DESIGN GUIDELINES AND EVALUATION OF AN ERGONOMIC CHAIR FEATURE CAPABLE OF PROVIDING SUPPORT TO FORWARD-LEANING POSTURES

A Dissertation

by

EDWARD MARTIN STEVENS, JR.

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2004

Major Subject: Interdisciplinary Engineering

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Major Subject: Interdisciplinary Engineering

ABSTRACT

Design Guidelines and Evaluation of an Ergonomic Chair Feature Capable of Providing Support to Forward-Leaning Postures. (December 2004)

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This research investigated the need, design, and evaluation of a product capable of providing support to forward-leaning postures. Due to the high occurrence of low-back pain in industry potentially due to workers performing their tasks while assuming forward-leaning postures, along with the biological plausibility of these postures causing low-back pain, the need was established for a product that provides forward-leaning support. An envelope was quantified, ranging from the 5th percentile female to the 95th percentile male, to establish the range of potential forward-leaning postures. The design of a Support-Arm for use with current ergonomic chairs was discussed and design feature specifications were then provided. A Latin Square statistical design was employed to evaluate a Support-Arm model alongside 8 other commonly used chairs over 3 different postures. Subjects, overall, had lower peak pressures for the buttock-thigh region, increased productivity, higher comfort levels, and higher buttock-thigh contact areas when seated in the Support-Arm model chair as compared to the other chairs. Subjects, overall, also ranked this chair first over the other chairs for preferred use after having sitting experience in all 9 chairs. In an additional part of the evaluation, subjects chose their own set-up of the Support-Arm model chair. Eleven of the 18 subjects chose to use the Support-Arm when their workstation was located 36” above the floor. Subjects confirmed the need to design a Support-Arm capable of providing forward leaning support to the entire envelope of forward-leaning postures. Statistical evaluation revealed several significant differences between the chairs. The results gave no indication that the use of a Support-Arm for forward-leaning support may cause detrimental effects to users or overall chair ergonomics. Future research could track workers’ use of a Support-Arm in industry and compare their occurrence of low-back pain to a control group.

DEDICATION

I would like to dedicate this dissertation to my family, without whom my accomplishments would not be possible. I would especially like to dedicate this dissertation to Nana for believing I'd be the famous one.

TABLE OF CONTENTS

Page

ABSTRACT iii

DEDICATION v

TABLE OF CONTENTS vi

LIST OF TABLES ix

LIST OF FIGURES xiv

1. INTRODUCTION 1

   1.1. Present Status of the Question 3
   1.2. Research Objectives 4

2. BACKGROUND ON ERGONOMIC PRODUCT DESIGN 7

   2.1. Ergonomic Product Design Guidelines 9
   2.2. Ergonomic Design Process 10

3. THE NEED 11

   3.1. The Need for Forward-Leaning Support 12
   3.2. The Back 16
   3.3. Providing Support to Forward-Leaning Postures 26
   3.4. Establishment of the Need 27
   3.5. A Product That Provides Forward-Leaning Support 27

4. ERGONOMIC CHAIR RESEARCH 29

   4.1. Optimum Sitting Postures 31
   4.2. Ergonomic Measures 33
   4.3. Summary of Research 36

5. THE DESIGN 39

   5.1. New Design Guidelines and Specifications 40
   5.2. The Support-Arm 48

Page

6. THE EVALUATION 51

6.1. The SA Model 53
6.2. Procedures 54

7. FEMALE SUBJECTS' RESULTS 73

7.1. Subjects' Information 73
7.2. Evaluation Part I – Female Subjects 76
7.3. Evaluation Part II – Female Subjects 96

8. MALE SUBJECTS' RESULTS 105

8.1. Subjects' Information 105
8.2. Evaluation Part I – Male Subjects 108
8.3. Evaluation Part II – Male Subjects 129

9. GENDER COMPARISON AND COMBINED SUBJECTS' RESULTS 141

9.1. Evaluation Part I – Gender Comparison and Combined Subjects 141
9.2. Evaluation Part II – Gender Comparison and Combined Subjects 160

10. DISCUSSION 171

10.1. Features of the Evaluation 171
10.2. Production Testing 173
10.3. Chosen Stool Set-Up 174
10.4. SA Model Versus the Proposed Support-Arm Design 175
10.5. Pros of the Evaluation 177
10.6. Cons of the Evaluation 178
10.7. Direction for Future Research 179

11. CONCLUSIONS 181

REFERENCES 183

APPENDIX A. ERGONOMIC PRODUCT DESIGN GUIDELINES 195

APPENDIX B. ERGONOMIC PRODUCT DESIGN PROCESS 199

APPENDIX C. DESIGNING FOR HUMAN USE 205

Page

APPENDIX D. ERGONOMIC PRODUCT EVALUATIONS 208

APPENDIX E. CHAIRS 219

APPENDIX F. CHAIR FEATURE MATRIX 229

VITA 230

LIST OF TABLES

Page

Table 1. Anthropometry Used for Support-Arm Envelope (in). Anthropometric Data from Chengalur, et al., (2004) and *Chaffin, et al., (1999). 44

Table 2. Forward-Leaning Envelope (in). 47

Table 3. The Three Postures Chosen for Evaluation Part I. 60

Table 4. Purdue Pegboard Production Testing Trials. 67

Table 5. Part I. Chair Codes. 68

Table 6. Part I. Posture Codes. 69

Table 7. Part I. Latin Square Design Matrix. 69

Table 8. Part II. Treatments. 72

Table 9. Part II. Randomized Treatments per Subject and Trial. 72

Table 10. Female Subjects' Participation. 73

Table 11. Female Subjects' Ages. 74

Table 12. Female Subjects' Hours Worked per Week, Job Title, and Time on the Job. 74

Table 13. Female Subjects' Injury History and Current Status. 75

Table 14. Female Subjects' Weight and Stature. 76

Table 15. Trial 1 Rankings (Appearance). Female Subjects. Conducted Prior to the Subjects Being Given any Information on the Chairs. 78

Table 16. Trial 2 Rankings (Knowledge). Female Subjects. Conducted After the Subjects Were Provided With the Chair Feature Matrix. 78

Table 17. Trial 3 Rankings (Sitting Experience). Female Subjects. Conducted After the Subjects had Sat in Every Chair During Part I of the Evaluation. 79

Page

Table 18. Summed Rankings Over the Three Ranking Trials (Appearance, Knowledge, Sitting Experience). Female Subjects. 80

Table 19. Intra-Rater Correlation Between Ranking Trials 1 to 2 and 2 to 3 (1, 2, 3: Appearance, Knowledge, Sitting Experience). Female Subjects. 81

Table 20. Inter-Rater Correlation During the Three Ranking Trials (1, 2, 3: Appearance, Knowledge, Sitting Experience). Female Subjects. 82

Table 21. Number of Buttock-Thigh Peak Pressure Recordings Below 4.06 psi per Chair. Female Subjects..83

Table 22. Mean Buttock-Thigh Contact Area by Chair (in^2). Female Subjects.............84

Table 23. ANOVA on Buttock-Thigh Contact Area. Female Subjects. 85

Table 24. Summed Production Values by Chair. Female Subjects...............................88

Table 25. ANOVA on Production Values. Female Subjects. 89

Table 26. Summed Comfort Survey Results by Chair (cm). Female Subjects. 90

Table 27. ANOVA on Comfort Survey Results. Female Subjects. 91

Table 28. Correlation Results. Female Subjects. 94

Table 29. Use of Support-Arm at 30” and 36” Table Heights. Female Subjects...........97

Table 30. ANOVA on Chosen Ankle Angle. Female Subjects. 97

Table 31. ANOVA on Chosen Knee Angle. Female Subjects......................................98

Table 32. ANOVA on Chosen Trunk-Thigh Angle. Female Subjects...........................99

Table 33. ANOVA on Chosen Seat-Tilt Angle. Female Subjects. 100

Table 34. Female Subjects’ Categorized Comments...103

Table 35. Males Subjects’ Participation...105

Table 36. Male Subjects’ Ages. 106

Page

Table 37. Male Subjects' Hours Worked per Week, Job Title, and Time on the Job...106

Table 38. Male Subjects' Injury History and Current Status. 107

Table 39. Male Subjects' Weight and Stature. 108

Table 40. Trial 1 Rankings (Appearance). Male Subjects. Conducted Prior to the Subjects Being Given any Information on the Chairs. 110

Table 41. Trial 2 Rankings (Knowledge). Male Subjects. Conducted After the Subjects Were Provided with the Chair Feature Matrix. 110

Table 42. Trial 3 Rankings (Sitting Experience). Male Subjects. Conducted After the Subjects had Sat in Every Chair During Part I of the Evaluation. 111

Table 43. Summed Rankings Over the Three Ranking Trials (Appearance, Knowledge, Sitting Experience). Male Subjects. 112

Table 44. Intra-Rater Correlation Between Ranking Trials 1 to 2 and 2 to 3 (1, 2, 3: Appearance, Knowledge, Sitting Experience). Male Subjects. 113

Table 45. Inter-Rater Correlation During the Three Ranking Trials (1, 2, 3: Appearance, Knowledge, Sitting Experience). Male Subjects. 114

Table 46. Number of Buttock-Thigh Peak Pressure Recordings Below 4.06 psi per Chair. Male Subjects. 115

Table 47. Mean Buttock-Thigh Contact Area by Chair (in^2). Male Subjects. 116

Table 48. ANOVA on Buttock-Thigh Contact Area. Male Subjects. 116

Table 49. Summed Production Values by Chair. Male Subjects. 120

Table 50. ANOVA on Production Values. Male Subjects. 121

Table 51. Summed Comfort Survey Results by Chair (cm). Male Subjects. 123

Table 52. ANOVA on Comfort Survey Results. Male Subjects. 124

Table 53. Correlation Results. Male Subjects. 127

Page

Table 54. Use of Support-Arm at 30” and 36” Table Heights. Male Subjects. 129

Table 55. ANOVA on Chosen Ankle Angle. Male Subjects. 130

Table 56. ANOVA on Chosen Knee Angle. Male Subjects. 131

Table 57. ANOVA on Chosen Trunk-Thigh Angle. Male Subjects. 134

Table 58. ANOVA on Chosen Seat-Tilt Angle. Male Subjects. 137

Table 59. Male Subjects’ Categorized Comments. 139

Table 60. Trial 1 Rankings (Appearance). Conducted Prior to the Subjects Being Given any Information on the Chairs. Gender Comparison. 143

Table 61. Trial 2 Rankings (Knowledge). Conducted After the Subjects Were Provided with the Chair Feature Matrix. Gender Comparison. 143

Table 63. Trial 3 Rankings (Sitting Experience). Conducted After the Subjects had Sat in Every Chair During Part I of the Evaluation. Gender Comparison. ..144

Table 64. Intra-Rater Correlation Between Ranking Trials 1 to 2 and 2 to 3 (1, 2, 3: Appearance, Knowledge, Sitting Experience). Gender Comparison. 145

Table 65. Inter-Rater Correlation During the Three Ranking Trials (1, 2, 3: Appearance, Knowledge, Sitting Experience). Gender Comparison. 146

Table 66. Number of Buttock-Thigh Peak Pressure Recordings Below 4.06 psi per Chair. Female and Male Subjects. 147

Table 67. ANOVA on Buttock-Thigh Contact Area. Combined Subjects. 148

Table 68. Mean Contact Area by Chair (in^2). Combined Subjects. 149

Table 69. ANOVA on Production Values. Combined Subjects. 153

Table 70. ANOVA on Comfort Survey Results. Combined Subjects. 155

Table 71. Summed Comfort Survey Results by Chair (cm). Combined Subjects. 156

Table 72. ANOVA on Chosen Ankle Angle. Combined Subjects. 161

Page

Table 73. ANOVA on Chosen Knee Angle. Combined Subjects. 162

Table 74. ANOVA on Chosen Trunk-Thigh Angle. Combined Subjects. 163

Table 75. ANOVA on Chosen Seat-Tilt Angle. Combined Subjects. 165

LIST OF FIGURES

Page

Figure 1. Human Spine.....19

Figure 2. Lumbar Spine and Intervertebral Discs. 20

Figure 3. Picture of a Current Chair Design Capable of Providing Support to Forward-Leaning Postures. 28

Figure 4. A Conceptual Model of Sitting Comfort and Discomfort (from Helander and Zhang, 1997).....35

Figure 5. Required Seat-Pan Tilt. Not to Scale. 42

Figure 6. Envelope's Range of Forward-Leaning. Not to Scale. 43

Figure 7. 5^{th} Percentile Female and Minimum Support-Arm Envelope (in). Not to Scale. 45

Figure 8: 95^{th} Percentile Male and Maximum Support-Arm Envelope (in). Not to Scale. 46

Figure 9. Required Adjustments of the Support-Arm. 48

Figure 10. Two Views of a Support-Arm Design. 49

Figure 11. The SA Model.....53

Figure 12. SA Model's Adjustments and Uses. 54

Figure 13. Location and Orientation of Body Part Angle Measurements......56

Figure 14. Representations of the Standard Sitting, Sit-Stand, and Forward-Leaning Sit-Stand Postures. 61

Figure 15. Experimental Set-Up and Xsensor Pressure Pad. 63

Figure 16. Purdue Pegboard. 66

Figure 17. Means and Tukey Test Results on Mean Buttock-Thigh Contact Area by Chair (in^2). Female Subjects.....86

Page

Figure 18. Means and Tukey Test Results on Mean Buttock-Thigh Contact Area by Posture (in^2). Female Subjects. 87

Figure 19. Means and Tukey Test Results on Comfort Survey Scores by Chair (cm). Female Subjects....................92

Figure 20. Means and Tukey Test Results on Comfort Survey Scores by Posture (cm). Female Subjects....................93

Figure 21. Means and T-Test Results on Chosen Seat-Tilt Angles by Stool (^{o}). Female Subjects....................101

Figure 22. Means on Chosen Seat-Tilt Angles by Stool*Table Height (^{o}). Female Subjects. 102

Figure 23. Means and Tukey Test Results on Mean Buttock-Thigh Contact Area by Chair (in^2). Male Subjects. 118

Figure 24. Means and Tukey Test Results on Mean Buttock-Thigh Contact Area by Posture (in^2). Male Subjects....................119

Figure 25. Means and Tukey Test Results on Comfort Survey Scores by Chair (cm). Male Subjects. 125

Figure 26. Means and Tukey Test Results on Comfort Survey Scores by Posture (cm). Male Subjects....................126

Figure 27. Means and T-Test Results on Chosen Knee Angles by Stool (^{o}). Male Subjects. 132

Figure 28. Means and T-Test Results on Chosen Knee Angles by Table Height (^{o}). Male Subjects. 133

Figure 29. Means and T-Test Results on Chosen Trunk-Thigh Angles by Table Height (^{o}). Male Subjects. 135

Figure 30. Means on Chosen Trunk-Thigh Angles by Stool*Table Height (^{o}). Male Subjects. 136

Figure 31. Means and T-Test Results on Chosen Seat-Tilt Angles by Stool (^{o}). Male Subjects. 138

Page

Figure 32. Means and Tukey Test Results on Mean Buttock-Thigh Contact Area by Chair (in^2). Combined Subjects....150

Figure 33. Means and Tukey Test Results on Mean Buttock-Thigh Contact Area by Posture (in^2). Combined Subjects....151

Figure 34. Summed Production Values by Gender. Combined Subjects....154

Figure 35. Means and Tukey Test Results on Comfort Survey Scores by Chair (cm). Combined Subjects....157

Figure 36. Means and Tukey Test Results on Comfort Survey Scores by Posture (cm). Combined Subjects....158

Figure 37. Means and T-Test Results on Chosen Trunk-Thigh Angle by Stool (^{o}). Combined Subjects....164

Figure 38. Means and T-Test Results on Chosen Seat-Tilt Angles by Stool (^{o}). Combined Subjects....166

Figure 39. Means and T-Test Results on Chosen Seat-Tilt Angles by Table Height (^{o}). Combined Subjects....167

Figure 40. Means of Chosen Seat-Tilt Angles by Stool*Table Height (^{o}). Combined Subjects....168

1. INTRODUCTION

Low-back pain (LBP) is one of the most common musculoskeletal disorders (MSDs) and has been reported to occur in 50-90% of all adults with recurrence rates of up to 90% (Andersson, 1981; Frymoyer et al., 1983; Horal, 1969; Leboeuf-Yde and Kyvik, 1998; McKenzie, 1981; Riihimaki et al., 1989; Svensson et al., 1988). Many industries are attempting to combat low-back disorders (LBDs) by purchasing ergonomic chairs and manipulating the working environment so workers' tasks may be completed while seated (Callaghan and McGill, 2001). Unfortunately, complaints about low-back pain are also widespread among seated workers (Kroemer et al., 1969; Leivseth and Drerup, 1997; Naqvi, 1994). In fact, it has been shown that intradiscal pressures in the lumbar region of the spine can actually be greater while seated than standing (Callaghan and McGill, 2001; Nachemson and Elfstrom, 1970).

While seated postures are believed to reduce stress on the lower body, the back and its associated musculoskeletal structures must still support the upper-body (Chaffin and Andersson, 1984). Providing support by the means of a backrest allows a seated person to transfer part of their upper-body load onto the chair, proving for lower intradiscal

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This dissertation follows the style and format of Applied Ergonomics.

pressure and increased relaxation of the supporting back muscles (Andersson and Ortengren, 1974a; Andersson and Ortengren, 1974b; Corlett and Eklund, 1984; Grandjean and Hunting, 1977; Nachemson, A., 1965; Naqvi, 1994). The more a person "leans-back", or opens the trunk-thigh angle, the more one is able to unload the weight of the upper-body onto the backrest and therefore provide greater relief to the musculoskeletal system (Andersson and Ortengren, 1974a; Andersson and Ortengren, 1974b; Nachemson, A., 1965; Naqvi, 1994; Grandjean and Hunting, 1977). Unfortunately, many jobs and tasks require workers to hold 90-degree or less angles (forward-leaning) between the trunk and thigh resulting in no unloading of upper-body weight onto a backrest.

Although it may be argued whether or not some sitting postures are associated with MSDs, it is generally agreed that holding static and forward-leaning postures are risk factors for LBDs (Adams and Hutton, 1983; Berguer, 1999; Eklund, 1967; Graf et al., 1995; Grandjean and Hunting, 1977; Hartvigsen et al., 2000; Langdon, 1965; Lengsfeld et al., 2000; Nachemson, 1976; Tougas and Nordin, 1987). Forward-leaning postures are believed to cause back pain due to the increased intradiscal pressure associated with these postures as compared to back-leaning, or even standing postures (Grandjean and Hunting, 1977; Lengsfeld et al., 2000). In addition, the lever-arms associated with the biomechanical aspect of the musculoskeletal system of the back actually place increased stress on the low-back as the degree of forward-leaning increases, resulting in localized muscle fatigue (Grandjean and Hunting, 1977; Lengsfeld et al., 2000; Nachemson, 1965).

1.1. PRESENT STATUS OF THE QUESTION

Even though ergonomic chair design has progressed significantly over the past 20 years, two problems exist that require attention: (1) workers are assuming forward-leaning postures, and (2) these postures are usually unsupported. To make matters worse, many of the same workers who must perform their work in forward-leaning postures must do so for long periods of time.

Past research has shown that workers from several industries suffer from back pain due to holding forward-leaning postures. Workers such as dentists, surgeons, hairdressers, dental hygienists, assembly workers, sewing machine operators, helicopter pilots, nurses, and scientists have complained of low-back pain and disease that may be due to holding unsupported forward-leaning postures (Berguer, 1999; Bridger et al., 2002; Finsen et al., 1998; Grandjean and Hunting, 1977; Grieco, 1986; Kant et al., 1992; Kihara, 1995; Kilroy and Dockrell, 2000; Nag et al., 1992; Nguyen, 2001; Smith et al., 2002; Yu and Keyserling, 1989).

An optimal ergonomic chair is one that is capable of assuming a large range of supported postures while accommodating many sizes and shapes (Gross et al., 1992; Helander et al., 1987). Therefore, an optimal chair design is one that can adapt and provide support to several postures, including forward-leaning, for the majority of the population. This dissertation includes the identification of a need, an introduction to a design, and an evaluation of a chair feature that provides support to seated forward-leaning postures.

1.2. RESEARCH OBJECTIVES

The research objectives of this dissertation are four fold:

1. Using previously published research, define the need for a product capable of providing support to forward-leaning postures by identifying several industries whose workers may develop low-back pain due to performing their tasks in unsupported forward-leaning postures.
2. Define a quantitative range (envelope) of potential forward-leaning postures for workers (5^{th} percentile female to 95^{th} percentile male) ranging from the vertical to the horizontal plane.
3. Provide design guidelines for an ergonomic chair "feature" that can be used in the above defined range (envelope) of postures that provides forward-leaning support.
4. Evaluate a chair affixed with a Support-Arm along with several other chairs to determine if differences exist in any of the criteria evaluated:

1.2.1. Evaluation Part I

Evaluate 8 chairs commonly used in industry, along with a "Support-Arm" model chair for differences in:

- Buttock-thigh peak pressure
- Buttock-thigh contact area
- Production
- Comfort
- Subjects' preferences (rankings) of the chairs on three separate occasions

The null hypothesis was that there were no differences in these parameters between the chairs under the prescribed conditions and tests performed.

1.2.2. Evaluation Part II

Compare the "Support-Arm" model chair/stool versus a "standard" style stool at two table heights for differences in:

- Subjects' chosen posture and use of the Support-Arm
    - Ankle angle
    - Knee angle
    - Trunk-thigh angle
    - Seat-tilt angle

In addition, subjects' comments on the "Support-Arm" model chair were solicited and recorded.

The null hypothesis was that the subjects’ chosen set-ups (configurations) were not different between the SA Model and the standard style stool.

2. BACKGROUND ON ERGONOMIC PRODUCT DESIGN

The designing of products is not new to humans. Cavemen used tools such as sharp rocks or bones to carve meat for food and animal skins for clothing. Product technology has significantly improved since then, creating new difficulties for product designers in the process.

Designing a product to fill a particular need is usually not enough. In the past, product designers needed only to create a product that could accomplish the task for which it was designed. As products became more sophisticated and capable, designers had to begin adding more criteria to their designs (e.g. aesthetics and safety features). The General Product Safety Regulations (Department of Trade and Industry, 1994) state that a safe product is a “product which under normal or reasonably foreseeable conditions of use, including duration, presents no risk or only the minimal risk compatible with the product’s use.” Also on the list of must-do’s for the designer came: product performance requirements, warranties, instructions/use documents, life cycle requirements, and many others.

Fortunately, there are several texts and handbooks available to guide designers down the correct path. When researching how to design a modern-day product, one will undoubtedly find that competition is rapidly increasing and designers must explore new and better ways to make their products more appealing to consumers. Most consumers demand products that are aesthetically pleasing, provide pride of ownership, and are simple as well as a pleasure to use (amongst other things). In today's marketplace, the use of ergonomics in product design is one way to accomplish this task (Butters and Dixon, 1998).

Ergonomists use principles from many disciplines including engineering, psychology, and even the medical field when designing products. According to Cushman and Rosenberg (1991), ergonomic products are designed to reduce accidents, injuries, human error, and frustration while increasing performance, production (if appropriate), and user satisfaction. Ergonomists may reduce accidents, injuries, human error, and frustration by designing products to be easily and safely operated. They can increase production by making a product more suitable to perform the function for which it was designed. User satisfaction can be increased by completing all the above and making a product comfortable in use as well as aesthetically pleasing.

Every product is designed (Stanton, 1998). The extent of the design is up to the designer. Unfortunately, too many designs end at the mechanical and electrical plans and fail to take the human user into account. Pointing out ergonomically correct products is not easy to do. It is usually much easier to point out non-ergonomically designed products. We are all familiar with products that are not easy to use (the common VCR is a great example) and, unfortunately, usually only realize these faults after we have already purchased the product and brought it home.

The history of ergonomics in product design is not easy to trace. One could assume it began when humans first started building and using tools for hunting and gathering. However, it appears that the importance of proper ergonomic design was realized during World War I when it was found that women could not use some of the equipment as easily as men (Oborne, 1982). Perhaps the first formal use of human factors in product design came about in World War II in the area of aircraft instrumentation and levers. Pilots were frequently making errors in reading their altitude displays and selecting the wrong controls such as the elevator control instead of the landing gear (Grether, 1949). One "human factors" solution was to place a small wheel on the landing gear lever to assist the pilot in selecting the appropriate lever.

2.1. ERGONOMIC PRODUCT DESIGN GUIDELINES

Ergonomic products are basically "enhanced" products. That is, they contain additional criteria above and beyond that of normal product designs. These criteria are all associated with one another and fit into four interweaving guidelines:

2.1.1. Ergonomic Product Design Guidelines

- Design for Increased Production
- Design for Decreased Injuries
- Design for Decreased Human Error
- Design for Increased User Satisfaction

See Appendix A for further details and a discussion on each of the above guidelines.

2.2. ERGONOMIC DESIGN PROCESS

The ergonomic design process closely follows the standard engineering design process. The differences involve a detailed study of, and amendments for, the human element within the design and evaluation phases. For more detailed information, please see Appendices B-D. Appendix B discusses the ergonomic design process; Appendix C contains information on designing for human use, and Appendix D discusses ergonomic product evaluations.

3. THE NEED

The first step in product design is establishing a need. As stated in Appendix B, there are many methods available to establish the need for a product: personal experience, research, interviews, and direct observation are just a few. In the world of ergonomics, one of the most powerful methods available to establish the need for a product is to determine areas where musculoskeletal disorders (MSDs) are occurring, find their potential cause(s), and finally identify a solution. This can be accomplished by consulting published articles on MSDs that are occurring in certain sectors of the population, talking to industry representatives, or any number of information gathering exercises. Once a population is identified that has common disorders, a common cause (exposure) may then be found. Furthermore, these exposures can then be researched to determine if other populations are at risk of developing the same MSDs. Not only can this method confirm the theory or the cause of the MSD, it can also identify the need for, and potential consumers, of a new product that is designed to minimize these MSDs.

An example of this method could be:

1. Research has found that football players frequently develop plantar warts.
2. It is theorized that the reason for this is that football players walk around barefoot in locker rooms and expose each other to the virus.
3. Research is then conducted to determine prevalence of plantar warts in other persons who walk around barefoot on locker room (or other) floors.

4. It is found that soccer players, baseball players, swimmers, and other athletes who commonly use locker rooms are developing plantar warts.
5. It is concluded that exposure to locker room floors while barefoot is causing this high occurrence of plantar warts.
6. A foot product is developed that protects athletes from direct skin exposure to locker room floors.
7. The product is then marketed to athletes.

3.1. THE NEED FOR FORWARD-LEANING SUPPORT

Even though it is known from personal experience that forward-leaning postures are normally assumed during everyday tasks such as working at a computer, washing the dishes, working in the laboratory, etc., it is still important to verify the need for a chair "feature" that provides support to forward-leaning postures. The verification of the need in industry is highly important due to the costs associated with ergonomic chairs and the ability and willingness of consumers to purchase the potential product. Even though workers may spend some time in forward-leaning postures, the need for a product may not arise unless these postures are creating some form of disorder, or a condition, that could be relieved by a product. Therefore, this relationship must be found to exist prior to continuing with an expensive and/or time-consuming design process.

Although it is not necessary to determine all the industries and job tasks that involve workers who perform their tasks in forward-leaning postures, it is important to determine that there is a need. In addition to determining whether or not there is a need, research can also provide valuable design specifications that will be required in the design stage. For example, if it is found that only auto mechanics need the support, then the product should be designed to be used in a garage (e.g. sturdy, cleanable, repels oil and other fluids).

Approximately 75% of the average worker's day is spent in the seated position (Hartvigsen et al., 2000). A review of published literature has determined there are several industries where workers are complaining of low-back pain potentially due to holding forward-leaning postures while working. Below is a brief synopsis.

3.1.1. Dentists

Finsen et. al (1998) found that the one year prevalence for low-back pain amongst dentists in their field study is approximately 63%. It was noted that 20-degree forward-leaning postures were found amongst dentists while performing their tasks. Kihara (1995) noted that the most common posture dentists assume is a right-forward flexion position due to the location of the patient. Kihara concluded that daily dental work may produce work-related disorders of the low-back due to the required "bent posture" regardless if a dentist stands or uses a stool. Visser and Straker (1994) found that dentists must flex their trunk forward in order to perform their tasks. They concluded that it is "likely that the postural demands of dental work place dental workers at risk of musculoskeletal disorders." Nordin et al, (1984) found that dentists spend close to twothirds of each treatment hour in a forward, bent sitting posture. Shugars et al. (1987) and Bassett (1983) concluded that the static postures associated with dental work add to the risk of low-back pain.

3.1.2. Dental Hygienists

Dental hygienists also complain of low-back problems (Osborn et al., 1990, Visser and Straker, 1994). Osborn et al. (1990) found that the location of pain reported most by dental hygienists is the lower back. Visser and Straker (1994) stated that due to the location the dental hygienists sit in relation to the dentist and patient during dental procedures, they actually have to assume a forward-leaning posture in excess of the dentist's.

3.1.3. Sewing Machine Operators

Sewing machine operators commonly experience pain in their low-back (Nag et al., 1992). Sewing operations require workers to sit in static, forward-leaning seated positions (Chan et al., 2002; Nag et al., 1992; Yu and Keyserling, 1989). Chan et al. (2002) reported on MSD's in sewing machine operators in the San Francisco Bay area and found workers routinely adopted 10-degree forward-leaning postures.

3.1.4. Crane Operators

Hellstrom and Lindell (1982) reported that about 70% of crane operators experience musculoskeletal discomfort mainly due to their required sitting position. Gustafson-

Soderman (1987) studied crane operators sitting angle(s) and determined that when lifts are performed close to the crane, the operators must assume forward-leaning positions to see the load. It was indicated that perhaps an adjustable seat could assist in reducing MSDs. Clark and Ridd (1984) found that crane operators at a power station's coal unloading dock adopted unsupported forward-leaning postures for over 4 of their 8-hour work shifts, possibly resulting in pain in the lumbar region of the spine.

3.1.5. Butchers

Due to the localization of MSD complaints in the low-back of butchers, Magnusson and Ortengren (1987) attempted to determine if an optimal table height and surface angle exists in meat cutting. Although they did not find an optimal table height, it was determined that when butchers work at "low" table heights they are forced to assume forward-leaning postures that could be the cause of the reported low-back pain.

3.1.6. Surgeons, Nurses, and other Medical Care Personnel

Surgical operations often force the surgeon, nurses, other operation room personnel to adopt unsupported forward-leaning postures (Berguer, 1999; Berguer et al., 1997; Kant et al., 1992; Lee and Chiou, 1995; Nguyen et al., 2001). Berguer et al. (1997) compared laparoscopic and open surgical procedures and found that surgeon's back positions were more often bent in open procedures than laparoscopic procedures. Brulin et al. (1998) investigated low-back pain complaints amongst home care personnel and found that forward-bent postures were commonly assumed.

3.1.7. Other Industries

Other industries reported in the literature whose workers may be at risk of developing MSDs due to assuming forward-leaning postures include microscope users (Kumar and Scaife, 1979), telephone switchboard operators (Grieco, 1986), cloth inspectors (Floyd and Ward, 1966), helicopter pilots (Bridger et al., 2002), automotive industry workers (Keyserling et al., 1988), manufacturing industry workers (Lu, 2003), accounting machine operators (Hunting et al., 1980), hairdressers (Arokoski et al., 1998; Nevala-Puranen et al., 1998), and even snowmobile drivers (McGill, 1997).

Given the numerous industries and their workers who assume forward-leaning postures, it is now necessary to determine if a biological plausibility exists between these postures and the complaint of low-back pain/disorders.

3.2. THE BACK

The back is one of the most commonly injured areas of the human body (Tawfik, 2001). It has been estimated that between 50 to 90% of all adults will have some sort of back disorder during their lifetime (Andersson, 1981; Frymoyer et al., 1983; Horal, 1969; Leboeuf-Yde and Kyvik, 1998; McKenzie, 1981; Riihimaki et al., 1989; Svensson et al., 1988). Many factors can account for back disorders ranging from acute to cumulative trauma. Although not all researchers agree on exactly what the causation is, very few would argue that there are risk factors involved and that the interaction of them increases the likelihood of developing a back-related MSD. Unfortunately, it is this interaction of risk factors, and their effects, that are mostly misunderstood (Burdorf and van Riel, 1996).

Epidemiological studies have shown that there is either "strong evidence" or "evidence" of a causal relationship between workplace exposures to forceful exertions, repetition, and awkward postures and MSDs of the neck, upper extremity, and low-back (NIOSH, 1997). Throwing "workplace exposures" into the mix only complicates the issue, as it is difficult to know if non-workplace exposures may have played a part. Even though a significant amount of study has gone into the causations of back dysfunction and many risk factors have been identified, the true mechanisms and their interactions leading to these disorders have proven to be elusive (Tawfik, 2001).

One problem with current research is the inability to test hypotheses due to the interaction of all these factors and the inability to control them over any sort of a longitudinal study. In vitro measures are heavily relied upon due to the reality that in vivo measures are highly complex and difficult to gather (Rohlmann et al., 2001b; Sato et al., 1999; Wilke et al., 1999). Use of cadavers in research has produced much data, but again, the inability to compare the associations between living and dead tissue results in many conclusions to be questioned (Wilke et al., 1999).

A review of the anatomy and physiology of the low-back is important to determine the biological plausibility of the occurrence of low-back disorders (LBDs) due to forward-leaning postures. Following is a brief anatomy and physiology review of the spine and its' reaction to forward-leaning postures.

3.2.1. Anatomy of the Spine

The anatomy of the back is one area that many researchers look to when explaining low-back MSDs. The musculoskeletal system of the back that is of most concern is the spine and its associative muscular attachments that support and allow movement of the upper-body. Spinal bodies composed of vertebrae, discs, and ligaments make up the supportive structure of the spine. Vertebrae tilt and/or rotate, ligaments stretch, and discs compress to allow for movement to occur. Although individual vertebral segments (composed of 2 vertebrae and their associated soft tissues) do not allow for much movement, the summation of each vertebral segment's movements permits major changes in upper-body postures including flexion, extension, and rotation of the trunk.

The spine consists of 33 (34 in some individuals) vertebrae separated by intervertebral discs and is held together by soft tissue attachments including muscles and ligaments. The main functions of the spine are support for the upper-body and protection of the spinal chord. It also serves as attachment points for a number of different muscles.

The spine is composed of 4 different regions characterized by their shape: cervical, thoracic, lumbar, and sacrum at indicated in Figure 1. The cervical region contains the neck, the thoracic contains the upper-back, the lumbar contains the low-back, and sacrum is the region between the low-back and pelvis. The lumbar section of the spine contains 5 vertebral bodies separated by intervertebral discs, while the sacrum is usually fused after the age of 26 (Van de Graaff and Fox, 1999). As a result, great amount of stress is concentrated on the L4-L5 and L5-S1 interface (see Figure 1), which happens to be the location of a majority of LBDs (Mandal, 1981; Tayyari and Smith, 1997). The lumbar region of the spine is usually the area that is most discussed when MSD's are of concern (Nachemson, 1966; Tawfic, 2001).

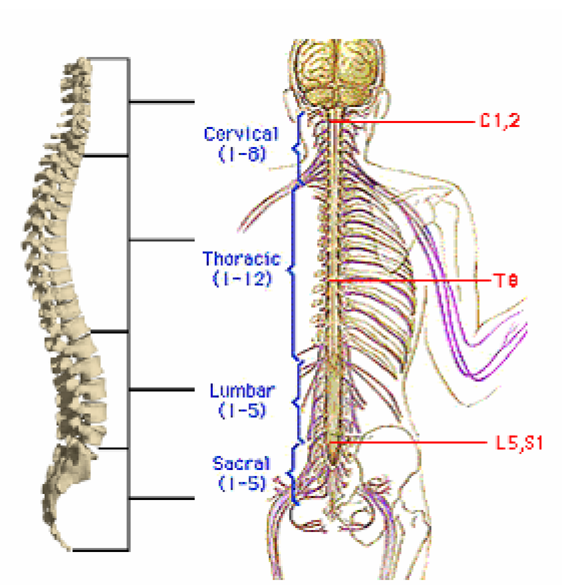

Figure 1. Human Spine.

In erect standing postures, the lumbar area of the spine contains a normal curve called lordosis (see Figure 1). This curve can straighten and even flex in the opposite manner during normal movement, including sitting (Bendix, 1984; Rohlmann et al., 2001a). It is believed that movement away from the normal lordotic posture can lead to low-back disorders (Tougas and Nordin, 1987). Posterior rotation of the hips, as seen in seated subjects along with forward-leaning can decrease lumbar lordosis (Rohlmann et al., 2001a). Lord et al. (1997) found that lumbar lordosis is 50% less in sitting than standing.

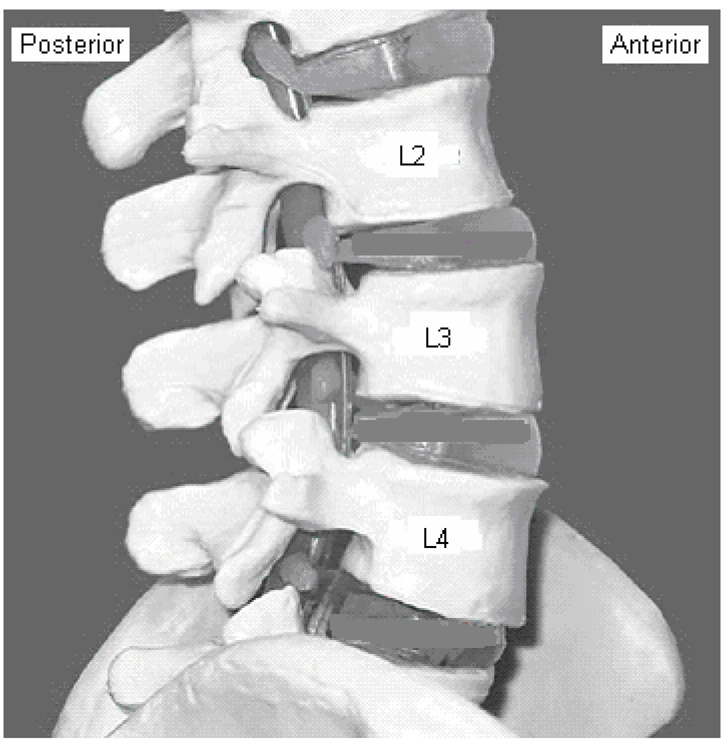

Figure 2. Lumbar Spine and Intervertebral Discs.

Intervertebral discs are the body's natural "shock absorbers." Located between vertebrae, as shown in Figure 2, they allow for proper spacing between one vertebrae and the next, as well as to allow the spine to compress and absorb vertical forces that are imposed upon the spine (Van de Graaff and Fox, 1999). Discs are composed of a gelatinous center termed the nucleus pulposus surrounded by a fibrous perimeter termed the annulus. The nucleus pulposus is mainly composed of water and acts hydrostatically while the annulus is composed of fibrous materials that house the nucleus inside the disk (Adams and Dolan, 1995). It is believed that the nucleus pulposus is primarily responsible for providing cushioning between two vertebrae (Nachemson, 1966).

The spinae erector muscles of the back are primarily responsible for extension of the spine/trunk (Floyd and Silver, 1955; Gupta, 2000; Macintosh et al., 1993). Much like the triceps in the upper arms that provide stability during flexion of the elbow (created by the biceps), the spinae erector muscles provide stability of the spine in flexion movements (created by the abdominal muscles). Additionally, they are also responsible for holding the torso stable during unsupported forward-leaning postures (Floyd and Silver, 1955; Gupta, 2000; Macintosh et al., 1993).

Biomechanically, the erector spinae muscles must exert great force during forward-leaning postures. Given a very short moment arm, even a slight forward lean of the torso will cause the erector spinae muscles to contract (Tveit et al., 1994). This is because the lever-arm from the spine to center of the upper-body can be much greater than the lever-arm of the erector spinae muscles, depending upon the degree of forward-leaning (Tveit et al., 1994). Much like a teeter-totter, the further from the pivot point, the easier it is create a moment. Furthermore, the center of gravity of the torso will move further away from the spine as a forward-leaning posture increases (up to horizontal). The more the torso is flexed from vertical, the more the erector spinae muscles must work to stabilize the upper-body (Floyd and Silver, 1955; Tveit et al., 1994). As full flexion is approached, the ligaments holding the spinal vertebrae together tighten to prevent excessive bending. Unfortunately, this action further increases the load on the spine and the pressure between the discs (Adams and Dolan, 1995; Callaghan and Dunk, 2002; Floyd and Silver, 1955; Kaigle, et al., 1998; Kayis and Hoang, 1999).

The lever-arm of the erector spinae muscles is generally accepted to be 2-inches. In a forward-leaning posture the lever-arm to the center of gravity of the upper-body can easily reach 8-inches. Therefore the amount of force required by the erector spinae muscles can be 4 times that of the weight of the upper-body. Nachemson (1966) found that approximately 59% of the body's weight is located above the L-4 disk. Therefore, a 200 lb man in a forward-leaning position can require 472-lbs of erector spinae force to keep the torso stable. If the man's hands and/or arms are extended, this amount of required force can greatly increase. To make matters worse, Tveit et al.'s (1994) found that the lever-arm of the back muscles actually decreases as the back is flexed, further increasing the mechanical disadvantage of the back.

When the spine is flexed both spinal loading and pressure on the intervertebral discs increases (Granata and Wilson, 2001; Kayis and Hoang, 1999, Nachemson, 1966; Nachemson and Elfstrom, 1970; Rohlmann et al., 2001a; Sato et al., 1999; Tveit et al., 1994; Wilke et al., 1999). This reaction is, in part, due to the origin and insertion points of the erector spinae muscles on the posterior of the lumbar vertebrae. They pull the vertebrae together to create the force required to stabilize the torso. Many studies have found that forward-leaning postures produced the greatest pressures on the intervertebral discs over vertical and back-leaning postures (Kayis and Hoang, 1999; Nachemson, 1966; Wilke et al., 1999; Wilke et al., 2001).

3.2.2. Physiology of the Spine

Normal muscle physiology pertains to the erector spinae muscles. Localized muscle fatigue, loss of energy producing nutrients, and an increase of lactic acid can all occur during normal muscle operation (Arndt, 1983; Tougas and Nordin, 1987). Holding static postures is especially detrimental to the musculoskeletal system as the required rest time between exertions does not occur (Tayyari and Smith, 1997). Without rest, the musculoskeletal system cannot replenish its' nutrient supply and eliminate muscle activity by-products (Arndt, 1983; Tayyari and Smith, 1997). Maintaining static postures can lead to MSDs over time (Arndt; 1983).

When considering the lumbar region of the spine, the physiology of the intervertebral discs is of major concern, especially that of the nucleus pulposus. When a disc is compressed, fluid inside the disc moves to the outside. Via diffusion, fluid re-enters the disc once the compression has ceased. This "pumping" of fluid out-of and back into the disc is thought to be a major contributor to the replenishment of intradiscal nutrients (Holm and Nachemson, 1983; van Duersen et al., 2000; Tayyari and Smith, 1997; Wilke et al., 1999). Since the interior of the spinal discs are avascular, this pumping is important for the health of the discs (Maroudas et al., 1975; Tayyari and Smith, 1997). Compression and decompression of the discs due to changes in posture is therefore beneficial (Holm and Nachemson, 1983; van Duersen et al., 2000; Wilke et al., 1999).

With age, the nucleus pulposus dehydrates and becomes less elastic, resulting in a reduced ability to absorb shock (Roberts et al., 1998). In addition, the height of the disc decreases with age resulting in less space between superior and inferior vertebral bodies and a shorter stature (Roberts et al., 1998). This decreased space may cause the rubbing together of vertebral bodies and/or the pinching of nerves, causing pain. Therefore, forward-leaning postures in older workers may be an even greater risk factor for LBDs than in younger workers.

3.2.3. Forward-Leaning as a Risk Factor

Mechanical over-loading of the lumbar spine is considered to be a causation of low-back disorders (Adams and Dolan, 1995; Burdorf and van Riel, 1996; Granata and Wilson, 2001). It has been shown in the previous review that during forward-leaning postures:

- Erector spinae muscle activity increases,
- Pressure on the intervertebral discs increases, and
- The overall spinal load increases.

Assimilating the above information, it is apparent why several researchers have concluded that seated postures, especially those requiring awkward postures such as assuming forward-leaning, are risk factors in causing LBDs (Andersson, 1981; Bendix et al., 1985; Nachemson, 1976; Pope, 1989; Selkowitz et al., 2001). Furthermore, holding forward-leaning postures for increasing periods of time (static postures) can further increase the risk of developing a low-back MSD (Andersson, 1981; Pope, 1989; Selkowitz et al., 2001; Tougas and Nordin, 1987).

This review of back anatomy and physiology provides a biological explanation for the development of low-back pain due, in part, to working in unsupported forward-leaning postures.

3.3. PROVIDING SUPPORT TO FORWARD-LEANING POSTURES

Providing support to forward-leaning postures may help to reduce the increased risk of LBDs associated with these awkward postures. Allowing the weight of the upper-body to be partially supported will reduce (1) the force required by the erector spinae muscles to keep the torso stable, and (2) the pressure produced on the intervertebral discs due to the forces between the vertebrae created by the action of the erector spinae muscles (Kayis and Hoang, 1999; Wilke et al., 1999).

Unloading the back onto a backrest during "back leaning" seating is known to reduce disc pressure and back muscle EMG activity (Kayis and Hoang, 1999; Rohlmann et al., 2001a; Wilke, 1999). It has also been shown that unloading the weight of the upper-body during forward-leaning postures will produce the same reduction of disc pressure (Wilke, 1999). The more upper-body weight unloaded onto a support, the less weight the spine will have to support. This can reduce the forces between vertebral segments and the associated soft tissue.

Use of a support during forward-leaning postures may be helpful. Muscles would not need to work as hard, pressure on intervertebral discs would be reduced, and a reduction in the risk of developing a low-back MSD may occur.

3.4. ESTABLISHMENT OF THE NEED

The evidence of a need for a product that provides forward-leaning support has been established:

- Multiple industries have been identified whose workers are complaining of low-back pain due to holding forward-leaning postures.
- A biological explanation has been established that links forward-leaning postures to an increased stress on the musculoskeletal system of back.
- Providing support to forward-leaning postures may help reduce the incidence of LBDs due to assuming these awkward postures.

The next steps of the design process include identifying, designing, and evaluating a product that is capable of providing forward-leaning support to workers in industry.

3.5. A PRODUCT THAT PROVIDES FORWARD-LEANING SUPPORT

It is proposed that developing an ergonomic chair feature capable of providing support to forward-leaning postures is the solution to the defined problem. Ergonomic chairs have previously given support to several postures and it is believed this new feature could easily be designed and added, making them capable of providing forward-leaning support.

A few chairs have been developed that are capable of providing support to some awkward postures. Dental chairs have been designed to provide some support to side-leaning postures by providing an "arm" that can be leaned on. Another design allows users to use the backrest as a forward leaning support when seating backwards on the chair. This process is, however, awkward and requires the user to mount the chair as one mounts a horse. This design does not provide the much-needed range of adjustments as a true ergonomic chair should while providing forward-leaning support. Another design that has recently been introduced involves a Support-Arm that rotates from the front to the back, thereby providing support to either forward-leaning or backward leaning postures, depending upon its position (see Figure 3). This stool better meets the needs of forward-leaning, yet still has room for improvement: mainly, a greater range of forward-leaning support.

Figure 3. Picture of a Current Chair Design Capable of Providing Support to Forward-Leaning Postures.

Prior to providing design details for the new chair feature, a review of ergonomic chair design and methods of evaluation will be provided. This will help to provide the reader with a base point for ergonomic chair design requirements and attributes.

4. ERGONOMIC CHAIR RESEARCH

In the world of ergonomic office products, chairs dominate the scene. Many tasks in today's work environment require the need for a seating device. It is known that prolonged seating can lead to low-back pain and that ergonomic seats can help to lower its incidence (Andersson, 1981; Kelsey, 1975; Damkot et al., 1984; Hales and Bernard, 1996). Good ergonomic chairs can reduce muscular aches, pains, and stresses while improving comfort and productivity (Ayoub, 1971).

The definition of an ergonomic chair is highly disputed. Some ergonomists may argue that an ergonomic chair is one that has many levers and adjustments that allow one to position their body in an "optimal" position. Others may say that an ergonomic chair is one that will provide proper seating for 95% of the population. Still others may say that an ergonomic chair is one that allows numerous positions to be assumed.

Ergonomic chair design, most would agree, entails the use of human attributes to design an ergonomic chair that is comfortable, aesthetically pleasing, and capable of allowing the user to sit in different postures. It must also be safe to use, durable, and easily maintained. (See Appendix A for information on ergonomic product design guidelines.)

Comfortable seating is one of the most desirable qualities consumers seek in chairs. Although the definition of comfort is not easily defined, most of us understand when we are feeling comfort and/or discomfort. Designing for comfort usually includes all other aspects of ergonomic design combined.

Aesthetics is a very important psychological consideration that most, if not all, humans are concerned with. The proper look, feel, and smell are three important considerations that an ergonomic design engineer must consider. Since humans differ on all these aspects, a designer can offer different coverings and colors that can be added to the final product design per order.

It is known that static postures are detrimental to the human body (Miedema et al., 1995). Frequent movement helps the body move blood around and infuse cells with much needed nutrients. Given this knowledge, a chair that is capable of producing multiple postures is favorable, ergonomically speaking, to chairs that are fixed in one position. Back-leaning, forward-leaning, sitting vertical, tilting of the pelvis forward and back, and any other movement is a positive in the ergonomic world of seating (as long as it is not static or extreme). High-end ergonomic chairs have multiple adjustments including seat height, seat-tilt, seat slide, arm rest with width/height/angle adjustments, seat backs with angle/height/depth/lumbar support adjustments, and some even have head rests with height/depth adjustments to name a few. All these adjustments should allow an ergonomic chair to properly fit an individual while assuming any number of preferred sitting positions.

Safety considerations are also a major aspect of ergonomic chair design. For example, chairs can tip over, injuring workers if they are not designed appropriately. Product life cycle and maintenance issues are two other issues, amongst many more, that are also of concern to the ergonomist when designing a chair.

Ergonomists have designed many chairs to date and several manufacturers specialize in high-end ergonomic office chairs. These chairs can cost $1,000.00 each, sometimes even more. Specialty chairs also have incorporated ergonomics into their designs. Dental style stools have been designed to provide an extendable arm that the dentist may use to lean against, or support their working arm while performing dental duties. Massage stools have been designed with features such as "face cut-outs" to place the massage receiver in total comfort while laying face down.

Ergonomic research in chair design, use, and comfort is still in its infancy. For example, some studies claim that sitting vertical is favorable, some claim that backward leaning positions are best, and some even claim that forward-leaning position are best for the body. While several ingenious designs have been imagined, designed, and built, there is room for improvement in the ergonomic design of chairs.

4.1. OPTIMUM SITTING POSTURES

For years, ergonomists have attempted to define an optimal sitting posture. These optimal postures have mostly come from different believes on what posture the body is "strongest" and meant to be in. Perhaps the most common *optimal* seated posture is the strict upright posture (vertical upper-body). Another posture thought by many to *optimal* was fully defined by NASA Reference Publication 1024 (1978), and has been shown to be the posture humans assume in a weightless environment. Keegan et al. (1953) believed that by tilting a chair's seat-pan forward, the pelvis was tilted forward creating the beneficial lordotic curve in the lumbar region that is associated with the "neutral posture." Further, a posture associated with a reclined torso was presented as being the "optimal" posture as it reduced disk pressure by unloading spinal and disk forces and pressures onto the seat's backrest (Kayis and Hoang, 1999).

Unfortunately, no seated posture has yet been proven to be optimal. Although most ergonomists would agree that the "neutral posture" is optimal, applying the posture to seating design is not straight-forward. Although chairs can be designed that place the body in its neutral position, proper orientation of this chair with respect to gravity is an unknown. There are also many issues related to this posture that may not make it an appropriate posture to assume in the workplace.

Provided the optimal seated posture can be found, strictly designing chairs for it should not be done. Having the ability to move from one supported posture to another is perhaps the most important design consideration of any ergonomic chair. Although this concept is not new, it is now thought to be optimum seating behavior (Andersson, 1981; Graf et al., 1993; Kroemer, 1994; Serber, 1994; Suzuki et al., 1994). Therefore, in addition to being capable of providing support to the optimum sitting posture, an ergonomic chair should be capable of allowing the user to assume numerous postures, including sit-stand positions.

This design concept does not negate the many studies completed in the past. Instead, it binds much of this prior research together, showing why there are many ideas on an optimal seating posture and chair design. In essence, for normal seating postures, there may be no one optimum posture. Perhaps the optimum posture is the posture that is most comfortable to the seated person at that particular time. This optimum posture should change several times throughout the day since the longer any one posture is held statically, the greater the amount of discomfort that will arise (Fenety et al., 2000). Changing posture allows the musculoskeletal system to recuperate from the past position that was being held. This, however, does not mean that any position can be an optimal position. Full upper-body flexion or hyperextension, extreme torso rotation, and other "extreme" postures will most likely never be termed optimal.

4.2. ERGONOMIC MEASURES

Many papers have been published that evaluate the "ergonomics" of ergonomic chairs. Several methods have been used and no standard has been accepted. Some investigators use measurements of the chairs while some use measurements of the human subject, or a combination of both. These measurements can be either objective or subjective while the obtained data can be categorized as either quantitative or qualitative. Examples of objective measurements used include EMG, spinal disc loading, seat-pan interface pressure, seat-pan contact area, changes in spinal length and leg volume, production measurements, and measures of anthropometry. Subjective examples include, but are not limited to, comfort and discomfort surveys, chair rankings and ratings, and recording of subjects' comments.

Objective readings are those that do not take the subject's opinion into consideration, therefore removing potential subject bias. However, in doing so, objective measures also fail to consider the human element, which is one of the most important aspects in ergonomic design. Optimally, chair evaluations should contain both subjective and objective measures, and compare their correlation to verify the results (Eklund and Corlett, 1986).

Comfort and discomfort measures have received much attention in ergonomic studies of chairs. It is now believed that the two are not the opposite of each other and are affected by distinctly different variables (Habsburg and Middendorf, 1978; Kleeman, 1981; Kamijo et al., 1982). In fact, it has been stated that discomfort has less to do with the actual chair than it does with the amount of time spent seated in it, and the measure of comfort is preferred over the measure of discomfort (Michel and Helander, 1994). Comfort on the other hand is based on feeling of well-being and the chairs' aesthetics (Helander and Zhang, 1997). Helander and Zhang (1997) proposed a possible relationship between comfort and discomfort. It is reproduced in Figure 4. Note that comfort and discomfort are not mutually exclusive.

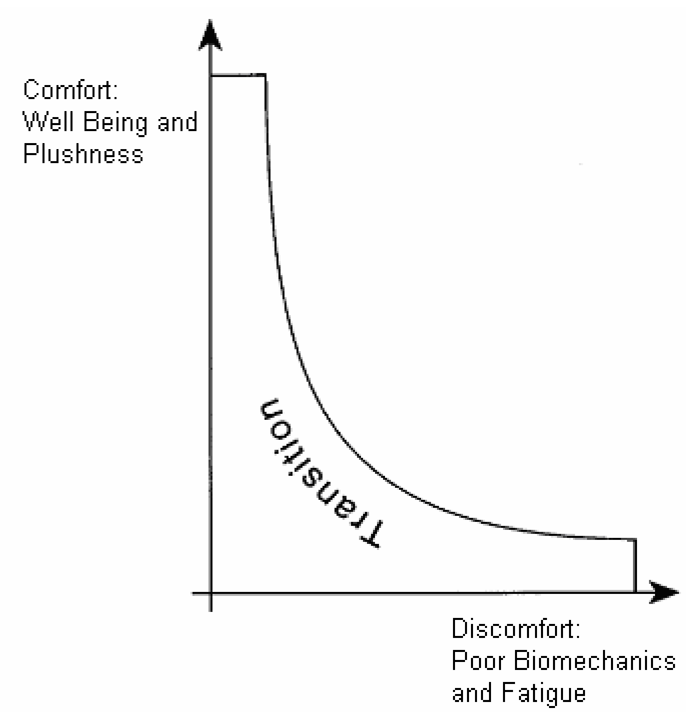

Figure 4. A Conceptual Model of Sitting Comfort and Discomfort (Adapted from Helander and Zhang, 1997).

As previously stated, ergonomics involves several disciplines. It is the merging of these disciplines that creates good ergonomic design. Therefore, an evaluation of a products' ergonomics should consider all the issues associated with the entire field of ergonomics at once. This task is rarely, if ever, possible to accomplish as the interactions between all the ergonomic disciplines are very complex, and still not completely understood.

4.3. SUMMARY OF RESEARCH

The design and evaluation of ergonomic chairs is not new. Several researchers have investigated different design specifications and reported their results in magazines, journals, and books. When reviewing the literature, one must understand that the evaluations of different design features may or may not be relevant to a particular specific design, such as a chair to be used in forward-leaning. Therefore, careful reading of the literature is very important to make sure optimal design specifications are not adopted out of context.

Below is a list of several points made in the literature:

- A larger contact area between the seat-pan and a subject's trunk-thigh region results in lower buttock-thigh pressure (Congleton et al., 1988; Vos, 2001)
- Comfort is proportionally related to contact area and inversely related to interface pressure (Congleton et al., 1988)
- Slumped forward sitting postures decrease lumbar lordosis (Corlett and Eklund, 1984)
- Use of a forward-sloping seat moves the back from kyphosis towards lordosis as the trunk-thigh angle increases (Corlett and Eklund, 1984; Bendix and Biering-Sorensen, 1983)
- When seated, most pressure and force is located at the ischial tuberosities (Congleton et al., 1988; Corlett and Eklund, 1984)

- Trunk muscles EMG and intradiscal pressure decreases as the trunk moves towards lumbar lordosis when using a backrest (Andersson et al., 1986; Corlett and Eklund, 1984; Andersson et al., 1974; Andersson and Ortengren, 1974a; Andersson and Ortengren, 1974b; Treaster, 1987)
- Lumbar back rest cushions may lead to increased lordosis (Coleman et al., 1998)
- Sitting postures are determined by the task (Hsiao and Keyserling, 1991; Bridger, 1988)
- Dynamic versus static sitting reduces load on the spine (van Deursen et al., 2000)
- A well designed seat should be able to accommodate a wide range of users and provide adequate support (Goonetilleke and Feizhou, 2001; Goonetilleke and Rao, 1999; Gross et al., 1992)
- When not supported, the body must work harder to provide stability (Ng et al., 1995)
- A chair should be designed to allow for easy changes in posture (Helander et al., 1987)
- Free swiveling seat-pans are advantageous when work is static (Hsiao and Keyserling, 1991; Toren and Oberg, 2001; Tougas and Nordin, 1987)
- Chairs designed for particular uses may help reduce commutative trauma disorders (Frey and Tecklin, 1986; Park et al., 2000)

- Chairs designed with the most amount of adjustments were judged the most comfortable (Helander et al., 1995)
- Sitting in the neutral posture may be preferable (Congleton et al., 1988)
- Research has found subjects prefer seats to tilt from 15 degrees backwards to 35 degrees forwards (Bendix and Biering-Sorensen, 1983)
- In forward-leaning work, a front tilting seat-pan is critical to prevent the trunk-thigh angle from getting too small and creating kyphosis (Tougas and Nordin, 1987)

Assimilating the above information, ten optimal design guidelines, or criteria, may be listed:

1. A larger seat-pan is preferable to a smaller one
2. A backrest needs to be provided
3. The lumbar support position should be adjustable
4. The seat-pan should swivel
5. The seat-pan should have fore and aft movement
6. The seat-pan should tilt (15 degrees backwards to 35 degrees forwards)
7. A chair should allow for changes in supported postures
8. If applicable, a chair should be designed for use during specific tasks
9. An ergonomic chair should be highly adjustable
10. An ergonomic chair should allow the user to assume the neutral posture, amongst others

5. THE DESIGN

It has been shown that much research has been conducted on ergonomic chair design. Several authors have provided chair feature specifications (summarized earlier), although not all are in agreement. Different experimental methods, including the postures the subjects assumed, may be the cause of these disagreements. It has also been shown, and is perhaps yet another reason for discrepancies in the literature, that static seating (holding the same posture over time) may create discomfort independent of a chair and/or posture.

Although these disagreements may create confusion to a chair designer, a closer inspection reveals the basis of ergonomic chair design. An ergonomic chair should provide for the following six items:

1. Allow for dynamic seating
2. Allow for several supported postures
3. Be aesthetically pleasing
4. Designed for the task at hand
5. Easily adjustable, and
6. Designed to fit the anthropometrical range of the potential user's population

Providing support to forward-leaning postures is the next step in the evolution of ergonomic chair design. A prototype must be built and evaluated to determine if "true" ergonomics has been met (and the consequences, if any, of providing forward-leaning support to workers). Prior to building a prototype, however, the chair must first be designed.

5.1. NEW DESIGN GUIDELINES AND SPECIFICATIONS

The primary addition to current ergonomic chair design this dissertation proposes is a feature that provides support to forward-leaning postures. Design guidelines (and some specifications) for "modern" ergonomic chairs have been summarized earlier. What are missing from the "formula" are the design guidelines and specifications for the newly proposed feature.

Previous research on workers who perform their work while assuming, at times, forward-leaning postures (see The Need section of this dissertation) has provided the information required to develop additional specifications for ergonomic chairs:

1. The set-pan must be height adjustable, capable of providing support ranging from normal sitting to sit-stand postures.
2. The seat-pan must have tilting capabilities to allow for forward-leaning in both normal sitting and sit-stand postures.
3. The chair must contain a feature capable of providing support to a wide range of potential forward-leaning postures.

Specifically, the design specifications required for the addition of the new feature are:

1. Range of seat-pan height
2. Range of seat-pan tilt
3. Maximum and minimum horizontal and vertical range of the forward-leaning support

5.1.1. Seat-Pan Tilt

Research (discussed earlier) has shown that seat-pans should be able to tilt backwards 15-degrees and forwards 30-degrees for *normal* chairs. Given that the proposed design is also adaptable to sit-stand and forward-leaning postures, new forward-tilting specifications must be found. For the seat-pan to be parallel to the upper leg while assuming a sit-stand neutral-posture (approximately 130-degree knee and trunk-thigh angles) the seat-pan should be able to tilt 50-degrees forward, as shown in Figure 5.

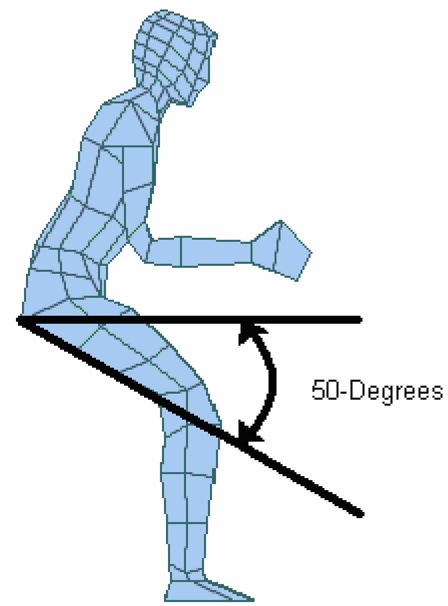

Figure 5. Required Seat-Pan Tilt. Not to Scale. Mannequin derived from 3DSSPP (University of Michigan).

5.1.2. Seat-Pan Height

The range in height of the seat-pan should extend from normal sitting to sit-stand heights. Using the 5th percentile female's seated popliteal height as the minimum and a 95th percentile male's buttock height at a neutral posture (130-degree knee angle, as shown in Figure 5), it is found that the seat-pan height should be adjustable from 14.8 to 37.0-inches above the floor (unclothed subjects). Adding a shoe allowance of 0.5-inches, the seat-pan height should be adjustable between 15.3 to 37.5 inches above the floor.

5.1.3. Forward-Leaning Envelope

The chair feature must be capable of providing support over the entire range of potential forward-leaning postures. The required range of this adjustability is contained in an envelope that follows the shoulder region from the vertical (b in Figure 6) to the horizontal (c in Figure 6) planes for the 95th percentile male and enclosed at the nook of the trunk-thigh region (a in Figure 6) for the 5th percentile female. This envelope looks like a slice of pie from the sagittal plane, as shown in Figure 6.

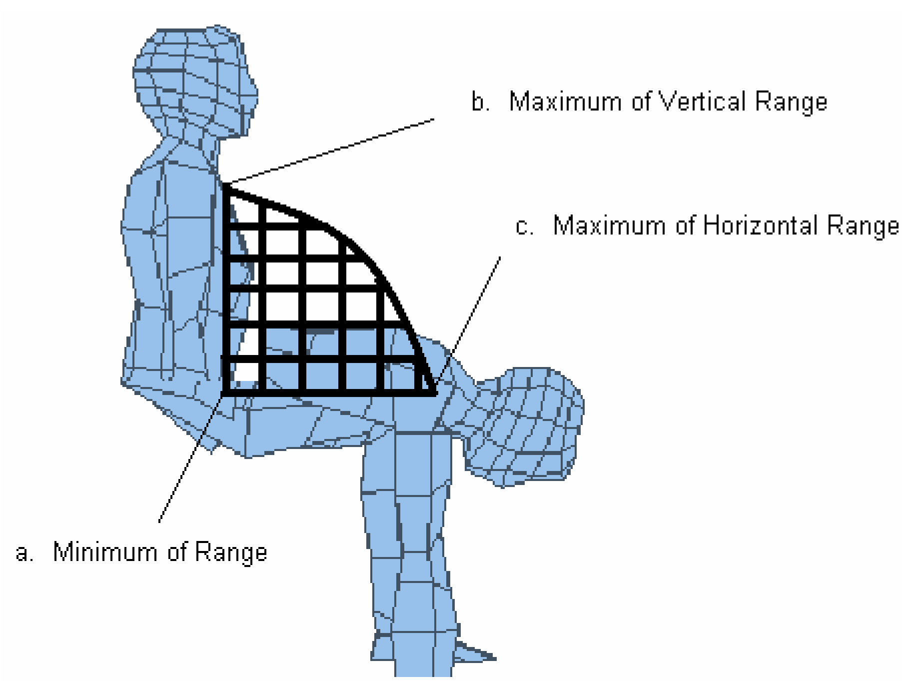

Figure 6. Envelope's Range of Forward-Leaning. Not to Scale. Mannequin derived from 3DSSPP (University of Michigan).

The envelope can now be quantified through the use of anthropometric data for the 5th percentile female and the 95th percentile male. The maximum vertical location is located at the 95th percentile male's shoulder height. The maximum horizontal location is equal to the length of the "radius arm" of the upper-body. This radius arm is defined by the distance between the center of rotation of the upper-body and the shoulder for the 95th percentile male. To be conservative, the center (both vertical and horizontal) of the pelvic region (the intersection of the center of seated thigh clearance above the seat-pan and the center of the buttock to abdomen) was chosen as the center of rotation. The anthropometrics used to define the forward-leaning envelope are provided in Table 1.

Table 1. Anthropometry Used for Support-Arm Envelope (in). Anthropometric Data from Chengalur, et al., (2004) and *Chaffin, et al., (1999).

SEATED ANTHROPOMETRY	5TH PERCENTILE FEMALE	95TH PERCENTILE MALE
Horizontal Distances		
Buttock to Abdomen	*8.2	*11.4
Vertical Distances		
Thigh Clearance	3.9	7
Shoulder Height	20.8	26.9

Figure 7 shows the required envelope for the 5th percentile female while Figure 8 provides the required envelope for the 95th percentile male. Note that the envelopes are defined from the mid-sagittal plane and the top of the seat-pan.

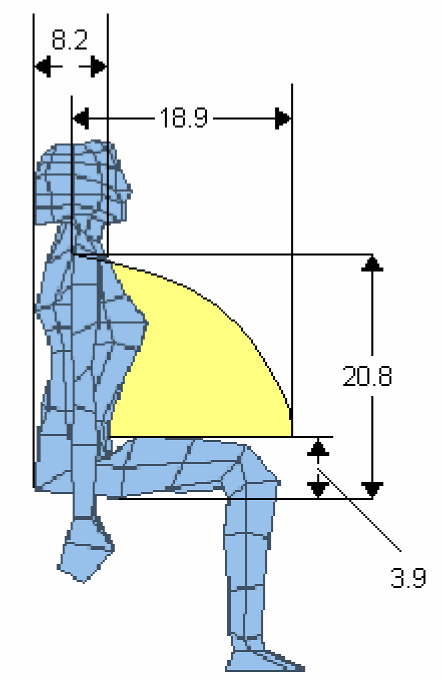

Figure 7. 5th Percentile Female and Minimum Support-Arm Envelope (in). Not to Scale. Mannequin derived from 3DSSPP (University of Michigan).

The 5th percentile female was used to define the minimum range of the envelope. Since the 95th percentile male will determine the maximum vertical and horizontal locations, only the location of the nook of the 5th percentile female's trunk-thigh region is required. It is located at 3.9-inches above the seat-pan and 4.1-inches (one-half of 8.2-inches as shown in Figure 4) anterior (forward) of the mid-sagittal plane.

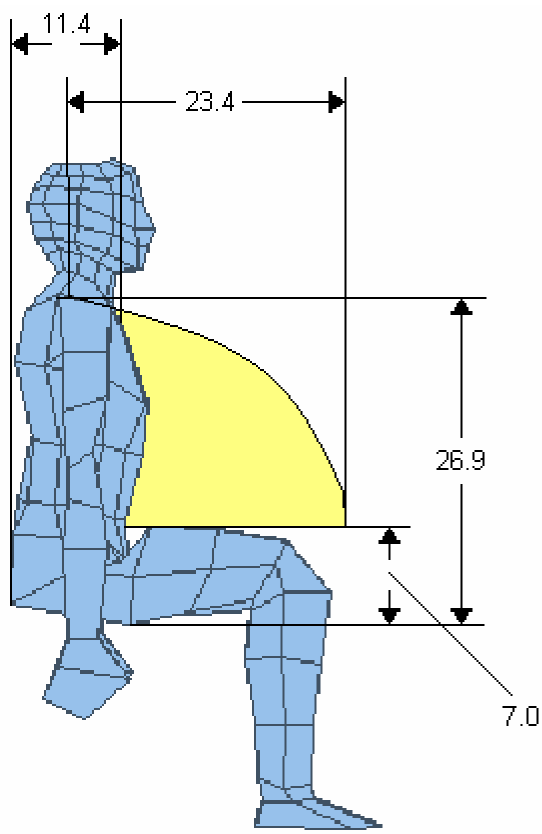

Figure 8: 95th Percentile Male and Maximum Support-Arm Envelope (in). Not to Scale. Mannequin derived from 3DSSPP (University of Michigan).

The 95th percentile male is used to define the maximum vertical and horizontal range of the envelope (see Figure 8). The maximum vertical location is 26.9-inches above the seat pan. Estimating the center of rotation the center of the pelvis, the radius arm of rotation of the upper-body, from the center of the pelvis to the should region, is then 23.4- inches long. Therefore, the maximum horizontal location is approximately 23.4-inches forward of the subject's mid-sagittal plane as shown in Figure 8.

Using the high and low ranges as provided above, the total envelope that encompasses the range of forward-leaning postures from the 5th percentile female to the 95th percentile male may now be quantified as shown in Table 2.

Table 2. Forward-Leaning Envelope (in).

Support-Arm Adjustments	Minimum	Maximum
Horizontal From Mid-Sagittal Plane	4.1	23.4
Vertical from Seat-Pan	3.9	26.9

A Support-Arm designed to provide support to forward-leaning postures should be adaptable for use anywhere inside this defined forward-leaning envelope. Note that the use of a Support-Arm in the breast region of females has unknown effects, as does the use of a Support-Arm by pregnant females.

It is assumed that the Support-Arm design will allow radial movement, allowing for the entire envelope to be accessible to forward-leaning support. Therefore, designers must take care when deciding upon the placement of the pivot point and length (and adjustment)of the Support-Arm. Figure 9 shows a Support-Arm and its required adjustments. The Support-Arm is described further in the next section.

Figure 9. Required Adjustments of the Support-Arm.

5.2. THE SUPPORT-ARM

Designing a Support-Arm (SA) that rotates from a fixed point, much like the upper-body flexes around the pelvic region, will provide for the full angular extent of the required envelope to be reached. Furthermore, by allowing the SA to extend and retract (increase or decrease the radial arm, see “D” in Figure 10) to the required extents will allow accommodation ranging from the 5th percentile female to the 95th percentile male as well as allow subjects to place the support in positions of their choosing (e.g. near the shoulder, chest, or abdomen regions).

The exact attachment location of the Support-Arm to the chair base is not covered in this dissertation. Although providing a full detailed design of the SA is not the mission of this dissertation, it is within the scope to give the readers a description a possible design that would allow for the full envelope to be supported. Figure 10 is a rendering of a possible Support-Arm design.

Figure 10. Two Views of a Support-Arm Design.

The two pictures Figure 10 shown a Support-Arm from the back and front-side views. Referring to Figure 10, section A is where the Support-Arm would attach to the seat post of an ergonomic chair. Section B is where the SA extends horizontally below the seat-pan of the chair. The SA has the ability to rotate at Point C to provide angular rotation along the sagittal plane, allowing support over the full range of forward-leaning postures. The SA then extends vertically along Section D (described earlier as the "radius arm"). It has the ability to change length, thereby allowing the SA to accommodate the previously defined envelope of forward-leaning postures. Section E is the area that is leaned into by the subject in a forward-leaning posture to provide support. Section E could be "customizable" to allow different attachments as required.

It may be seen that this design could easily be adaptable for use in back leaning as well by simply rotating the Support-Arm to the back of the chair. This dissertation does not provide any guidelines on the use of the Support-Arm in the back leaning position.

6. THE EVALUATION

Developing and then evaluating a prototype are the next two steps of the design process. Unfortunately, due to monetary considerations, building a prototype of the proposed ergonomic chair and Support-Arm is not feasible. Fortunately, a newly designed chair that contains several of the proposed design features, including a Support-Arm (SA), forward tilting seat-pan, and chair height adjustment, was available for use. This chair and Support-Arm design will be termed the "SA Model" throughout the rest of this dissertation. It is pictured in Figures 3 and 9 above and Figure 11 below.

The objectives of this evaluation are twofold:

1. Evaluation Part I was designed to determine if differences exist between the SA Model and eight commonly used chairs, over three postures, on the subjects':
    - Preferences of chairs,
    - Buttock-thigh peak pressures,
    - Buttock-Thigh contact areas,
    - Production values, and
    - Comfort survey results.
2. Evaluation Part II was designed to determine if differences exist between subjects' chosen body postures and chair configurations between the SA Model and a standard style stool at two different table heights.

The null hypothesis of Evaluation Part I was that no chairs performed differently under the prescribed conditions and tests performed. The null hypothesis of Evaluation Part II was that the subjects' chosen set-ups (configurations) were not different between the SA Model and the standard style stool.

The results of this evaluation will determine whether or not subjects perform differently in a number of different criteria while using a chair designed with a Support-Arm versus more traditional chairs (including the previously mentioned dental chairs and other unique chair designs that are capable of providing support to forward-leaning and awkward postures). Lessons learned from this evaluation might aid chair designers by identifying design guidelines and/or specifications not provided earlier in the Design Section of this dissertation. Additionally, results may provide valuable input on users' acceptance of a Support-Arm.

6.1. THE SA MODEL

Figure 11. The SA Model.

The SA Model has numerous adjustments available including seat-tilt, seat-height, seat-depth, and Support-Arm (an attachment fitted with a cushioned pad similar to Support-Arm on the proposed optimal chair design) that can be rotated around the chair from the back position (used as a backrest) to the front position. Figure 11 shows a picture of the SA Model with the Support-Arm located in the back position. Additionally, the Support-Arm can ascend/descend at a fixed angle (as it extends, it moves both vertically and horizontally away from the seat-pan). The cushioned pad on the Support-Arm has a four-position stop, all at 90 degrees to one another. The pad has an elliptical shape that provides different contact areas and depth (horizontal width or horizontal distance to a seated person) depending upon its' rotated position. See Appendix F for additional specifications and features.

Figure 12. SA Model's Adjustments and Uses.

Figure 12 shows different adjustments and potential uses of the SA Model. Although there are similarities between the SA Model's Support-Arm and the proposed Support-Arm, there are a few important differences that will be presented and discussed later in this paper.

6.2. PROCEDURES

The Institutional Review Board – Human Subjects in Research at Texas A&M University reviewed and approved the protocol for this evaluation (Protocol Number 2003-0420).

The experimental procedures were all conducted in a large room located on the second floor of an office building, in a private area free of interruptions, located in Bryan, Texas. The room temperature was kept at 72-degrees Fahrenheit with an electronic thermostat. The subjects completed the evaluation procedures separately.

Following initial greetings, an introduction was presented informing the subjects of the purposes of the evaluation (to determine if there are differences between the chairs over the test variables). Following the verbal introduction, subjects were asked to read and sign an Informed Consent Form describing the evaluation, their part in the evaluation, and a brief summary of the evaluation’s procedures. Next, subjects were asked to fill in a Personal Information Form to provide information such as prior work experience as well their history of low-back injuries. Subjects were then weighed and their height was measured using a medical scale, which were recorded confidentially onto the Personal Information Form.

Once the subjects’ weight and height were measured, an explanation of different postures that may be assumed while working was given and demonstrated. A standard style stool that was used only in Part II of the evaluation was used to demonstrate four commonly adopted seated postures. These four postures were:

1. Normal sitting (approximately 90^o ankle, 90^o knee, and 90^o trunk-thigh angles),

2. Forward-leaning in a sitting position (approximately 90^o ankle, 90^o knee, and 70^o trunk-thigh angle);
3. A sit-stand position (approximately 90^o ankle, 127^o knee, and 127^o trunk-thigh angles), and
4. A forward-leaning sit-stand position (approximately 90^o ankle, 127^o knee, and 110^o trunk-thigh angles).

Figure 13 indicates the locations and orientations of these indicated body part angles. Subjects were told that these four postures, or a mixture of them, are commonly chosen depending upon the type of work being completed as well as the height of a given work surface.

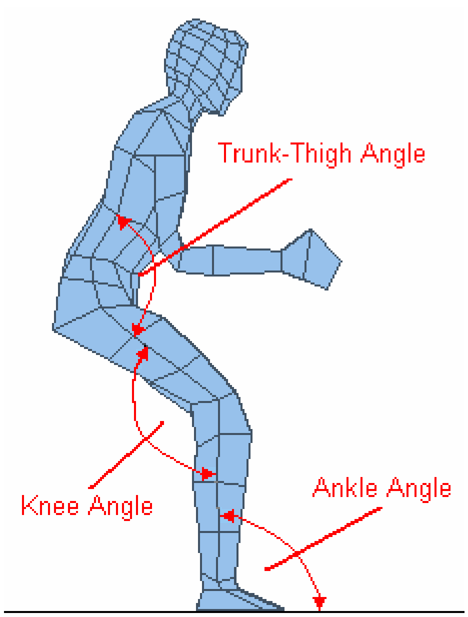

Figure 13. Location and Orientation of Body Part Angle Measurements. Mannequin derived from 3DSSPP (University of Michigan).

6.2.1. Evaluation Part I

Subjects

Eighteen subjects (9 females and 9 males) completed Part I of the evaluation. Subjects were coded by both gender (F for female and M for male) and number. All subjects, except one, were randomly (other than gender) hired from a temporary staffing agency (temp agency) located in Bryan, Texas. One female subject was recruited from within the office building where the evaluation was taking place. She had no previous knowledge of the evaluation or any of the chairs.

No subjects had previous knowledge of the chairs used in the evaluation, or of the evaluation itself. Subjects had no outside influence in their responses to any of the evaluation questions posed to them nor were they aware of any of chairs' manufacturers prior to or during the evaluation.

Chairs

Nine chairs were chosen for the evaluation, including the SA Model that contains an Support-Arm that is similar to the Support-Arm design introduced in this dissertation. As optimal chair designs are capable of several types of postures, including sit/stand postures, chairs were chosen that may be best described as stools due to their ability to provide seated support at greater heights (as apposed to an office chair). The 8 chairs along with the SA Model are believed to represent the wide variety of chairs being used in industry by workers (as discussed earlier) who commonly assume forward-leaning postures. The chairs' designs cover a wide range of capabilities including those adaptable to sit-stand, normal seated, and forward-leaning postures.

In an attempt to remove potential bias all distinguishing labels, marks, symbols, etc. were removed and/or covered up so as to keep the chairs' manufacturer from being revealed.

See Appendix E for pictures of the chairs and Appendix F for the features of the chairs used in this evaluation.

Chair Rankings

Subjects were asked to "rank the chairs in order of 1 through 9, 1 being your favorite and 9 being your least favorite, in order of which you would choose them for tasks requiring postures consistent with those demonstrated earlier." The chairs were all lined up against a wall with their associated letter designation displayed above them. Subjects' ranked the chairs using the Chair Ranking Form on three separate occasions. The chairs were positioned in the same manner for all subjects for all three chair rankings. Chairs a, b, e, and f were all positioned in the manner in which they would, or could, be used while performing forward-leaning tasks (they all contained Support-Arm designs).

Subjects were told the chairs were positioned in such a manner as to make use of their design features.

The three ranking trials were completed as follows:

1. The first chair ranking occurred at the beginning of the evaluation, immediately following a brief introduction as previously described. Subjects were instructed to not touch or sit in any of the chairs and to rank them on appearance alone.
2. Immediately following the first ranking, subjects were provided with a Chair Feature Matrix (CFM; see Appendix F). A chair that was not part of the evaluation was used to define and demonstrate all the features listed on the matrix. A presentation was then given, one chair at a time, using the CFM as a guide that identified the chairs' features. The subjects were not allowed to touch or sit in any of the chairs during this process. Any questions that were asked as to the features of the chairs were answered. Upon completing the CFM presentation, the subjects were asked to again rank the chairs using the same criteria as ranking #1, except now using the gained knowledge obtained from the CFM. The subjects were allowed to use the CFM as a reference.
3. Subjects performed the third chair ranking procedure immediately following the conclusion of the first part of the evaluation, after having sat in all the chairs in their respective postures. Subjects were asked to rank the chairs using the same

criteria as in ranking #2, along with their added sitting experience. Subjects were again allowed to use the CFM as a reference.

Postures

Following the second round of chair rankings, subjects were informed of the experimental procedures associated with the remainder of Evaluation Part I. Using a standard style stool, an explanation and demonstration of the 3 postures the subjects would assume was given.

Table 3. The Three Postures Chosen for Evaluation Part I.

	ANGLE (DEGREES)			
POSTURE	**Ankle**	**Knee**	**Trunk-Thigh**	**Seat-Tilt (Forward)**
Standard	90	90	90	5
Sit-Stand	90	127	127	10
Forward-Leaning Sit-Stand	90	127	110	10

Table 3 provides the body angles and posture "terms" associated with the 3 postures utilized in Part I of the evaluation. Figure 14 provides demonstrations of these postures. Note that the seat-pan tilting was always a forward tilt, meaning the front of the seat was lower than the rear. Chairs lacking seat-tilt abilities were evaluated over all postures, only with their seat-pans in their fixed tilt angles (generally a 0^o seat-pan tilt). For those that did have tilting capabilities, the seat-pans were tilted to meet the treatments as stipulated. An inclinometer was used to measure seat-tilt angle. For those seat-pans that could not tilt as far as stipulated per posture treatment, they were tilted to their farthest possible extent (refer to Appendix F the Chair Feature Matrix for the chairs' seat-tilting capabilities).

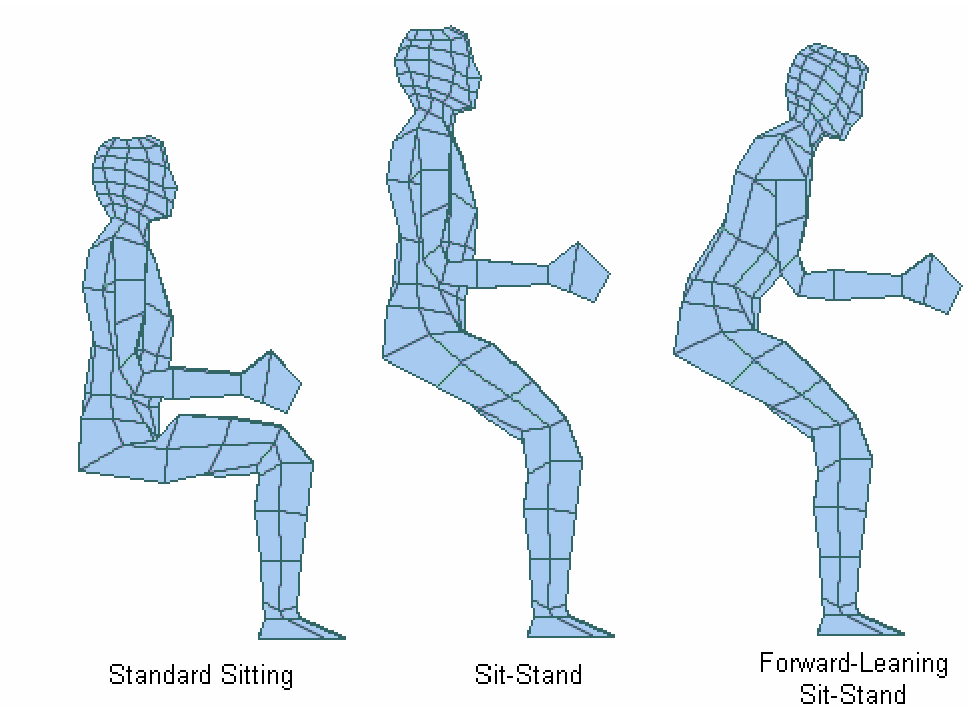

Figure 14. Representations of the Standard Sitting, Sit-Stand, and Forward-Leaning Sit-Stand Postures. Mannequins derived from 3DSSPP (University of Michigan).

Pre-cut angle jigs were cut out of heavy-duty cardboard of 90, 110, and 127-degree angles. These jigs were used to place the subjects in the appropriate postures in the sagittal plane. Anatomical landmarks were used to determine the points of reference for the angle measurement. The lateral malleolus, lateral epicondyle, greater trochanter, and acromian were used for the ankle, knee, hip, and shoulder points of reference, respectively (refer to Figure 13 for the locations and orientations of the angle measurements). Seat height was either raised or lowered to obtain the correct knee angle.

During the evaluation subjects were asked to hold their assigned posture as best as possible. Postures were checked periodically with the angle jigs to maintain consistency. Deviations from the assigned postures were immediately corrected.

Peak Pressure and Contact Area

Peak pressure and buttock-thigh contact area were measured with an Xsensor pressure mapping system along with the manufacturer's software. The Xsensor pressure map is a 36x36 sensor pad made of a thin (< 1mm thick) yet durable nylon shell encompassing 1296 pressure sensors. The pad was placed on the chairs' seat-pan prior to the subjects sitting down. The Xsensor system was calibrated by Xsensor technicians prior to experimentation, and had a maximum threshold of 4.06 psi with a refresh rate of 5000 sensor samples per second. Figure 15 shows the Xsensor pad on the SA Model's seat-pan. Note that the Support-Arm is located in the back-leaning position in this figure.


Figure 15. Experimental Set-Up and Xsensor Pressure Pad.

The Xsensor system was checked for accuracy prior to conducting the experimental procedures for every subject. The peak pressure readings and the seat-pan contact areas were recorded onto a Gateway 600xl laptop computer. Each trial was recorded separately per subject and coded appropriately.

The chairs were first adjusted to allow for the posture treatments with the subject seated on the seat-pan prior to placing the Xsensor pad on the chairs' seat-pans. The reason for doing this is that once the Xsensor pad is placed on a chair, and the subject then sits on top of it, it is difficult to make adjustments without the Xsensor pad shifting its position under the subject. Once the chair was properly adjusted for the subject per posture treatment, the Xsensor pad was placed on the chair's seat-pan and held by the investigator while the subject sat on the chair. The investigator then helped to properly position the subject at the testing table by either pushing or pulling the chair to the appropriate location.

Once the subject was placed in the appropriate location, the table height was adjusted to the subjects' elbow height. In addition, the table (shown in Figure 15) was either slid towards or pushed away from the subject to place the far end of the Purdue Pegboard at the subject's metacarpophalangeal joints (commonly termed the "knuckles" of the hand) while his/her arms were fully extended and parallel to the floor.

Recording of the peak pressure and contact area were initiated upon proper placement of the subject, chair, and table. The Xsensor software was set to record the data once every second. Values that best represented the data during the fourth task associated with the Purdue Pegboard were used (the Purdue Pegboard is discussed below) because the subjects were using both hands at the same time (their weight distributions were similar during this trial period).

Production

After sitting in each chair per appropriate posture treatment and properly adjusted as previously described, the subjects had their production performance tested using a Purdue Pegboard, shown in Figures 15 and 16. This test evaluates hand-eye coordination, gross movements of the fingers, hands, and arms, and fine fingertip dexterity (LIC, 1999). The Purdue Pegboard is used by Human Resource Directors and Temporary Staffing Agencies as a pre-employment screening and selection tool (LIC, 1999). "An applicant's performance on the Purdue Pegboard can indicate their ability to perform in a job/task that requires manual dexterity" (LIC, 1999). The Purdue Pegboard involves having subjects place pegs, washers, and collars, in a predetermined manner, in holes located on a board over a specific period of time (LIC, 1999).

In the current evaluation, the number of pieces placed correctly (production) during the time period can be compared over the chairs and postures. Inter-individual (between-subject) differences are not of concern. The assumption is that intra-individual (within a subject) production differences are due to the chair design and/or posture assumed.

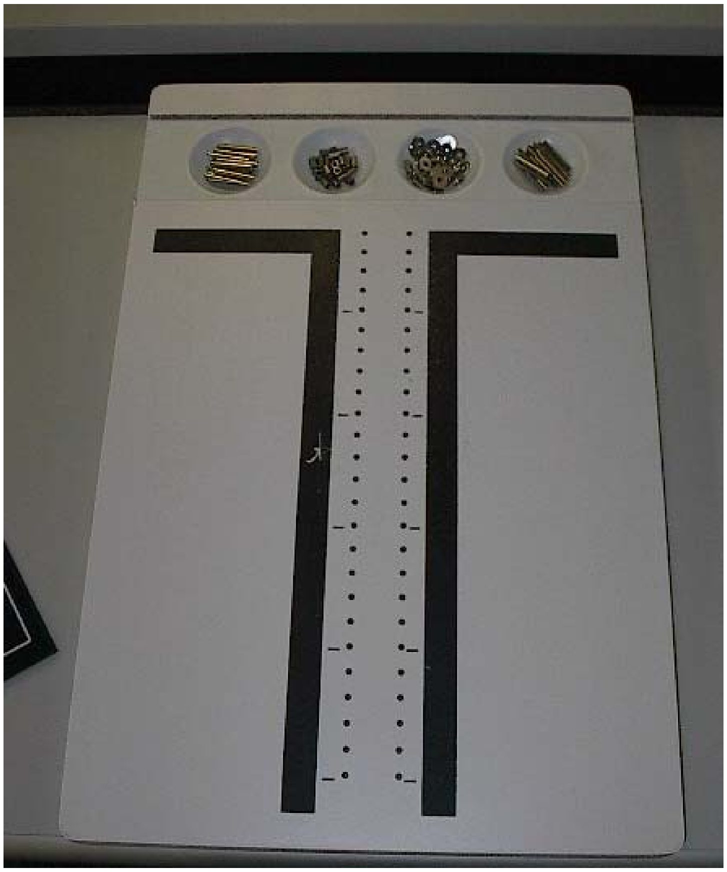

Figure 16. Purdue Pegboard.

The testing procedures followed those provided in the Purdue Pegboard's Test Administrator's Manual, or TAM (LIC, 1999). Prior to testing, subjects were given an introduction as to what the Purdue Pegboard is and the four tests they would be performing. Every subject then completed a trial run through the four tests to allow them an opportunity to become familiar with the pegs, washers, and collars as per the TAM.

The four production tests/tasks completed with the Purdue Pegboard are shown in Table 4, along with their associated trial numbers.

Table 4. Purdue Pegboard Production Testing Trials.

Trial	Hand	Task	Time (Seconds)
1	Left	Peg Placement	30
2	Right	Peg Placement	30
3	Both	Peg Placement	30
4	Both	Assembly Task	60

Subjects were told to not lean against the table or pegboard during the testing.

Comfort

Once the pressure, contact area, and production tests were completed (approximately 10 minutes of sitting time), each subject completed a Helander and Zhang (1997) chair comfort survey. The comfort survey made use of a continuous 10-cm VAS (Visual Analog Scale) with verbal anchors (per Helander and Zhang) to answer the 7 questions that best determine chair comfort (Helander and Zhang, 1997).

After the subjects finished filling out the chair comfort survey, they ended Part I of the evaluation by completing the third ranking trial.

Part I Experimental Design

The order in which the subjects saw the chairs and posture treatments were obtained using a Latin Square matrix design according to Lentner and Bishop (1993). Each posture was used 3 times per subject, and each subject sat in all 9 chairs. Each posture was used the same number of times in each chair for both the female and male subjects in total.

The advantages of a Latin Square design are greater efficiency with more accurate treatment comparisons, and greater sensitivity (Lentner and Bishop, 1993). The disadvantage of the Latin Square design is that interactions (chair*posture) cannot be investigated, which are not a concern of this evaluation.

The chairs were randomly coded a through i and the postures were randomly coded values a through c. Tables 5 and 6 provide the coding used for each chair and posture, respectively.

Table 5. Part I. Chair Codes.

CHAIR DESCRIPTION	CHAIR CODE
Dental Chair	a
SA Model	b
Industrial Stool	c
Office Stool	d
Office Chair	e
Dental Stool	f
Sit-Stand Stool	g
Sit-Stand Stool	h
Task Chair	i

Table 6. Part I. Posture Codes.

POSTURE DESCRIPTION	POSTURE CODE
Standard Sitting	a
Sit-Stand	b
Forward-Leaning Sit-Stand	c

See Table 3 for the full definitions of these three postures.

A Latin Square statistical design (see Table 7) was then used to assign postures to the subjects and chairs per standard convention (Lentner and Bishop, 1993).

Table 7. Part I. Latin Square Design Matrix.

	SUBJECT (F, M)								
CHAIR	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
a	a	a	c	c	b	b	a	b	c
b	a	a	c	c	b	b	a	b	c
c	c	c	b	b	a	a	c	a	b
d	a	a	c	c	b	b	a	b	c
e	c	c	b	b	a	a	c	a	b
f	b	b	a	a	c	c	b	c	a
g	b	b	a	a	c	c	b	c	a
h	b	b	a	a	c	c	b	c	a
i	c	c	b	b	a	a	c	a	b

Chairs and postures were then combined per subject and a matrix was created for subjects and trial numbers per the posture and chair treatments. These were then randomized per subject and treatments used per subject and trial were determined. Each gender's corresponding subject number was assigned the same treatment schedule (e.g. Subject 1F had the same treatment schedule as 1M, subject 2F the same as 2M).

6.2.2. Evaluation Part II

Subjects

Eighteen subjects (9 females and 9 males) completed Part II of the evaluation. The same 9 males from Part I participated in Part II while 8 of the 9 females from Part I participated in Part II. Subjects 1F-8F and 10F participated in Part II of the evaluation.

Chairs

Two chairs were chosen for Part II of the evaluation, including the SA Model. The other chair was a "standard" style stool with a mostly flat platform type of seat. This standard stool was the same stool used for demonstration purposes as described earlier. See Appendix F for more information on the chairs used in this evaluation.

Chosen Posture

The subjects were given demonstrations of how the chairs' features were used and were asked to choose their preferred posture with two stool at two table heights, 30 and 36-inches. Subjects were told they could set the chair up in any available manner. Additionally, several sized foot rests (which were also height adjustable) were provided, which the subjects were allowed to use. The only item they could not change was the given table height. The table heights and chairs were randomized for all subjects (see the Experimental Design section below).

Once the subjects adopted their chosen chair configuration and posture, their ankle, knee, and trunk-thigh angles (measured with a goniometer), along with their chosen use of the Support-Arm, were measured and recorded. The subjects were then asked to raise from the chair, and their chosen seat-tilt angle was then measured with an inclinometer and recorded.

Comments

At the end of the evaluation, subjects were asked to verbally comment on the features, comfort, likes, dislikes, or anything else regarding Chair b, the SA Model. Comments were recorded onto a Microsoft Word document by the researcher as the comments were made. Every attempt was made to record the exact words spoken by the subjects. The evaluator immediately edited the comments after the subjects were dismissed for spelling and added information in () when necessary to make the comments legible at a later time. All comments were then saved as individual documents per subject.

Part II Experimental Design

Subjects were asked to choose their own set-up of their given chair (the SA Model and the standard stool) and at table heights of 30" and 36". The treatments were formed by combining the chairs with table heights (see Table 8).

Table 8. Part II. Treatments.

	TABLE HEIGHT	
CHAIR DESCRIPTION	**30"**	**36"**
SA Model	a	b
Standard Stool	c	d

These treatments (a-d) were then randomly assigned to the subjects to determine their treatment per trial (see Table 9). corresponding subject numbers of both genders were assigned identical treatments (e.g. 1F = 1M). Note that subject 10F used the treatments listed as subject 9 below.

Table 9. Part II. Randomized Treatments per Subject and Trial.

	TRIAL			
SUBJECT (M, F)	**10**	**11**	**12**	**13**
1	a	b	d	c
2	d	b	a	c
3	d	a	b	c
4	d	c	a	b
5	b	d	c	a
6	a	d	c	b
7	c	a	b	d
8	b	c	a	d
9	c	b	d	a

7. FEMALE SUBJECTS' RESULTS

7.1. SUBJECTS' INFORMATION

Nine females participated in both parts of the evaluation between May 20th and June 5th, 2003. Both parts of the evaluation were conducted on the same day (per subject). Table 10 illustrates the females' participation in both parts of the evaluation.

Table 10. Female Subjects' Participation.

	EVALUATION	
SUBJECT	Part I	Part II
1F	X	X
2F	X	X
3F	X	X
4F	X	X
5F	X	X
6F	X	X
7F	X	X
8F	X	X
9F	X	
10F		X

Note that subject 9F only participated in Part I, and subject 10F only participated in Part II of the evaluation.

The ages of the female subjects are provided in Table 11.

Table 11. Female Subjects' Ages.

SUBJECT	AGE (Years)
1F	23
2F	16
3F	21
4F	17
5F	40
6F	25
7F	25
8F	28
9F	50
10F	37

Female subjects ranged from 16-50 years old with a mean of approximately 28.

Table 12 provides the average number of hours the female subjects work per week, their representative job titles, and approximate duration of time spent doing this particular type of work.

Table 12. Female Subjects' Hours Worked per Week, Job Title, and Time on the Job.

SUBJECT	HOURS WORKED PER WEEK	REPRESENTATIVE JOB TITLE	MONTHS OF CURRENT WORK
1F	40	Marketing Assistant	<1
2F	40	Labor	192
3F	Variable	Miscellaneous	<1
4F	Variable	Miscellaneous	<1
5F	25	Office Clerk	120+
6F	15	Clerical	4
7F	40+	Receptionist	36
8F	30	Office Clerk	3
9F	Variable	Light Industrial Labor	60
10F	40	Receptionist	29

Eight of the 10 subjects were employed and recruited from a temporary staffing service. Two full-time workers, in addition to the temporary workers, were recruited for participation in the evaluation (Subject 1F was a marketing assistant and Subject 10F was a receptionist). Most subjects perform general office type tasks and work 30-40 hours per week. A few subjects work a variety of jobs (job titles) and hours, depending upon the temporary job assignment.

Table 13. Female Subjects' Injury History and Current Status.

SUBJECT	PRIOR NECK OR BACK INJURY WITHIN 1 YEAR	ANY PRIOR NECK OR BACK INJURY	CURRENTLY INJURED
1F	no	no	no
2F	no	car crash	no
3F	car crash	no additional	no
4F	no	no	no
5F	no	no	no
6F	no	no	no
7F	no	car crash	no
8F	no	no	no
9F	no	no	no
10F	no	no	no

Table 13 provides information received from the Personal Information Form. No subjects were currently pregnant or injured. Three subjects had previously been in a car crash (one within the past year) and sustained minor neck/back injuries. Neither of them reported any lingering injuries or effects due to the wreck at the time of the evaluation. After being informed of the scope of the evaluation and the postures they would be required to assume, no subject reported that they expected to be harmed during the evaluation.

Table 14. Female Subjects' Weight and Stature.

SUBJECT	WEIGHT (lbs)	STATURE (in)
1F	144	62
2F	239	66
3F	312	65.5
4F	109.5	63
5F	123	61.75
6F	245	63
7F	151	61
8F	131	60.5
9F	226	65
10F	123.5	66

Table 14 shows the female subjects' body weight and stature. Weight and stature were measured with a medical scale to the ½-pound and ¼-inch, respectively. Subjects ranged in weight from 109.5-312.0 with a mean of 180-pounds. The female subjects stature ranged from 60.5-66.0, with a mean of approximately 63.5-inches.

7.2. EVALUATION PART I – FEMALE SUBJECTS

Nine female subjects participated in Part I of the Evaluation. Data from subjects 1F-9F was used to obtain the results provided below.

As discussed in the Procedures Section, the data collected for all subjects included:

- Chair rankings (on three occasions: appearance, knowledge, and sitting experience)
- Peak buttock-thigh pressure (psi)
- Buttock-thigh contact area (in^2)
- Production values
- Comfort survey scores

The null hypothesis was that no chairs performed differently under the prescribed conditions and tests performed.

7.2.1. Chair Rankings

All nine female subjects ranked the chairs on three separate occasions as detailed in the Methods Section. The subjects were asked to rank the chairs (from 1 to 9 with 1 being the most “preferred” chair) in order of which they would choose to use them in tasks requiring postures used in industry, as described earlier. The first ranking trial (termed “appearance”) was conducted prior to the subjects being given any information on the chairs (nor could they touch them). The second ranking trial (termed “knowledge”) was conducted after the subjects were provided with the Chair Feature Matrix (see Appendix F) and given a demonstration of each of the chairs’ features. The third ranking trial (termed “sitting experience”) was conducted after the subjects had sat in each chair during Part I of the evaluation. The results are provided in Tables 15-17 for the three ranking trials.

Table 15. Trial 1 Rankings (Appearance). Female Subjects. Conducted Prior to the Subjects Being Given any Information on the Chairs.

	SUBJECT								
CHAIR	**1F**	**2F**	**3F**	**4F**	**5F**	**6F**	**7F**	**8F**	**9F**
Dental Chair	5	4	7	5	4	4	1	6	1
SA Model	6	5	1	4	8	7	2	8	2
Industrial Stool	1	2	5	2	1	9	4	5	4
Office Stool	8	6	2	6	9	1	7	1	6
Office Chair	3	8	6	8	3	6	6	9	3
Dental Stool	7	7	9	9	6	3	5	7	5
Small Seat Sit-Stand	9	9	4	3	7	5	9	4	9
Contoured Seat Sit-Stand	4	3	3	1	5	2	8	2	8
Task Chair	2	1	8	7	2	8	3	3	7

On the first ranking trial (appearance), the female subjects chose the dental chair, industrial stool, and the office stool equally for their number one choice (two #1 picks for each chair). The three chairs all had backrests, interestingly. For their least favorite pick, four subjects chose the small seat sit-stand chair.

Table 16. Trial 2 Rankings (Knowledge). Female Subjects. Conducted After the Subjects Were Provided With the Chair Feature Matrix.

	SUBJECT								
CHAIR	**1F**	**2F**	**3F**	**4F**	**5F**	**6F**	**7F**	**8F**	**9F**
Dental Chair	3	4	2	3	3	3	1	6	2
SA Model	1	3	1	1	4	1	3	4	1
Industrial Stool	4	1	3	4	2	8	4	8	5
Office Stool	8	6	7	9	6	4	8	3	8
Office Chair	2	5	6	2	5	7	6	2	3
Dental Stool	5	8	5	5	8	5	5	7	4
Small Seat Sit-Stand	9	9	9	8	7	6	9	5	9
Contoured Seat Sit-Stand	7	7	8	7	9	2	7	1	6
Task Chair	6	2	4	6	1	9	2	9	7

On the second ranking trial (knowledge), 5 of the 9 female subjects chose the SA Model as their top choice. Five of the 9 nine female subjects chose the small seat sit-stand as their least favorite chair (9^{th} ranking).

Table 17. Trial 3 Rankings (Sitting Experience). Female Subjects. Conducted After the Subjects had Sat in Every Chair During Part I of the Evaluation.

	SUBJECT								
CHAIR	**1F**	**2F**	**3F**	**4F**	**5F**	**6F**	**7F**	**8F**	**9F**
Dental Chair	4	1	4	2	3	8	5	5	4
SA Model	1	2	1	1	9	1	2	8	1
Industrial Stool	8	8	7	9	2	3	4	6	7
Office Stool	6	3	3	8	6	5	3	2	9
Office Chair	2	5	2	4	5	2	9	3	3
Dental Stool	3	6	6	3	8	9	8	7	2
Small Seat Sit-Stand	7	9	8	5	4	7	6	9	8
Contoured Seat Sit-Stand	5	4	5	7	7	4	7	1	5
Task Chair	9	7	9	6	1	6	1	4	6

On the third ranking trial (sitting experience), the same 5 subjects who chose the SA Model as their first choice in the second ranking trial again chose it as their first choice. For their least favorite choice, two subjects chose the small seat sit-stand and two others chose the task chair.

Summed Subject Rankings

In order to determine the overall rank order of the chairs, all the subjects' rankings were summed over each chair per ranking trial, and then re-ranked with the lowest value given a ranking of 1 and the highest a ranking of 9. Table 18 provides the female subjects' results of these rankings for all three ranking trials.

Table 18. Summed Rankings Over the Three Ranking Trials (Appearance, Knowledge, Sitting Experience). Female Subjects.

CHAIR	TRIAL 1 (Appearance)	TRIAL 2 (Knowledge)	TRIAL 3 (Sitting Experience)
Dental Chair	3	2	2
SA Model	5	1	1
Industrial Stool	1	4	7
Office Stool	6	8	4,5
Office Chair	7	3	3
Dental Stool	8	6	8
Small Seat Sit-Stand	9	9	9
Contoured Seat Sit-Stand	2	7	4,5
Task Chair	4	5	6

The results show that the female subjects ranked the SA Model first during the second and third ranking trials. The industrial stool was favored in the first ranking but dropped in ranking during the second ranking and again during the third ranking. The dental chair, dental stool, small seat sit-stand, and task chairs had similar ratings over all three trials. The small seat sit-stand was the subjects' least favorite chair over all three ranking trials.

Intra-Rater Correlation Between Ranking Trials

In order to determine if the subjects ranked the chairs in the same order from one trial another (intra-rater), an intra-rater correlation study was performed (i.e. did Subject 1 rank the chairs in the same order from the first trial to the second?). Spearman's Rho was the statistic used to perform this analysis. The results for trials 1 to 2 and 2 to 3 are provided in Table 19.

Table 19. Intra-Rater Correlation Between Ranking Trials 1 to 2 and 2 to 3 (1, 2, 3: Appearance, Knowledge, Sitting Experience). Female Subjects.

RANKING TRIALS	SPEARMAN'S RHO	SIGNIFICANCE
Trail 1 to 2 (Appearance to Knowledge)	0.43	0.000
Trial 2 to 3 (Knowledge to Sitting Experience)	0.47	0.000

The statistics show average correlation between ranking trials 1 to 2 (appearance to knowledge) and 2 to 3 (knowledge to sitting experience). The female subjects' intra-rater correlation increased slightly from ranking trials 1-2 (appearance to knowledge) to ranking trials 2-3 (knowledge to sitting experience). These results show that the female subjects, individually, changed their minds slightly less on their chair rankings between the knowledge to sitting ranking trial (2 to 3) than the appearance alone to the knowledge ranking trial (1 to 2).

Inter-Rater Correlation within Ranking Trials

In order to determine if the subjects ranked the chairs in the same order during the individual ranking trials (inter-rater), an intraclass correlation coefficient (ICC) was used (i.e. did subjects 1 and 2 agree on their chair rankings during the first ranking trial?). The ICC was calculated using a two-way mixed model, with absolute values and single measures.

Table 20 provides the results of the inter-rater correlation study for the female subjects during the 3 ranking trials.

Table 20. Inter-Rater Correlation During the Three Ranking Trials (1, 2, 3: Appearance, Knowledge, Sitting Experience). Female Subjects.

RANKING TRIAL	ICC	95% Confidence Interval		SIGNIFICANCE
		Lower Bound	Upper Bound	
1 (Appearance)	0.05	-0.05	0.35	0.214
2 (Knowledge)	0.39	0.16	0.73	0.000
3 (Sitting Experience)	0.12	-0.02	0.46	0.048

The results show relatively low correlation between the subjects' rankings. The inter-rater correlation for the female subjects was better during the second ranking trial (knowledge) than the first (appearance). Note that only the statistics for the second and third ranking trials are statistically significant ($p < 0.05$). These results indicate that the female subjects, for the most part, did not rate the chairs in the same relative order during the rankings.

7.2.2. Buttock-Thigh Peak Pressure

The Xsensor pad and software was calibrated by the manufacturer to a range of 0.10-4.06 psi. Unfortunately, values above this range were required by the evaluation. Although the data is not usable for statistical purposes, the data does provide some useful information.

Table 21. Number of Buttock-Thigh Peak Pressure Recordings Below 4.06 psi per Chair. Female Subjects.

CHAIR	NUMBER OF RESULTS < 4.06 PSI
Office Stool	0
Small Seat Sit-Stand	0
Contoured Seat Sit-Stand	0
Dental Chair	1
Industrial Stool	1
Office Chair	1
Dental Stool	2
Task Chair	2
SA Model	6

Table 21 shows the total number of peak pressure recordings collected per chair that were below 4.06 psi. The SA Model had 6 female subjects with peak pressures' below 4.06 psi. The office stool, small seat sit-stand, and contoured seat sit-stand chairs had no peak pressure recordings less than 4.06 psi. Interesting, none of these three chairs have a Support-Arm design. These results indicate that the SA Model is best suited for providing lower peak pressures over the three postures assumed (statistical significance not known).

7.2.3. Buttock-Thigh Contact Area

Buttock-thigh contact area is the total area in contact at the interface between the subjects' buttock-thigh region and the seat-pan of the chair, as measured with the Xsensor equipment. Table 22 provides the female subjects' mean contact area by chair.

Table 22. Mean Buttock-Thigh Contact Area by Chair (in^2). Female Subjects.

CHAIR	CONTACT AREA (in^2)
Small Seat Sit-Stand	84.0
Dental Stool	126.4
Industrial Stool	128.9
Office Stool	131.8
Task Chair	134.2
Contoured Seat Sit-Stand	134.6
Dental Chair	135.8
SA Model	152.1
Office Chair	153.0

For the female subjects, the results show that the office chair and SA Model provided the greatest contact areas with 153.0 in^2 and 152.1 in^2, respectively. The small seat sit-stand chair provided the least amount of contact area with 84.0 in^2.

In order to determine if any statistically significant differences exist between the chairs for buttock-thigh contact area an analysis of variance (ANOVA) was conducted.

Table 23. ANOVA on Buttock-Thigh Contact Area. Female Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	83146.58	18	4619.25	7.38	0.000
Intercept	1394301.76	1	1394301.76	2226.47	0.000
CHAIR	28841.98	8	3605.25	5.76	0.000
POSTURE	8946.38	2	4473.19	7.14	0.002
SUBJECT	45358.22	8	5669.78	9.05	0.000
Error	38826.85	62	626.24		
Total	1516275.19	81			
Corrected Total	121973.43	80			

R Squared = .682 (Adjusted R Squared = .589)

Analysis of variance over all females' buttock-thigh contact area results (Table 23) shows there are significant differences between chairs ($p < 0.001$), postures ($p < 0.01$) and subjects ($p < 0.001$). Given this information, further investigations into the buttock-thigh contact area by chair and by posture are warranted.

Buttock-Thigh Contact Area by Chair

The ANOVA results indicated differences between the buttock-thigh contact area by chair. A Tukey HSD test on the females' buttock-thigh contact area revealed two groups that were statistically different from one another. Graphically, Figure 17 shows the means of the buttock-thigh contact area along with the results of the Tukey HSD test (statistically similar chair groupings are identified by the yellow horizontal line).

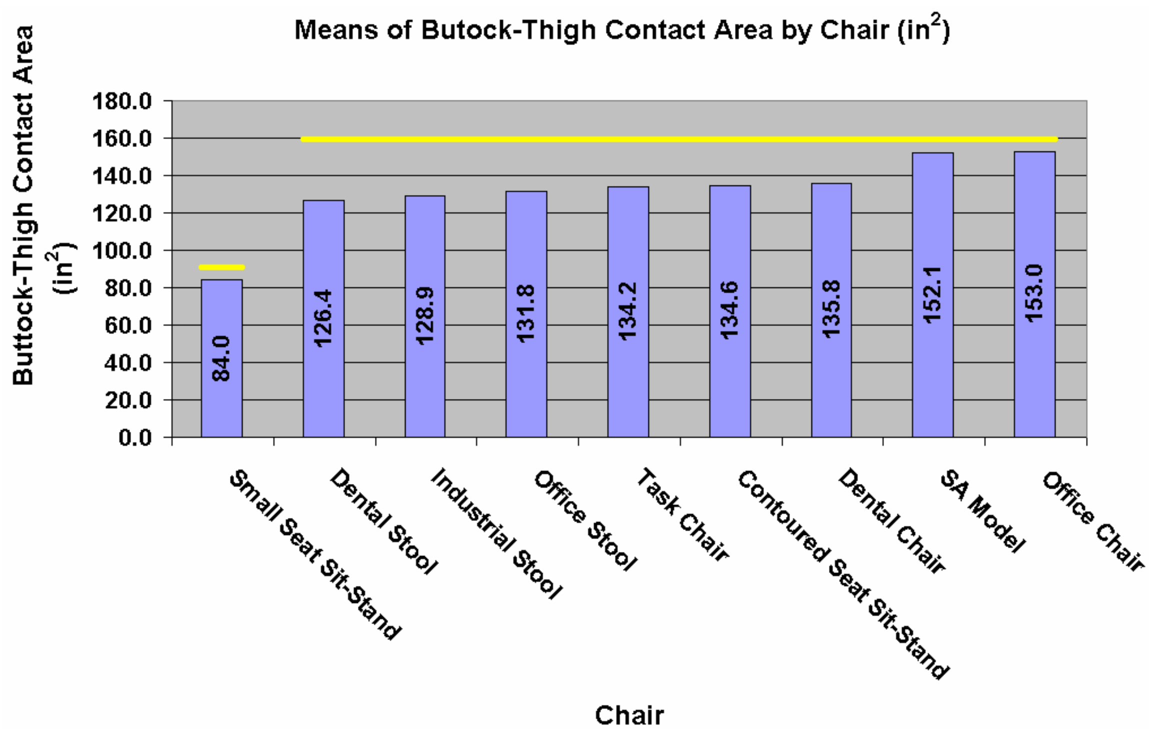

Figure 17. Means and Tukey Test Results on Mean Buttock-Thigh Contact Area by Chair (in^2). Female Subjects.

The small seat sit-stand chair produced a statistically lower mean buttock-thigh contact area than the other chairs.

Buttock-Thigh Contact Area by Posture

The ANOVA results indicated significant differences between the buttock-thigh contact areas by posture. The Tukey HSD test on buttock-thigh contact area by posture revealed two groups that were statistically different from one another. Figure 18 shows the means of the buttock-thigh contact area by posture along with the results of the Tukey HSD test (statistically similar posture groupings are identified by the yellow horizontal line).

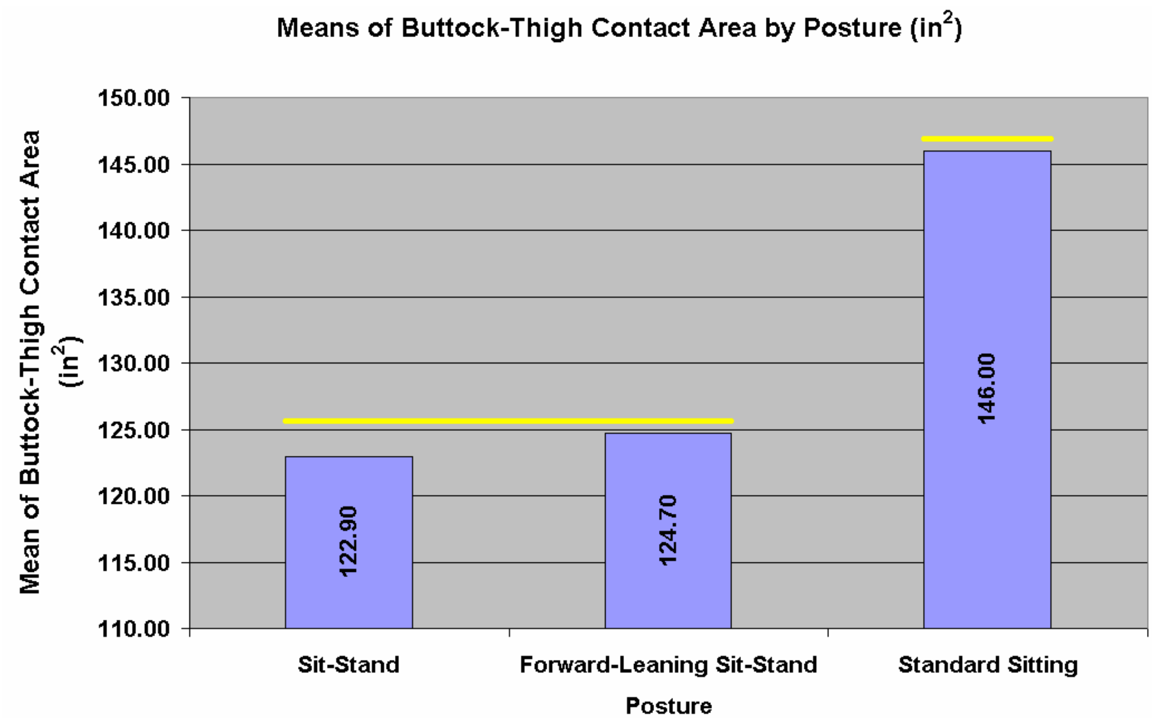

Figure 18. Means and Tukey Test Results on Mean Buttock-Thigh Contact Area by Posture (in^2). Female Subjects.

Figure 18 shows that the standard sitting posture produced a statistically higher mean buttock-thigh contact area than the other postures. These results were expected as the majority of the chairs were designed for normal sitting postures.

7.2.4. Production

The Purdue Pegboard results were calculated as the sum of pieces that were properly placed according to the PPB instructions over all four tests (see the Procedures Section).

The female subjects' highest production value was 131 while the lowest production value was 64. On average, the female subjects placed approximately 95 Purdue Pegboard pieces, as summed over all four trials.

Summed Production Values

In order to evaluate the results of the production testing, the values obtained over the four Purdue Pegboard testing trials were summed together over the chairs and subjects. The summed production values produced by the female subjects are provided in Table 24 for production by chair.

Table 24. Summed Production Values by Chair. Female Subjects.

CHAIR	PRODUCTION
Small Seat Sit-Stand	801
Task Chair	835
Office Chair	837
Contoured Seat Sit-Stand	847
Dental Stool	856
Office Stool	863
Industrial Stool	867
Dental Chair	878
SA Model	886

Mean production values by chair ranged from 886 to 801, with a mean value of approximately 852. This increase in production of approximately 10% between the lowest and highest "producing" chairs agrees with previous research by Congleton (1983), who reported a 4-10% increase in production, due to chairs alone, between the lowest and highest "producing" chairs. Note that the highest production value came from the SA Model while the lowest production value came from the small seat sit-stand chair.

In order to determine if any statistically significant differences exist between the chairs for buttock-thigh contact area an analysis of variance (ANOVA) was conducted.

Table 25. ANOVA on Production Values. Female Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	18428.30	18	1023.79	23.14	0.000
Intercept	726282.72	1	726282.72	16416.23	0.000
CHAIR	592.62	8	74.08	1.67	0.123
POSTURE	130.84	2	65.42	1.48	0.236
SUBJECT	17704.84	8	2213.11	50.02	0.000
Error	2742.99	62	44.24		
Total	747454.00	81			
Corrected Total	21171.28	80			

R Squared = .870 (Adjusted R Squared = .833)

Analysis of variance over all females' production results (Table 25) shows there are no significant differences between chairs or postures ($p < 0.05$). Subjects' individual production values were significant different ($p < 0.001$).

7.2.5. Comfort Survey

A metric ruler was used to measure the 10cm VAS (visual-analog scale) used in the Helander and Zhang (1997) chair comfort survey. Each survey (one for each chair/posture treatment per subject) was given a total score, which was the sum of the

VAS measures over the survey's 7 questions per chair (in centimeters). The maximum possible score was therefore 70 (cm). The higher the total, the more perceived comfort existed.

Chair comfort rating scores for the female subjects ranged from 1.3 in the small seat sit-stand to 70.0 in the SA Model, with a mean of 32.5.

To make the comfort survey results understandable, the chair comfort rating scores (the individual subjects' total scores for each chair and posture over the 7 questions) were summed over the chairs.

Table 26. Summed Comfort Survey Results by Chair (cm). Female Subjects.

CHAIR	COMFORT SCORE
Small Seat Sit-Stand	168.3
Contoured Seat Sit-Stand	218.3
Industrial Stool	253.8
Office Stool	272.3
Dental Stool	298.2
Task Chair	315.6
Office Chair	328.9
Dental Chair	358.1
SA Model	417.8

After summing the chair comfort survey scores for the female subjects (Table 26), the SA Model had the highest scores. The small seat sit-stand was the least comfortable.

In order to determine whether or not statistically significant differences existed between the chairs regarding comfort, an ANOVA was completed.

Table 27. ANOVA on Comfort Survey Results. Female Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	10640.54	18	591.14	3.25	0.000
Intercept	85461.38	1	85461.38	470.35	0.000
CHAIR	4970.70	8	621.34	3.42	0.003
POSTURE	3899.25	2	1949.63	10.73	0.000
SUBJECT	1770.58	8	221.32	1.22	0.304
Error	11265.14	62	181.70		
Total	107367.06	81			
Corrected Total	21905.68	80			

R Squared = .486 (Adjusted R Squared = .336)

The ANOVA was calculated using the individual subjects' score per chair. The results of the analysis of variance on the females' comfort scores (Table 27) show there are significant differences between chairs ($p < 0.01$) and postures ($p < 0.001$). Given this information, further investigations into the comfort survey results by chair and by posture are warranted.

Comfort by Chair

The ANOVA results indicated differences between the comfort survey scores by chair. The Tukey HSD test on comfort survey scores revealed three groups that were statistically different from one another. Figure 19 shows the means of the comfort survey scores by chair along with the results of the Tukey HSD test (statistically similar chair groupings are identified by the yellow horizontal line).

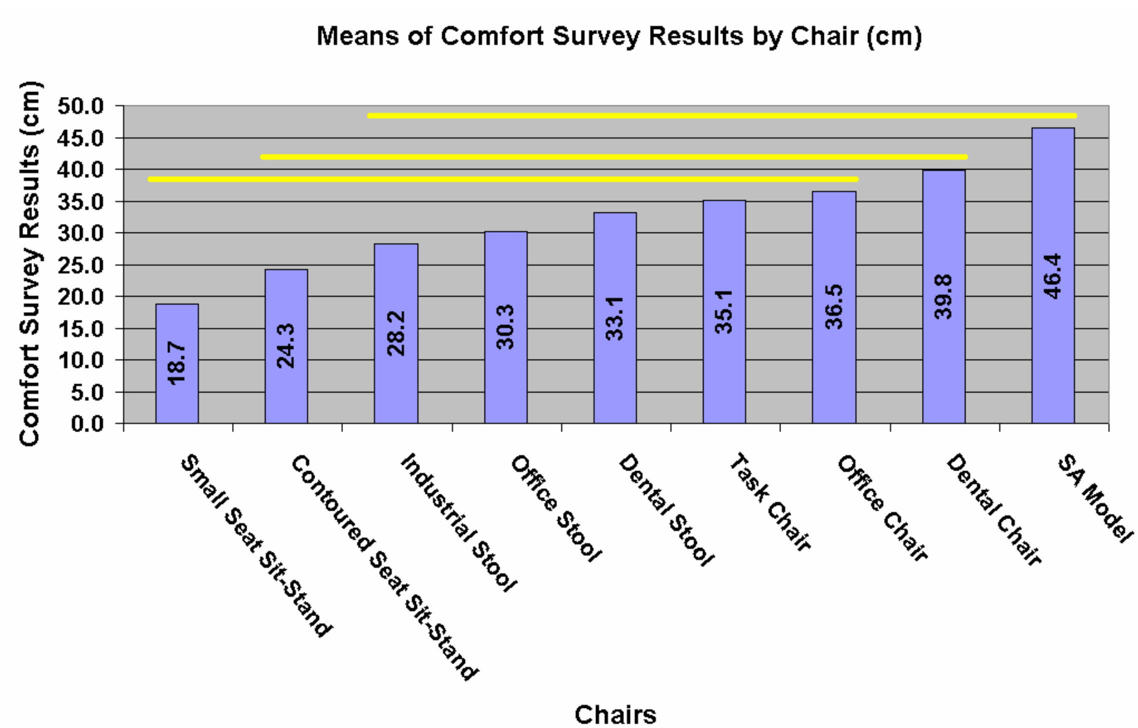

Figure 19. Means and Tukey Test Results on Comfort Survey Scores by Chair (cm). Female Subjects.

Figure 19 shows that the SA Model was placed in the most comfortable chair grouping.

Comfort by Posture

The ANOVA results indicated differences between the comfort survey scores by chair. Further investigation of the differences may now be conducted. A Tukey HSD test on comfort survey scores revealed two groups that were statistically different from one another. Graphically, Figure 20 shows the means of the comfort survey scores by posture along with the results of the Tukey HSD test (statistically similar posture groupings are identified by the yellow horizontal line).

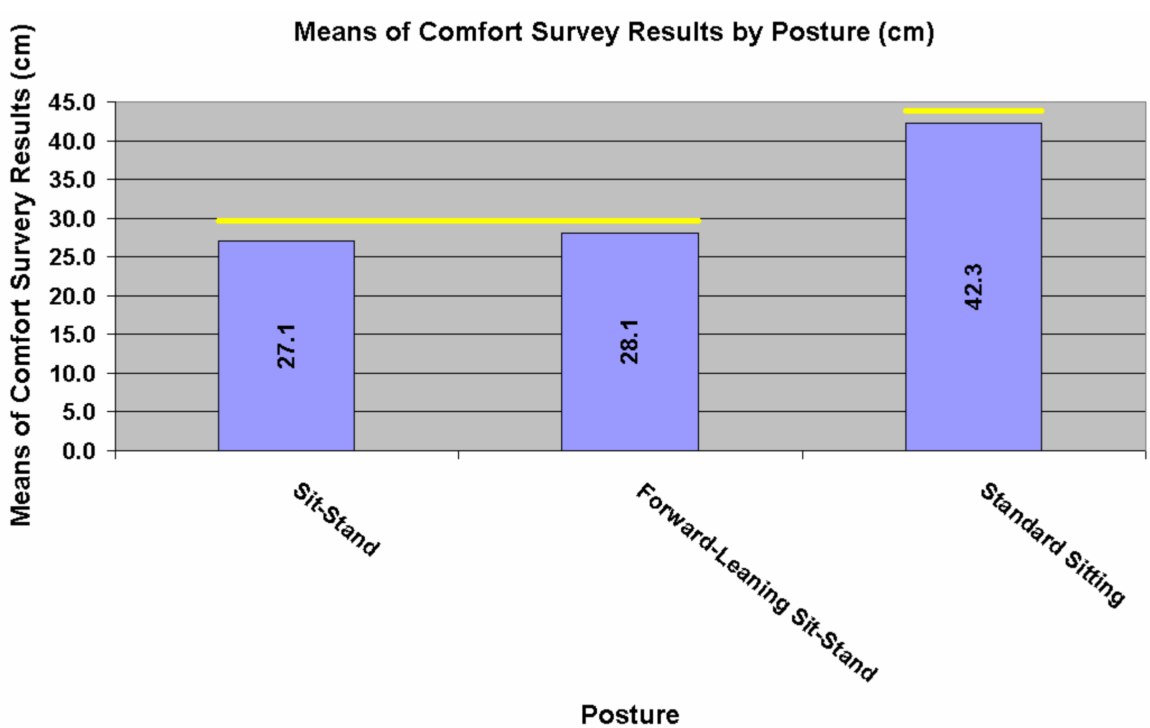

Figure 20. Means and Tukey Test Results on Comfort Survey Scores by Posture (cm). Female Subjects.

Figure 20 shows that the standard sitting posture was the most comfortable posture. The sit-stand and forward-leaning sit-stand postures were not significantly different regarding comfort. These results were expected as the majority of the chairs were designed for normal sitting postures.

7.2.6. Correlations

Correlations were run on the female subjects' results to determine if any associations existed between the variables, and if so, how strong these associations were. Correlations between comfort, production, contact area, and rankings were performed. Only the values from the third ranking trial were used because they were completed after having sat in the chairs and being given the knowledge of all the chairs' features.

Table 28. Correlation Results. Female Subjects.

VARIABLE	SPEARHMAN'S RHO	SIGNIFICANCE	N
Comfort & Ranking Trial III	**-0.67**	0.000	81
Comfort & Contact Area	**0.43**	0.000	81
Contact Area & Ranking Trial III	**-0.42**	0.000	81
Contact Area & Production	**-0.34**	0.002	81
Comfort & Production	0.13	0.248	81
Production & Ranking Trial III	-0.03	0.800	81

Bold Values are Statistically Significant ($p < 0.05$)

The results in Table 28 show several significant correlations ($p < 0.05$), although most were not strong. Comfort & Ranking Trial III is the strongest significant correlation with a Spearman's Rho statistic of –0.67. Note that Ranking Trial III was a value with 1 being best (highest ranked) and 9 being worst (lowest rank). Therefore, the negative

Spearman’s Rho values indicate a positive correlation between Ranking Trial III and the other variables (for example, there is a positive correlation between Comfort and Ranking Trial III). Also of interest is the negative correlation between contact area and production (a fairly weak significant correlation).

These results indicate that the female subjects preferred the chairs that were perceived as the most comfortable, and that the most comfortably perceived chairs were those that had larger buttock-thigh contact areas. These results agree with past research performed by Congleton and Ayoub (1988) who found that comfort was correlated with buttock-thigh contact area. Additionally, the production values were negatively correlated with contact area (although significant, this correlation was fairly weak).

7.2.7. Evaluation Part I Summary

The results show that there are indeed differences between chairs in regards to the variables tested during the evaluation. The SA Model provided the most buttock-thigh peak pressure recordings below 4.06 psi, the second highest buttock-thigh contact area, the highest production values, and received the highest comfort survey scores. In addition, the ranking results show that after the subjects sat in each chair, they ranked the SA Model first over all the other chairs.

Statistically, several chairs performed similarly. The SA Model was consistently placed in the "best" category with a Tukey HSD test. None of the results suggest negative consequences regarding the addition, and use, of a Support-Arm.

7.3. EVALUATION PART II – FEMALE SUBJECTS

Part II of the evaluation involved having the subjects choose their own posture and chair "set-up" for both the SA Model and a standard style of stool at two different table heights. The purpose of this part of the evaluation was to determine if the subjects set up (configured) the SA model differently than they did the standard stool.

Nine female subjects participated in Part II of the Evaluation. Data from subjects 1F-8F along with subject 10F were used to obtain the results provided below. The null hypothesis was that the subjects' chosen set-ups (configurations) were not different between the SA Model and the standard style stool.

7.3.1. Chosen Set-Up

When the female subjects were allowed to choose their own posture, and whether or not to use the Support-Arm on the SA Model, it was found that no subjects chose to use the Support-Arm when the table was at the 30" height. However, at the 36" table height 6 of the 9 (67%) female subjects chose to use the Support-Arm as shown in Table 29.

Table 29. Use of Support-Arm at 30" and 36" Table Heights. Female Subjects.

	SUPPORT-ARM USE	
TABLE HEIGHT	**Yes**	**No**
30"	0	9
36"	6	3

Chosen Ankle Angle

Table 30. ANOVA on Chosen Ankle Angle. Female Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1443.92	11	131.27	4.59	0.001
Intercept	308580.25	1	308580.25	10782.71	0.000
STOOL	0.69	1	0.69	0.02	0.878
TBLE_HT	3.36	1	3.36	0.12	0.735
SUBJECT	1438.50	8	179.81	6.28	0.000
STOOL * TBLE_HT	1.36	1	1.36	0.05	0.829
Error	686.83	24	28.62		
Total	310711.00	36			
Corrected Total	2130.75	35			

R Squared = .678 (Adjusted R Squared = .530)

The ANOVA in Table 30 indicates that the female subjects' chosen ankle angles were not significantly different ($p < 0.05$) by stool, table height, or stool*table height interaction.

Chosen Knee Angle

Table 31. ANOVA on Chosen Knee Angle. Female Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3452.14	11	313.83	4.76	0.001
Intercept	479094.69	1	479094.69	7267.42	0.000
STOOL	61.36	1	61.36	0.93	0.344
TBLE_HT	140.03	1	140.03	2.12	0.158
SUBJECT	3126.06	8	390.76	5.93	0.000
STOOL * TBLE_HT	124.69	1	124.69	1.89	0.182
Error	1582.17	24	65.92		
Total	484129.00	36			
Corrected Total	5034.31	35			

R Squared = .686 (Adjusted R Squared = .542)

The ANOVA results in Table 31 indicate that the female subjects had no statistically different ($p < 0.05$) chosen knee angles between the stool, table heights, or stool*table height interaction.

Chosen Trunk-Thigh Angle

Table 32. ANOVA on Chosen Trunk-Thigh Angle. Female Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1641.25	11	149.20	1.21	0.331
Intercept	362203.36	1	362203.36	2944.35	0.000
STOOL	462.25	1	462.25	3.76	0.064
TBLE_HT	6.25	1	6.25	0.05	0.824
SUBJECT	889.39	8	111.17	0.90	0.529
STOOL * TBLE_HT	283.36	1	283.36	2.30	0.142
Error	2952.39	24	123.02		
Total	366797.00	36			
Corrected Total	4593.64	35			

R Squared = .357 (Adjusted R Squared = .063)

ANOVA results (Table 32) on the female subjects' chosen trunk-thigh angle revealed no statistically significant results ($p < 0.05$).

Chosen Seat-Tilt Angle

Table 33. ANOVA on Chosen Seat-Tilt Angle. Female Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	313.56	11	28.51	2.74	0.019
Intercept	2025.00	1	2025.00	194.83	0.000
STOOL	69.44	1	69.44	6.68	0.016
TBLE_HT	36.00	1	36.00	3.46	0.075
SUBJECT	133.00	8	16.63	1.60	0.177
STOOL * TBLE_HT	75.11	1	75.11	7.23	0.013
Error	249.44	24	10.39		
Total	2588.00	36			
Corrected Total	563.00	35			

R Squared = .557 (Adjusted R Squared = .354)

The ANOVA on the female subjects' (Table 33) chosen seat-pan tilt angle show significant differences (<0.05) between the stools and stool*table height interaction. Further investigation into these differences are warranted.

Chosen Seat-Tilt Angle by Stool

The ANOVA indicated significant differences between the female subjects' chosen seat-tilt angle by stool. The differences are represented in Figure 21.

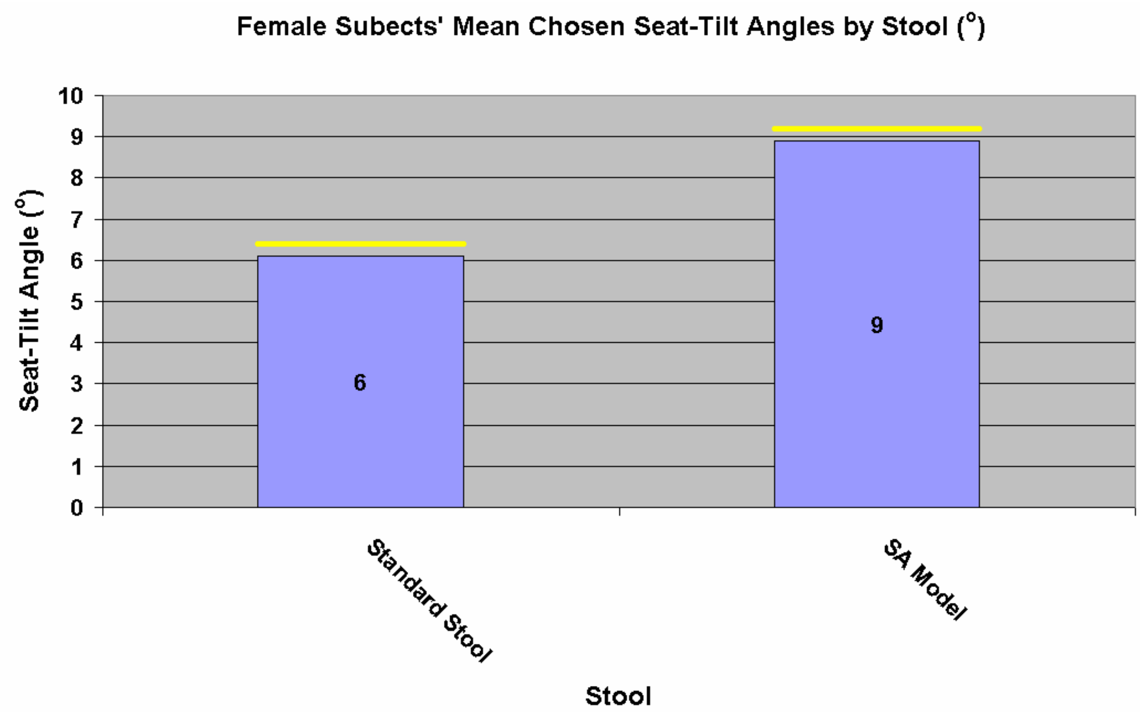

Figure 21. Means and T-Test Results on Chosen Seat-Tilt Angles by Stool (°). Female Subjects.

The female subjects chose significantly greater seat-tilt angles with the SA Model, according to a paired, two-tailed t-Test ($t < 0.05$), as shown in Figure 21.

*Chosen Seat-Tilt Angle by Chair*Table Height Interaction*

The ANOVA indicated significant differences between the female subjects' chosen seat-tilt angle by stool*table height interaction. The differences are represented in Figure 22.

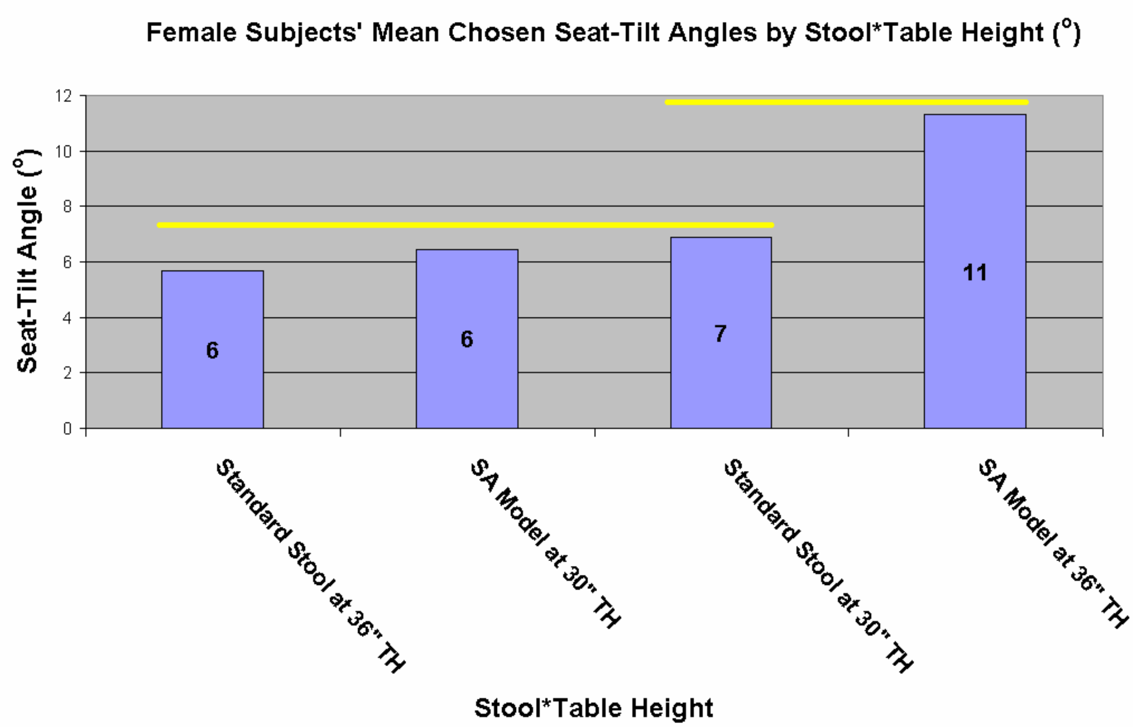

Figure 22. Means on Chosen Seat-Tilt Angles by Stool*Table Height (°). Female Subjects.

Results of a paired, two-tailed t-Test indicates that the female subjects chose greater seat-tilt angles at the 36" table height with the SA Model than with the standard style stool at both table heights ($t < 0.05$). No other significant differences existed between the stool*table height interaction ($t < 0.05$).

7.3.2. Female Subjects' Comments on the SA Model

After the second evaluation was completed, every subject was given the chance to comment on the SA Model. These comments were typed into a Word Processor and saved for each subject as their comments were made. The comments could all be placed into 5 comment “categories” as shown in Table 34. The subjects’ full comments are provided in Appendix J.

Table 34. Female Subjects’ Categorized Comments.

COMMENT CATEGORY	NUMBER OF COMMENTS
I Like It	7
I Don't Like It	2
I'm not Sure if I Like It	0
Support-Arm Pad is Too Big	6
SA Needs More Adjustments	4

The last two comment categories were in direct relation to the non-use of the Support-Arm at the 30” table height. The Support-Arm pillow posed as too large an obstacle during standard sitting postures, placing the subjects too far away from the desk’s working surface.

7.3.3. Evaluation Part II Summary

The results of Part II of the evaluation show that the majority of the female subjects preferred to use the Support-Arm at the 36” table height. Statistically significant differences were not found for the chosen ankle, knee, or trunk-thigh angles. Statistical differences were found between the chosen seat-tilt angles by both stool and stool*table height interaction.

Overall, the female subjects chose significantly greater forward seat-tilt angles with the SA Model. They also chose significantly greater seat-tilt angles while seated on the SA

Model at the 36” table height than at the 30” table height. Statistically significant differences did not exist between table heights with the standard stool.

Subjects’ comments indicated that most liked the SA Model, although they thought it should have a smaller Support-Arm pillow and allow for more adaptability to provide support to the entire forward-leaning envelope.

8. MALE SUBJECTS' RESULTS

8.1. SUBJECTS' INFORMATION

Nine males participated in both parts of the evaluation between May 22nd and June 2nd, 2003. Both parts of the evaluation were conducted on the same day (per subject). Table 35 illustrates the males' participation in both parts of the evaluation.

Table 35. Males Subjects' Participation.

	EVALUATION	
SUBJECT	**Part I**	**Part II**
1M	X	X
2M	X	X
3M	X	X
4M	X	X
5M	X	X
6M	X	X
7M	X	X
8M	X	X
9M	X	X

The ages of the male subjects are provided in Table 36.

Table 36. Male Subjects' Ages.

SUBJECT	AGE (Years)
1M	26
2M	21
3M	21
4M	22
5M	24
6M	31
7M	30
8M	24
9M	31

Male subjects ranged from 21-31 years old with a mean of approximately 26.

Table 37 provides the average number of hours the male subjects work per week, their representative job titles, and approximate duration of time spent doing this particular type of work.

Table 37. Male Subjects' Hours Worked per Week, Job Title, and Time on the Job.

SUBJECT	HOURS WORKED PER WEEK	REPRESENTATIVE JOB TITLE	MONTHS OF CURRENT WORK
1M	35	Miscellaneous	89
2M	30	Construction	27
3M	43	Labor	6
4M	Variable	Miscellaneous	<1
5M	40	Labor	60
6M	40	Heavy Equipment Op	120
7M	Variable	Miscellaneous	<1
8M	15	Sales Representative	<1
9M	8	Labor	4

All nine subjects were employed and recruited from a temporary staffing service. Most subjects perform manual labor tasks and work 30-40 hours per week. A few subjects work a variety of jobs (job titles) and hours, depending upon the temporary job assignment.

Table 38. Male Subjects' Injury History and Current Status.

SUBJECT	PRIOR NECK OR BACK INJURY WITHIN 1 YEAR	ANY PRIOR NECK OR BACK INJURY	CURRENTLY INJURED
1M	no	no	no
2M	no	no	no
3M	no	no	no
4M	no	no	no
5M	no	no	no
6M	no	no	no
7M	no	no	no
8M	no	no	no
9M	no	no	no

Table 38 provides information received from the Personal Information Form regarding the male subjects' health and whether or not they expected to be put in any harm while performing the duties of the evaluation. None of the male subjects reported any current or past neck or back injuries. After being informed of the scope of the evaluation and the postures they would be required to assume, no subject reported that they expected to be harmed during the evaluation.

Table 39. Male Subjects' Weight and Stature.

SUBJECT	WEIGHT (lbs)	STATURE (in)
1M	166	68
2M	213	66.5
3M	166.5	63.25
4M	154	66
5M	159	72.75
6M	205	73.25
7M	200	71
8M	188	73
9M	159	64.25

Table 39 shows the male subjects' body weight and stature. Weight and stature were measured with a medical scale to the ½-pound and ¼-inch, respectively. Subjects ranged in weight from 154.0-205.0 with a mean of 179.0 pounds. The male subjects' stature ranged from 63.25-73.25, with a mean of approximately 68.75-inches.

8.2. EVALUATION PART I – MALE SUBJECTS

Nine male subjects participated in Part I of the Evaluation. Data from subjects 1M-9M was used to obtain the results below.

As discussed in the Procedures Section, the data collected for all subjects included:

- Chair rankings (on three occasions: appearance, knowledge, and sitting experience)
- Peak buttock-thigh pressure (psi)
- Buttock-thigh contact area (in^2)
- Production values

- Comfort survey scores

The null hypothesis was that no chairs performed differently under the prescribed conditions and tests performed.

8.2.1. Chair Rankings

All nine male subjects ranked the chairs on three separate occasions as detailed in the Methods Section. The subjects were asked to rank the chairs (from 1 to 9 with 1 being the most “preferred” chair) in order of which they would choose to use them in tasks requiring postures used in industry, as described earlier. The first ranking trial (termed “appearance”) was conducted prior to the subjects being given any information on the chairs (nor could they touch them). The second ranking trial (termed “knowledge”) was conducted after the subjects were provided with the Chair Feature Matrix (see Appendix F) and given a demonstration of each of the chairs’ features. The third ranking trial (termed “sitting experience”) was conducted after the subjects had sat in each chair during Part I of the evaluation. The results are provided in Tables 40-42 for the three ranking trials.

Table 40. Trial 1 Rankings (Appearance). Male Subjects. Conducted Prior to the Subjects Being Given any Information on the Chairs.

	SUBJECT								
CHAIR	**1M**	**2M**	**3M**	**4M**	**5M**	**6M**	**7M**	**8M**	**9M**
Dental Chair	3	1	4	4	6	7	2	3	1
SA Model	5	5	1	6	5	3	3	8	6
Industrial Stool	1	2	8	3	1	5	4	1	2
Office Stool	8	8	5	7	8	2	6	7	8
Office Chair	4	4	9	1	2	6	1	2	3
Dental Stool	6	7	6	5	4	8	7	6	4
Small Seat Sit-Stand	9	9	2	9	9	9	9	9	9
Contoured Seat Sit-Stand	7	6	7	8	7	1	8	5	7
Task Chair	2	3	3	2	3	4	5	4	5

On the first ranking trial (appearance), three male subjects chose the industrial stool for their number one choice. For their least favorite choice, eight of the nine males chose the small seat sit-stand chair.

Table 41. Trial 2 Rankings (Knowledge). Male Subjects. Conducted After the Subjects Were Provided with the Chair Feature Matrix.

	SUBJECT								
CHAIR	**1M**	**2M**	**3M**	**4M**	**5M**	**6M**	**7M**	**8M**	**9M**
Dental Chair	4	1	3	4	4	5	5	3	3
SA Model	5	5	1	2	6	6	2	2	2
Industrial Stool	2	2	7	3	1	4	3	4	6
Office Stool	8	8	9	5	7	7	7	9	8
Office Chair	1	4	4	1	3	1	1	1	1
Dental Stool	6	6	2	7	5	8	6	6	5
Small Seat Sit-Stand	9	9	5	9	9	9	9	7	9
Contoured Seat Sit-Stand	7	7	6	6	8	2	8	8	7
Task Chair	3	3	8	8	2	3	4	5	4

On the second ranking trial (knowledge), six male subjects chose the office chair as their first pick. Seven of the males now chose the small seat sit-stand as their least favorite chair.

Table 42. Trial 3 Rankings (Sitting Experience). Male Subjects. Conducted After the Subjects had Sat in Every Chair During Part I of the Evaluation.

	SUBJECT								
CHAIR	**1M**	**2M**	**3M**	**4M**	**5M**	**6M**	**7M**	**8M**	**9M**
Dental Chair	1	1	6	3	5	4	1	9	3
SA Model	4	5	1	2	6	3	4	6	2
Industrial Stool	5	8	9	7	3	8	9	2	9
Office Stool	7	3	7	6	9	5	3	8	5
Office Chair	2	2	3	8	2	2	2	1	1
Dental Stool	6	4	2	1	4	7	5	3	4
Small Seat Sit-Stand	9	7	5	4	7	9	7	7	6
Contoured Seat Sit-Stand	8	6	8	5	8	6	8	5	7
Task Chair	3	9	4	9	1	1	6	4	8

On the third ranking trial (sitting experience), three male subjects chose the dental chair for their first pick. Three males chose the industrial stool as their least favorite choice..

Summed Subject Rankings

In order to determine the overall rank order of the chairs, all the subjects' rankings were summed over each chair per ranking trial, and then re-ranked with the lowest value given a ranking of 1 and the highest a ranking of 9. Table 43 provides the male subjects' results of these rankings for all three ranking trials.

Table 43. Summed Rankings Over the Three Ranking Trials (Appearance, Knowledge, Sitting Experience). Male Subjects.

CHAIR	TRIAL 1 (Knowledge)	TRIAL 2 (Appearance)	TRIAL 3 (Sitting Experience)
Dental Chair	2,3	3,4	2,3
SA Model	5	2	2,3
Industrial Stool	1	3,4	7
Office Stool	8	8	6
Office Chair	4	1	1
Dental Stool	6	6	4
Small Seat Sit-Stand	9	9	8,9
Contoured Seat Sit-Stand	7	7	8,9
Task Chair	2,3	5	5

The results show that the male subjects ranked the office chair first during the second and third ranking trials. They also ranked the SA Model second during both the second and third ranking trials (tied for second place with the dental chair in the third ranking trial). The industrial stool was favored in the first ranking but dropped in ranking during the second and third rankings. The dental chair, office stool, dental stool, small seat sit-stand, contoured seat sit-stand, and task chairs had similar ratings over all three trials. The small seat sit-stand was the subjects' least favorite chair over all three ranking trials (tied for last in the third ranking trial).

Intra-Rater Correlation Between Ranking Trials

In order to determine if the subjects ranked the chairs in the same order over the separate trials, an intra-rater correlation study was performed (i.e. did Subject 1 rank the chairs in the same order from the first trial to the second?). Spearman's Rho was the statistic used to perform this analysis. The results for trials 1 to 2 and 2 to 3 are provided in Table 44.

Table 44. Intra-Rater Correlation Between Ranking Trials 1 to 2 and 2 to 3 (1, 2, 3: Appearance, Knowledge, Sitting Experience). Male Subjects.

RANKING TRIALS	SPEARMAN'S RHO	SIGNIFICANCE
Trail 1 to 2 (Appearance to Knowledge)	0.66	0.000
Trial 2 to 3 (Knowledge to Sitting Experience)	0.47	0.000

The statistics show average to good intra-rater correlation between ranking trials 1 to 2 (appearance to knowledge), and average correlation between rankings 2 to 3 (knowledge to sitting experience). The male subjects' intra-rater correlation was lowest between ranking trials 1 to 3 (appearance to sitting experience), as expected. These results show that the male subjects, individually, changed their minds slightly more on their chair rankings between the knowledge to sitting ranking trial (2 to 3) than the appearance alone to the knowledge ranking trial (1 to 2).

Inter-Rater Correlation within Ranking Trials

In order to determine if the subjects ranked the chairs in the same order during the individual ranking trials (inter-rater), an intraclass correlation coefficient (ICC) was used (i.e. did subjects 1 and 2 agree on their chair rankings during the first ranking trial?). The ICC was calculated using a two-way mixed model, with absolute values and single measures.

Table 45 provides the results of the inter-rater correlation study for the male subjects during the 3 ranking trials.

Table 45. Inter-Rater Correlation During the Three Ranking Trials (1, 2, 3: Appearance, Knowledge, Sitting Experience). Male Subjects.

RANKING TRIAL	ICC	95% Confidence Interval		SIGNIFICANCE
		Lower Bound	Upper Bound	
1 (Appearance)	0.39	0.16	0.74	0.000
2 (Knowledge)	0.60	0.35	0.86	0.000
3 (Sitting Experience)	0.28	0.08	0.65	0.001

The results show average-to-low inter-rater correlation between the subjects' rankings during the first (appearance) and third trial rankings (sitting experience). Inter-rater correlation was average-to-good during the second ranking trial (knowledge). The inter-rater correlation for the male subjects was better during the second ranking trial (knowledge) than the first (appearance).

8.2.2. Buttock-Thigh Peak Pressure

The Xsensor pad and software was calibrated by the manufacturer to a range of 0.10-4.06 psi. Unfortunately, values above this range were required by the evaluation. Although the data is not usable for statistical purposes, the data does provide some useful information.

Table 46. Number of Buttock-Thigh Peak Pressure Recordings Below 4.06 psi per Chair. Male Subjects.

CHAIR	NUMBER OF RESULTS < 4.06 PSI
Industrial Stool	0
Office Stool	0
Small Seat Sit-Stand	0
Contoured Seat Sit-Stand	0
Office Chair	1
Dental Stool	1
Task Chair	1
Dental Chair	2
SA Model	4

Table 46 shows the number of total recordings collected per chair for the male subjects that were less than 4.06 psi. The SA Model provided 4 peak pressures recordings below 4.06 psi. The industrial stool, office stool, small seat sit-stand, and contoured seat sit-stand chairs provided no peak pressures below 4.06 psi. These results indicate that the SA Model is best suited for providing lower peak pressures over the three postures assumed (statistical significant not known).

8.2.3. Buttock-Thigh Contact Area

Buttock-thigh contact area is the total area in contact at the interface between the subjects' buttock-thigh region and the seat-pan of the chair, as measured with the Xsensor equipment. Table 47 provides the male subjects' mean contact area by chair.

Table 47. Mean Buttock-Thigh Contact Area by Chair (in^2). Male Subjects.

CHAIR	CONTACT AREA (in^2)
Small Seat Sit-Stand	85.9
Industrial Stool	99.4
Contoured Seat Sit-Stand	109.3
Office Stool	123.8
Task Chair	128.7
Dental Chair	134.2
Office Chair	140.7
Dental Stool	149.7
SA Model	154.9

The results show that the SA Model provided the greatest contact area with 154.9 in^2. The small seat sit-stand chair provided the least amount of contact area with 85.9 in^2.

In order to determine if any statistically significant differences exist between the chairs for buttock-thigh contact area an analysis of variance (ANOVA) was conducted.

Table 48. ANOVA on Buttock-Thigh Contact Area. Male Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	49613.09	18	2756.28	7.19	0.000
Intercept	1269440.37	1	1269440.37	3311.59	0.000
CHAIR	38505.05	8	4813.13	12.56	0.000
POSTURE	2972.21	2	1486.10	3.88	0.026
SUBJECT	8135.83	8	1016.98	2.65	0.014
Error	23766.60	62	383.33		
Total	1342820.06	81			
Corrected Total	73379.69	80			

R Squared = .676 (Adjusted R Squared = .582)

Analysis of variance over all males' contact area results (Table 48) shows there are significant differences between chairs ($p < 0.001$), postures ($p < 0.05$) and subjects ($p < 0.05$). Given this information, further investigations into the buttock-thigh contact area by chair and by posture are warranted.

Buttock-Thigh Contact Area by Chair

The ANOVA results indicated differences between the buttock-thigh contact areas by chair. A Tukey HSD test on the males' buttock-thigh contact area revealed five groupings of chairs that were statistically different from one another. Graphically, Figure 23 shows the means of the buttock-thigh contact area along with the results of the Tukey HSD test (statistically similar chair groupings are identified by the yellow horizontal line).

The SA Model, dental stool, office chair, dental chair, and task chair all provided a greater amount of buttock-thigh contact area than did the other chairs.

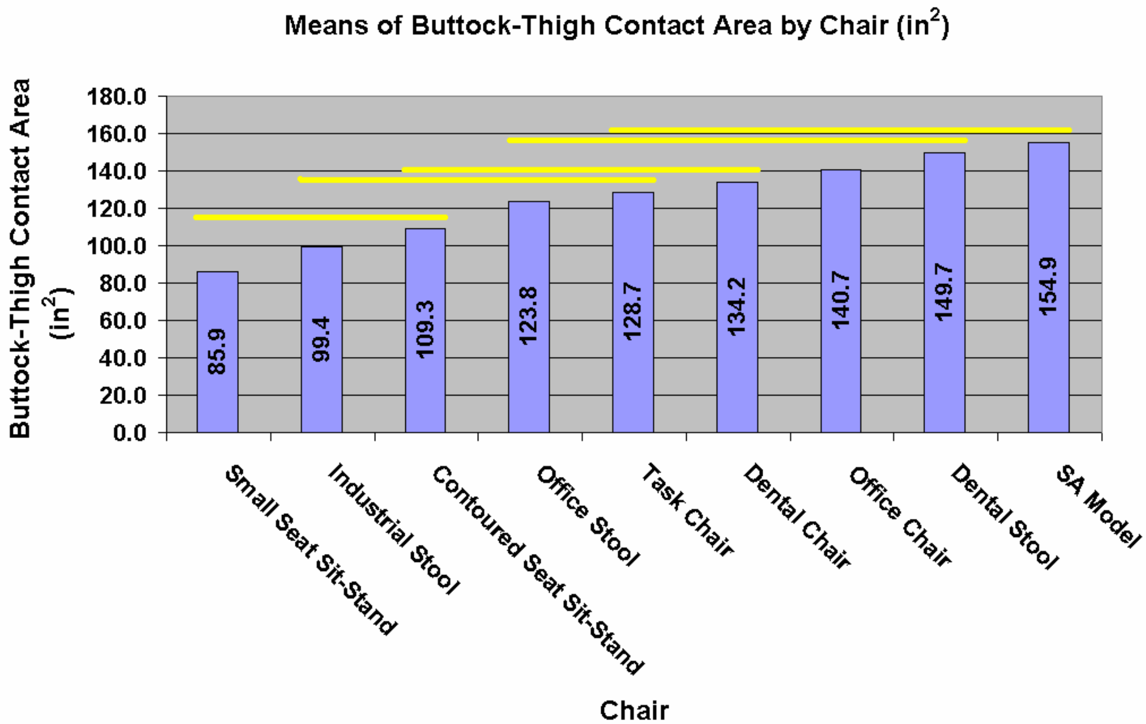

Figure 23. Means and Tukey Test Results on Mean Buttock-Thigh Contact Area by Chair (in^2). Male Subjects.

Buttock-Thigh Contact Area by Posture

The ANOVA results indicated differences between the buttock-thigh contact areas by posture. The Tukey HSD test on buttock-thigh contact area by posture revealed two groups that were statistically different from one another. Figure 24 shows the means of the buttock-thigh contact area along with the results of the Tukey HSD test (statistically similar posture groupings are identified by the yellow horizontal line).

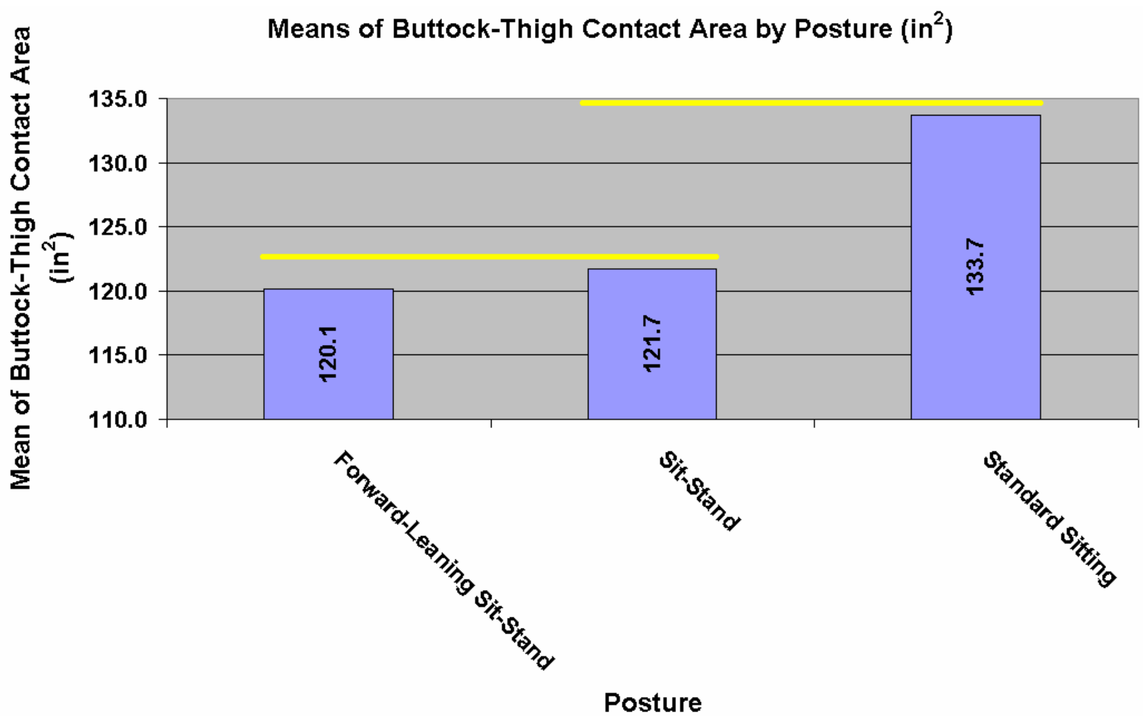

Figure 24. Means and Tukey Test Results on Mean Buttock-Thigh Contact Area by Posture (in^2). Male Subjects.

The results of the Tukey test (Figure 24) on surface contact are by posture show that sit-stand and the standard sitting postures were placed in the highest buttock-thigh contact area grouping. These results were expected as the majority of the chairs were designed for normal sitting postures.

8.2.4. Production

The Purdue Pegboard results were calculated as the sum of pieces that were properly placed according to the PPB instructions over all 4 tests (see the Procedures Section).

The male subjects' highest production value was 110 while the lowest production value was 55. On average, the male subjects placed approximately 88 Purdue Pegboard pieces, as summed over all four trials.

Summed Production Values

In order to evaluate the results of the production testing, the values obtained over the four Purdue Pegboard testing trials were summed together over the chairs and subjects. The summed production values produced by the male subjects are provided in Table 49 for production by chair.

Table 49. Summed Production Values by Chair. Male Subjects.

CHAIR	PRODUCTION
Small Seat Sit-Stand	758
Dental Stool	768
Office Chair	773
Office Stool	794
Industrial Stool	796
Contoured Seat Sit-Stand	796
Dental Chair	799
Task Chair	808
SA Model	819

Mean production values by chair ranged from 758 to 819, with a mean value of approximately 790. This increase in production of approximately 8% between the lowest and highest "producing" chairs agrees with previous research conducted by Congleton (1983), who reported a 4-10% increase in production, due to chairs alone, between the lowest and highest "producing" chairs. Note that the highest production value came from the SA Model while the lowest production value came from the small seat sit-stand chair.

In order to determine if any statistically significant differences exist between the chairs for buttock-thigh contact area an analysis of variance (ANOVA) was conducted.

Table 50. ANOVA on Production Values. Male Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	5451.04	18	302.84	5.03	0.000
Intercept	624275.57	1	624275.57	10375.60	0.000
CHAIR	347.88	8	43.49	0.72	0.671
POSTURE	24.62	2	12.31	0.21	0.816
SUBJECT	5078.54	8	634.82	10.55	0.000
Error	3730.40	62	60.17		
Total	633457.00	81			
Corrected Total	9181.43	80			

R Squared = .594 (Adjusted R Squared = .476)

The analysis of variance in Table 50 over all males' results shows there were no significant differences between chairs or postures ($p < 0.05$). The male subjects produced statistically different production values ($p < 0.001$).

8.2.5. Comfort Survey

A metric ruler was used to measure the 10cm VAS (visual-analog scale) used in the Helander and Zhang (1997) chair comfort survey. Each survey (one for each chair/posture treatment per subject) was given a total score, which was the sum of the VAS measures over the survey's seven questions per chair (in centimeters). The maximum possible score was therefore 70 (cm). The higher the total, the more perceived comfort existed.

Chair comfort rating scores for the male subjects ranged from 2.1 in the industrial stool to 69.6 for the dental chair, with a mean of 38.5.

To make the comfort survey results understandable, the chair comfort rating scores (the individual subjects' total scores for each chair and posture over the seven questions) were summed over the chairs.

Table 51. Summed Comfort Survey Results by Chair (cm). Male Subjects.

CHAIR	COMFORT SCORE
Industrial Stool	231.9
Small Seat Sit-Stand	245.0
Contoured Seat Sit-Stand	283.4
Office Stool	291.3
Dental Chair	330.2
Task Chair	350.5
Dental Stool	379.7
SA Model	384.6
Office Chair	401.7

After summing the chair comfort survey scores for the male subjects (Table 51), the Office chair and SA Model had the to two highest comfort rating scores. The Industrial Stool was the least comfortable.

In order to determine whether or not statistically significant differences existed between the chairs regarding comfort, an ANOVA was completed.

Table 52. ANOVA on Comfort Survey Results. Male Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	13302.02	18	739.00	5.23	0.000
Intercept	103699.74	1	103699.74	734.50	0.000
CHAIR	3440.99	8	430.12	3.05	0.006
POSTURE	3299.79	2	1649.89	11.69	0.000
SUBJECT	6561.24	8	820.16	5.81	0.000
Error	8753.41	62	141.18		
Total	125755.18	81			
Corrected Total	22055.43	80			

R Squared = .603 (Adjusted R Squared = .488)

The ANOVA was calculated using the individual subjects score per chair. The results of the analysis of variance on the males' comfort scores (Table 52) shows there were significant differences between chairs ($p < 0.01$) and postures ($p < 0.001$). Subjects were also statistically different ($p < 0.001$). Given this information, further investigation into the comfort survey results by chair and by posture are warranted.

Comfort by Chair

The ANOVA results indicated differences between the comfort survey scores by chair. The Tukey HSD test on comfort survey scores revealed groups that were statistically different from one another. Figure 25 shows the means of the comfort survey scores by chair along with the results of the Tukey HSD test (statistically similar chair groupings are identified by the yellow horizontal line).

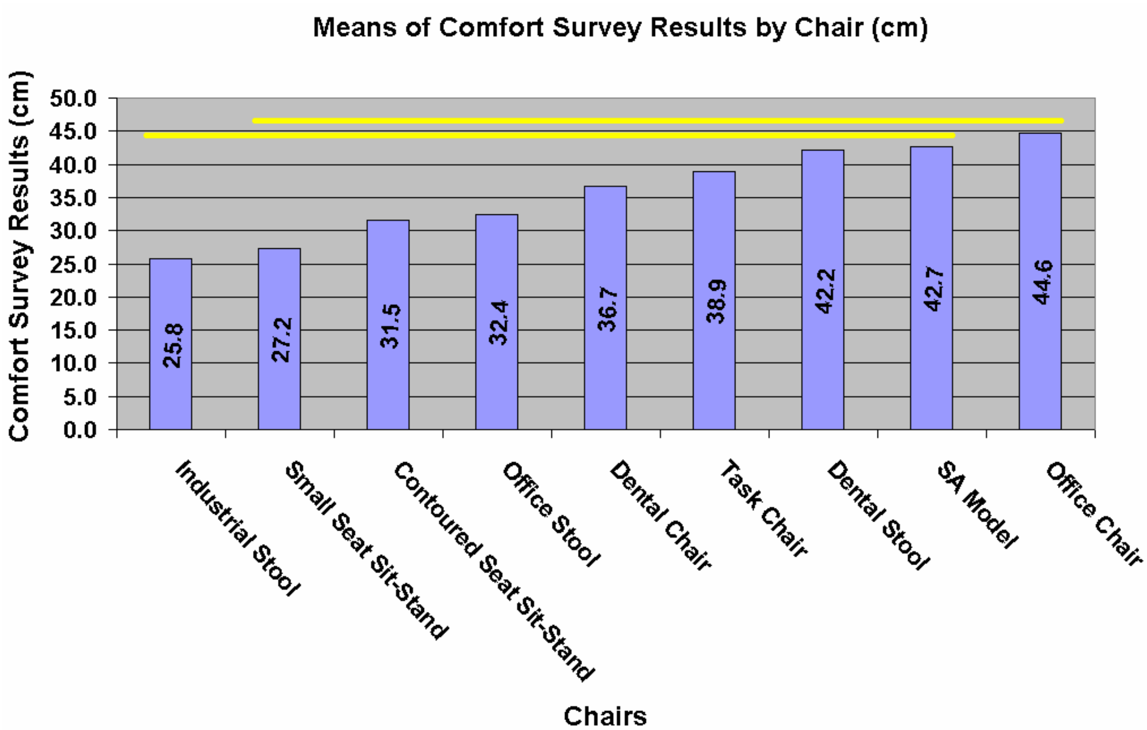

Figure 25. Means and Tukey Test Results on Comfort Survey Scores by Chair (cm). Male Subjects.

Figure 25 shows that the SA Model was placed in the most comfortable chair grouping.

Comfort by Posture

The ANOVA results indicated differences between the comfort survey scores by chair. Further investigation of the differences may now be conducted. A Tukey HSD test on comfort survey scores revealed 2 groups that were statistically different from one another. Graphically, Figure 26 shows the means of the comfort survey scores by posture along with the results of the Tukey HSD test (statistically similar posture groupings are identified by the yellow horizontal line).

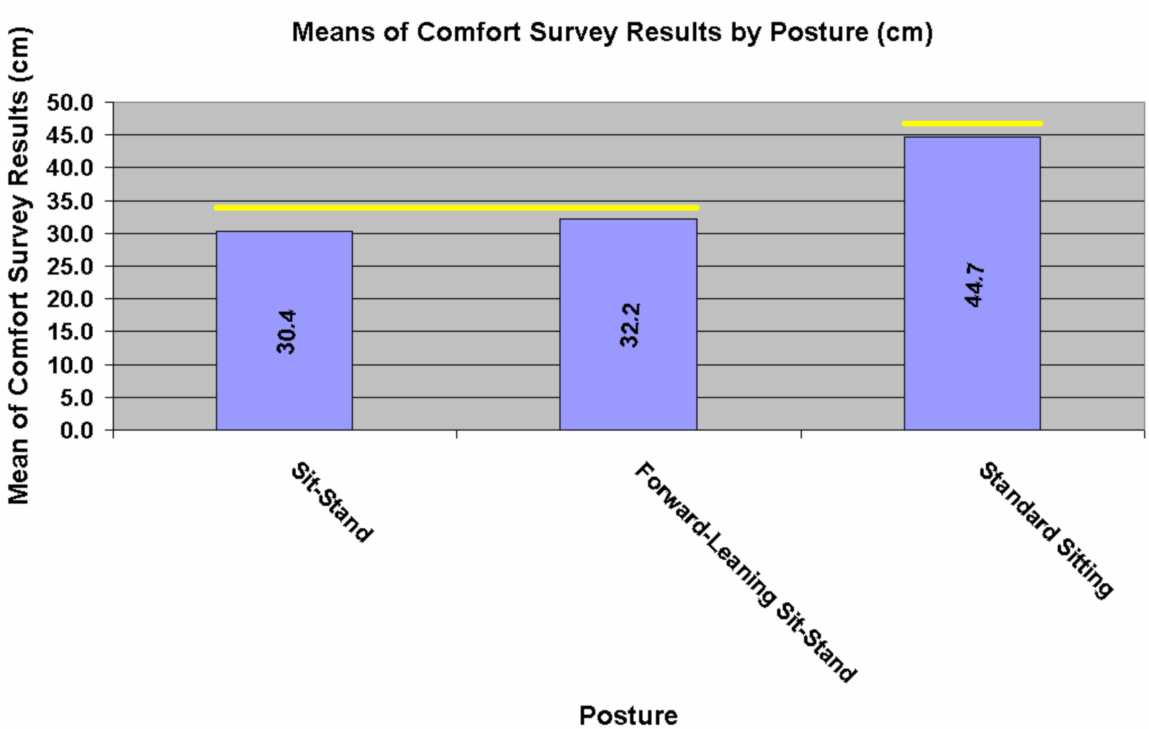

Figure 26. Means and Tukey Test Results on Comfort Survey Scores by Posture (cm). Male Subjects.

Figure 26 shows that the standard sitting posture was the most comfortable posture. The sit-stand and forward-leaning sit-stand postures were not significantly different regarding comfort. These results were expected as the majority of the chairs were designed for normal sitting postures.

8.2.6. Correlations

Correlations were run on the male subjects' results to determine if any associations existed between the variables, and if so, how strong these associations were. Correlations between comfort, production, contact area, posture, and rankings were performed. Only the values from the third ranking trial were used because they were completed after having sat in the chairs and being given the knowledge of all the chairs' features.

Table 53. Correlation Results. Male Subjects.

VARIABLE	SPEARHMAN'S RHO	SIGNIFICANCE	N
Comfort & Ranking Trial III	**-0.52**	0.000	81
Contact Area & Ranking Trial III	**-0.48**	0.000	81
Comfort & Contact Area	**0.27**	0.013	81
Comfort & Production	**0.25**	0.027	81
Contact Area & Production	0.08	0.477	81
Production & Ranking Trial III	0.02	0.869	81

Bold Values are Significant at the <0.05 Level

The results in Table 53 show several significant correlations ($p < 0.05$), although not very strong. Comfort & Ranking III is the strongest significant correlation with a Spearman's Rho statistic of –0.52 followed by Contact Area and Ranking III with –0.48. Contact Area and Production and Production and Ranking Trial 3 showed no significant correlations ($p < 0.05$). Note that Ranking III was a value with 1 being best (highest ranked) and 9 being worst (lowest rank). Therefore, the negative Spearman's Rho values indicate a positive correlation between Ranking III and the other variables (for example, there is a positive correlation between Comfort and Ranking Trial III).

These results indicate that the male subjects preferred the chairs that were perceived as the most comfortable, and that the most comfortably perceived chairs were those that had larger buttock-thigh contact areas. These results agree with past research performed by Congleton and Ayoub (1988) who found that comfort was correlated with buttock-thigh contact area. Additionally, higher production values were correlated with higher ratings of comfort (although statistically significant, this correlation was fairly weak).

8.2.7. Evaluation Part I Summary

The results show that there are indeed differences between chairs in regards to the variables tested during the evaluation. The SA Model provided the lowest peak pressures, the highest contact area, and the highest production values. The dental chair was ranked first overall while the SA model was ranked second. Regarding comfort, the dental chair was the most comfortably rated chair while the SA Model once again came in second place.

Statistically, several chairs performed similarly. The SA Model was consistently placed in the "best" category with a Tukey HSD test. None of the results suggest negative consequences regarding the addition, and use, of a Support-Arm.

8.3. EVALUATION PART II – MALE SUBJECTS

Part II of the evaluation involved having the subjects choose their own posture and chair "set-up" for both the SA Model and a standard style of stool at two different table heights. The purpose of this part of the evaluation was to determine if the subjects set up (configured) the SA model differently than they did the standard stool.

Nine male subjects participated in Part II of the evaluation. Data from subjects 1M-9M were used to obtain the results provided below. The null hypothesis was that the subjects' chosen set-ups (configurations) were not different between the SA Model and the standard style stool.

8.3.1. Chosen Set-Up

When the male subjects were allowed to choose their own posture, and whether or not to use the Support-Arm on the SA Model, it was found that no subjects chose to use the Support-Arm when the table was at the 30" height (see Table 54). However, at the 36" table height, 5 of the 9 (56%) male subjects chose to use the Support-Arm.

Table 54. Use of Support-Arm at 30" and 36" Table Heights. Male Subjects.

	SUPPORT-ARM USE	
TABLE HEIGHT	Yes	No
30"	0	9
36"	5	4

Chosen Ankle Angle

Table 55. ANOVA on Chosen Ankle Angle. Male Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	765.86	11	69.62	2.54	0.027
Intercept	303417.36	1	303417.36	11070.63	0.000
STOOL	42.25	1	42.25	1.54	0.226
TBLE_HT	0.69	1	0.69	0.03	0.875
SUBJECT	688.89	8	86.11	3.14	0.014
STOOL * TBLE_HT	34.03	1	34.03	1.24	0.276
Error	657.78	24	27.41		
Total	304841.00	36			
Corrected Total	1423.64	35			

R Squared = .538 (Adjusted R Squared = .326)

The ANOVA in Table 55 indicates that the male subjects' chosen ankle angles were not significantly different (<0.05) by stool, table height, or stool*table height interaction.

Chosen Knee Angle

Table 56. ANOVA on Chosen Knee Angle. Male Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2310.19	11	210.02	4.52	0.001
Intercept	471282.25	1	471282.25	10148.24	0.000
STOOL	200.69	1	200.69	4.32	0.048
TBLE_HT	650.25	1	650.25	14.00	0.001
SUBJECT	1403.00	8	175.38	3.78	0.005
STOOL * TBLE_HT	56.25	1	56.25	1.21	0.282
Error	1114.56	24	46.44		
Total	474707.00	36			
Corrected Total	3424.75	35			

R Squared = .675 (Adjusted R Squared = .525)

The ANOVA results (Table 56) on the chosen knee angle indicate that the male subjects had statistically different knee angles between stool ($p < 0.05$) and table height ($p = 0.001$), as well as amongst themselves ($p < 0.01$). Further investigations into the chosen knee angles by stool and by table height are warranted.

Chosen Knee Angle by Stool

Figure 27 shows the differences between the male subjects' chosen knee angles by stool.

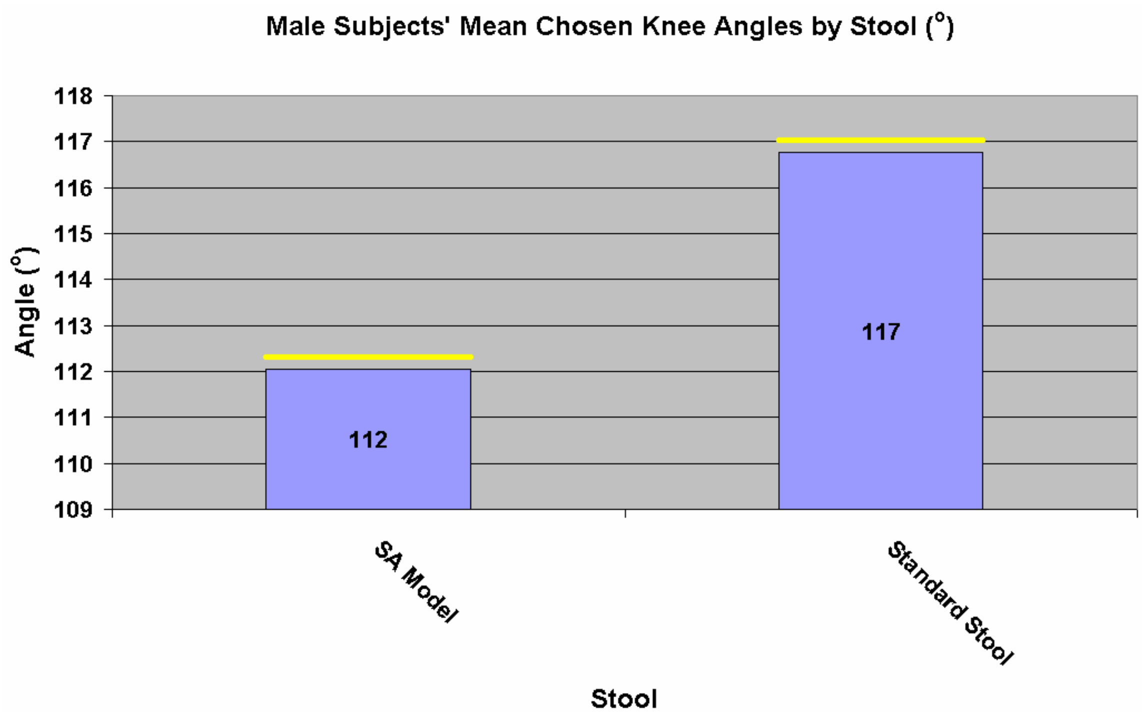

Figure 27. Means and T-Test Results on Chosen Knee Angles by Stool (°). Male Subjects.

The male subjects chose larger knee angles with the standard stool than with the SA Model, according to a paired, two-tailed t-Test ($t < 0.05$) as shown in Figure 27.

Chosen Knee Angle by Table Height

Figure 28 shows the differences between the male subjects' chosen knee angles by table height.

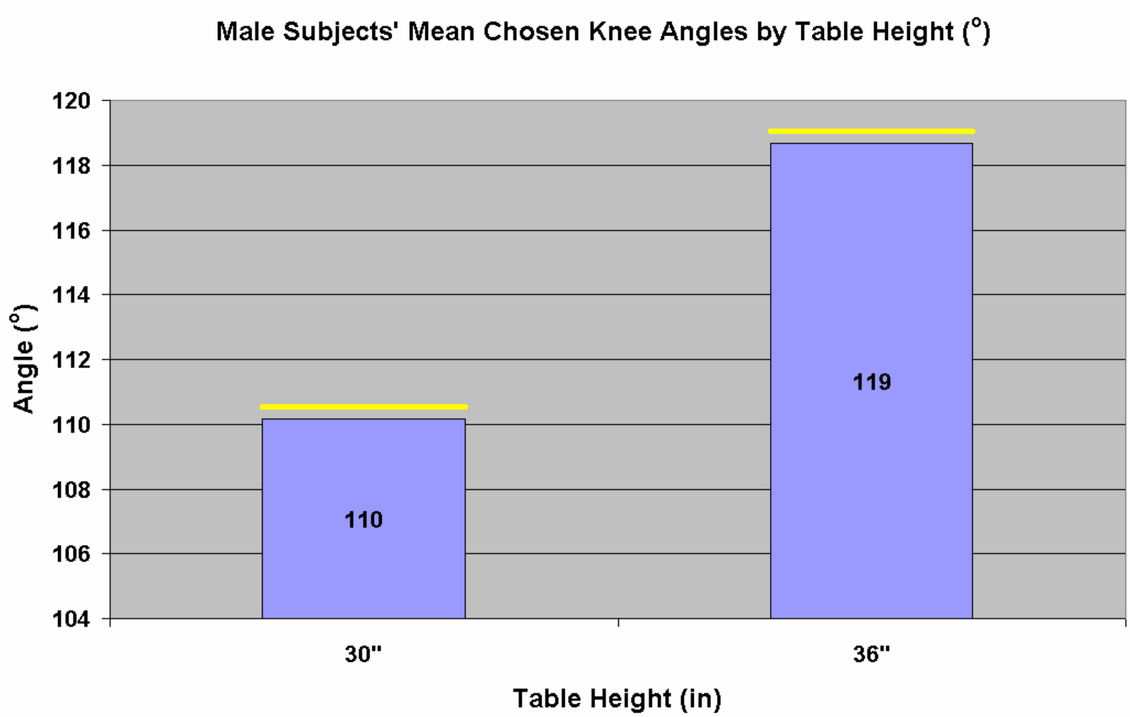

Figure 28. Means and T-Test Results on Chosen Knee Angles by Table Height (°). Male Subjects.

The male subjects chose statistically larger knee angles at the 36" table height, according to a paired, two-tailed t-Test ($t < 0.01$). This indicates that the subjects chose more of a sit-stand posture at the higher table height.

Chosen Trunk-Thigh Angle

Table 57. ANOVA on Chosen Trunk-Thigh Angle. Male Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3185.44	11	289.59	3.87	0.003
Intercept	360400.11	1	360400.11	4814.85	0.000
STOOL	186.78	1	186.78	2.50	0.127
TBLE_HT	324.00	1	324.00	4.33	0.048
SUBJECT	2160.89	8	270.11	3.61	0.007
STOOL * TBLE_HT	513.78	1	513.78	6.86	0.015
Error	1796.44	24	74.85		
Total	365382.00	36			
Corrected Total	4981.89	35			

R Squared = .639 (Adjusted R Squared = .474)

ANOVA results in Table 57 show that the males subject differed on their chosen trunk-thigh angle by table height ($p < 0.05$) and by stool*table height interaction ($p < 0.05$), as well as amongst themselves ($p < 0.01$). Further investigations are warranted.

Chosen Trunk-Thigh Angle by Table Height

Figure 29 shows the differences between the male subjects' chosen trunk-thigh angles by table height.

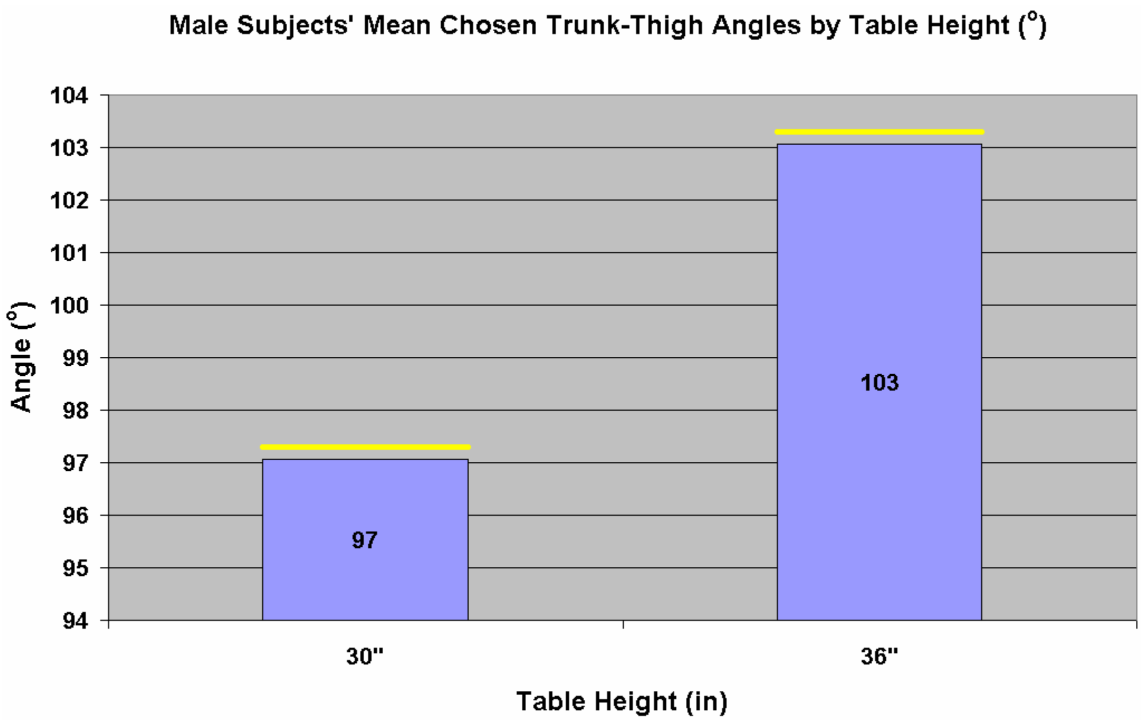

Figure 29. Means and T-Test Results on Chosen Trunk-Thigh Angles by Table Height (°). Male Subjects.

The male subjects, in total chose larger trunk-thigh angles at the 36” table height than at the 30” table height. A paired, two-tailed t-Test indicated the differences were not statistically different ($t < 0.05$).

*Chosen Trunk-Thigh Angle by Stool*Table Height Interaction*

Figure 30 shows the differences between the male subjects’ chosen trunk-thigh angles by stool*table height.

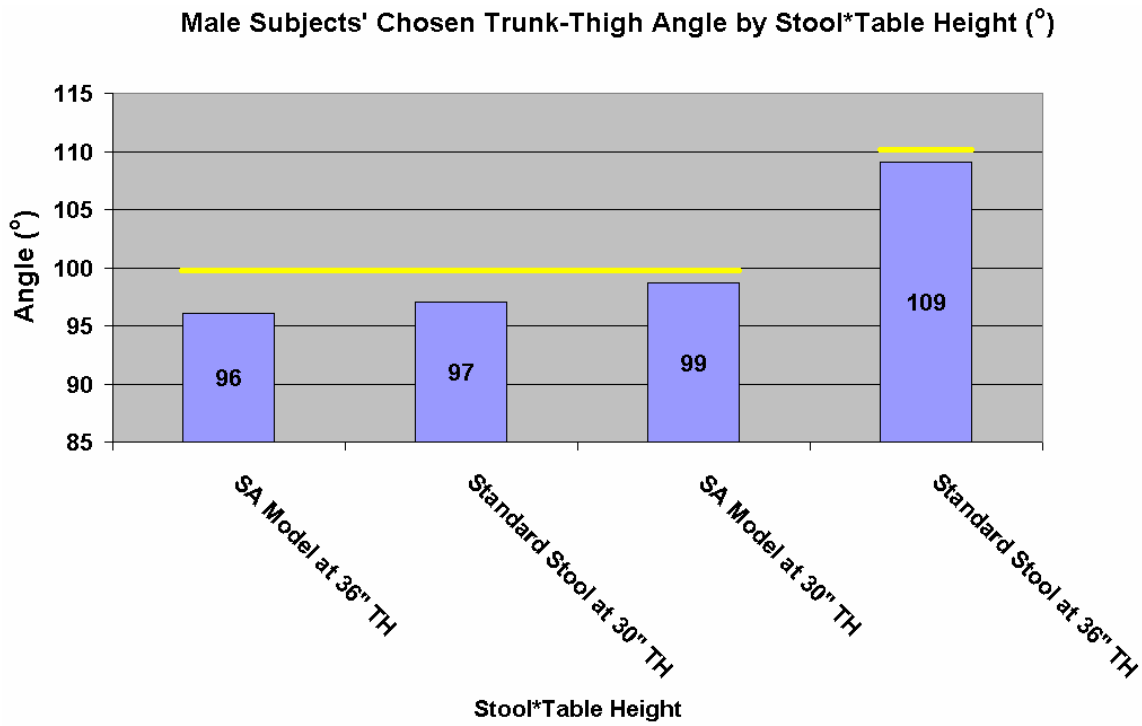

Figure 30. Means on Chosen Trunk-Thigh Angles by Stool*Table Height (°). Male Subjects.

While seated in the standard style stool, the male subjects chose significantly larger trunk-thigh angles (less forward-leaning) at the higher table height, according to a paired, two-tailed t-Test ($t < 0.05$). There were no other significant differences between chosen trunk-thigh angles by chair*posture interaction ($t < 0.05$).

Chosen Seat-Tilt Angle

Table 58. ANOVA on Chosen Seat-Tilt Angle. Male Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	371.86	11	33.81	3.01	0.012
Intercept	2193.36	1	2193.36	195.13	0.000
STOOL	103.36	1	103.36	9.20	0.006
TBLE_HT	42.25	1	42.25	3.76	0.064
SUBJECT	222.89	8	27.86	2.48	0.041
STOOL * TBLE_HT	3.36	1	3.36	0.30	0.590
Error	269.78	24	11.24		
Total	2835.00	36			
Corrected Total	641.64	35			

R Squared = .580 (Adjusted R Squared = .387)

The ANOVA on the male subjects' (Table 58) chosen seat-pan tilt angle shows significant differences between the stools ($p < 0.01$) and subjects ($p < 0.05$). Further investigation into the chosen seat-tilt angles by stool is warranted.

Chosen Seat-Tilt Angle by Stool

Figure 31 shows the differences between the male subjects' chosen seat-tilt angles by stool.

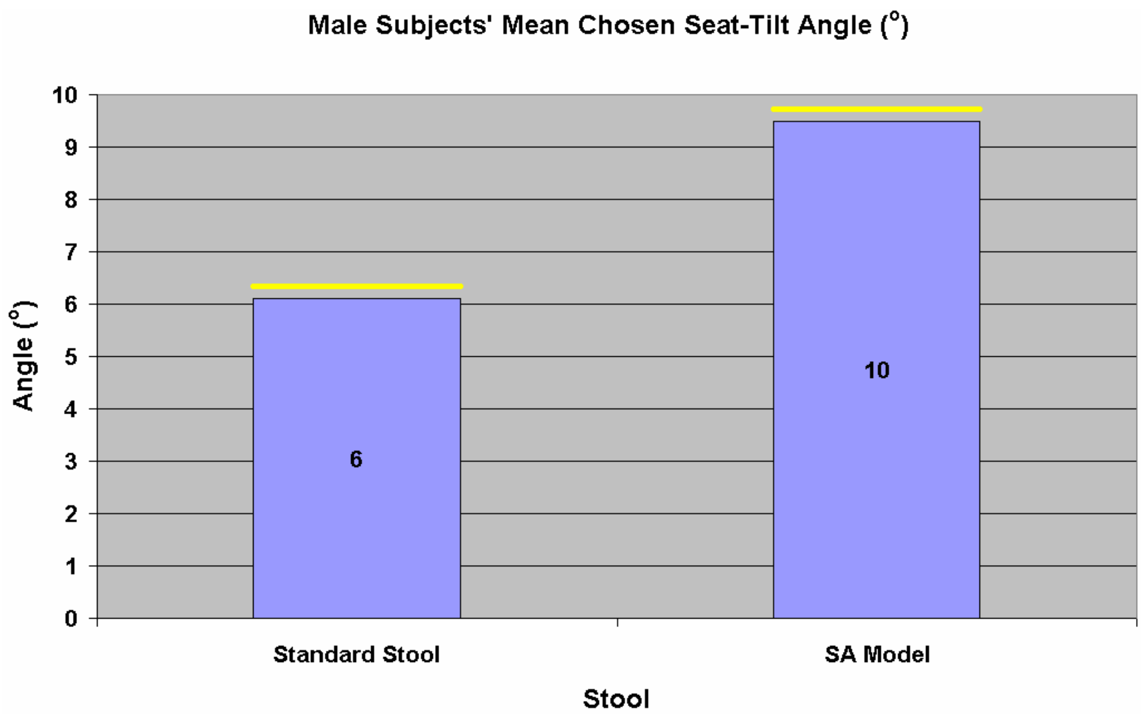

Figure 31. Means and T-Test Results on Chosen Seat-Tilt Angles by Stool (°). Male Subjects.

The male subjects chose significantly greater seat-tilt angles with the SA Model, as averaged over both table heights, according to a paired, two-tailed t-Test ($t < 0.05$).

8.3.2. Male Subjects' Comments on the SA Model

After the second evaluation was completed, every subject was given the chance to comment on the SA Model. These comments were typed into a Word Processor and saved for each subject as their comments were made. The comments could all be placed into 5 comment "categories" as shown in Table 59. The subjects' full comments are provided in Appendix J.

Table 59. Male Subjects' Categorized Comments.

COMMENT CATEGORY	NUMBER OF COMMENTS
I Like It	7
I Don't Like It	0
I'm not Sure if I Like It	2
Support-Arm Pad is Too Big	4
SA Needs More Adjustments	4

The last two comment categories were in direct relation to the non-use of the Support-Arm at the 30" table height. The Support-Arm pillow posed as too large an obstacle during standard sitting postures, placing the subjects too far away from the desk's working surface.

8.3.3. Evaluation Part II Summary

The results of Part II of the evaluation show that the majority of the male subjects preferred to use the Support-Arm at the 36" table height. Statistically significant differences were found between chosen knee angles by stool and table height, between chosen trunk-thigh angles by table height and stool*table height interaction, and between chosen seat-tilt angles by stool

Overall, the male subjects chose significantly larger knee angles with the standard style stool versus the SA Model. They also chose significantly larger knee angle at the 36" table height than at the 30" table height.

Overall, the male subjects chose significant larger trunk-thigh angles at the 36” table height than at the 30” table height. They also chose significantly larger trunk-thigh angles with the standard stool at the 36” table height than at the 30” table height. While seated on the SA Model, chosen trunk-thigh angles were not statistically different between the table heights.

Overall, the male subjects chose larger forward seat-tilt angles with the SA Model than with the standard style stool.

Subjects’ comments indicated that most liked the SA Model, although they thought it should have a smaller Support-Arm pillow and allow for more adaptability to provide support to the entire forward-leaning envelope.

9. GENDER COMPARISON AND COMBINED SUBJECTS' RESULTS

Female and male subjects' results were separated into different results sections because known differences exist between male and female genders. Lumping the results into a "combined subject" analysis would not be proper unless it is found that significant differences do not exist. Statistical testing for differences between genders was conducted on buttock-thigh contact area, production values, and comfort ratings for Part I of the evaluation, and on the subjects' chosen ankle, knee, and trunk-thigh angles, along with the chosen seat-tilt angles for Part II of the evaluation.

When statistically significant gender differences are found, the data can not be combined, and only the gender differences will be discuss.. When statistically significant differences are not found between the genders, their results will be combined and evaluated further for significant differences between the evaluated variables.

9.1. EVALUATION PART I – GENDER COMPARISON AND COMBINED SUBJECTS

Eighteen subjects participated in Part I of the Evaluation. Results from subjects 1F-9F and 1M-9M were used to obtain the results provided below. The null hypothesis was that no chairs performed differently under the prescribed conditions and tests performed.

9.1.1. Chair Rankings

All 18 subjects ranked the chairs on 3 separate occasions as detailed in the Methods Section. The subjects were asked to rank the chairs (from 1 to 9 with 1 being the most "preferred" chair) in order of which they would choose to use them in tasks requiring postures used in industry, as described earlier. The first ranking trial (termed "appearance") was conducted prior to the subjects being given any information on the chairs (nor could they touch them). The second ranking trial (termed "knowledge") was conducted after the subjects were provided with the Chair Feature Matrix (see Appendix F) and given a demonstration of each of the chairs' features. The third ranking trial (termed "sitting experience") was conducted after the subjects had sat in each chair during Part I of the evaluation.

Summed Subject Rankings

In order to determine the overall rank order of the chairs, all the subjects' rankings were summed over each chair per ranking trial, and then re-ranked with the lowest value given a ranking of 1 and the highest a ranking of 9.

Table 60. Trial 1 Rankings (Appearance). Conducted Prior to the Subjects Being Given any Information on the Chairs. Gender Comparison.

CHAIR	FEMALE SUBJECTS	MALE SUBJECTS
Dental Chair	3	2,3
SA Model	5	5
Industrial Stool	1	1
Office Stool	6	8
Office Chair	7	4
Dental Stool	8	6
Small Seat Sit-Stand	9	9
Contoured Seat Sit-Stand	2	7
Task Chair	4	2,3

Table 60 shows that during the first ranking trial (appearance) both genders agreed upon the industrial stool as their first preference, and the small seat sit-stand as their last choice in chairs. The largest difference between the genders was the preference for the contoured seat sit-stand, with the female subjects ranking it second and the male subjects ranking it seventh.

Table 61. Trial 2 Rankings (Knowledge). Conducted After the Subjects Were Provided with the Chair Feature Matrix. Gender Comparison.

CHAIR	FEMALE SUBJECTS	MALE SUBJECTS
Dental Chair	2	3,4
SA Model	1	2
Industrial Stool	4	3,4
Office Stool	8	8
Office Chair	3	1
Dental Stool	6	6
Small Seat Sit-Stand	9	9
Contoured Seat Sit-Stand	7	7
Task Chair	5	5

Table 62 shows that during the second ranking trial (knowledge) both genders ranked the dental chair, SA Model, and office chair within their top three rankings (the males had the dental chair and industrial stool tied for third). In addition, both genders ranked the industrial stool fourth (the male subjects had it tied for third/fourth), the task chair fifth, the dental stool sixth, the contoured seat sit-stand seventh, the office stool eighth, and the small seat sit-stand ninth.

Table 63. Trial 3 Rankings (Sitting Experience). Conducted After the Subjects had Sat in Every Chair During Part I of the Evaluation. Gender Comparison.

CHAIR	FEMALE SUBJECTS	MALE SUBJECTS
Dental Chair	2	2,3
SA Model	1	2,3
Industrial Stool	7	7
Office Stool	4,5	6
Office Chair	3	1
Dental Stool	8	4
Small Seat Sit-Stand	9	8,9
Contoured Seat Sit-Stand	4,5	8,9
Task Chair	6	5

Table 63 shows that during the third ranking trial (sitting experience) both genders ranked the dental chair, SA Model, and office chair within their top three rankings (the males had the dental chair and industrial stool tied for third). Both genders also ranked the small seat sit-stand ninth (the male subjects had the small seat sit-stand tied for eighth/ninth place). The largest differences between the rankings were with the dental stool and the contoured seat sit-stand chair. The female subjects ranked the contoured seat sit-stand higher than the males, and the males ranked the dental stool higher than the females.

Intra-Rater Correlation Between Ranking Trials

In order to determine if the subjects ranked the chairs in the same order from one trial to another (intra-rater), an intra-rater correlation study was performed (i.e. did Subject 1 rank the chairs in the same order from the first trial to the second?). Spearman's Rho was the statistic used to perform this analysis. Both genders results for trials 1 to 2 and 2 to 3 are provided in Table 64.

Table 64. Intra-Rater Correlation Between Ranking Trials 1 to 2 and 2 to 3 (1, 2, 3: Appearance, Knowledge, Sitting Experience). Gender Comparison.

RANKING TRIALS	SPEARMAN'S RHO	SIGNIFICANCE
Trail 1 to 2 (Appearance to Knowledge)		
Female Subjects	0.43	0.000
Male Subjects	0.66	0.000
Trial 2 to 3 (Knowledge to Sitting Experience)		
Female Subjects	0.47	0.000
Male Subjects	0.47	0.000

The statistics show better correlation between the male subjects rankings between trials 1 to 2 (appearance to knowledge). Both genders had the same correlations between ranking trials 2 to 3 (knowledge to sitting experience). The female subjects' intra-rater correlation increased slightly from ranking trials 1 to 2 (appearance to knowledge) to ranking trials 2 to 3 (knowledge to sitting experience) while the male subject's decreased.

Inter-Rater Correlation within Ranking Trials

In order to determine if the subjects ranked the chairs in the same order during the individual ranking trials (inter-rater), an intraclass correlation coefficient (ICC) was used (i.e. did subjects 1 and 2 agree on their chair rankings during the first ranking trial?). The ICC was calculated using a two-way mixed model, with absolute values and single measures.

Table 65 provides the results of the inter-rater correlation study for the female and male subjects during the 3 ranking trials.

Table 65. Inter-Rater Correlation During the Three Ranking Trials (1, 2, 3: Appearance, Knowledge, Sitting Experience). Gender Comparison.

RANKING TRIAL	ICC	95% Confidence Interval		SIGNIFICANCE
		Lower Bound	Upper Bound	
1 (Appearance)				
Female Subjects	0.05	-0.05	0.35	0.214
Male Subjects	0.39	0.16	0.74	0.000
2 (Knowledge)				
Female Subjects	0.39	0.16	0.73	0.000
Male Subjects	0.60	0.35	0.86	0.000
3 (Sitting Experience)				
Female Subjects	0.12	-0.02	0.46	0.048
Male Subjects	0.28	0.08	0.65	0.001

The results show relatively low correlation between both genders' rankings, with the exception of the male subjects' rankings during the second ranking trial, which was average to good. The inter-rater correlations for the male subjects during all three ranking trials were better than were the females. All statistics are significant ($p < 0.05$) except the female subjects' correlation during the first ranking trial.

9.1.2. Buttock-Thigh Peak Pressure

The Xsensor pad and software were calibrated by the manufacturer to a range of 0.10-4.06 psi. Unfortunately values above this range were required by the evaluation. Although the data is not usable for statistical purposes, the data does provide some useful information.

Table 66 shows a comparison between the female and male subjects in their number of buttock-thigh peak pressure recordings below 4.06 psi.

Table 66. Number of Buttock-Thigh Peak Pressure Recordings Below 4.06 psi per Chair. Female and Male Subjects.

	NUMBER OF RESULTS < 4.06 PSI	
CHAIR	**FEMALE**	**MALE**
Dental Chair	1	2
SA Model	6	4
Industrial Stool	1	0
Office Stool	0	0
Office Chair	1	1
Dental Stool	2	1
Small Seat Sit-Stand	0	0
Contoured Seat Sit-Stand	0	0
Task Chair	2	1

The results indicate similar occurrences of peak pressure recordings below 4.06 psi. The SA Model produced the majority of results below threshold for both genders. The office stool, small seat sit-stand, and contoured seat sit-stand chairs had no peak pressure recordings less than 4.06 psi. Interesting, none of these three chairs have a Support-Arm design. These results indicate that the SA Model is best suited for providing lower peak pressures over the three postures assumed.

9.1.3. Buttock-Thigh Contact Area

Buttock-thigh contact area is the total area in contact at the interface between the subjects' buttock-thigh region and the seat-pan of the chair, as measured with the Xsensor equipment. In order to determine if the buttock-thigh contact area results were statistically different between genders an ANOVA was completed.

Table 67. ANOVA on Buttock-Thigh Contact Area. Combined Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	133900.77	27	4959.29	9.73	0.000
Intercept	2661124.50	1	2661124.50	5221.53	0.000
CHAIR	65590.66	8	8198.83	16.09	0.000
GENDER	1437.08	1	1437.08	2.82	0.095
POSTURE	13305.68	2	6652.84	13.05	0.000
SUBJECT (GENDER)	53567.36	16	3347.96	6.57	0.000
Error	68292.36	134	509.64		
Total	2863317.63	162			
Corrected Total	202193.13	161			

R Squared = .662 (Adjusted R Squared = .594)

The analysis of variance (Table 67) over all subjects' results shows no significant differences between genders for buttock-thigh contact area ($p < 0.05$). The combined subjects' buttock-thigh contact area results show statistically significant differences by chair ($p<0.001$) and by posture ($p < 0.001$).

Buttock-Thigh Contact Area by Chair

The ANOVA results indicated no differences between the genders, and hence the subjects (genders) results may be combined for further study. The ANOVA results in Table 67 show statistically different ($p < 0.001$) buttock-thigh contact areas by chair. Table 68 provides the subjects combined mean buttock-thigh contact area by chair.

Table 68. Mean Contact Area by Chair (in^2). Combined Subjects.

CHAIR	CONTACT AREA (in^2)
Small Seat Sit-Stand	85.0
Industrial Stool	114.2
Contoured Seat Sit-Stand	121.9
Office Stool	127.8
Task Chair	131.5
Dental Chair	135.0
Dental Stool	138.1
Office Chair	146.8
SA Model	153.5

The results show that the SA Model provided the greatest contact area with a mean of 153.4 in^2. The small seat sit-stand chair provided the least amount of contact area with a mean of 85.0 in^2. A Tukey HSD test on the combined subjects buttock-thigh contact area revealed 4 groupings of chairs that were statistically different from one another. Figure 32 shows the means of the buttock-thigh contact area along with the results of the Tukey HSD test (statistically similar chair groupings are identified by the yellow horizontal line).

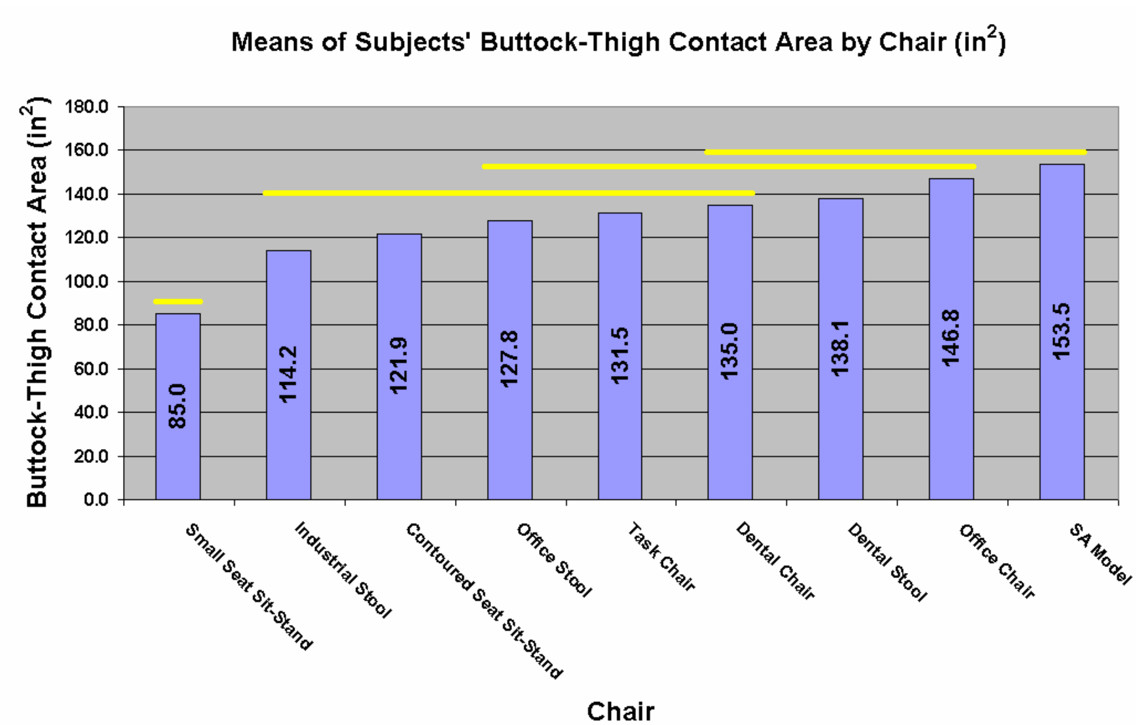

Figure 32. Means and Tukey Test Results on Mean Buttock-Thigh Contact Area by Chair (in^2). Combined Subjects.

The SA Model was placed in the grouping of the chairs that provided the highest buttock-thigh contact area.

Buttock-Thigh Contact Area by Posture

The ANOVA results indicated differences between the buttock-thigh contact areas by posture. The Tukey HSD test on buttock-thigh contact area by posture revealed two groups that were statistically different from one another. Figure 33 shows the means of the buttock-thigh contact area along with the results of the Tukey HSD test (statistically similar posture groupings are identified by the yellow horizontal line).

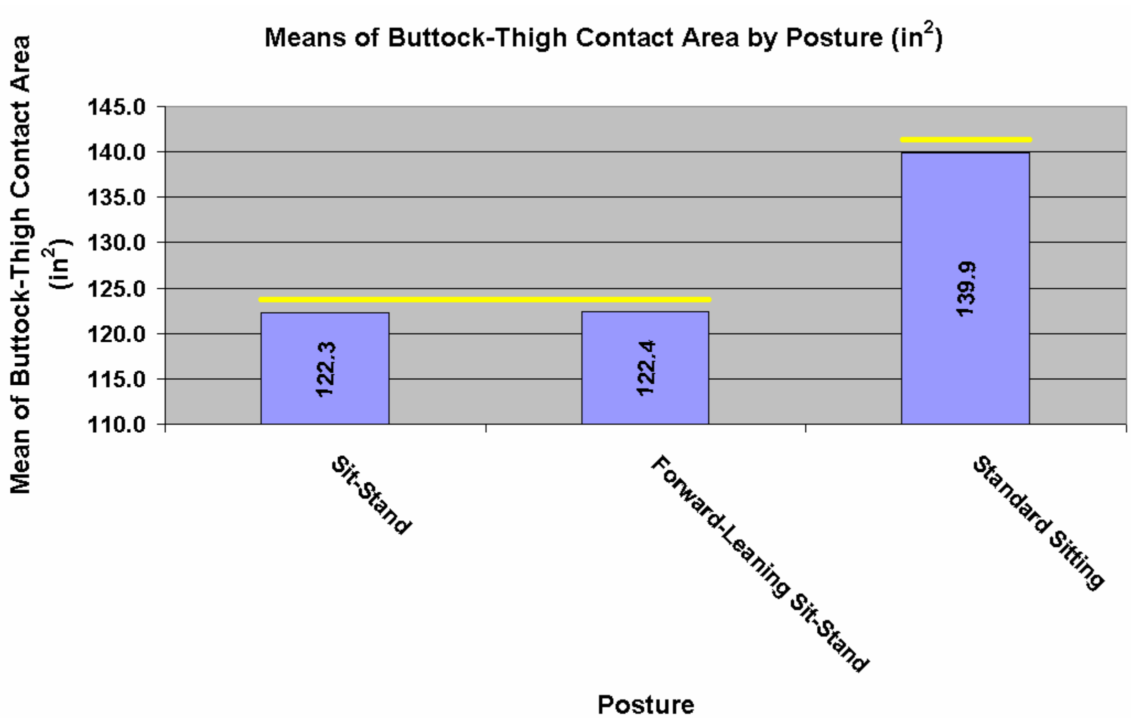

Figure 33. Means and Tukey Test Results on Mean Buttock-Thigh Contact Area by Posture (in^2). Combined Subjects.

The results of the Tukey test (Figure 33) on surface contact are by posture shows that standard sitting posture was rated the most comfortable posture. These results were expected as the majority of the chairs were designed for normal sitting postures.

9.1.4. Production

The Purdue Pegboard results were calculated as the sum of pieces that were properly placed according to the PPB instructions over all four tests (see the Procedures Section).

Summed Production Values

In order to evaluate the results of the production testing, the values obtained over the four Purdue Pegboard testing trials were summed together over the chairs and subjects. An ANOVA was completed to determine if production results were statistically different between genders.

Table 69. ANOVA on Production Values. Combined Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	25584.83	27	947.59	18.96	0.000
Intercept	1348629.39	1	1348629.39	26985.57	0.000
CHAIR#	783.22	8	97.90	1.96	0.056
GENDER	1928.90	1	1928.90	38.60	0.000
POSTURE#	89.33	2	44.67	0.89	0.412
SUBJECT (GENDER)	22783.38	16	1423.96	28.49	0.000
Error	6696.78	134	49.98		
Total	1380911.00	162			
Corrected Total	32281.61	161			

R Squared = .793 (Adjusted R Squared = .751)

Analysis of variance (Table 69) over all subjects' production results show there was a significant difference ($p < 0.001$) between genders.

Production by Gender

The ANOVA results indicated significant differences between production values by gender. No further relationships will be investigated. Figure 34 shows, graphically, the differences between the sums of the production values by gender.

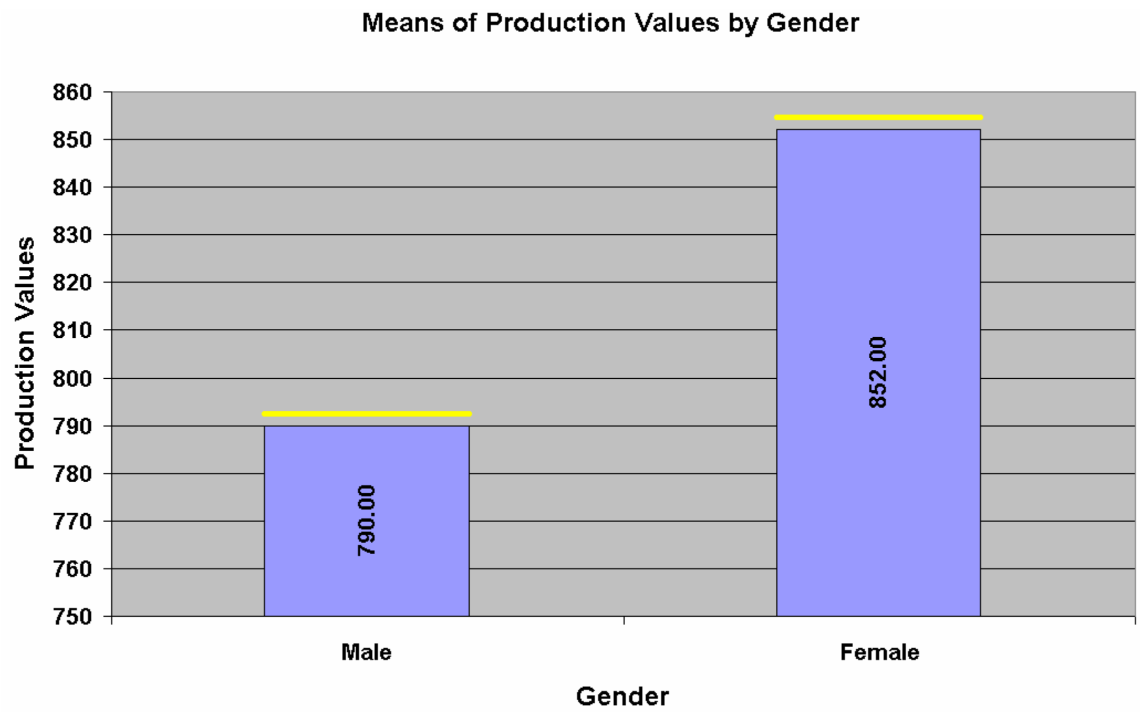

Figure 34. Summed Production Values by Gender. Combined Subjects.

The higher production values by female subjects agrees with previous research by LIC (1999). Potential reasons for the higher production by the female subjects could be due to better finger dexterity, smaller fingers (more able to pick up the Purdue Pegboard pieces), or other factors.

9.1.5. Comfort Survey

A metric ruler was used to measure the 10cm VAS (visual-analog scale) used in the Helander and Zhang (1997) chair comfort survey. Each survey (one for each chair/posture treatment per subject) was given a total score, which was the sum of the VAS measures over the survey's seven questions per chair (in centimeters). The maximum possible score was therefore 70 (cm). The higher the total, the more perceived comfort existed.

In order to determine if the comfort survey results were statistically different between genders, an ANOVA was completed.

Table 70. ANOVA on Comfort Survey Results. Combined Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	23359.51	27	865.17	5.51	0.000
Intercept	188720.47	1	188720.47	1201.80	0.000
CHAIR#	7407.49	8	925.94	5.90	0.000
GENDER	440.65	1	440.65	2.81	0.096
POSTURE#	7179.55	2	3589.77	22.86	0.000
SUBJECT (GENDER)	8331.82	16	520.74	3.32	0.000
Error	21042.25	134	157.03		
Total	233122.23	162			
Corrected Total	44401.76	161			
R Squared = .526 (Adjusted R Squared = .431)					

Analysis of variance (Table 70) over all subjects' comfort survey results shows no statistically significant differences between the genders ($p < 0.05$). The combined subjects' comfort survey results are statistically different by chair ($p<0.001$) and by posture ($p < 0.001$).

Comfort by Chair

The ANOVA results indicated no differences between the genders, and hence all subjects' results may be combined for further study. With the genders' combined results, statistical differences ($p < 0.001$) regarding comfort were found between the chairs (see Table 70). Table 71 provides the results of the subjects' summed comfort survey results by chair.

Table 71. Summed Comfort Survey Results by Chair (cm). Combined Subjects.

CHAIR	COMFORT SCORE
Small Seat Sit-Stand	413.3
Industrial Stool	485.6
Contoured Seat Sit-Stand	501.6
Office Stool	563.5
Task Chair	666.1
Dental Stool	677.9
Dental Chair	688.3
Office Chair	730.6
SA Model	802.4

With the genders combined, the subjects found the small seat sit-stand chair to be the least comfortable and the SA Model the most. A Tukey HSD test on the combined subjects comfort survey results revealed 4 groupings of chairs that were statistically different from one another. Figure 35 shows the means of the comfort survey results by chair along with the results of the Tukey HSD test (statistically similar chair groupings are identified by the yellow horizontal line).

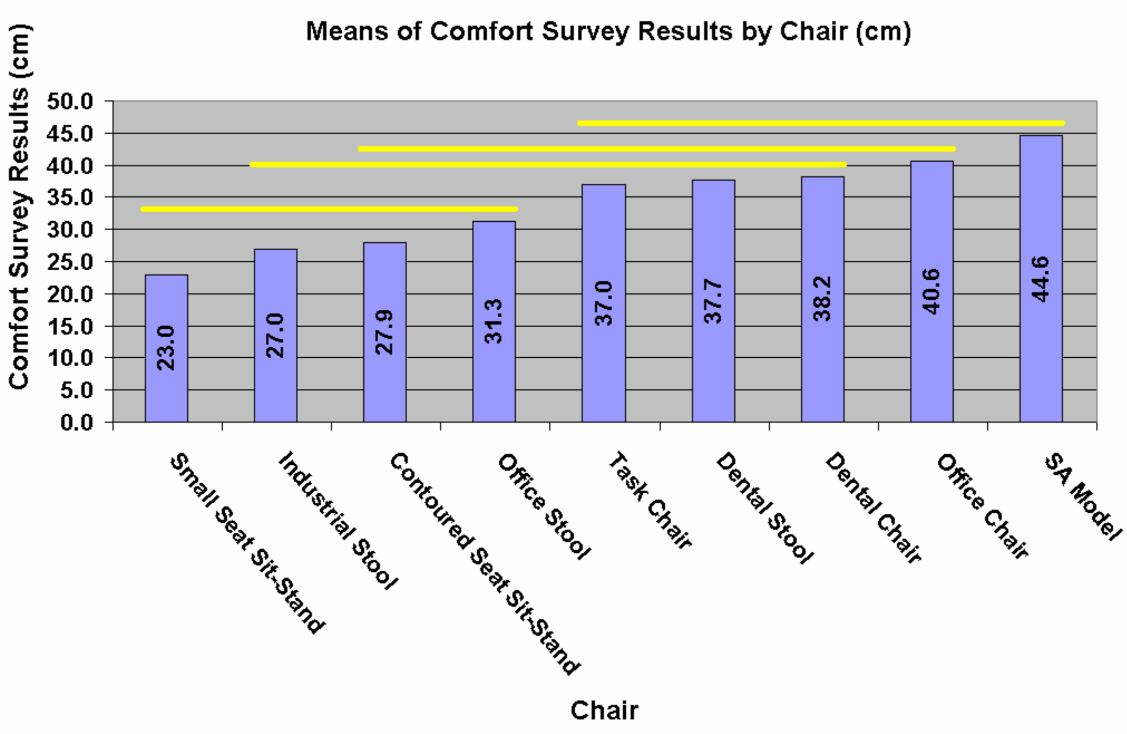

Figure 35. Means and Tukey Test Results on Comfort Survey Scores by Chair (cm). Combined Subjects.

Figure 35 shows that the SA Model was placed into the most comfortable grouping of chairs.

Comfort by Posture

The ANOVA results indicated differences between the comfort survey scores by chair. Further investigation of the differences may now be conducted. A Tukey HSD test on comfort survey scores revealed two groups that were statistically different from one another. Graphically, Figure 36 shows the means of the comfort survey scores by posture along with the results of the Tukey HSD test (statistically similar posture groupings are identified by the yellow horizontal line).

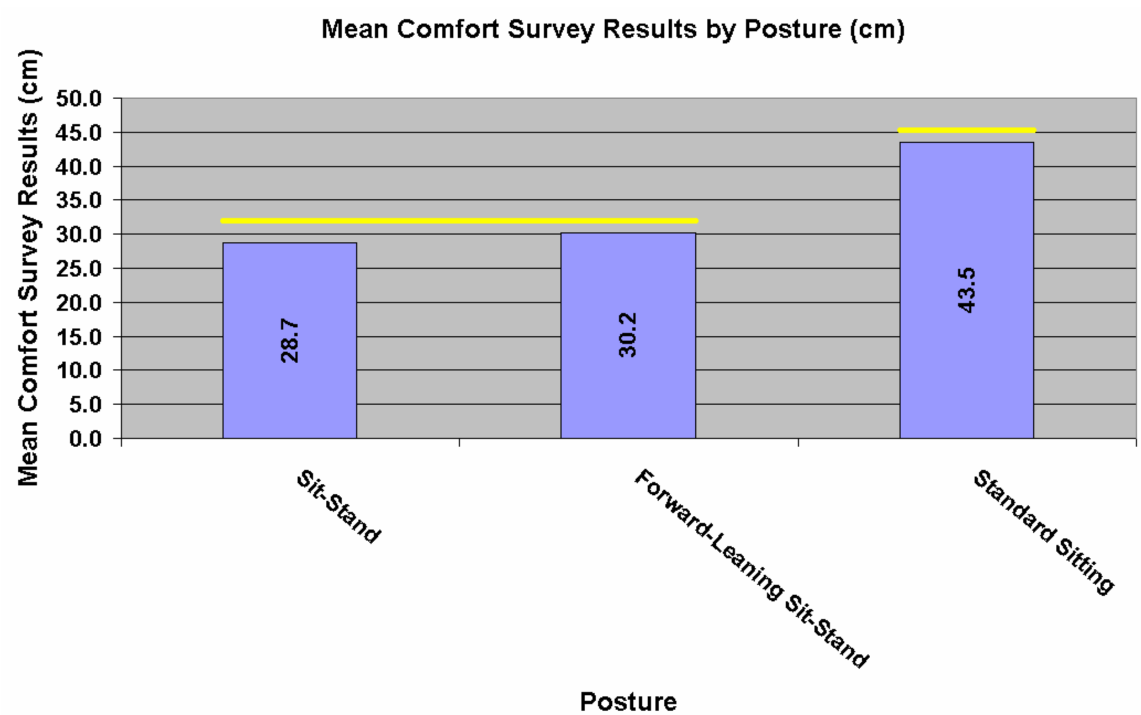

Figure 36. Means and Tukey Test Results on Comfort Survey Scores by Posture (cm). Combined Subjects.

Figure 36 shows that the standard sitting posture was the most comfortable posture. The sit-stand and forward-leaning sit-stand postures were not significantly different regarding comfort. These results were expected as the majority of the chairs were designed for normal sitting postures.

9.1.6. Correlations

Correlations were run on the subjects' results to determine if any associations existed between the variables, and if so, how strong these associations were. Correlations between comfort, production, contact area, and rankings were performed. Only the values from the third ranking trial were used because they were completed after having sat in the chairs and being given the knowledge of all the chairs' features.

Both genders' results indicate that the strongest, statistically significant correlations existed between comfort and ranking trial III (sitting experience), contact area and ranking trial III, and comfort and contact area. These results indicate that the subjects preferred the chairs that were perceived as the most comfortable, and that the most comfortably perceived chairs were those that had larger buttock-thigh contact areas. These results agree with past research performed by Congleton and Ayoub (1988) who found that comfort was correlated with buttock-thigh contact area.

9.1.7. Evaluation Part I Summary

Gender differences and combined results were discussed for chair rankings, buttock-thigh peak pressure results, and correlations, and investigated for buttock-thigh contact area, production values, and the subjects' comfort survey results.

Both genders' ranked the chairs similarly. The combined subjects' results placed the SA Model as the top ranked chair (most preferred). Buttock-thigh peak pressure results were also similar, with both genders having the most recordings below 4.06 psi while seated in the SA Model. Both subjects also had the highest significant correlations between comfort and ranking trial III (sitting experience), contact area and ranking trial III, and comfort and contact area.

Differences between the genders were detected only in the subjects' production values as obtained through the Purdue Pegboard testing. This research confirms previous reports, showing shown that female subjects are able to perform better with the Purdue Pegboard than are males subjects (LIC, 2003).

Combined subjects' results found statistically significant differences for buttock-thigh contact area by chair and the comfort survey results by chair. The SA Model was placed in the highest grouping of chairs for both buttock-thigh contact area and comfort.

9.2. EVALUATION PART II – GENDER COMPARISON AND COMBINED SUBJECTS

Part II of the evaluation involved having the subjects choose their own posture and chair "set-up" for both the SA Model and a standard style of stool at two different table heights. The purpose of this part of the evaluation was to determine if the subjects set up (configured) the SA model differently than they did the standard stool. The null hypothesis was that the subjects' chosen set-ups (configurations) were not different between the SA Model and the standard style stool.

Eighteen subjects participated in Part II of the Evaluation. Data from subjects 1F-8F, 10F, and 1M-9M were used to obtain the results provided below.

9.2.1. Chosen Set-Up

Chosen Ankle Angle

In order to determine if there were statistically significant differences between genders for their chosen ankle angle, an ANOVA was completed.

Table 72. ANOVA on Chosen Ankle Angle. Combined Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2179.33	20	108.97	4.01	0.000
Intercept	611986.72	1	611986.72	22519.89	0.000
STOOL	16.06	1	16.06	0.59	0.446
GENDER	10.89	1	10.89	0.40	0.530
TBLE_HT	0.50	1	0.50	0.02	0.893
SUBJECT (GENDER)	2127.39	16	132.96	4.89	0.000
STOOL * TBLE_HT	24.50	1	24.50	0.90	0.347
Error	1385.94	51	27.18		
Total	615552.00	72			
Corrected Total	3565.28	71			

R Squared = .611 (Adjusted R Squared = .459)

The ANOVA results (Table 72) show that no statistically significant results ($p < 0.05$) were found between genders. Combined results show that only the subjects within genders were statistically significant ($p < 0.001$).

Chosen Knee Angle

In order to determine if the chosen knee angles were statistically different between genders, an ANOVA was completed.

Table 73. ANOVA on Chosen Knee Angle. Combined Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2179.33	20	108.97	4.01	0.000
Intercept	611986.72	1	611986.72	22519.89	0.000
STOOL	16.06	1	16.06	0.59	0.446
GENDER	10.89	1	10.89	0.40	0.530
TBLE_HT	0.50	1	0.50	0.02	0.893
SUBJECT (GENDER)	2127.39	16	132.96	4.89	0.000
STOOL * TBLE_HT	24.50	1	24.50	0.90	0.347
Error	1385.94	51	27.18		
Total	615552.00	72			
Corrected Total	3565.28	71			

R Squared = .611 (Adjusted R Squared = .459)

The ANOVA results (Table 73) show that no statistically significant results ($p < 0.05$) were found between genders. Combined results show that only the subjects within genders were statistically significant ($p < 0.001$).

Chosen Trunk-Thigh Angle

In order to determine if the chosen trunk-thigh angles were statistically different between genders, an ANOVA was completed.

Table 74. ANOVA on Chosen Trunk-Thigh Angle. Combined Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3806.89	20	190.34	1.68	0.069
Intercept	722602.35	1	722602.35	6387.21	0.000
STOOL	618.35	1	618.35	5.47	0.023
GENDER	1.12	1	1.12	0.01	0.921
TBLE_HT	120.13	1	120.13	1.06	0.308
SUBJECT (GENDER)	3050.28	16	190.64	1.69	0.080
STOOL * TBLE_HT	17.01	1	17.01	0.15	0.700
Error	5769.76	51	113.13		
Total	732179.00	72			
Corrected Total	9576.65	71			

R Squared = .398 (Adjusted R Squared = .161)

The results in Table 74 indicate that the subjects were not statistically different between chosen trunk-thigh angles ($p < 0.05$). Combined subjects' results found statistical differences for the subjects' chosen trunk-thigh angles between stools ($p < 0.05$). Given this information, further investigation into the subjects' chosen differences between trunk-thigh angles by stool is warranted.

Chosen Trunk-Thigh Angle by Stool

ANOVA results indicated different chosen trunk-thigh angles by stool. Figure 37 graphically shows the differences between the means of the subjects' chosen trunk-thigh angles.

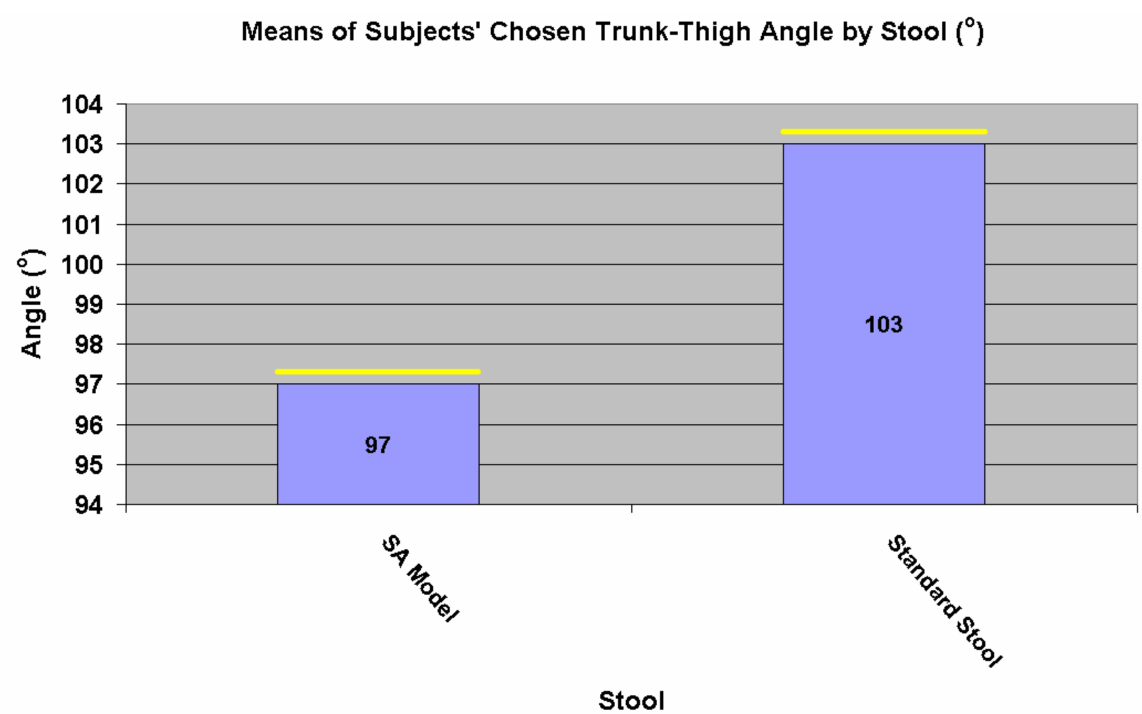

Figure 37. Means and T-Test Results on Chosen Trunk-Thigh Angle by Stool (°). Combined Subjects.

Subjects chose smaller trunk-thigh angles with the SA Model than with the standard style stool, according to a paired, two-tailed t-test ($t < 0.05$). This indicates that the subjects chose a more forward leaning posture with the SA Model than with the standard style stool.

Chosen Seat-Tilt Angle

In order to determine if the chosen seat-tilt angles were statistically different between genders, an ANOVA was completed.

Table 75. ANOVA on Chosen Seat-Tilt Angle. Combined Subjects.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	661.94	20	33.10	3.10	0.001
Intercept	4216.68	1	4216.68	395.04	0.000
STOOL	171.13	1	171.13	16.03	0.000
GENDER	1.68	1	1.68	0.16	0.693
TBLE_HT	78.13	1	78.13	7.32	0.009
SUBJECT (GENDER)	355.89	16	22.24	2.08	0.024
STOOL * TBLE_HT	55.13	1	55.13	5.16	0.027
Error	544.38	51	10.67		
Total	5423.00	72			
Corrected Total	1206.32	71			

R Squared = .549 (Adjusted R Squared = .372)

The ANOVA in Table 75 shows no statistically significant differences between the genders for their chosen seat-tilt angles ($p < 0.05$). With the combined subjects' results, significant differences were found between stools ($p < 0.001$) and stool*table height interaction ($p < 0.05$). Given this information, a further investigation into these results is warranted.

Chosen Seat-Tilt Angle by Stool

The combined subjects' ANOVA results found significant differences between the subjects' chosen seat-tilt angles by stool. Figure 38 shows the means of the subjects' chosen seat-tilt angles by stool.

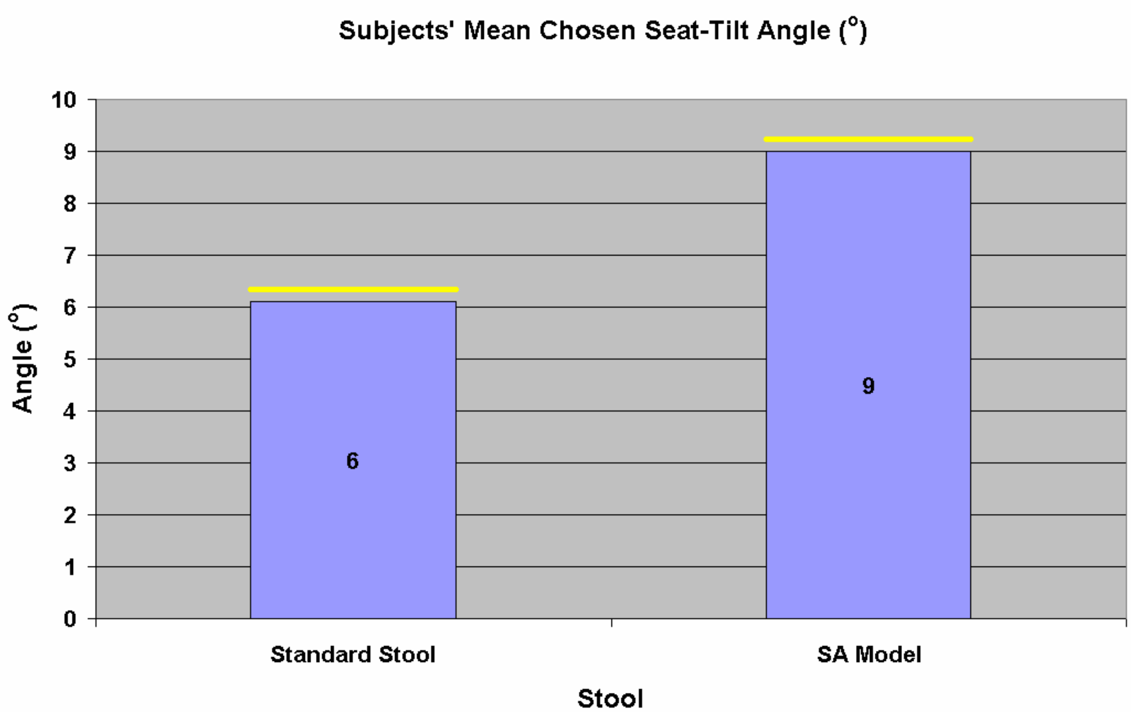

Figure 38. Means and T-Test Results on Chosen Seat-Tilt Angles by Stool (°). Combined Subjects.

Subjects chose significantly larger forward seat-tilt angles with the SA Model than the standard stool, according to a paired, two-tailed t-Test (t < 0.001).

Chosen Seat-Tilt Angle by Table Height

The combined subjects ANOVA results found significant differences between the subjects' chosen seat-tilt angles by table height. Figure 39 shows the means of the subjects' chosen seat-tilt angles by table height.

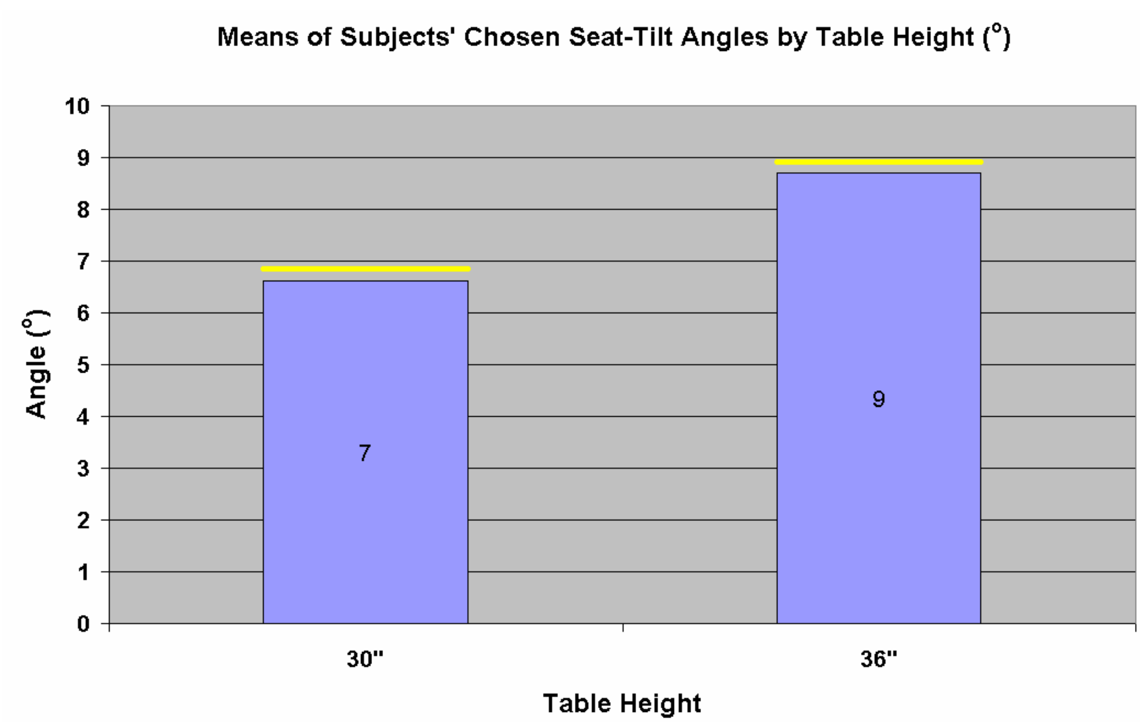

Figure 39. Means and T-Test Results on Chosen Seat-Tilt Angles by Table Height (°). Combined Subjects.

Subjects chose larger seat-tilt angles (forward) at the 36” table height than at the 30” table height, according to a paired, two-tailed t-Test ($t < 0.05$).

*Chosen Seat-Tilt Angle by Stool*Table Height Interaction*

The combined subjects’ ANOVA results found significant differences between the subjects’ chosen seat-tilt angles by the stool*table height interaction. Figure 40 shows the means of the subjects’ chosen seat-tilt angles by stool*table height.

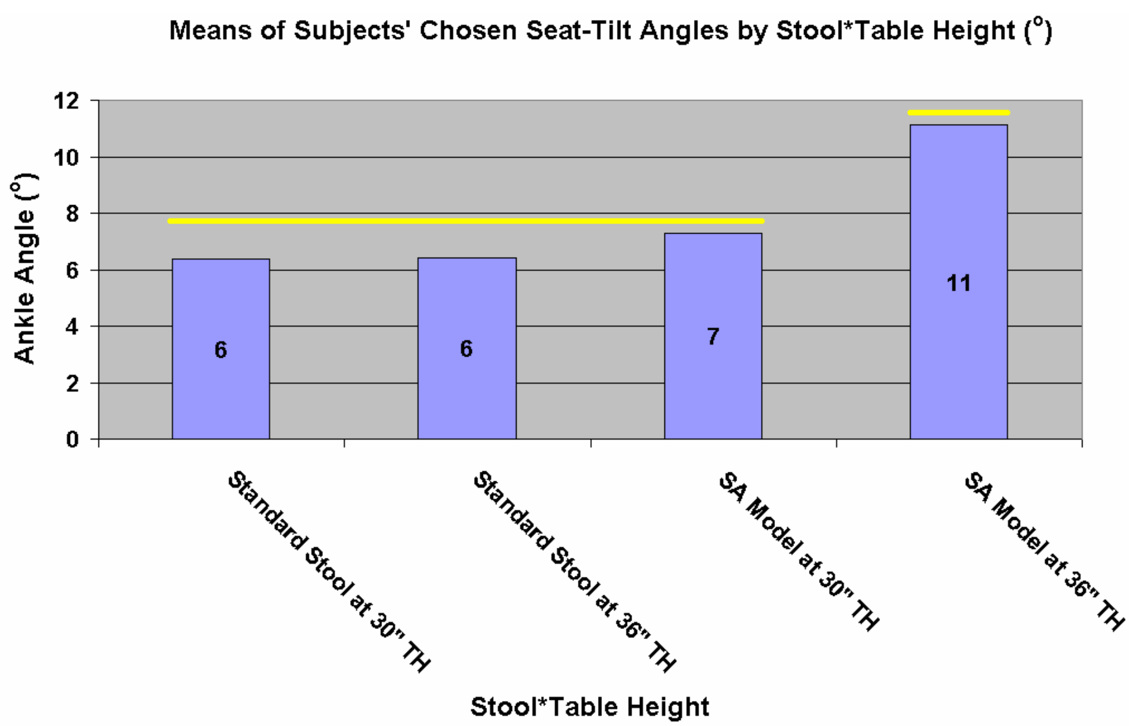

Figure 40. Means of Chosen Seat-Tilt Angles by Stool*Table Height (°). Combined Subjects.

Results from a two-tailed t-Test on the SA Model indicate that the subjects chose statistically larger seat-tilt angles at the 36” table height versus the 30” table height ($t < 0.05$). T-Test results also indicated significant differences between the subjects’ chosen seat-tilt angles between the SA Model at the 36” table height and the standard stool at both table heights ($t < 0.01$).

9.2.2. Evaluation Part II Summary

When the subjects’ results were not significantly different between the genders, comparisons using the combined subjects results were made. When differences did exist between the genders’ results, these differences were discussed.

Results were not statistically different between the genders’ chosen ankle and knee angles. Further investigation found no significant differences were found between the combined subjects for either ankle or knee angles.

Results were not statistically different between the genders’ chosen trunk-thigh angles. ANOVA on the combined subjects found statistically different chosen trunk-thigh angles by stool. Subjects, in total, chose larger trunk-thigh angles with the standards stool than with the SA Model. This indicates that he subjects chose a more forward-leaning posture with the SA Model than with the standard style stool.

Results were not statistically different between the genders' chosen seat-tilt angles. ANOVA results on the combined subjects found statistically different chosen seat-tilt angles by stool and stool*table height interaction. Subjects, in total, chose larger forward seat-tilt angles with the SA Model. Additionally, significant difference existed with the SA Model between table heights. Subjects chose statistically greater seat-tilt angles with the SA Model at the 36" table height than at the 30" table height. Significant differences did not exist between table heights with the standard style stool.

10. DISCUSSION

10.1. FEATURES OF THE EVALUATION

10.1.1. Evaluation Part I

The objective of the first part of the evaluation was to determine if differences existed between the SA Model and eight commonly used chairs in industry where forward-leaning postures may be causing low-back pain. Subjects sat in nine chairs with three postures according to a Latin Square statistical design. The chairs were ranked on three different occasions to investigate the subjects' preferences as well as to determine whether or not their rankings changed as the evaluation proceeded. Buttock-thigh peak pressures and contact area were measured with an Xsensor Pressure Mapping System. A Purdue Pegboard was used to determine if production values were independent of the chairs.

The null hypothesis was that no chairs performed differently under the prescribed conditions and tests performed.

10.1.2. Evaluation Part II

The second part of the evaluation allowed the subjects to choose their preferred set-up of the SA Model and a standard stool at two table heights. The objectives of this part of the evaluation were to determine if the subjects would set up (configure) the SA Model differently from a standard stool and to find out if they would choose to use the Support-Arm option of the SA Model.

The null hypothesis was that the subjects' chosen set-ups (configurations) were not different between the SA Model and the standard style stool.

10.1.3. Subjects

The subjects represented a wide range of the workforce. Most were from the industrial sector and were laborers while a few were from the office sector (including marketing and human resource assistants as well as a sales representative.) Nine subjects of each gender were used for both Parts I and II of the evaluation. No subjects had any back or neck injuries at the time of the evaluation. Anthropometric measures of the subjects also indicated a good range in sizes, characteristic of what may be expected to be found throughout the workforce. It is believed that they provided a good representation of workers who may assume forward-leaning postures while at work.

10.1.4. Chairs

The nine chairs used in Part I of the evaluation represent a wide range of chairs used by those who work, at times, at elevated heights. They were chosen based on selling volume and the advice of a manager of a office furniture store that specializes in "high-end" products. Most of the chairs could be termed *stools* as they were designed to allow higher than "normal" seating heights, although some do not fit entirely into this category. The SA Model best characterizes a chair affixed with a Support-Arm, as proposed in this dissertation.

The stool used in Part II of the evaluation was chosen to represent a more generic type of stool. The seat-pan was relatively flat and was covered with black vinyl. Although generic looking, this stool did offer seat height and seat-tilt adjustments that allowed users to manipulate the stool's set-up to best match their chosen seating posture and provide for a better comparison of chosen body postures between it and the SA Model.

Pictures of the chairs used in the evaluation and the Chair Feature Matrix are provided in Appendices E and F, respectively.

10.2. PRODUCTION TESTING

Measuring production of workers can be completed on many levels and choice of a method is paramount. After contacting the temporary staffing agency, from where approximately 90% of the subjects were recruited, it was found that they conduct performance testing on all their temporary workers with the Purdue Pegboard (PPB) to evaluate potential performance. Given the nature of the research and the chairs chosen for the evaluation, including the SA Model, it was determined that use of the PPB would be an optimal means to measure production. In addition to its application in the industrial workforce (requirement of hand-eye coordination and manual finger, hand, and arm dexterity), a great majority of the subjects already had previous experience with its application, reducing any potential "learning curve." Additionally, having the subjects perform trial runs for each of the four PPB tests further rectified any potential learning curve.

10.3. CHOSEN STOOL SET-UP

The majority of the subjects chose to use the Support-Arm at the 36” table height. Regardless of the use of the Support-Arm, the subjects, on average, chose more of a sit-stand forward-leaning posture with the SA Model as compared to the standard style stool. In addition, the subjects also chose a greater forward tilting seat-pan with the SA Model, perhaps due to the chosen sit-stand forward-leaning posture.

No subjects chose to use the Support-Arm while sitting at the 30” table height. The subjects’ comments revealed that, while seated in normal sitting postures, the Support-Arm pillow was too wide and posed as too large of an obstacle when placed in the forward-leaning support position. It simply would not allow the subjects close enough access to the table’s work space. The proposed Support-Arm described herein contains a modular pillow, or pad, that would allow a user to choose an appropriate pillow/pad for the task and seating position desired.

It was noticed that several male subjects chose not to change the set-ups of either stool from their original positions, regardless of the table height (30 or 36-inches). In fact, two of the male subjects even chose not to raise their seat-pan height when the table was raised from the 30-inch to the 36-inch position. Reasons for these occurrences could include boredom with the evaluation and an attempt to speed up the process, machismo considerations, or simply that the subjects just didn't care to use any of the ergonomic features of the chairs. Whatever the reason, it could be assumed that the non-use of the Support-Arm, or not changing the set-up of an ergonomic chair, will occur in the workplace due to any number of reasons. Proper training and education on the use and benefits associated with ergonomic chairs, including a Support-Arm, may help to reduce the number of workers who choose not to use a chair's ergonomic features.

10.4. SA MODEL VERSUS THE PROPOSED SUPPORT-ARM DESIGN

The SA Model's Support-Arm was chosen to substitute for the proposed Support-Arm in the evaluation. It is believed the SA Model provided valuable results that are directly comparable to the proposed Support-Arm (and associated chair design features) as discussed in this dissertation.

There are a several differences between the SA Model's Support-Arm and the proposed Support-Arm. Subjects' comments in Part II of the evaluation pinpointed two important design limitations of the SA Model: the size of the Support-Arm "pillow" and its limited ability to provided support within the entire forward-leaning envelope.

The first limitation of the SA Model entails the size of the Support-Arm pillow. Although extremely well-padded and comfortable, due to its size and location when used in forward-leaning postures, subjects could not position themselves close enough to their workstation at the 30” table height (even with the available depth adjustment of the oblong pillow). The pillow butted-up to the worktable, creating an obstacle that kept the subjects from reaching the table’s work area.

The proposed Support-Arm, as outlined in this dissertation, allows for multiple attachments that are suited for individual job tasks and preferences. The optimal design would allow, for example, a thinner “pad” to be attached when workers need close access to their workstations, especially when seated at lower table heights (results of the evaluation indicate that the effect of the size of the SA Model’s “pillow” was minimized in sit-stand postures).

The second limitation of the SA Model was the lack of mobility of the Support-Arm itself. Although it can pivot around the chair’s base for use as either a backrest or a forward-leaning rest, it does not have an angle adjustment (“C” in Figure 10) allowing for major movement of the Support-Arm along the sagittal plane. The current adjustments that are present on the SA Model are not enough to counteract this lack of an angular adjustment. The Support-Arm design, as proposed in this dissertation, contains angular and length adjustment (“C” and “D” in Figure 10) that allow the user to place the Support-Arm in any position inside the forward-leaning envelope.

10.5. PROS OF THE EVALUATION

The features and characteristics of the SA Model and the proposed Support-Arm Design are similar enough to directly compare the results of the evaluation, with the only exception being Part II at the 30” table height. The reason for this is that the SA Model’s pillow was too large and created an obstruction between the subject and the workspace. The effects of the size of the SA Model’s pillow at the 36” table height was negated due to majority of the subjects assuming sit-stand forward-leaning postures.

The chairs used in the evaluation are believed to adequately represent those used throughout industry where forward-leaning postures are assumed. Additionally, the subjects who participated in the evaluation are believed to adequately represent individuals who, at times, assume forward-leaning postures while performing their working tasks.

It appears no study in the past has compared more than just a few variables during chair evaluations. The evaluation herein contained the results from 9 males and 9 female subjects over 3 postures and 9 chairs for subjects preferences (3 ranking trials), buttock-thigh peak pressure and contact area, production values, ratings of comfort, and subjects’ chosen use of the Support-Arm, chair set-up, and chosen postures. Additionally, subjects’ comments on the SA Model were solicited and recorded.

10.6. CONS OF THE EVALUATION

The exact proposed Support-Arm model design was not available for evaluation. However, a prototype model was used that was similar to the proposed design. It is believed that only the results obtained from Part II of the Evaluation, specifically at the 30” table height, may have been different had the proposed model been available.

The threshold level of the Xsensor Pressure Mapping System was set by the manufacturer at 4.06 psi. Unfortunately, the majority of the recordings were above the threshold. Although informative peak buttock-thigh pressure results were discussed, statistical evaluation of the results could not be completed nor could the results of the mean pressure data be used. Although this is a con of this study, past research has shown correlations between mean and peak buttock-thigh pressures, buttock-thigh contact area, and comfort (Congleton and Ayoub, 1988; Vos, 2001). This research also found significant correlations between buttock-thigh contact area and comfort, and found that the SA Model performed in the top grouping of chairs by buttock-thigh contact area and comfort. It is believed that the SA Model would have also performed in the top grouping of chairs if statistical analysis were available for both the peak and mean buttock-thigh pressure data.

This evaluation did not contain pressure or contact area recordings at the interface of the subjects’ upper body and the Support-Arm. Data on pressures and contact areas would help to quantify the interface and support biomechanical analysis of the effects of supporting forward-leaning postures.

10.7. DIRECTION FOR FUTURE RESEARCH

Now that it has been shown that the use of a Support-Arm does not appear to adversely affect a user, performing the evaluation again using a full factorial design would be beneficial in investigating the interacting effects between chairs and postures. Information regarding the placement of the Support-Arm during different postures and the associated ramifications would be useful. Additionally, determining the amount of force and pressure placed on the Support-Arm during forward-leaning postures would be valuable.

Performing the ranking and comfort survey trials with the chairs' aesthetics constant may have produced different results. It was noted that some subjects complained of slippery seat-pans when the Xsensor pad was placed on them, while others made comments on the appearances of several chairs, potentially due to color and/or material. Although aesthetics are a major concern in ergonomic designs, removing any potential bias when attempting to evaluate a Support-Arm would be beneficial.

Long term studies involving both comfort and discomfort surveys with the design being used in several industrial environments would be highly beneficial to further investigate the ramifications of using a Support-Arm for different tasks and periods of time.

Comparing subjects' recordings of discomfort over time between a chair affixed with a Support-Arm versus a standard style chair during forward-leaning postures may show that discomfort can be reduced while using a Support-Arm.

Performing different types of production testing may also prove to be beneficial as the Purdue Pegboard test produces results that may only be applicable to tasks requiring finger tip dexterity. Other types of production testing could include typing speed and accuracy, reading and comprehension, and/or others. In addition, the production values obtained herein were subject to only 2.5 minutes of testing. Production testing over a longer duration of time may have found significant differences between the chairs.

The design of armrests for use with a Support-Arm could be a direction for future design adaptations. Evaluating the use of a Support-Arm with armrest attachments would then be applicable.

Lastly, use of a Support-Arm by workers who have experienced, are experiencing, or are at risk of developing low-back pain, especially due to forward-leaning unsupported postures, may be highly advantageous. Designing a longitudinal study that entails the use of a Support-Arm by these subjects would be beneficial.

11. CONCLUSIONS

This dissertation set out to define the need for, provide design guidelines of, and evaluate an ergonomic chair feature designed to provide support to forward-leaning postures. A need for the product was shown, a design was presented, and a comparable design prototype, the SA Model, was evaluated. Although the SA Model's Support-Arm does not contain all the elements of the proposed Support-Arm, it does incorporate many of the essential features, including those necessary to provide support to seated, forward-leaning postures.

When evaluated alongside eight commonly used stools in industries where workers adopt forward-leaning postures, the SA Model obtained the following overall results:

1. Ranked number one by the female subjects and tied for the second ranking by the male subjects during the "sitting" ranking trial,
2. Provided the lowest number of buttock-thigh peak pressures below 4.06 psi,
3. Provided the largest mean buttock-thigh contact area,
4. Provided the highest production values (Purdue Pegboard), and
5. Rated the most comfortable chair.

When the subjects were allowed to choose their own posture and set-up of the SA Model at a 36" table height, the following results were obtained:

1. A majority of subjects preferred to use the Support-Arm,

2. Most subjects preferred to assume forward-leaning sit-stand postures and,
3. Subjects chose a greater mean forward seat-tilt angle over a standard style stool.

Statistically speaking, the SA Model placed in the top category (the "best" category) on all variables where statistically significant differences were observed. There was no evidence of negative consequences regarding the use of a Support-Arm feature affixed to an ergonomic chair.

Several results of past work completed on chair evaluations were confirmed and possible reasons for conflicting theories regarding optimal chair design and seated postures were presented.

This dissertation introduced a new feature to ergonomic chair design. It not only has the potential of reducing low-back pain amongst seated workers, but may aid in the rehabilitation of those who have experienced or are currently experiencing low-back disorders. This research will best serve chair designers by providing design guidelines and Support-Arm specifications for a chair feature that is capable of providing support to forward-leaning postures.

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APPENDIX A

ERGONOMIC PRODUCT DESIGN GUIDELINES

Ergonomic Product Design Guidelines

1. Design for Increased Production
2. Design for Decreased Injuries
3. Design for Decreased Human Error
4. Design for Increased User Satisfaction

Increased Production

Industrial engineers have long been concerned with increasing production in manufacturing settings. Ergonomic engineers look beyond the manufacturing settings and attempt to make all tasks more productive. This can be accomplished both by making products/machines more efficient as well as making the "worker" more efficient.

Decreased Injuries

Injuries, both of cumulative and acute natures, need to be designed out of products as best as possible. This is accomplished mainly by taking the users' physical characteristics into account and designing the product so its use does not place the user in awkward positions or require more applied force than is necessary.

Cumulative trauma injuries occur over time due to several factors including the requirement(s) of high force, high repetition, an extended duration of use, and/or awkward postures. Although product designers cannot keep users from using their products for extended periods of time, they can design the product to fit the users' anthropometry and working abilities. Doing so can reduce the force and awkward postures required to operate a product, thereby reducing the risk of injury. In addition, making the product's use more productive, the duration the user uses the product may be reduced.

Acute injuries occur immediately as opposed to over a larger time span and have the potential for serious harm. Some products, such as power tools, may require back-up safety devises to properly protect the user and others from injury.

Decreased Human Error

All humans make errors that can lead to injuries and decreased production. Designing to minimize these errors is a goal that ergonomic designers strive to accomplish. Errors can be greatly reduced by designing to the users capabilities. Understanding human characteristics, such as cognitive processes, is essential in designing certain products. Making products less sophisticated may help to reduce human error.

Increased User Satisfaction

User satisfaction can be increased in several ways and usually is a good indicator of a product's ergonomics. Increasing production, decreasing injuries, and decreasing human error can all increase a user's satisfaction. The role aesthetics takes in an ergonomic product design is often overlooked in product design literature. A product's aesthetics has a great psychological impact on its user and should not be overlooked. The greater the aesthetics, the more pleasure the user will receive from using the product, as well as making the product more sellable (Jordan, 1998). Aesthetics refers to the outward appearance of an item, but is not limited to mere sight. Aesthetics takes into account all the human senses and therefore, ergonomic designers must take each sense into account when designing products. The sound a product makes, its texture, and for some products perhaps its taste, are all-important aspects of an ergonomic design. Consider the sound of a Harley Davidson or the sleek curves of a Ferrari. Using soft leather, silk, or cotton fabric can completely change the way a product is perceived. Aesthetics may be the only reason a consumer will purchase one product over another.

These design principles all act on one another and are difficult to separate. The absence of any of these design guidelines' criteria *may* indicate that a product is not truly ergonomic. There are many products on the market that are listed as "ergonomic", but potentially only those that were designed using these guidelines deserve to use the term. Again, these guidelines are generic and may not pertain to some products.

The descriptions of the guidelines above are merely summaries of the characteristics of ergonomic products. It is out of the scope of this paper to completely define every guideline's characteristics for all potential product designs. An enormous amount of information on each of the guidelines' characteristics is available and should be referenced by the ergonomic product designer.

APPENDIX B

ERGONOMIC PRODUCT DESIGN PROCESS

The design process is completed through a number of stages (not necessarily in any particular order). Once a stage is completed, it is rarely forgotten. The design process usually takes several turns, and with each turn the prior stage(s) may have to be revisited. An ergonomic product design follows the same formula as general product design, except for the added emphasis on the human element.

In general, the steps in ergonomic product design are:

1. Fill a Need
2. Idea Formation
3. Research
4. Conceptual Design
5. Prototype
6. Evaluation
7. Continuous Monitoring and Improvement

Fill a Need

Any successful product must fill a need. In general, ergonomic products must fill the needs of greater production, decreased injuries, decreased human error, and increased user satisfaction. There are many ways to find users' needs including research, questionnaires, studies, personal experiences, surveys, and direct observation.

Idea Formation

Ergonomic product designs may grow from new and innovative ideas, from re-engineering of older product designs to incorporate better ergonomics, or a combination of both. Many times a new design may be born from a prior model, with only minimal design changes. In these circumstances, the stages of design may proceed quickly since there are only a few new features that need to be explored (ideally, the remainder of the design has already completed the design stages). Idea formation can come about from multiple places. A dream, focus groups, scenario building, and mistakes can all lead to new and/or better product designs (Suri and Marsh, 2000).

Research

Once an idea is formulated, it must be researched. In fact, in many instances it may be the research that leads to a product idea. Performing research is a process every product designer needs to accomplish. By becoming familiar with past research and the current technology in similar products and product features, the designer can keep from performing mistakes already made by others (don't redesign the wheel). In addition, knowing what the competition has to offer can help considerably.

There are several journals that focus on ergonomics/human factors issues that may be consulted. There are also several electronic databases, such as Medline, that allows a researcher to search several publications at once. Public and private companies may also have research available from past studies that may be consulted. Patent searches must also be conducted, not only regarding legal issues, but also to investigate current as well as past ideas regarding particular product designs.

Sometimes there is not research available that meets the needs of the designer. In these cases, the required information must be collected through the use of descriptive, experimental, or evaluation methods. Descriptive studies involve simply collecting data such as human capabilities, sizes, and shapes. Experimental methods involve obtaining dependent results from the manipulation of independent parameters. Evaluations can be a mix of descriptive and experimental methods and usually involve recording data while a product is being used, such as user preferences.

Information collected through research may also used in an evaluation. Methods previously used in the evaluation of a particular product will become evident and can help guide a designer during his/her evaluation, including data that may be collected as well as the best methods available to collect them. Further discussion on the evaluation step is described below.

Conceptual Design

Once a product has been researched and the features have been explored, the next step is to develop a conceptual design. Here, the design is placed on paper where all the functions and performance features are described making sure the ergonomic guidelines are addressed and accounted for. Undoubtedly, this step will bring forth many problems not previously considered such as placement of levers, knobs, controls, etc. The designer must rely on the research that has already been completed to help guide the actual paper design. It can become very expensive if this step is hastily completed, as it may have to be revisited time and again.

Prototype

After the conceptual design has been completed, a prototype of the design should be built. Here, the conceptual design becomes tangible. Moving from the conceptual stage to the prototype stage is a big leap and many unforeseen problems may arise that were previously not addressed in the concept. When the designer must return back to the previous steps to solve any of these previously unforeseen problems, he/she should also make sure that the research is not forgotten. Moving levers, controls, and other items around just to make them “fit” may compromise the ergonomic design of the product.

Evaluation

The evaluation of a product usually begins with the formulation of the idea. Product evaluation does not only entail formal studies, but critical thought processes as well.

Simply thinking about how a product will be used is in fact part of an evaluation. Due to its importance and potential complexity, ergonomic product evaluations are discussed in more detail in Appendix D.

Continuous Monitoring and Improvement

Most designs are not flawless when they reach the marketplace. Unforeseen problems and product liability issues may arise as a product is put through uses not tested in the evaluation period. Errors in the original design that come about during consumers' use may have to be addressed and design modifications may have to be made to accommodate any unforeseen problems, especially those concerning safety issues. Hence, once the product has been manufactured and sold to consumers, the design must not be considered final.

Continuous improvements are cause for new and better designs and help to foster the goal of perfection. This process can be considered a continuation of a product evaluation that may essentially never end.

The steps of the design process may be revisited several times prior to the final product being built, marketed, and sold. It is up to the designer, along with other interested parties, to decide when the product is ready for, or submitted to, the market. Many times designers must submit their prototype to market before meeting their satisfaction.

Reasons may include funding, timing, final price of the product, and “encouragement” from stockholders and employers.

Properly designed ergonomic products can be very expensive due to the amount of time and research that has been put into them. The benefits to the users must outweigh the product’s costs.

Designing an ergonomic product is obviously very specific to the product itself. The above guidelines and steps are general and are meant to lead the designer down the correct path. The role of the ergonomic design evaluation is critical and is a continuous process that begins the moment an idea is born. Of course, prior to actual *formal* testing of a design, a conceptual model must be in place and a prototype must be built. However, the designer should not wait until a prototype is built before considering the evaluation. Knowing how to evaluate an ergonomic design can foster a better design in the first place. An evaluation of an ergonomic design is simply a study into the ergonomics of the design itself, and as a result, a designer should not consider the design and evaluation process to be separate entities.

APPENDIX C

DESIGNING FOR HUMAN USE

Meeting ergonomic design goals can only be accomplished by taking the potential human user into consideration. Ergonomists must understand anatomy, physiology, and human factors issues in order to design a product for human use. Knowing the locations of nerves, muscles, etc. can help to guide the physical form a product should, or should not, take. Reviewing past research may provide the answers to many human factors' questions, including reaction times and the amount of weight a healthy adult is willing to carry. Other human factors issues may have to be found experimentally to determine how consumers may react to a specific product.

Anthropometry is the measurement of the human body and its biomechanical characteristics. Human anthropometry must be taken into consideration when designing an ergonomic product. Fortunately, a great deal of anthropometric data has been gathered and is readily available to designers.

In addition to anthropometrics, ergonomic products must be designed within the cognitive abilities of potential users. For example, the requirement of having the mental capabilities of a "rocket scientist" to be capable of working a stapler is not appropriate. It also means that ergonomic products should work as expected. Unfortunately, "common sense" is not very common. Conducting a product evaluation with potential users can help to determine what is usable and what is not.

Designing for human use can be accomplished in three ways: designing to the average, extreme, and range of the population.

Designing for the Average

Designing for the average person is usually discouraged and may indicate that a product is not ergonomic. Examples of designing for the average include most restaurant seats, table heights, and "one size fits all" products. In general, no human is average in more than three or four anthropometric dimensions. Designing for the average person simply means that the product will not fit anyone perfectly.

Designing for the Extreme

Designing for the extreme is accomplished by designing to the 5^{th} or 95^{th} percentile of the population. An example of when designing to the extreme is appropriate is a doorway's clearance. By making the doorway height higher than the population of potential users, it allows everyone to pass under it without hitting their heads.

Designing for the Range

Designing for the range is the design criteria that should normally be used in ergonomic product design. This means that the product is adaptable to the majority of the population (usually 5th percentile to the 95th percentile). Designing for the range usually means that the product has features that allow it to change configuration to adapt to a populations' characteristics. A belt and a car seat are two examples of products that are designed for the range.

APPENDIX D

ERGONOMIC PRODUCT EVALUATIONS

Just as there is a multitude of literature available on product design, there is a wide body of material available to assist in product evaluations. The following discussion is meant to only give the reader some insight into an ergonomic product evaluation process. For detailed information, designers/evaluators are urged to conduct further research into product evaluations.

There are several evaluation methods available to assess a product's design. Use of any, or a combination, of them may be appropriate for any given product. Some examples of popular methods used in ergonomic product evaluations include: heuristics, checklists/guidelines, observation, interviews, questionnaires, link analysis, layout analysis, hierarchical task analysis, systematic human error reduction and prediction approach (SHERPA), task analysis for error identification, repertory grids, keystroke level mode, and the BeSafe method (Stanton, 1998).

Evaluations can also be of an experimental nature. Experimental methods are perhaps the most time intensive and expensive of all methods. They may also be the most powerful. A brief introduction to product evaluations using experimental methods is provided below.

Steps of Experimental Design Evaluations

There are specific steps that most formal experimental evaluations should follow. The following is a reproduction of 10 steps Lentner and Bishop (1993) recommend:

1. Formulation of the research plan. Included here is a precise statement of the problems to be solved and the objectives of the research. What does the researcher plan to study and why?
2. Choice of factors to be used. After the problem has been formulated, a decision about pertinent factors can be made. All important factors must be included but too many factors may result in an unwieldy experiment. Can any factors be omitted without seriously affecting the planned research? The range and specific values of each factor must be considered. To reflect the impact of a factor, a sufficient number of values must be used.
3. Choice of variables to be measured. A variable should be measured if it provides information about the phenomenon under investigation. Important variables are retained while less important variables may be discarded at the analysis stage. Costs of measuring each variable must be weighed against its importance.
4. Choice of the inference space. This may be defined briefly as the set of populations to which the inferences may be applied. The inference space, once decided upon, will have an influence on the size of the experiment (the number of populations to sample) as well as the applicability of the experimental results.
5. Selection of experimental material. The type and amount of material required may depend upon the objectives, the factors, the inference space, the researcher's budget, availability, and so on.
6. Choice of an experimental design. This refers to the manner in which the factors are assigned to the experimental material. Should this be a completely randomized allocation or some other type of random assignment?

7. Formulation of a model. It is customary to give a mathematical model to describe the observations anticipated under the experimental plan. The model should include all factors and components to provide an adequate representation of the observations.
8. Collection of the data. Extreme care should be exercised to insure that the entire experimental plan (particularly the randomization) is carried out correctly and that the observations are properly and accurately recorded. When deemed necessary, a system of "checks-and-balances" should be used.
9. Analysis of the data. Depending upon the model and the design, necessary computations must be performed. Complex or large experiments may require a computer to perform some of these computations.
10. Conclusions and interpretations. This step is extremely important. The practical implications of the experimental results must be presented clearly and objectively together with any qualifying remarks regarding applicability of the results. Limitations of the study should be noted.

Experimental evaluations can be completed in two general ways. The first is to investigate the product by itself and compare the results to past studies, if available, and the second is to evaluate the product along with other similar products. If a product has competition, it may be beneficial to evaluate an ergonomic design against other designs to show its superiority. Both methods have their merits and may be superior to the other in any given circumstance.

In an experimental product evaluation, deciding which measures will be recorded is of utmost concern. In general, there are two categories of evaluation measures: objective and subjective measures.

Objective Measures

Objective measures are those that do not contain a source of bias. Objective measures can be used to evaluate the physical features of a product. They can include, but are not limited to, dimensions (length, width, etc.), pressures, forces, temperatures, and contact area.

Subjective Measures

Subjective measures are usually used to measure specific human characteristics such as comfort, ease of use, and preferences. Subjective measures are inherently biased and can lead to misleading information. It is of utmost concern to the researcher to remove possible confounding factors that may influence the outcome. Obtaining subjective measures can include subject surveys, ratings, rankings, as well as recording of subject's comments.

Examples

Below are some examples of product characteristics that could be investigated, along with some potential subjective and objective measures that could be used.

Aesthetics

Measuring the aesthetics of a product is usually best completed with subjective measures. As humans have different ideas of what pleasing aesthetics are, measures should be taken with subjects who are the probable users of the product. For example, using senior citizens to obtain aesthetic measures on children's' toys may not be advisable.

Objective measures may also be used, depending upon the product, as it may be known that a certain aesthetic feature is preferred over another. In these cases, evaluating a feature using known aesthetic guidelines may be appropriate. For example, sports car enthusiasts may generally prefer the aesthetics of chrome vs. steel wheels.

Human Factors

Objective and subjective measures should both be used for measuring the ease of human use of a product. Objective information, such as forces needed to operate a product and the dimensions of the product, can be compared to human anthropometric data to determine what percent of the population will be able to use the product. Subjective measures are required to determine how humans actually perceive and use the design. Knowing that 95% of the population can create enough force to turn on a light switch doesn't provide information such as human willingness to use a certain amount of force to operate the switch.

In considering cognitive function, both subjective and objective measures should be used as well. Determining how many times a function is used improperly as well as if subjects feel that a product is confusing to use are both very important aspects of product evaluations.

As product use must be designed with the user in mind, measurement of the functional aspects of the design should also be studied. Obtaining measures on the function(s) of a product should incorporate both subjective and objective measures. Objective measures can determine to what extent the function works, while subjective measures can determine its effectiveness according to potential users.

Subjective and objective measures should also be used to measure the reliability of a product. For example, it can be found objectively how many pulls it takes to start a lawnmower, but it must be found subjectively if this is acceptable to humans.

Safety

Product safety is another aspect of product design that should be evaluated both objectively and subjectively. Objectively, the operation of the product as well as its safety mechanisms can be tested. Subjectively, human use of the product can be perceived as safe or not. If a consumer uses a product and feels that it is not safe, they may return it and purchase a different product. There are several safety standards associated with product design that designers need to be aware of.

Maintenance and Reliability

General maintenance and product reliability should also be specifically addressed. For example, oil change schedules for lawnmowers should be designed to human expectations. These types of issues, if appropriate, should be subjected to both objective and subjective measures.

Using both subjective and objective measures is critical in the evaluation of ergonomic product designs. The combination of these two measures is the only way to determine if the goal of ergonomic design has been reached.

As mentioned in Appendix B, conducting research on a product is vital to a designer/evaluator. Evaluation methods may have already been devised and will help to expedite this stage of the design process. In addition, previous studies may provide the information necessary to negate the need to perform certain evaluations. For example, when evaluating an updated design, the safety of the original product may have already been completed and it may not be necessary to re-evaluate it. Note that this assumption should not be made with considerable thought. It may not be evident whether or not a slight design change may impact the safe use of the product. It may take an evaluation to discover the answer to this question.

Statistics in Product Evaluations

While discussing statistical designs is not within the scope of this dissertation, the importance of the use of statistics cannot be emphasized enough. When statistics are used properly, an evaluation leads to scientifically sound conclusions (Lentner and Bishop, 1993). Not only do the correct statistics need to be used, but also the correct experimental design. Prior to conducting an evaluation it is imperative to first decide upon the experimental design, measures to be analyzed, and use of proper statistics. It is much easier to manipulate the design prior to conducting an evaluation than to try to find an applicable design and statistic(s) that matches what has already been completed.

Interpretation and Use of an Ergonomic Product Evaluation

Obtaining the results of an evaluation should be relatively simple if the experimental design and the use of appropriate statistics were considered prior to the collection of data. Ideally, the associations and results one wants to obtain from the study have already been mapped out and it is just a matter of inputting the data into the appropriate statistical software package and running the calculations.

Once the data has been analyzed and valid results have been found, the next step is to interpret and put the results into use. Interpretation of the results usually includes proper interpretation of the statistics, and hence, knowledge of the statistic(s) used is of utmost importance.

Comparing objective and associated subjective results can prove to be very powerful in determining if the ergonomics were correctly designed into the product. Furthermore, if similar studies have been completed in the past, comparing the results to already published studies can further validate the evaluation.

Results of an evaluation can be used to find weaknesses in a product's ergonomics, provide marketing ammunition that spotlight a product's superior features, and to providing salespersons with the knowledge necessary to sell a product. When weaknesses are found during an evaluation and the product is redesigned, a new study may need to be performed. This re-evaluation can sometimes be a scaled down version of the first and provide an opportunity to further investigate features and/or clear up ambiguous results obtained from the earlier study.

Ergonomic evaluation results need not end with the finalization of the product design. Providing proof of a product's ergonomics is highly beneficial when marketing an ergonomic product, especially in light of so many false claims. Marketing experts can eloquently state the results of an ergonomic evaluation and provide the information to the consumer to help them choose the superior product (hopefully yours). A designer/evaluator must understand that marketing experts are not necessarily equipped with the knowledge to understand ergonomic evaluations and will usually need to be fully briefed, in layman's terms, exactly what the results mean and how to place them in the correct context. It also must be noted that an ergonomist may not be the proper person to write-up the marketing plan, as they are not necessarily equipped with the knowledge of a professional marketer.

Salespersons can also greatly benefit from being knowledgeable of an ergonomic evaluation when discussing products with customers. Knowing an evaluation found one chair more comfortable to sit in versus another can guide the salesmen to have the customer sit in different chairs while he/she explains the study and shows his/her knowledge of the product. If a study found that the aesthetics of a design are greater than its comfort, the salesperson can focus on the outward appearance of the design. Additionally, if an evaluation compared one product to another, a salesperson can inform the consumer of the results of the study so they purchase the superior product (again, hopefully yours).

In addition to using your results for your own purposes, it is beneficial to share gained knowledge with the general population. There are many places that ergonomic product design and evaluation information can be shared. Conferences, journals, trade publications, and texts are just a few avenues through which information and knowledge can be disseminated. Simply adding more data to the ergonomics and human factors knowledge base can prove to be both rewarding to a designer and extremely helpful to society in general. Knowledge gained from one product may be able to be transferred to another, where it can be further perfected, and shared once more. This cycle is beneficial to the economy as well as the human race by helping to foster the development of ergonomic products.

Ethics

Sound ethics in product evaluations is of utmost concern. A researcher should only claim results that were found, and they should be referenced in the correct context. Providing false results or reporting results in the wrong context is not only unethical but will usually prove to be harmful in the end, not only to a user of a product, but to the credibility of the designer as well. Increased profits, the bottom line for many designers, are usually not the result of unethical behavior.

Designing for "human use" can be extremely complex and performing an ergonomic evaluation can prove to be a daunting task. There are many design issues incorporated into ergonomic products and, in order to evaluate them all, an evaluator must take several factors into mind. Some of these factors include available resources such as funding, time, equipment, and subjects. Usually it is not feasible to complete an evaluation that takes all possible issues into mind. It is up to the designer/evaluator to decide which of these issues are most important to the product evaluation.

APPENDIX E

CHAIRS

Evaluation Part I

Nine chairs were used in Part I of the Evaluation. Table F1 provides the makes and names of the chairs along with the code used during the evaluation. Table F2 indicates the chairs' seat-pan material and color.

Table F1. Chair Makes and Models for Evaluation Part I

CHAIR TYPE	CHAIR MAKE	CHAIR MODEL
Dental Chair	Brewer	3345BR
SA Model	Neutral Posture	AbStool
Industrial Stool	Lyon	Platinum Plus
Office Stool	Human Scale	Freedom Saddle Seat
Office Chair	HAG	Capisco
Dental Stool	Galaxy	1066
Small Seat Sit-Stand	Neutral Posture	Sit-Stand Aid
Contoured Seat Sit-Stand	Neutral Posture	TS 400
Task Chair	Neutral Posture	Task Stool

Table F2. Chairs' Material and Color for Evaluation Part I.

CHAIR TYPE	MATERIAL TYPE	MATERIAL COLOR
Dental Chair	Vinyl/Leather	Black
SA Model	Vinyl/Leather	Black
Industrial Stool	Plastic/Rubber Composite	Grey
Office Stool	Cloth	Black
Office Chair	Cloth	Red
Dental Stool	Vinyl/Leather	Blue
Small Seat Sit-Stand	Plastic/Rubber Composite	Black
Contoured Steat Sit-Stand	Cloth	Black
Task Chair	Vinyl/Leather	Black

Evaluation Part II

Two chairs were used in Part II of the Evaluation. Table F3 provides the makes and names of the chairs along with the code used during the evaluation. Table F4 indicates the chairs' seat-pan material and color. Note that the SA Model (Neutral Posture Ab-Stool) was used in both Parts I & II of the evaluation.

Table F3. Chair Make and Model for Evaluation Part II.

CHAIR TYPE	CHAIR MAKE	CHAIR MODEL
SA Model	Neutral Posture	AbStool
Standard Stool	Neutral Posture	PS400

Table F4. Chairs' Material and Color for Evaluation Part II.

CHAIR TYPE	MATERIAL TYPE	MATERIAL COLOR
SA Model	Vinyl/Leather	Black
Standard Stool	Vinyl/Leather	Black

Chair Pictures

Figures F1-F10 are pictures of the chairs used in the evaluation. Notes have been provided when the pictures do not accurately depict the exact color of the model used in the evaluation. All models are the same as used in the evaluation unless otherwise noted.

Figure F1. Dental Stool.

Figure F2a.
SA Model with SA in Back Position.

Figure 2b.
SA Model with SA in Front Position

Figure F3. Industrial Stool

Figure F4. Office Stool.

Figure F5. Office Chair.

Figure F6. Dental Stool.


Figure F7. Small Seat Sit-Stand.


Figure F8. Contoured Seat Sit-Stand.

Figure F9. Task Chair.

Figure F10. Standard Stool.

APPENDIX F

CHAIR FEATURE MATRIX

Table F6.Chair Features Matrix.

FEATURE	ADJUSTMENT	CHAIR								
		a	b	c	d	e	f	g	h	i
Backrest										
	Present	X	X	X		X				X
	Angle	X	X	X		X				
	Height		X	X		X				X
	Depth	X	X			X				X
Lumbar Support										
	Present	X	X	X		X				X
	Height		X	X		X				X
	Depth	X	X							
Armrest										
	Present	X	X			X	X			
	Style	Dental Arm	Support-Arm			Backrest Arms	Dental Arm			
	Angle	X	X			X	X			
	Height	X	X			X	X			
	Width	X	X			X	X			
Seat-Pan										
	Height	X	X	X	X	X	X	X	X	X
	Slide (Front to Back)		X			X				
	Swivel	X	X	X	X	X	X	X	X	X
	Contoured	X	X	X	X	X		X	X	X
	Tilt (^{0})		0 to 17	0 to 10		**0 to -13		0 to 10	-3 to 10	
	Tilt Tension		X			X			X	
Forward-Leaning Support										
	Present	X	X			X	X			
	Style	Dental Arm	Ab-Bar			Backrest (t Shape)	Dental Arm			
	Vertical	X	Angular			X	X			
	Horizontal	X	Angular			X	X			

VITA

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