and the SWU groups when comparing the existing bench rig with the KH+100 rig. Analysis of WU group data using Friedman test, produced a significance value of $p = 0.010$, and for the SWU group $p = 0.002$. There is therefore a significant improvement in performance for both groups at the preferred bench height, and the null hypothesis must be rejected.

3.7 Subjective rating of the working heights

Subjects rated the working height upon completion of all seven tasks, at each level. Figure 11 below shows the mean results of these ratings, for the WU group, using error bars with a confidence limit of 95%. Zero on the Y-axis indicates a working height of **'too low' 5 is 'adequate' and 10 is 'too high'.**

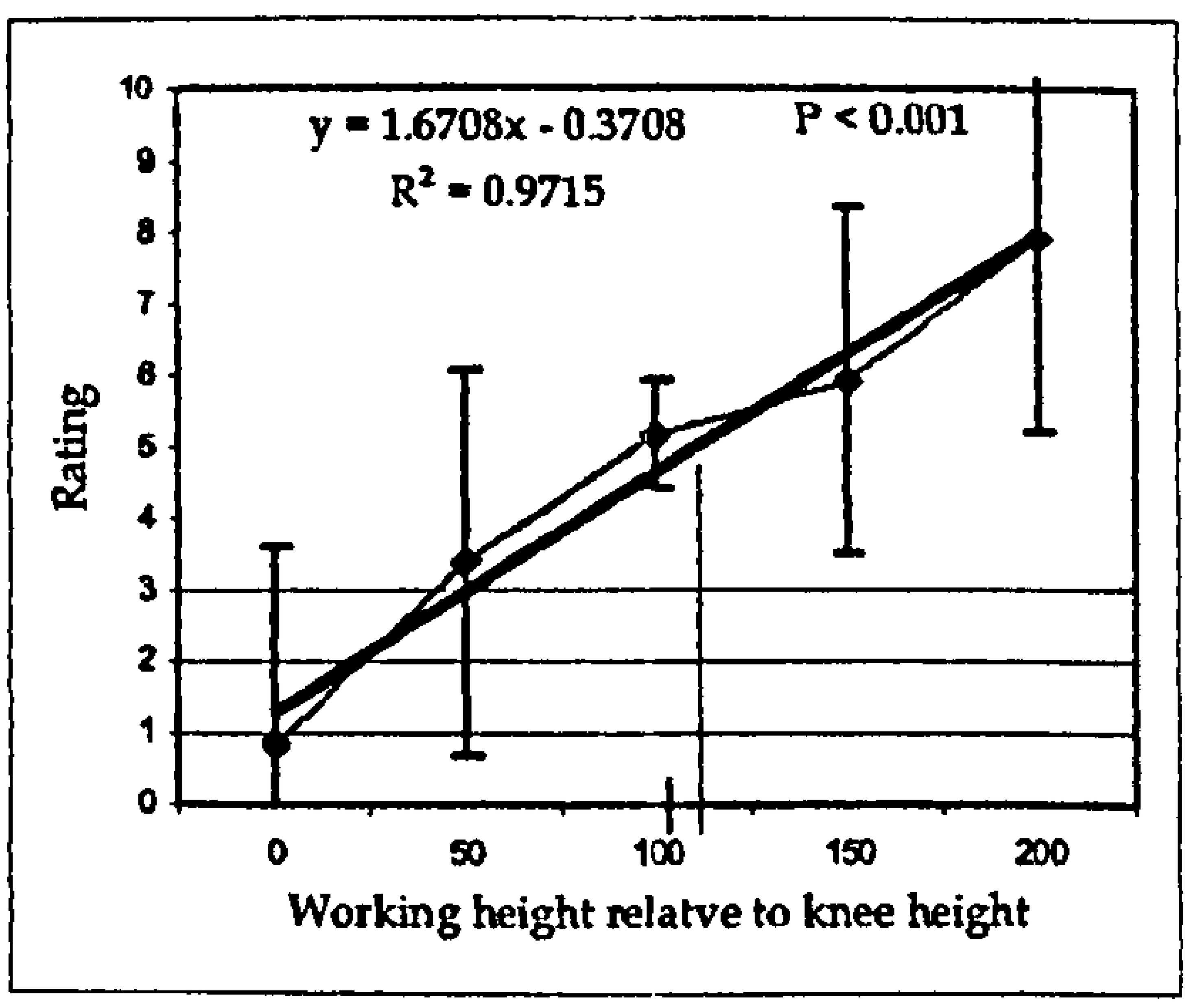

Figure 11. Working heights rating - WU test group

The first test used when analysing the results was to determine if the data was normally distributed. This was done by carrying out the Kolmogorov-Smirnov and Sharpio-Wilk tests which indicated that the results were not normally distributed ($P<0.05$). Therefore the results were further analysed using the Friedman test. These results indicated that the working height had a significant effect on the subjects rating ($p<0.001$) for both groups, as seen in Figures 11 and 12.

After the Freidman test, a Wilcoxon test between pairs of working heights was carried out to identify if there were significant differences between the ratings. The results identify that there was no significant difference between KH+100 and KH+150($P=0.054$) for the WUs and similar results for pairings for the SWUs. However, there was a significant difference between all others. The results suggest that there is a near perfect correlation between working height and rating as $r=0.988$ and a positive linear relationship exists.

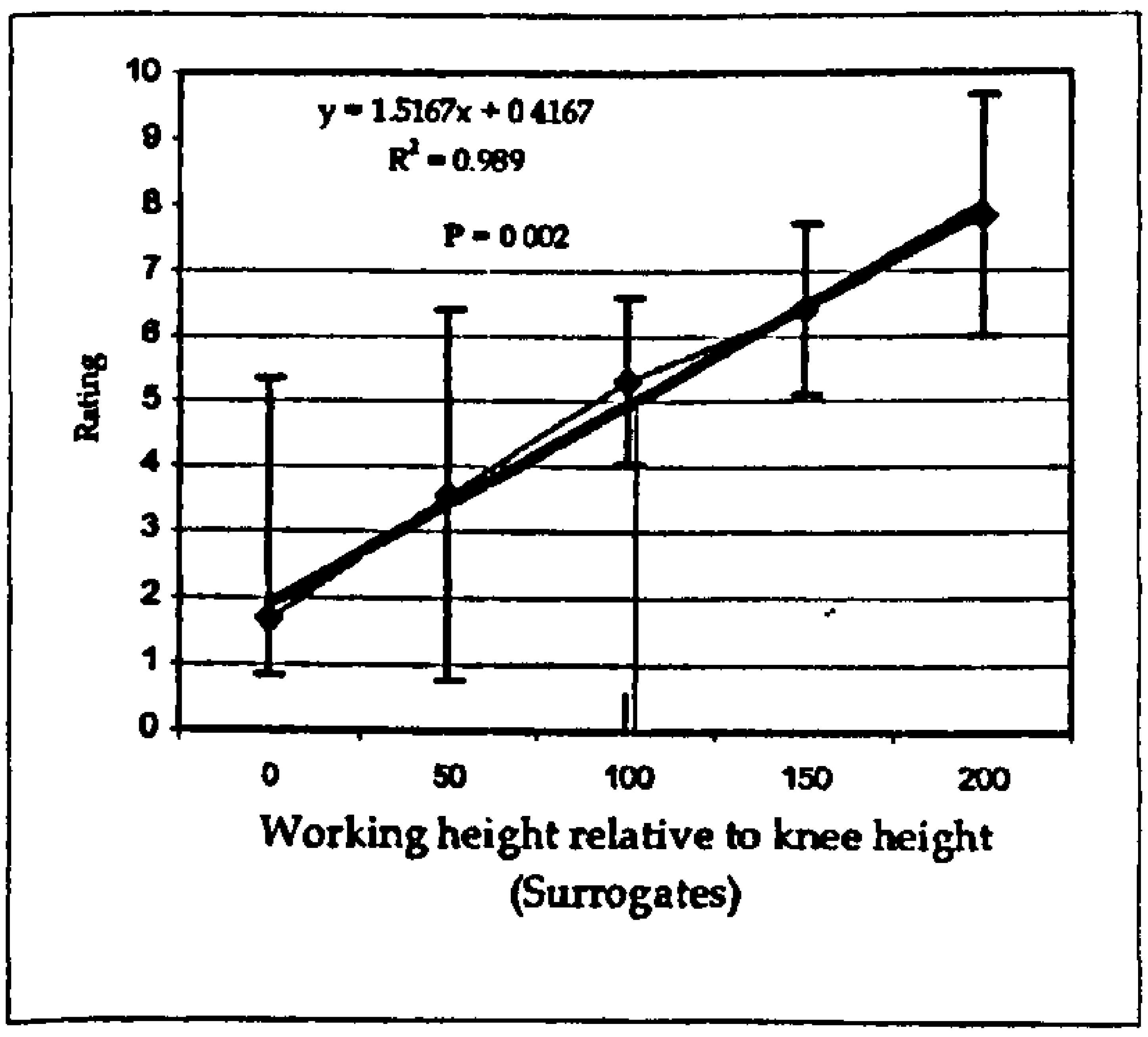

Figure 12. Working heights rating - SWU test group

The line, right of the +100 mark, indicates that just over this mark is the ideal for both groups with the preference for the WUs being slightly higher. *Overall, there is no necessity to apply a factor-of difference for working heights, between the two groups, as the subjective rating was almost identical for both.*

4. Existing workbench design vs. preferred working height on test workbench

As an optimum height was identified (KH+100), it is now possible to compare this height with the existing workbench, in order to analyse the effects of workbench design on BPD, completion times and estimated endurance time.

4.1 Estimated endurance times for existing workbench vs. preferred workbench height

The results of the mean estimated endurance time indicate that subjects will work on average two hours (1.75) on the existing workbench, while they will work six hours (3.5) on the new accessible height (100mm above knee level). A Wilcoxon non-parametric test was used to identify whether the populations had the same means. The results ($p=0.002$) indicate that the scores are not from the same population resulting in a significant difference between the scores. This indicates that there is a positive increase in working time as a result of working at KH+100 on the newly designed workbench.

4.2 Productivity of comparisons for existing workbench and preferred height workbench

Comparisons were made for the 'existing workbench' scores, the 'best-fit' workbench scores, in order to compare the effects of workbench design on productivity.

The completion times were analysed first, to test for normality of the data. For all but three of these, the Kolmogorov-Smirnov and Sharpio-Wilk tests indicated that the results were not normally distributed. Accordingly, these results were further tested using the Wilcoxon test. For the other three the Kolmogorov-Smirnov and Sharpio-Wilk tests indicated differences of significant level. As a result, a natural log transform of the data was applied. This indicated that the 'large' and 'small tapping' tests were normally distributed and the 'one hole' test was not normally distributed. Therefore a paired sample test, a 't test' was applied to the natural log results for small and large tapping tasks, while a Wilcoxon test was applied to the natural log values data for the one hole test.

The results indicated that productivity has increased in all tasks with the largest increase being for the three-pin plug assembly. The results of all tests show that there was a significant difference for all completion times, with the exception of the grooved pegboard, as a result of working on different workbenches. This indicates that productivity has increased as a result of identifying a best-fit workbench height at KH+100.

A similar increase in productivity was established for the SWU group at the KH+100 bench height. The improved productivity for the three pin electric plug was highly significant for both groups. The raw score for the WU group for this element was better than that of the surrogates.

5. Discussion

The research set out to establish a best-fit datum for working heights for wheelchair users at industrial tasks and to determine if surrogate wheelchair users may also be used in establishing the data. The following conclusions were seen as significant.

- The most appropriate height for wheelchair users (including surrogate wheelchair users) was found to be at Knee Height plus 100 millimetres, i.e. KH+100.
- Working at this height improved productivity and reduced body part discomfort.
- An endurance curve and equation has been devised which will allow the calculation of estimated endurance for a range of heights.
- Moving from the identified optimum in either direction will result in reduced endurance times and increased body part discomfort.
- The comparisons between working at the existing/traditional engineering bench, and the best-fit KH+100 bench produces highly significant statistical evidence of reduced body part discomfort, and improved productivity and work endurance times.
- There was a distinct correlation between the WU group and the SWU group in nearly all facets of the test results, with the exception of some elements of BPD. There was however, a very good match, in the BPD analysis of back and shoulders for both groups.
- There appears to be no reason why surrogate wheelchair users may not be used as substitute test subjects in research relating to bench design to accommodate wheelchair users at industrial tasks. The research shows that the test subject group may be mixed.

The combined group of WUs and SWUs have not been analysed as a whole. However the findings show that the can be. This will increase the test cohort for the overall research. It will also allow easier access to test suitable test subjects. *The research has significantly extended ergonomic data for wheelchair users at work- benches.*
All the surrogates stated that they now had much greater empathy with wheelchair users, in issues relating to accessibility.

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Inclusive Design Ergonomics for Workbenches

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Abstract

Industrial workbenches have developed over the centuries so that today we have a variety of 'standard' bench-types, categorised according to their use. This type standardisation, whether in an industrial or in an educational setting, means that regardless of stature, the users are forced to work at a height level which might be quite uncomfortable, thereby reducing efficiency and which over time may lead to repetitive strain injury. This research investigates how a means of providing best-fit workbenches may be devised. In endeavouring to be fully inclusive the objective of making a best-fit bench available to all is considered. This means including people in a seated position (wheelchair users) and ambulant users who may be of short or tall stature. This paper examined best-fit ergonomics for workbench users in engineering environment. A best-fit working height has been established through a comparative analysis of the ergonomic data for working heights, which minimises body part discomfort (BPD) and maximises endurance. Functions, which may be used as indicators for BPD, Endurance and Subjective height, have been established. The best-fit workbench greatly reduces BBD and is therefore likely to make a significant contribution to the reduction of RSI for such operatives. Gender differences are also considered. A universal auto-adjustable workbench has been designed which can accommodate a broad range of users.
Key Words: *Inclusive design, Workbench ergonomics, Body Part Discomfort, Best-fit work heights.*

Introduction

Musculoskeletal disorders (MSDs) are one of the most common work-related ailments affecting millions of European workers, incurring costs of billions of euro to the EU economy. The main group is back pain/injuries and work related upper limb disorders commonly known as repetitious strain syndrome (RDS or RSI – Repetitive Strain Injury). Unless effective steps are taken the workforce suffering will increase and the cost to the economy will continue to rise. (EASHW 2000). In the USA the situation is similar. In Washington State alone, from 1992-2000 there were 380,485 compensations paid for MSD's relating to the neck, back and upper extremities. The result, in addition to the pain and discomfort was $2.9 billion in costs, (Washington State Department of Labor & Industries, 2001). In Canada the reports on MSD's and RDS's paint the same picture. The Canadian Centre for Occupational Health and Safety (CCOSH) reports: "When job design ignores the basic need of the human body (and individual workers), work can cause discomfort in the short term and eventually lead to severe and chronic health problems, (CCOSH, 1998).

On August 3rd 2001 in a letter responding to the US OHSA's regulatory approaches to address 'ergonomic hazards' the Independent Lubricant Manufacturing Association (ICMA) said that the OSHA had failed to identify what were 'significant risks' and stated that scientific knowledge had yet to identify a 'close – response relationship' between risk factors and biophysical effect, e.g. force repetition and awkward postures' (Metallo, M.C. 2001).

Using a term like 'ergonomic hazards' is like using the term 'safety hazards'. Design ergonomics are used to identify and reduce hazards, and these workplace hazards abound. One element that requires much ergonomics intervention is the workstation, traditionally known as the 'workbench'. These have been a very important part of the equipment in engineering shops, carpentry and joinery and cabinet making shops for centuries and even millennia. Yet it is the piece of equipment, which changes least. Evaluating a large number of benches for this project revealed that the height range for workbenches varied only 60mm, from 800 mm to 860 mm, however the users height range was up to 500 mm (20 inches). The prime objective of this research was to examine workbench design ergonomics in the context of Universal Design i.e. to make the design of the workbench as inclusive as possible. This means including the 5th and the 95th percentile or perhaps as Dreyfuss (1993) suggests 'the 1st and 99th percentile'.

This research project covered a broader range of workbench users, 12 to 18 year olds, adults and wheelchair users. However this paper is concerned with adult users and wheelchair users/surrogate wheelchair users. While some general guidelines, have been established for standing work (see Figure 1), there is little or no design ergonomic data established for task-related bench processes relating to engineering or woodwork bench processes.

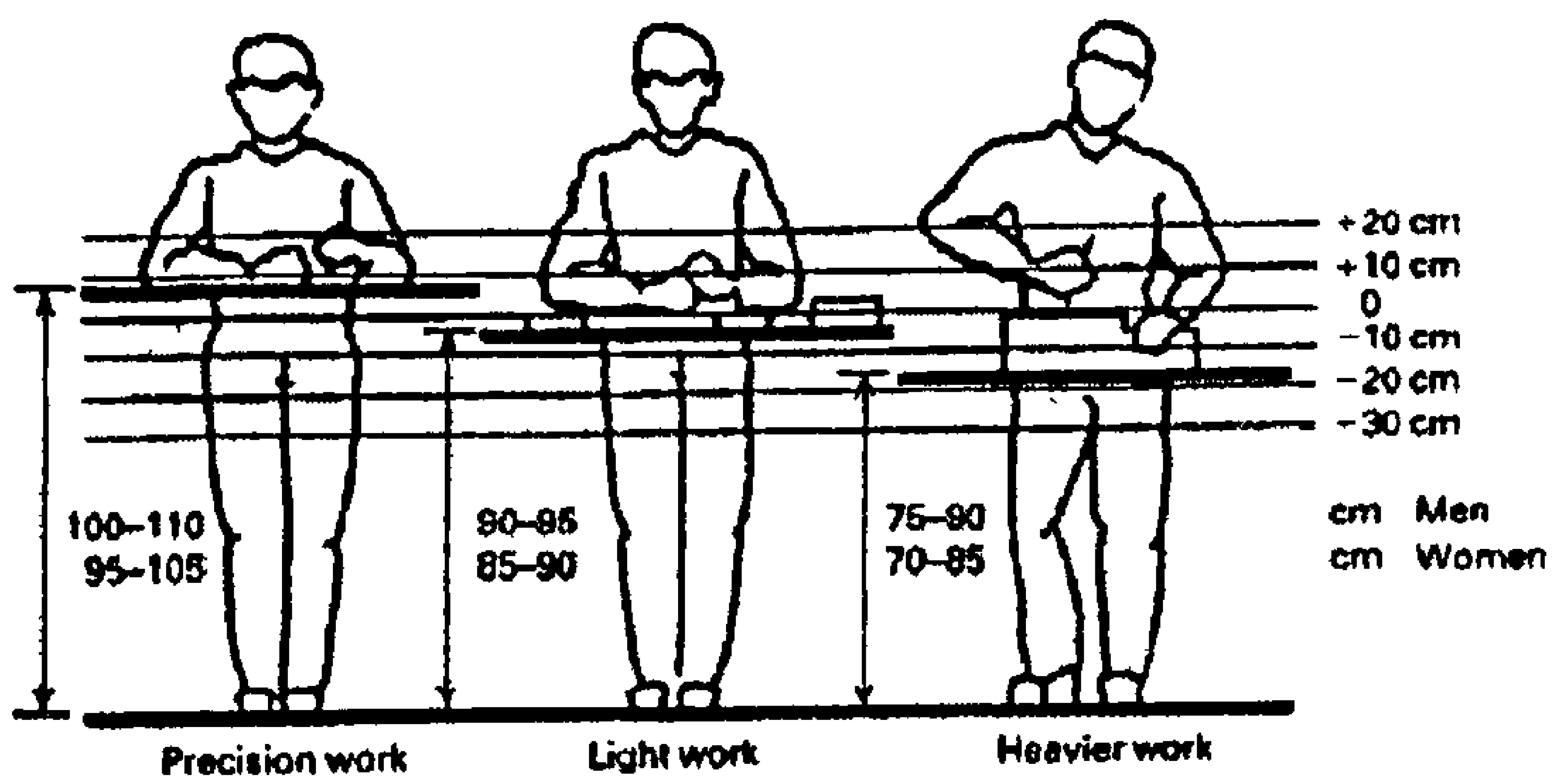


Figure 1: Work heights from Kroemer and Grandjean, 2000

All test groups, addressed in this paper are for adult workbench users. These were divided approximately 50% male and female. The ambulant adult test group consisted of twenty adults, ten male and ten female. Average age: 28 (male: 31, female: 25). All subjects had experience at bench work processing, and all were volunteers.

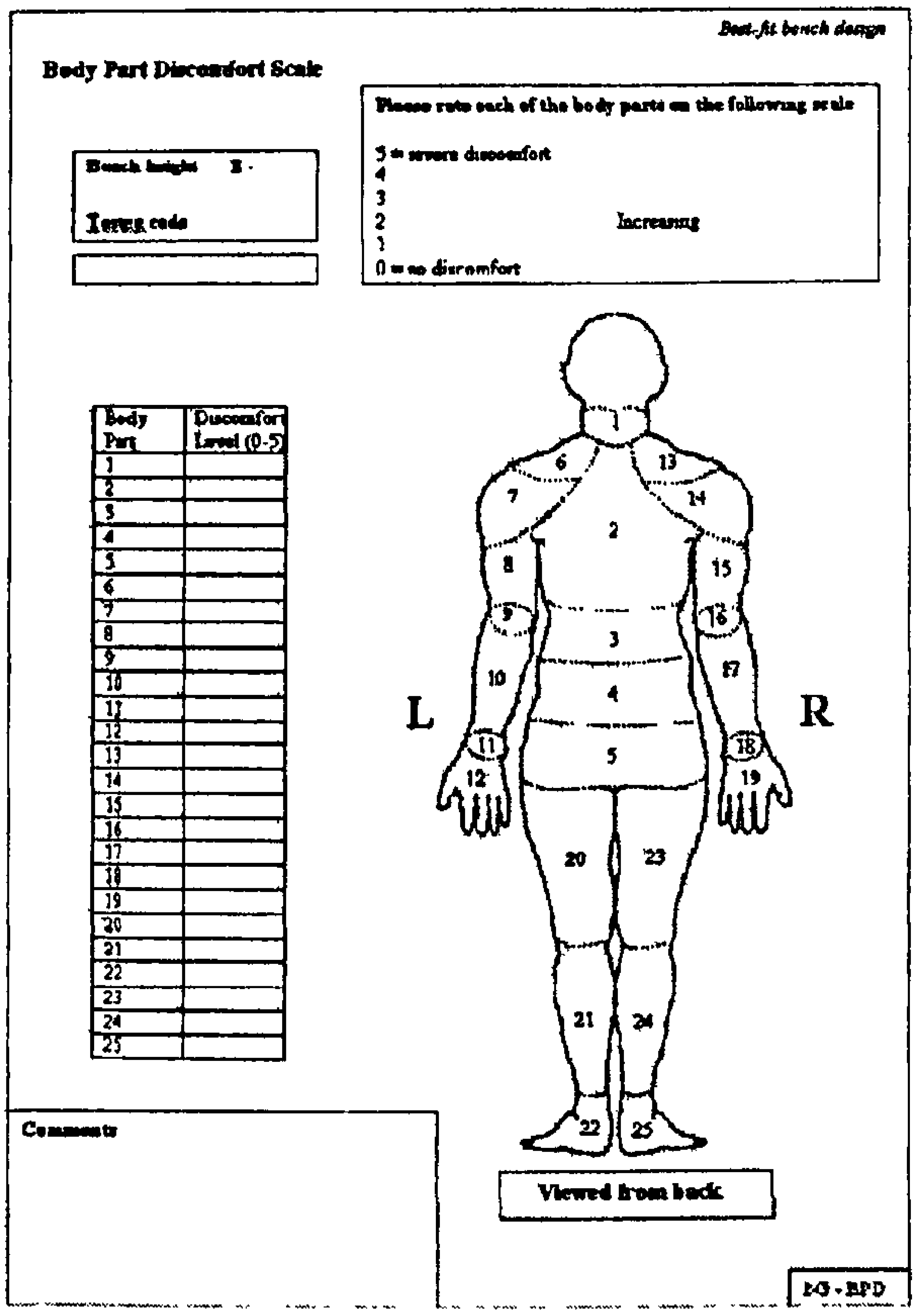
Design of Experiments

Ten experienced bench users (ranging from 10-40 years experience, with an average of 25 years experience, on engineering and woodworking disciplines were interviewed to determine the most common bench processes. Including 'marking-out' the top processes identified were: wood planing, metal filing, wood sawing, metal sawing and assembly (common to both disciplines). These five processes made up the test bank for the experiment. The range of bench heights would relate, as is common practice, to the subjects elbow height (Das & Arijit 1996, Kroemer & Grandjean, 1997). A pilot study, using five experienced bench users tested heights ranging from elbow-height to 350 mm height below elbow-height. The heights were set at 50 mm intervals. All pilot test subjects agreed that the elbow height and elbow height minus 50 were too high for the test bank and that 350 and 300 mm below elbow height were too low. As a result the complete test would have five heights elbow – 100 (E-100, E-150, E-200, E-250 and existing bench height (800 mm). In some instances the latter was well in excess of 400mm below elbow height. The existing bench height, while fixed, would vary in relation to the subjects elbow heights.

All the test bank elements were timed with a stopwatch and the height levels and test elements were randomised using the Latin Square Order. The tests would measure body part discomfort (BDP) subjective height evaluations, estimated endurance scales and efficiency.

A body map based on Corbett & Bishops model 1976 (see figure 2) was used for BPD evaluation. Comfort levels ranged from 0 (none) to a 5 rating (severe discomfort), for subjective height rating a linear scale 0-10 was used, working above and below 5, above to high and below too low and 5 being satisfactory. Endurance was measured on five levels: 5 less than 2 hours, 4 - 2 to 4 hours, (see figure 3). The extent of each process was set to allow the complete test bank to be complete in 1.5-2 hours. This included marking out for the wood and metal processing elements. The assembly task consisted of assembling three electric (9 part) plug tops, using a part-bin arrangement and an assembly fixture.

An auto-adjustable test rig bench was built using a telescopic column with a rack and pinion movement, powered by an electric motor and controlled with push-button rise and fall switches. The test bench had a load capacity of 2000n and had surface dimensions of 1500m x 800mm. A low-level, 90mm engineering vise was fitted. This was a compromise height, which mediated between the 'flush' woodworkers vise and the 180mm engineering vise.



Analysis of Test Results:
The test data gathered was analysed using Excel and SPSS,

Figure 2: Body part discomfort map and record table – adapted from Corbett & Bishops, 1976

Body Part Discomfort Analysis.

The objective was to analyse which height produced the best-fit ergonomic position as regards comfort. This was analysed in two ways to examine the discomfort relating to the 25 body parts and to determine at which height the discomfort was least. Figure 3 shows the graph produced for the discomfort of the 25 body parts.

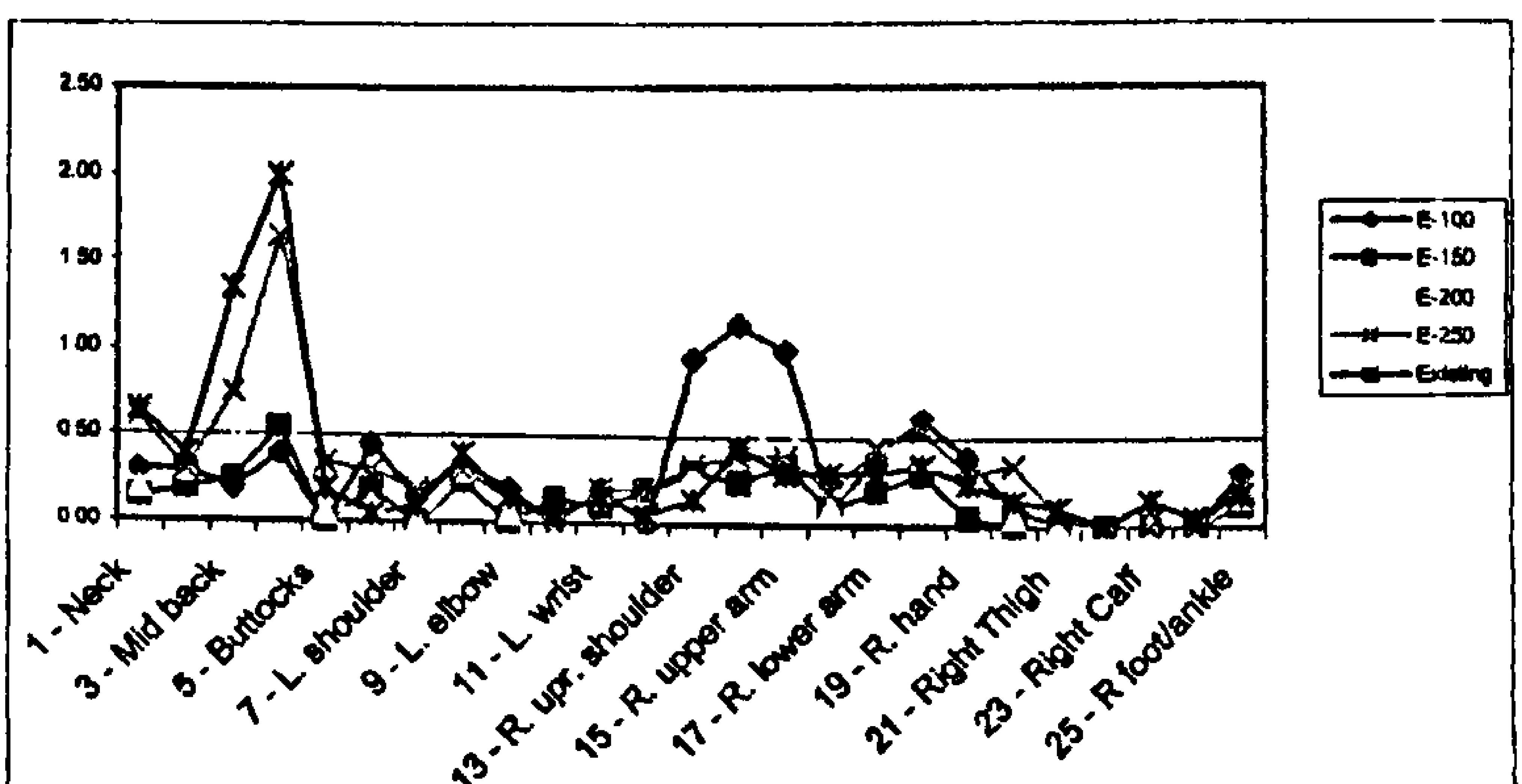


Figure 3: BPD for all subjects at five heights

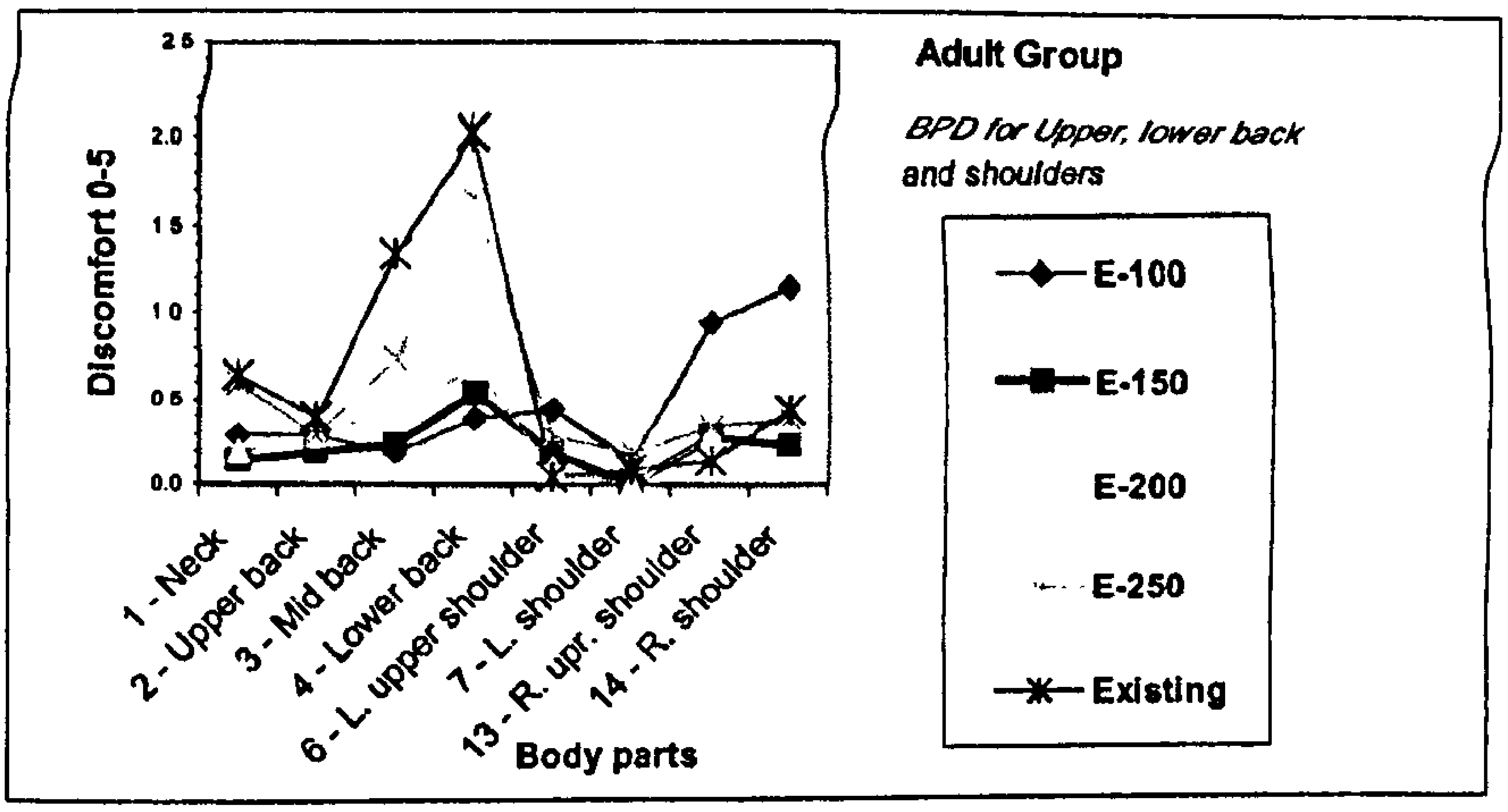


Figure 4: BPD Neck, Back and Shoulders

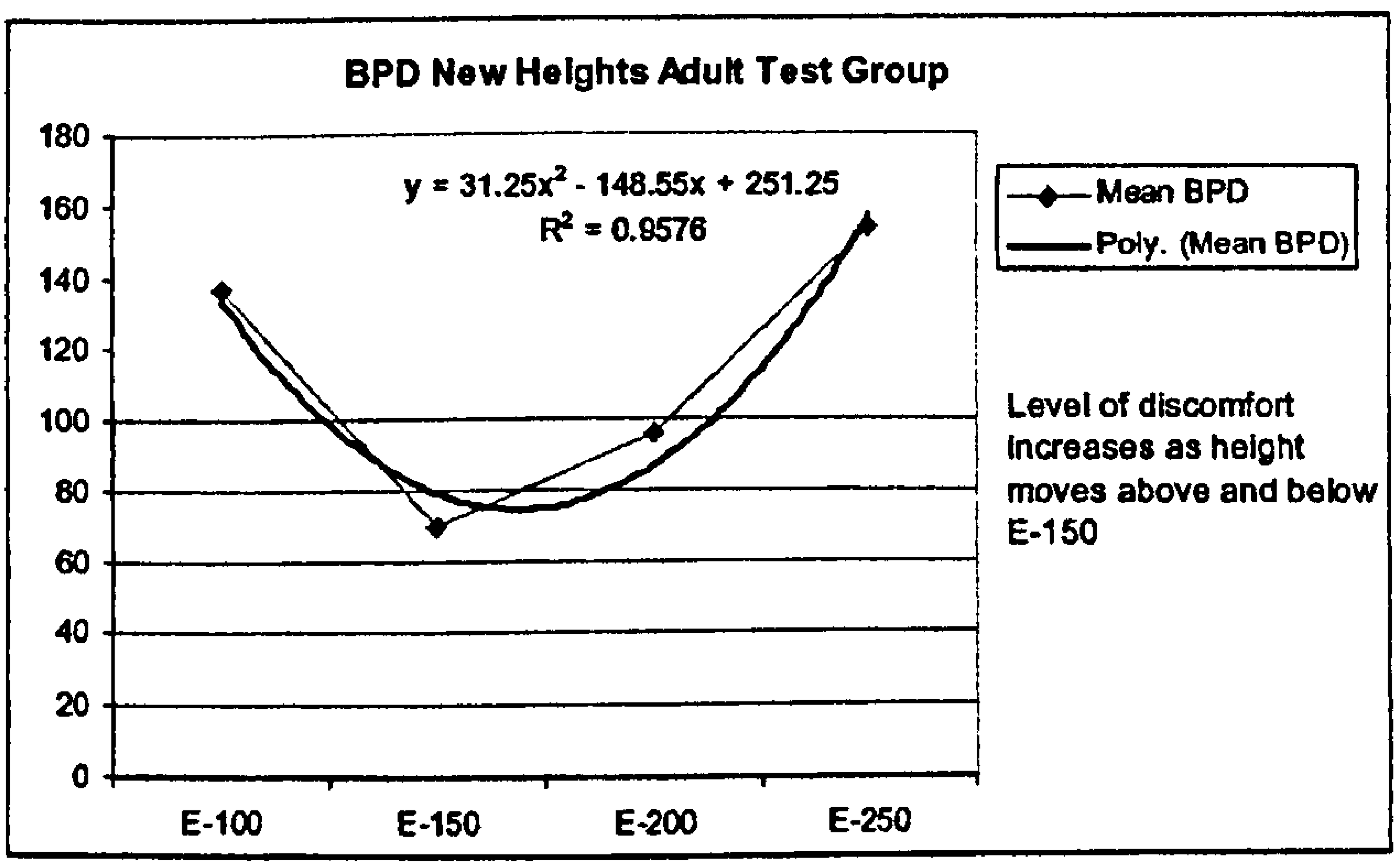


Figure 5: The Quadratic Function Discomfort Indicator – the 'QFDI'

Figure 4, focuses on the areas most affected. The back discomfort is reduced while other areas increase slightly at E-150, however this is not to a significant degree. This is further amplified by the graph on aggregate discomfort, Figure 5. While individual body parts are normally used to express BPD, there appears however to be a good case for scoring aggregate discomfort as a general discomfort indicator. This also takes into account the necessity to find a compromise, such that there is no significant discomfort in any one area. A quadratic equation allows the calculation of a 'discomfort indicator' for any height the R^2 value is high and the P value, of $P =< 0.002$ is highly significant. We may therefore refer to this approach as the 'Quadratic Function Discomfort Indicator – the 'QFDI' for any given height within the range.

The graph shows that the E-150 produced the least amount of discomfort. The existing bench height (800 mm) produced the greatest discomfort bur there was not a significant difference between it and E-250. At heights E-100 the discomfort increases on the shoulder and arms but not to a statistically significant degree. The curve also indicates a robust position that can move 50 mm below E-150 but it is not so tolerant above E-150. Figures 6 & 7 show the discomfort comparisons between males and females. The graphs show that there are significant increases in BPD for both, but with less tolerance for the E-100 level.

Analysis of the BPD data, for the female adult sub-group show that there are significant differences between heights, with the least discomfort at level E-150 (see Figure 6). The data reveals a sharp rise in discomfort at E-100; this was concentrated in the shoulder and upper arms. The height range from E-200 to Existing bench height produced the greatest discomfort in the lower back region. In examining BPD for the existing bench height, the level of discomfort is lower than that for E-250. This resulted from the mean distance below elbow, for the existing bench, being less than the E-250 level, at a mean of 237mm. Only one female subject found the existing bench height to be ergonomically acceptable, her stature was 1580mm (5' 2.2") and her elbow height was 995mm.

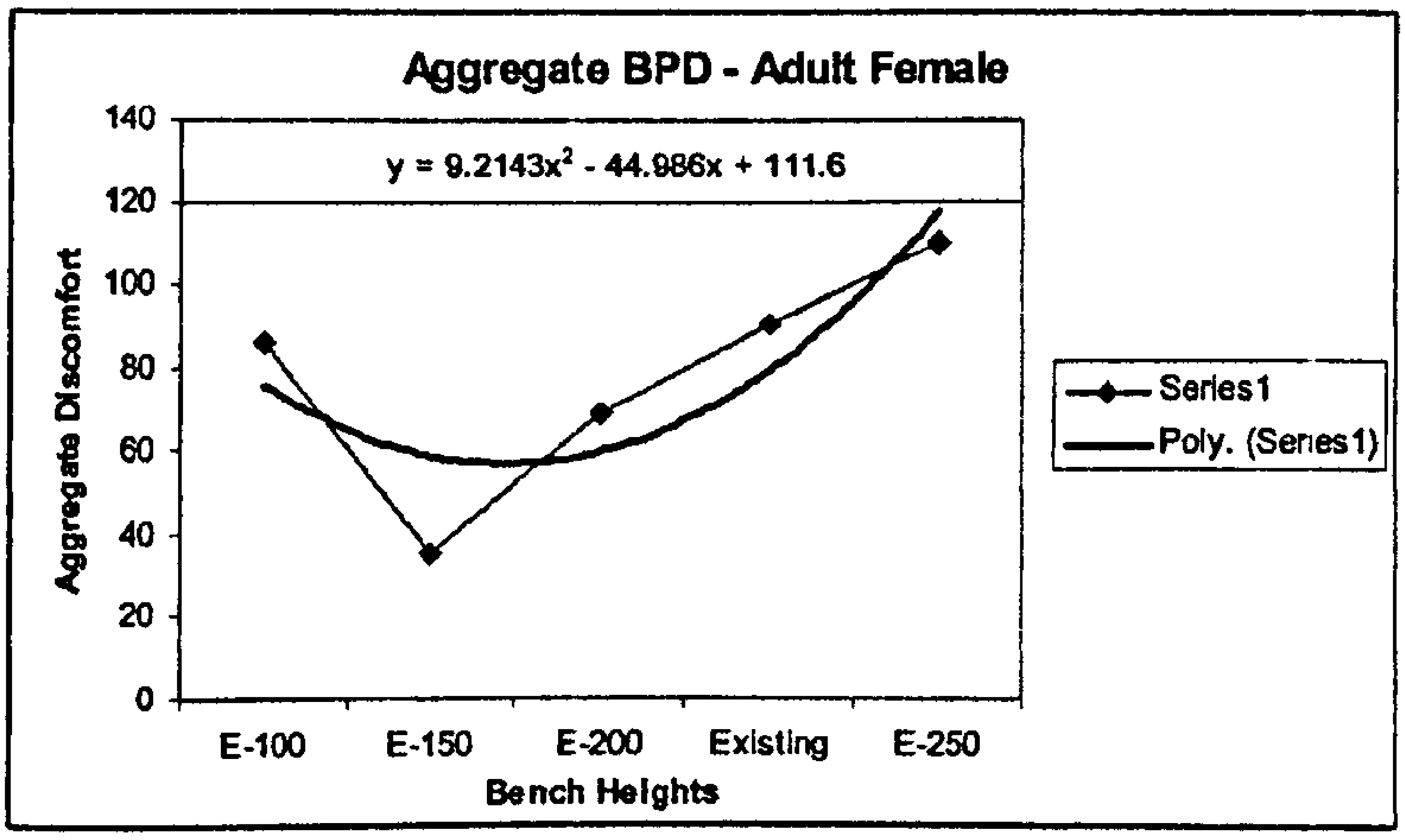


Figure 6: Adult female aggregate BPD with QFDI

Analysis of the data for the male adult sub-group show that there are significant differences in comfort levels for each of the bench heights. The greatest level of discomfort was at the existing bench height, which was at a mean distance of 336mm below elbow. The least discomfort was recorded for E-200 and examination of the quadratic curve shows that there is a robust position ranging between E-150 and E-225, with little compromise on discomfort levels. However the curve for female BPD shows less tolerance to heights above and below the identified optimum, allowing only 25mm above and below E-150 for a 10-point increase in discomfort. The discomfort also rises to only 35, less than a 10-point increase for a more robust position. While aggregate BPD for both sub-groups is statistically significant between levels, the upper limits for females is significantly higher and the position of least BPD score for the male sub-group is much lower than for the females. The difference between means for male and female was 99mm.

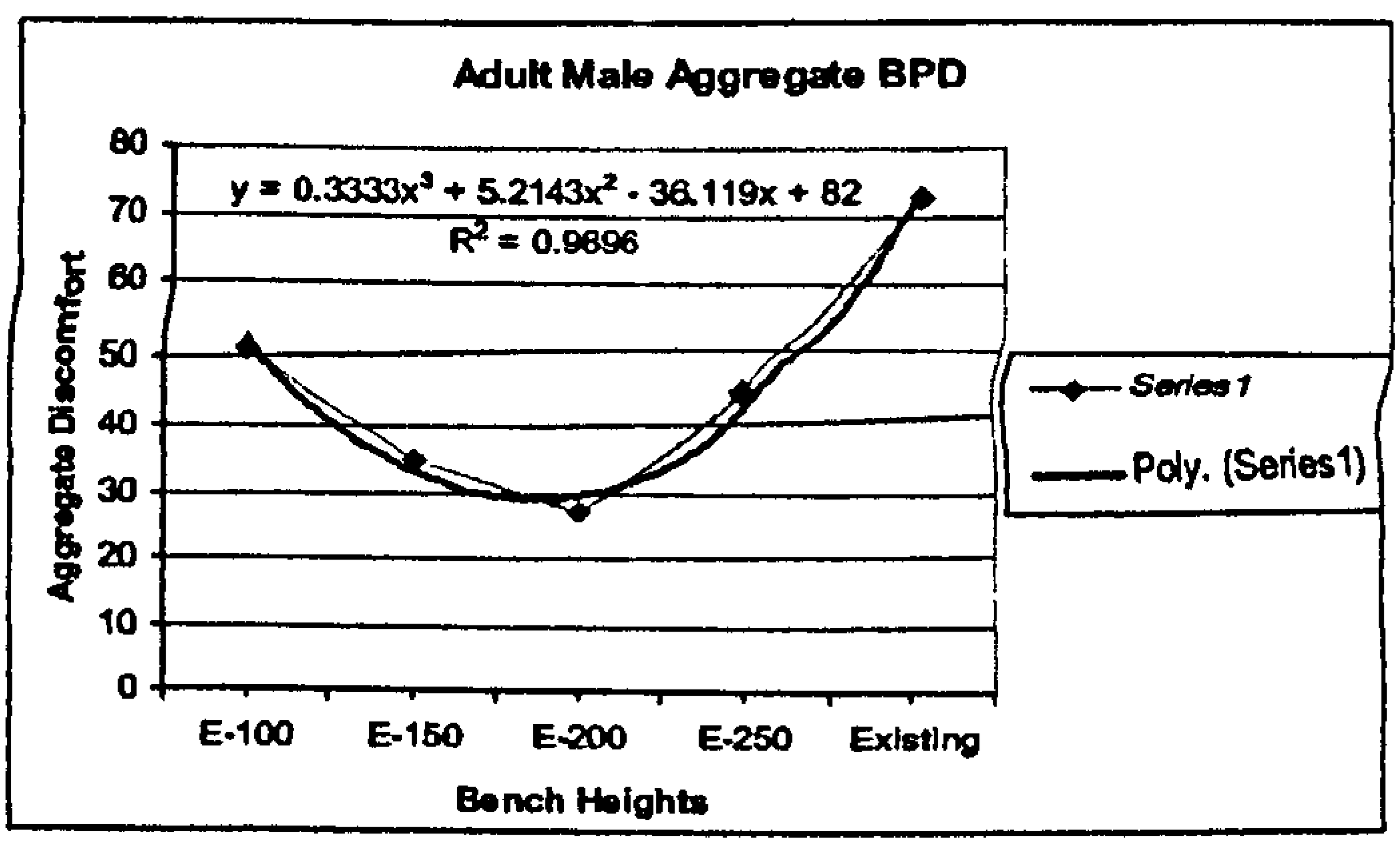


Figure 7: Adult male aggregate BPD with QFDI

We may therefore conclude that female adults record a higher level of BPD at all levels of the bench heights for the processing test-bank used. They were also more tolerant of the existing bench height, when compared with the other heights than were the males, but recorded a higher BPD for that level. While both sub-groups recorded significant BPD differences between levels the female discomfort was more acute.

Endurance Ratings

Subjects gave a subjective estimate of endurance after completing the test-bank at each height level. They were asked to estimate how long they could do work of the kind associated with the test-bank. The ranges were from 5 to 1 as seen in Figure 8. The difference in endurance is highly significant. Height E-150 produced the best results with a mean value under 3, converting to greater than six hours endurance. The endurance falls sharply as the height moves above and below E-150. There was no significant difference between E-100 and the existing bench height.

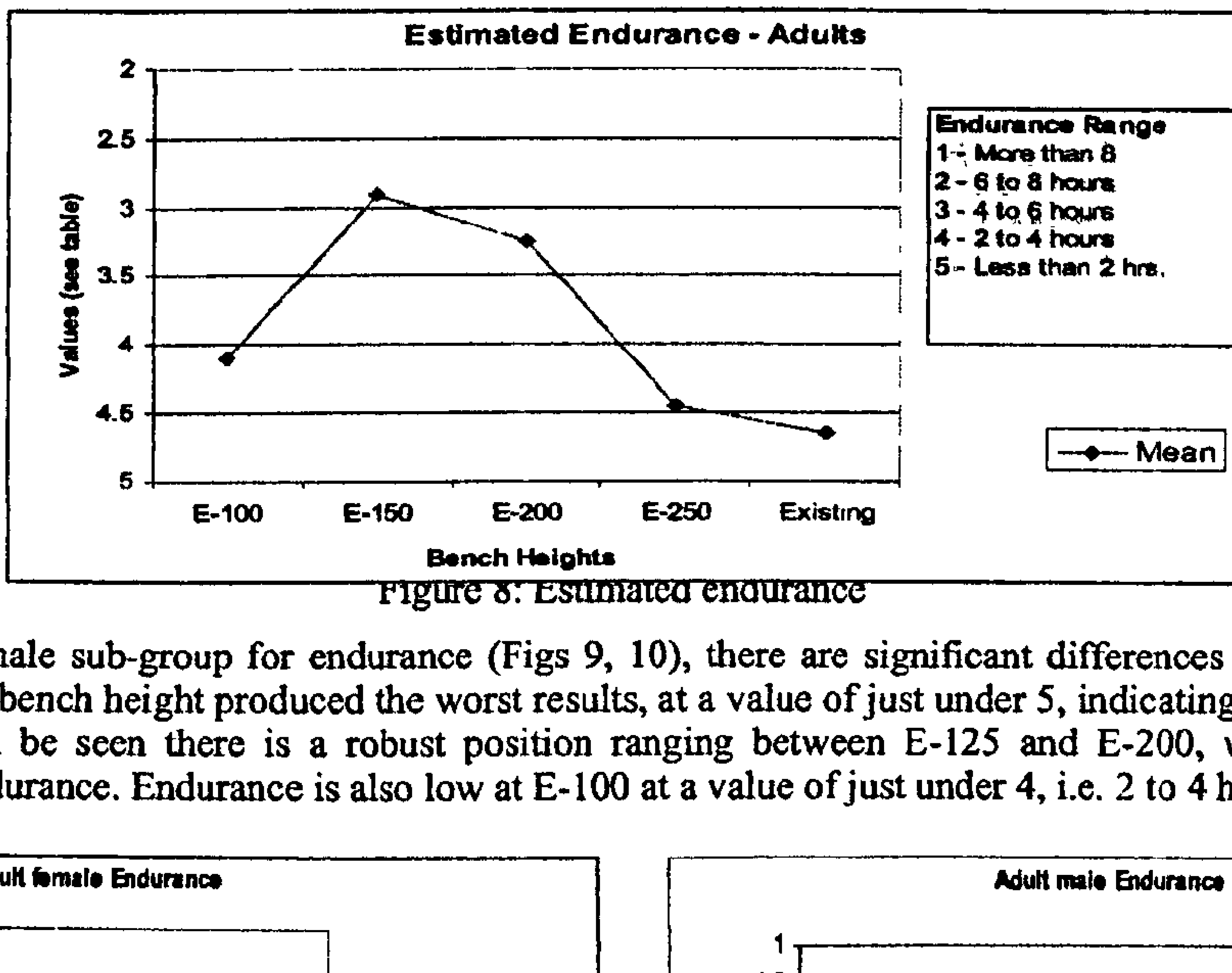


Figure 8: Estimated endurance

Looking at the female sub-group for endurance (Figs 9, 10), there are significant differences according to height level. The existing bench height produced the worst results, at a value of just under 5, indicating less than two hours endurance. As can be seen there is a robust position ranging between E-125 and E-200, where there is little compromise on endurance. Endurance is also low at E-100 at a value of just under 4, i.e. 2 to 4 hours. Again the

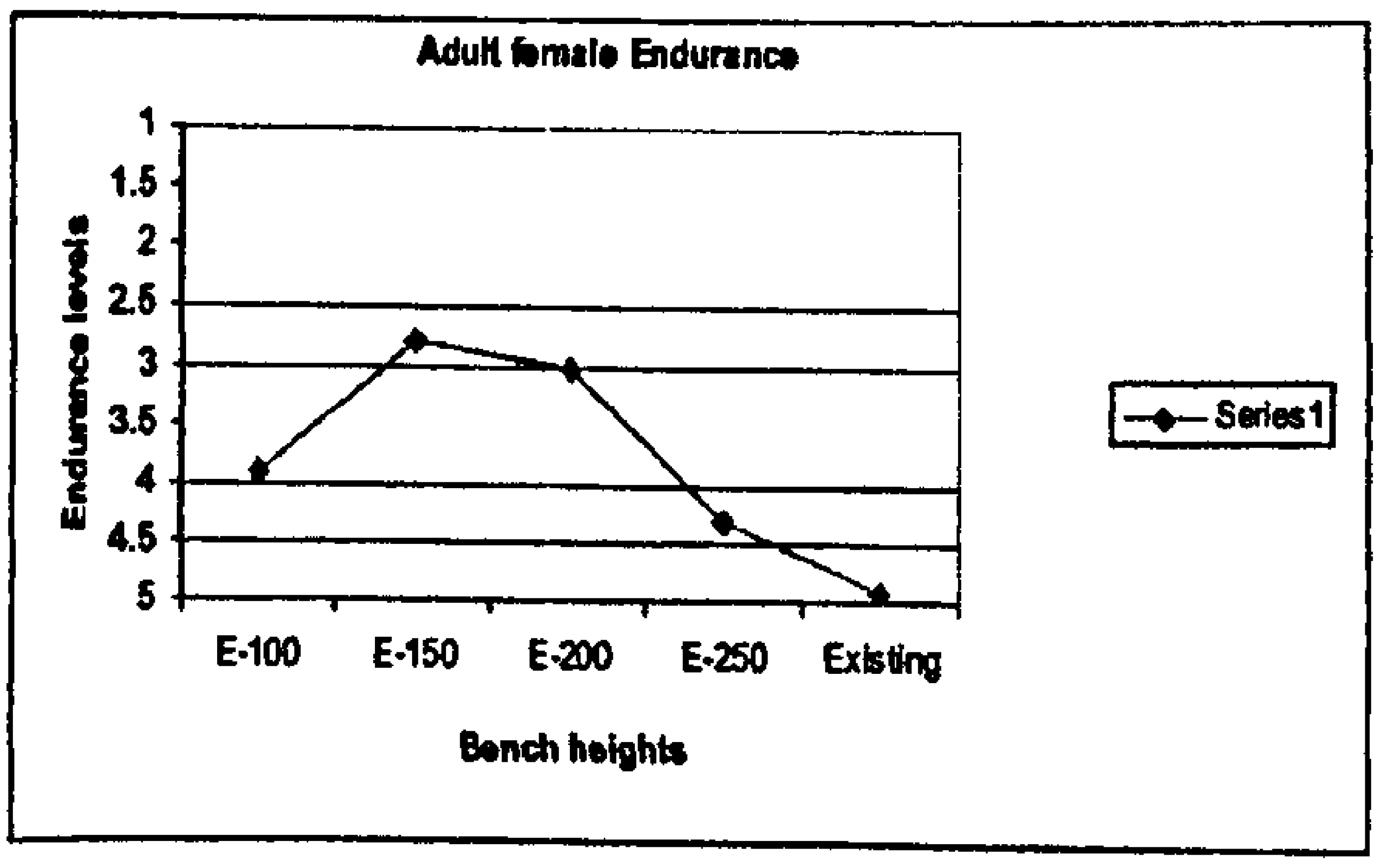


Figure 9: Estimate endurance – Female Adults

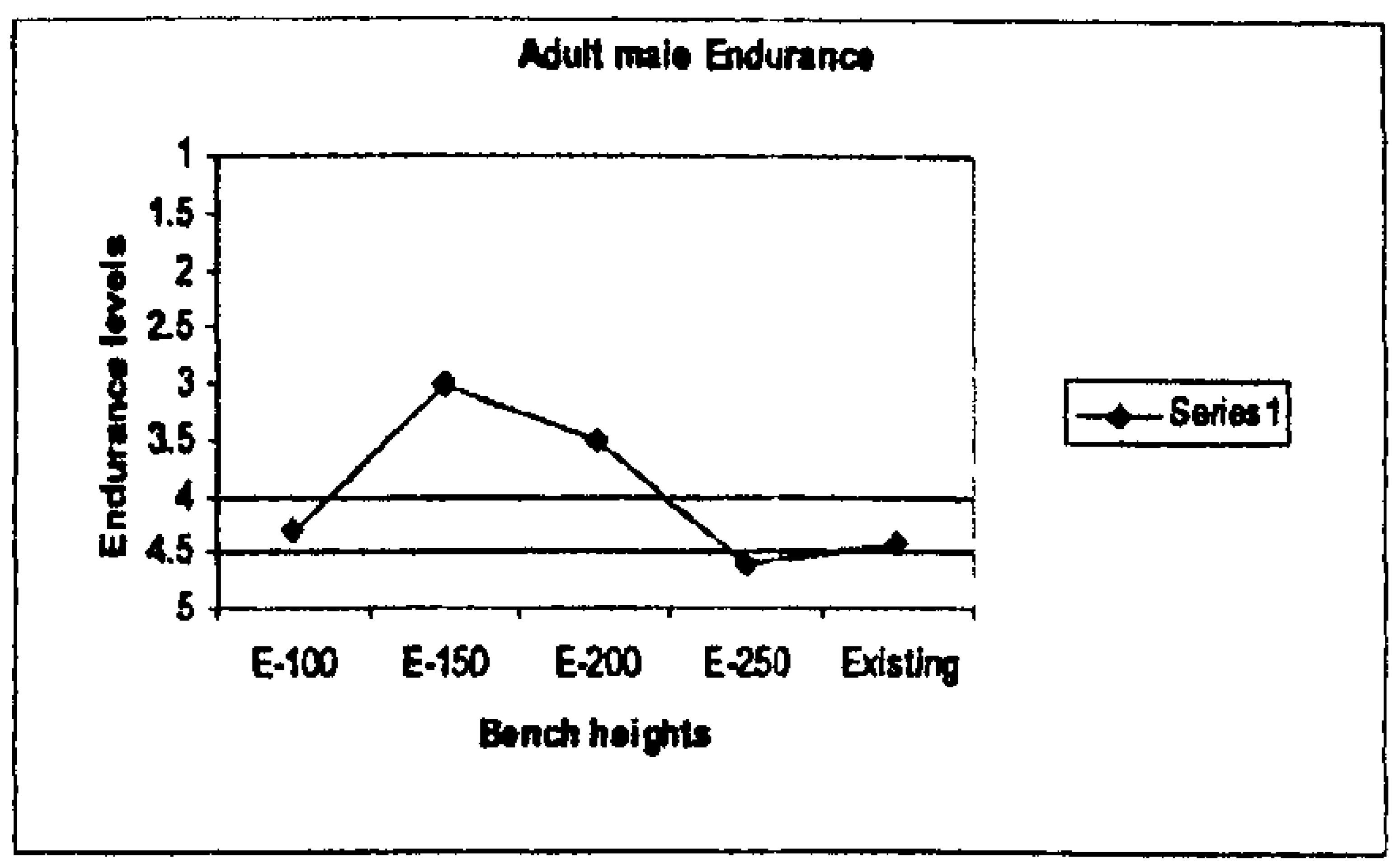


Figure 10: Estimate endurance – Male Adults

examination of the data relating to the adult males sub-group show significant differences in endurance between all levels, with the exception of E-250 and existing bench height. While there is greater endurance at the lower levels than for the females, there is less endurance at the preferred level of E-150. This is interesting in that while there is complete correlation between female endurance and BPD, the endurance estimates for males showed a preference for E-150 but their BPD score was most satisfactory at E-200. Overall there was no significant difference between male and female estimated endurance levels. However the males were more tolerant at the lower levels but less so at the upper level Of E-100. Females recorded higher BPD but recorded greater endurance estimates

Subjective Height Ratings

Test subjects were asked to rate the various heights on a scale of 0 to 10, with 0 being the extreme of low and 10 being the extreme of high. The ideal height was the mean of 5. A vertical tick was placed at a point along the line to indicate satisfaction level with the height. The position of the tick was measured as a fraction of the line to produce the rating value.

Figure 11 shows the graph of the subjective height rating. As can be seen there is an increase above and below the ideal height score of five and as the height moves above and below this satisfaction diminishes. At the E-100 a significant level of dissatisfaction was recorded, at 50mm lower, E-150 the bench height is nearest the ideal height. There is a highly significant difference when the bench drops to the existing height, recording a mean satisfaction level of 1.5, 3.5 below the ideal height. There was a highly significant statistical difference between E-150 and all other heights (p=<0.001).

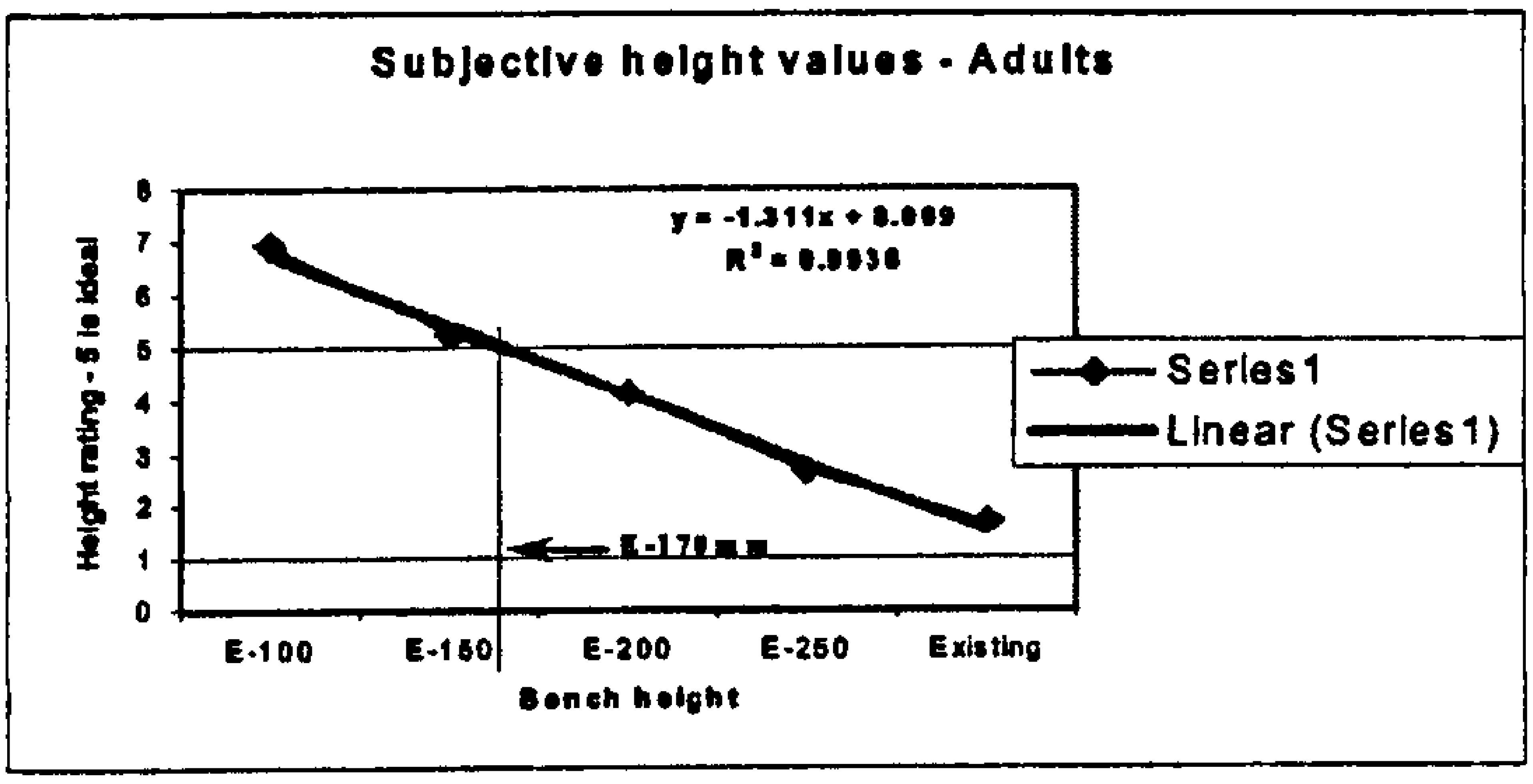


Figure 11: Subjective height ratings – Adults

On analysis of the female sub-group the range of dissatisfaction for E-100 level was similar to that of the males. However, as can be observed in Figure 12, the lower levels of E-250 and Existing height were not as unsatisfactory as for the females, deviating just two points below the ideal height, compared with nearly double that (4) for the males in relation to the Existing height. While the satisfaction level at bench height E-150 is almost on the ideal height level of 5, the trendline crosses the '5 line' at approximately E-175. For the female sub-group there appears to be no significant difference between E-150 and E-200. The existing height bench recorded a more satisfactory score than E-250, because the mean height below elbow was higher, at minus 237mm.

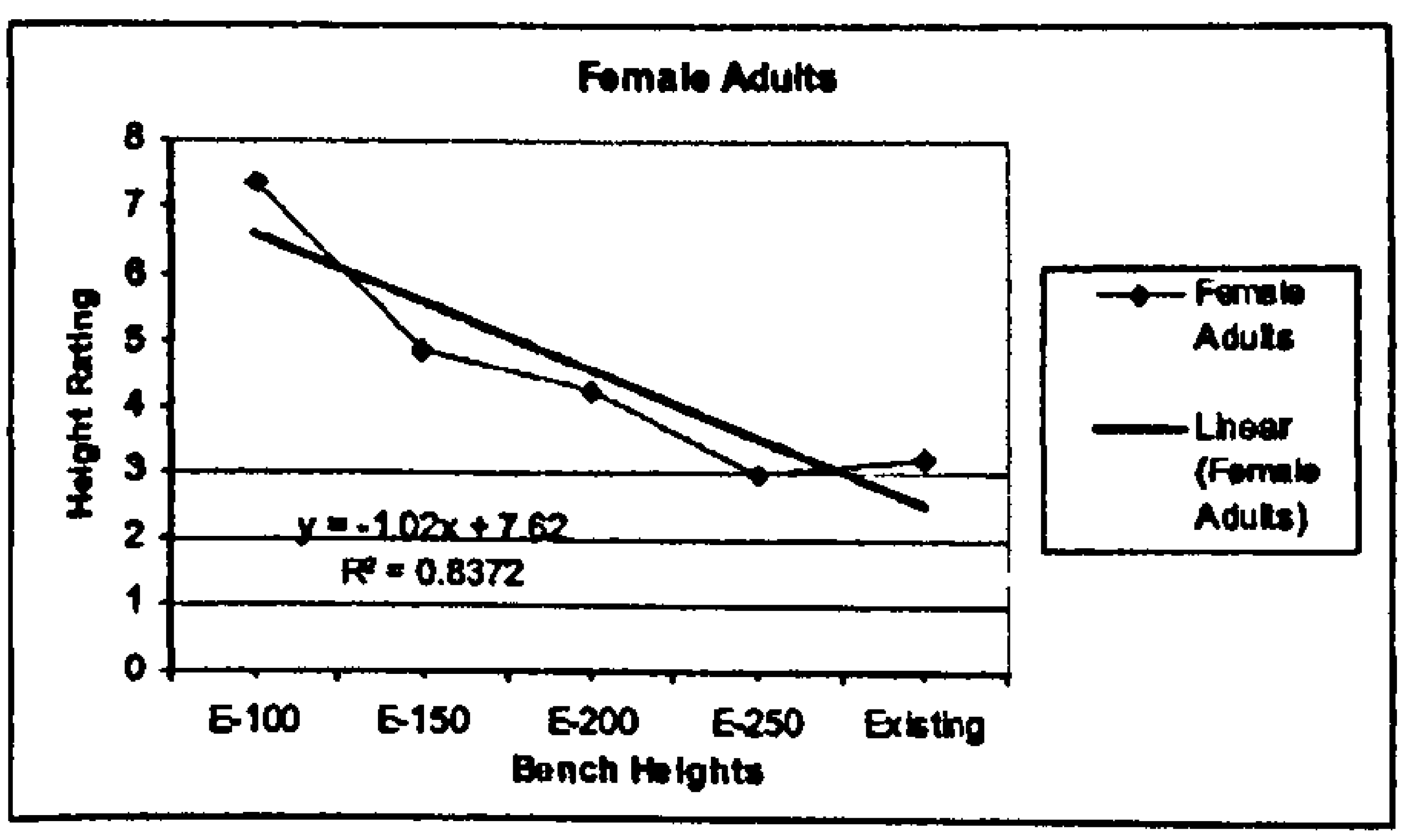


Figure 12: Subjective height ratings – Female

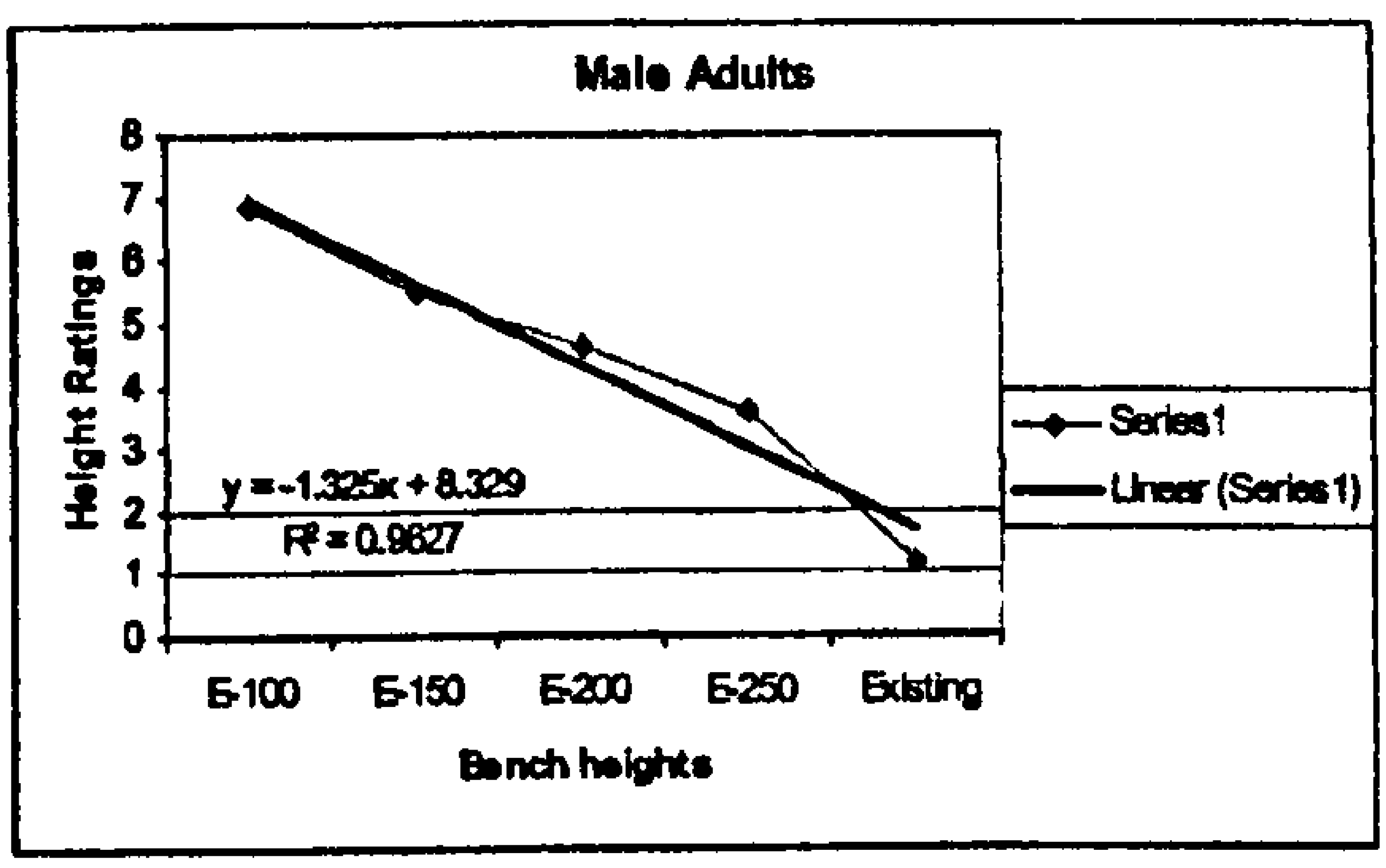


Figure 13: Subjective height ratings – Male

The adult male sub-group distributed their most satisfactory height preferences between E-150 and E-200, as can be seen in Figure 13. For the males there is less dissatisfaction with the with the E-100 level than for the females but a dramatic difference in relation to the Existing bench height level – almost four points below the '5 line'. As the height range between E-100 and Existing is far greater for males than for females, as reflected in the R^2 value, the range of height ratings is broader. The satisfaction level as measured by the trendline is almost the same, but there was a distinct preference for the E-150 level for the females, while the males are distributed between the levels, E-150 and E-200. As there is no significant difference between E-150 and E-200, this range can be identified as a robust position and is also reflected in PBD as well as endurance.

Discussion:

Reducing BPD for people using workbenches can make a significant contribute to lowering incidences of MSDs and RPIs therefore improving the health of the workforce, productivity and profits, applying design ergonomics to engineering workbenches produces a better-for-all solution. The research has established that for the type of processing activity described a general work height of 150mm below elbow height produced the best results. BPD is lowest at this level and subject endurance is highest. Subjective height ratings produced a graph which indicated that 170mm below elbow height was the preferred height. While efficiency ratings are not discussed in this paper the preferred height increased efficiency, though not significantly. As the bench height moved above and below the E-150 level, BPD increased and satisfaction decreased. Endurance ratings at E-150 were best and the existing bench height of 800 mm produced the least satisfactory results. A Quadratic Function Discomfort Indicator (QFDI) was established which allows the calculation of discomfort ratings for heights above and below the best-fit height. A function which can be used to predict endurance in relation to elbow height work height as also been established this may be referred to as the QFEI. Mid to lower back discomfort, decreases significantly as the bench height moves into the range of 150mm to 225mm below elbow height for male adults, indicating a robust position in a range of 75mm. The best-fit height for females was less robust, with a 50mm range, 25mm above and below E-150.

Conclusions

- Generally the existing bench height was most unsatisfactory results for comfort, endurance and height rating.
- A height of 150mm below elbow height (E-150) produced the most satisfactory results for endurance and height rating.
- Body part discomfort (BPD) significantly decreased at the E-150 bench height.
- The best-fit position was for females was less robust than for males
- Females experienced greater body part discomfort at all levels but their endurance estimates exceeded the male estimates
- Quadratic functions have been established which may be used as indicators for BPD and endurance.
- A best-fit working height of 150mm below elbow height is recommended as the most suitable for the whole cohort

Resulting from the established ergonomic data a prototype universal workbench has been designed and produced. The 'ergo-bench' and has a height range which suits users of small and tall stature as well as wheelchair users.

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