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POSTURE AND FORCE MEASURES OF MID-SIZED MEN IN SEATED POSITIONS

By

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ABSTRACT

POSTURE AND FORCE MEASURES OF MID-SIZED MEN IN SEATED POSITIONS

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To better understand seating biomechanics, the normal and shear forces, chair positions, and seated postures of twenty-three mid-sized male subjects were measured and analyzed. These data were examined in relation to one another and the affects of chair position on both body posture and support forces were determined. Force data were collected and analyzed for both static and dynamic conditions using six multi-axis force plates mounted to an experimental chair under the thighs, under the buttocks, behind the pelvis, behind the thorax, and to a steering wheel and foot support. Postural data and chair movement data were collected using a motion measurement system.

These data were analyzed to determine what degree of motion was necessary in the experimental chair, in terms of recline and back support articulation, to produce statistically significant postural and loading changes for the mid-sized men. Significant differences were found across the subject sample in both the static and dynamic test trials.

The support force data in conjunction with subject anthropometry were also used to estimate the internal loading in the lumbar spine and evaluate that loading for one subject as his posture was varied.

Currently, the data presented for this dissertation are the only data of their kind. It is expected that the availability of these data will have a significant impact on seating design, seating evaluation and the tools used for design and evaluation.

Dedication

I would like to dedicate this dissertation to my family including my husband, Neil, daughter Brittany, parents Richard and Pamela, brother Paul and grandparents Don, Jean, Helen and Harlan.

My family has given me the determination, the strength, and the support to continue onward with this challenging, and seemingly endless endeavor.

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I would like to thank my committee members, Robert Hubbard, Roger Calantone, Joseph Vorro, Dahsin Liu and Roger Haut for their advice and diligence in working with me during the development of this dissertation.

I would especially like to thank my major advisor, mentor and friend Robert Hubbard for an exceptional experience as a doctoral student. You have assisted me in every way possible and have played a large part in the success of my career.

To Phaedra Gutowski, I would like to thank you for your friendship and all of your hard work during the testing of the subjects and tracking of the data.

Cliff Beckett, our technical wizard also deserves special thanks for keeping the equipment running and the computers virus free.

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Introduction

With the transition of the work place into an information based facility, a trend currently exists to replace heavy work load tasks with seated, light work, or mental tasks[1]. Many people spend not only the work day seated, but they are also seated in automobiles, trains or planes on the way to and from work, and once home they may even spend the evening seated in front of the television, or at a theater[2]. Due to the changing work environments and extended commuting time, there is an increase in the number of people seated during the workday thus increasing the duration they assume seated postures.

With people in seated positions for prolonged periods of time, it would be beneficial to better understand the seated body and interactions occurring between the body and the seat. The factors that have been proven to affect how people sit and their interactions with the seat include: general health, age, activity level of the individual, shear and normal forces, and the distribution of these forces at the seat-body interface, temperature and humidity, and body posture[3]. Hobson also included psychological deficits as a factor attributing to the seated position, especially when referring to individuals spending long time periods in wheelchairs.

One approach to studying seated postures, has been the use of epidemiological evaluations on the relationship between occupation and back pain. In a study of over 3000 individuals across eight different occupations, Magora[4, 5] investigated the relationship between low back pain (LBP) and occupation. In the 1970 Magora[4] study, data analysis was concentrated on comparing the factors of age, sex, ethnic group and occupation to LBP. In terms of LBP and its relationship to occupations, Magora[4] found that the highest incidence of LBP was in nurses and heavy industry workers; occupations which required high physical effort and movement. The lowest incidence of LBP was found in policemen, who spent the majority of their time either standing, or walking. Magora[4] also found an increasing linear relationship between age and LBP; in comparisons between men and women, women tended to have a higher incidence of LBP in occupations requiring high amounts of physical effort. When the data were analyzed in terms of ethnicity, the Asian ethnic group recorded the lowest LBP incidence while individuals in the western hemisphere had the highest.

A second paper in 1972 by Magora[5] divided each occupation into three different sub-categories relating to time sitting, time standing, and weight lifted. The subjects were placed into each category based on the amount of time they spent standing, sitting or lifting an object (with a minimum mass of 5 kg). With this more detailed analysis, Magora[5] found a significant relationship between LBP and the individuals who predominantly stood or were in a predominantly seated posture throughout the work day. Weight lifting or the frequency of lifting an object did not play a significant role in the causation or triggering of low back pain. LBP occurred in a higher percentage of those who never lifted a 5 kg object during their work as compared to those who performed lifting tasks[5].

The difference between the outcomes of the Magora 1970 [4] and 1972 [5] results were clearly due to the incorporation of the time factor into the statistical analysis. These results were supported by Pope[6] and Zacharkow[7], who both stated that uninterrupted sitting and uninterrupted standing had a profound causal effect on musculoskeletal disease, specifically, low back pain.

Magora[5] noted that the discrepancy between his findings and other studies that also concluded the lifting of a weight to be a cause of LBP was primarily due to the fact that other studies were performed in a retrospective fashion on subjects who had already developed LBP. Magora used a group of controls along with those experiencing LBP. Because of lack of standardization in terms of either the measurements used or the diagnostic classifications chosen by the medical staff, Troup[8] also agreed that retrospective studies tended to be unreliable.

One author[8] felt that there was a link between driving and back problems, or sore backs. A study investigating the relationship between herniated intervertebral lumbar discs and driving found that individuals who spent more than half of their working hours driving were three times more likely to suffer lumbar disc herniation than those who did not[8]. The risks for development of a herniated lumbar disc were even greater for the professional truck drivers than for other drivers; the truck drivers also displayed an increased number of bone deformities as compared to other drivers[8].

Low back pain has been an extensive problem, affecting a large portion of the population; studies[6] cited that 70% of the United States population experienced low back pain at one time in their life. Researchers such as Magora[4,5] and Troup[8] have performed work attempting to identify causes of back problems, mainly trying to link LBP to occupations.

Another approach to identifying the cause of back problems, aside from the collection of epidemiological data, involved the study of the biomechanical factors of sitting; including seated postures[9,10], muscle activity[11], chair design [12] and pressure or force distribution[13]. The approach of evaluating the interaction of the body with a physical device, in terms of biomechanical factors, was the approach taken for the work discussed in the following dissertation.

To better understand seated postures, research conducted for this dissertation included data collection and analysis of the following biomechanical factors: shear and normal forces, chair position, and seated postures. Currently, the data presented in this dissertation are the only data of their kind. It is expected that the availability of these data will have a significant impact on seating design, seating evaluation and the tools used for seating design and evaluation.

First, a brief scope of the research will be presented, followed by an overview of the related literature. Following the literature review, is a detailed discussion of the equipment and methods used for testing. The final sections summarize the results and findings, interpret the meaning of these data and discuss the relevance of these findings.

Scope of Research

Data

One facet of this research was to experimentally measure how mid-sized male subjects loaded an experimental test seat that was placed in an automotive-like environment. The seat and surrounding package, including the steering wheel and foot rest, were moved through various configurations to promote an array of postures that would be representative of positions in a mid-sized automobile interior package. One set of tests involved static measures where the position of the seat was set, then posture and support force data were collected simultaneously on this single position. In a second set of trials, the subjects were dynamically moved through several positions while taking quasi-static force and posture measures. With these data, comparisons were made between the different seated postures and the transfer of seated support loads during postural changes.

Because of the application of the support force and posture data to the development of computer models, a second objective of this research was to develop a mathematical model for determining the approximate joint forces and moments in a section of the lumbar spine. Once the mathematical steps were developed, a set of data from one subject was used to test the methodology and evaluate the results.

Usage of Data

Two research projects have already incorporated the results of this investigation. The first use for this data was through a project entitled ASPECT

(Automotive Seat and Package Evaluation Tools)[13]. This research was funded by eleven automotive manufactures and seat suppliers (Johnson Controls, Magna Interior Systems, Lear Corporation, General Motors, Chrysler, Ford, Volkswagen, Volvo, PSA Peugeot - Citroën, BMW and Toyota) through the Society of Automotive Engineers. The Biomechanical Design Research Laboratory at Michigan State University and the University of Michigan Transportation Research Institute were the two organizations that performed the research. The primary task of this project was to develop a new three-dimensional, full size, automotive seat evaluation and design tool to replace the current Society of Engineers (SAE) Recommended Practice J826 that uses the three dimensional SAE manikin (Figure 1)[14]. The new ASPECT manikin (Figure 2) was a more human-like representation of a mid-size male seated occupant based upon the JOHN computer model developed at Michigan State University[15]. (Details of the JOHN model are located in the Methods Section).

The main design changes in the ASPECT manikin included an articulating torso, with additional joints in the torso to allow changes of lumbar curvature, legs made of lightweight aluminum (not containing significant mass as in the current SAE legs)[16], and human-like body contours and mass distribution[17, 13].

Since the ASPECT manikin without legs, arms, or a head, should load the seat like a human (deforming the seat back and seat pan like a human), obtaining the appropriate loading for each of the body segments was an important portion of the new manikin development. Data collected by Bush[13] determined the appropriate mass distribution for a more human-like loading into the seat by the newly developed ASPECT manikin.

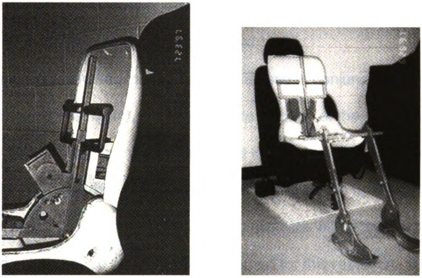


Figure 1: SAE Oscar Manikin

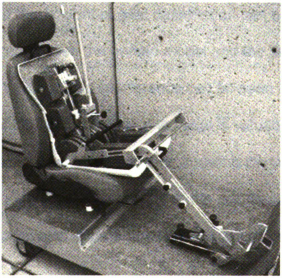


Figure 2: ASPECT Manikin Prototype

A second project currently underway, incorporates the data from this dissertation into a computer model used to predict seated posture and support forces. The initial phases of this simulation have already begun by Bush[13], and incorporate a human body representation in a seated environment. The human body representation has a linkage like the JOHN model and the new ASPECT manikin, and rigid segments with an articulating torso. Each segment has been assigned a human-like amount of mass, and the human model interacts with a computer representation of an automotive seat.

A more sophisticated model, to be developed in conjunction with a software company (TecMath), will allow key descriptors of the automotive interior package to be entered into the computer, and the posture of the human model to be predicted. With the predicted posture, the loading on the seat pan for the human model can be estimated. This loading estimate will be based on the posture and support force relationships measured for this research. Even though these models will be treated as rigid shapes, the back and buttocks will have a deformed contour and the amount of seat deformation can be estimated by the amount of interference between the human model and the seat. A basic two-dimensional representation of this interference can be seen in Figure 3.

The position of the human model in the seat is valuable to seat designers and to automotive interior package designers; knowing the occupant location allows the designer to identify the placement of the occupant restraints, estimate vision restrictions and develop appropriate foam distances from seat structures.

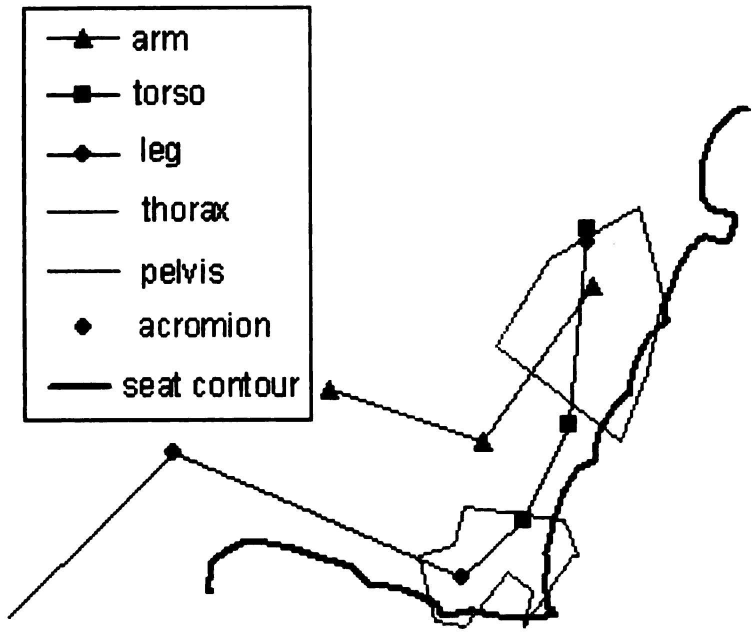


Figure 3: A two-dimensional representation of an interference model to estimate deformation into an automotive seat.

The final phase of the incorporation of these data into a computer model will be accomplished with TecMath, a German modeling company that supplies more that half of the automotive companies world-wide with automotive interior package and human comfort analysis.

Literature Survey

Spinal Column

To appreciate the importance of seated postures, it is first necessary to understand the anatomy and physiology of the spinal column and intervertebral discs[18]. The spinal column is typically composed of 33 bones called vertebrae. These bones are stacked on top of one another with discs between the vertebrae. Each vertebra is named with respect to the region of the body in which the bone is located. There are 5 different sections of the spinal column: cervical, thoracic, lumbar, sacral, and coccygeal region, Figure 4 . The cervical region contains seven vertebra, named from top to bottom as C1-C7. The thoracic region, which is sometimes termed the thorax, contains the rib cage and twelve vertebrae, named T1-T12 from top to bottom. The lumbar region contains 5 vertebrae and is referred to as L1-L5. The sacral region is part of the pelvis and also has five vertebrae, but unlike the previously mentioned sections, these vertebrae are fused together at birth and referred to as the sacrum. The final region, the coccygeal region also has 4 fused vertebrae and is termed the coccyx.

The spinal column has several purposes including support, mobility, and protection[6]. It is the framework for the underlying structures and supports the upper body including the rib cage, head and arms. The spinal column allows for twisting, and bending of the body; this flexibility is provided by the shape of the individual vertebrae and the intervertebral discs. Lastly, the series of vertebrae that form the column provide protection for the spinal cord and nerves.

In the natural erect standing posture, the spinal column is normally straight from the anterior/posterior perspective, but from the medial/lateral perspective, it has sections of curvature. The cervical and lumbar regions have a lordosis, or curvature inward toward the front of the body (concave anterior), Figure 5, and the thoracic region has kyphosis or a curvature away from the front of the body (concave posterior), Figure 5.

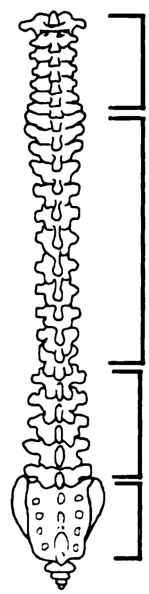


Figure 4: Sections of a human spine.

Between each pair of the vertebral bodies, there is an intervertebral disc. The disc is primarily composed of two structures, the annulus fibrosus and nucleus pulposus. The outer-most portion of the disc is called the annulus fibrosus and is composed of rings of collagenous fibers. Each fibrous layer contains a different fiber orientation and the lamination of these layers provides the strength of the disc structure[6]. The center of the intervertebral disc, called the nucleus pulpous, is a softer, highly elastic, fluid filled section[19], which is contained by the annulus. The nucleus is 80% water and gradually desiccates with ages[20].

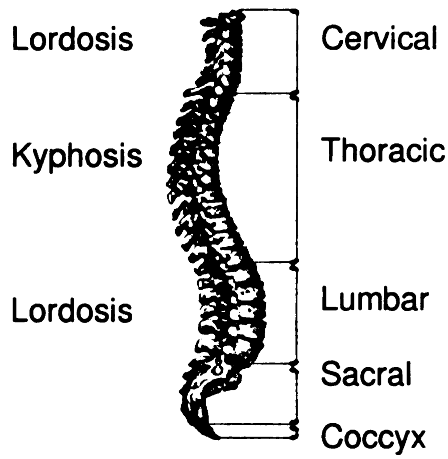


Figure 5: The vertebral column from a side view, demonstrating kyphosis and lordosis.

Since the discs of adults are avascular, the supply of nutrients depends on the diffusion of substances from surrounding areas,[1, 19] rather than directly from the supply of blood. A relationship between hydrostatic pressure and osmotic pressure drive the nutrient absorption, Figure 6. As the pressure inside the disc is increased due to the weight of the torso, or movement of the torso, the disc bulges and some of the fluid content in the disc is pushed out into surrounding fluid. As the pressure is released, the disc reabsorbs nutrients from the surrounding fluids. This method of nutrient distribution has also been referred to as a ‘bellows" or “pump” action[20].

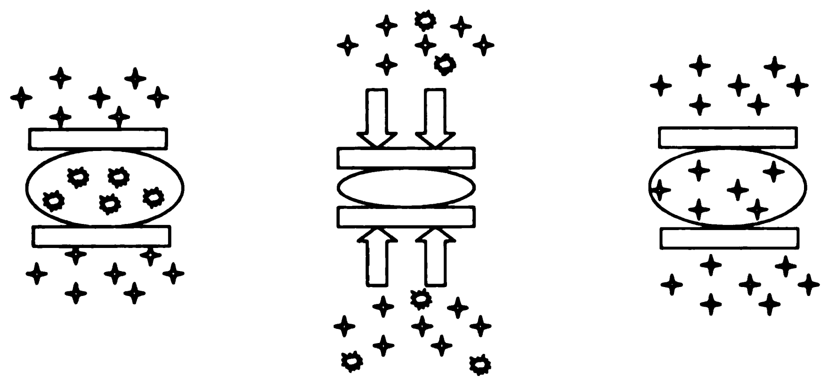


Figure 6: Method for intervertebral discs obtaining nutrients.

Posture

The relative positions of the vertebrae define a person's torso posture. Compared to normal standing posture, slouching, or having a slumped posture, causes the upper part of the pelvis to be rotated rearward, Figure 7, which results in lumbar spine flattening. Lumbar spine flattening removes the lordotic curvature found in the lumbar spine during standing and produces a flat or straight lumbar spine[6, 21]. When this occurs, additional pressure is placed on the anterior sides of intervertebral discs while the posterior portions of the annuli fibrosi are stretched, Figure 8. Maintaining this slumped position for prolonged periods of time, without frequent movement, increases the risk of back problems[22]. As a result, repeated compression of the discs in the flat lumbar spine condition can cause the nucleus pulposus to protrude rearward through the annulus placing pressure on spinal nerves; this condition is called a herniated disc.

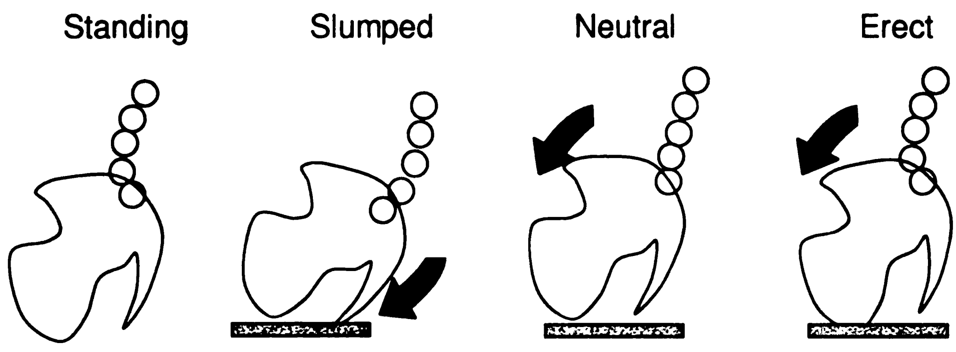


Figure 7: Posture of the spine and pelvis in standing, slumped, neutral and erect sitting conditions.

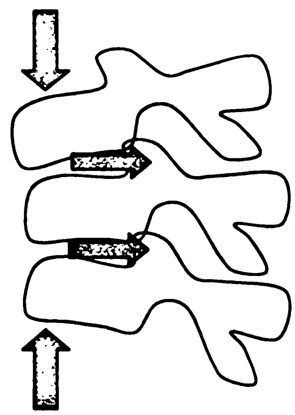


Figure 8: Lumbar region in a slouched posture, excessive amount of pressure placed on the anterior portion of the disc.

Verifying that a slouched posture increased disc pressure, Headman[23] measured the compressive loads in discs by placing a thin load cell and pressure sensitive film between lumbar vertebrae. Headman[23] tested 12 lumbo-sacral (L1-S1) spines in saline solution, he flexed and extended the spines while measuring force between the vertebrae. The force sensing material was placed under both the anterior and posterior portions of the vertebrae (between the posterior facets of L3-L4 and L4-L5 and in the anterior, superior portion of L4 and L5 vertebra). He concluded that high anterior disc pressures resulted when the spine was in a flexed position, corresponding to a flat lumbar spine; while the anterior disc forces were low for the extended spinal position, corresponding to lumbar lordosis.

Not only is posture important in preventing spinal injuries, but posture also plays an important role in keeping intervertebral discs healthy. Since, intervertebral discs rely on pressure changes to maintain a supply of nutrition, good posture and frequent changes of posture help keep the discs healthy[6, 22, 23]. Headman[23] cited a case study, which agreed with Magora[5], where people who rarely sat had the highest incidence of back pain followed by those who predominantly sat. Those who sat frequently for brief periods of time had virtually no back problems[23]. Headman concluded that prolonged standing and uninterrupted sitting should be avoided and that the integrity of the spine could be best preserved by frequent changes in posture.

Seymour[22] also agreed that the spine needed to be moved. Seymour[22] theorized that back problems endured in people who spent long periods driving, not necessarily because of poor seat designs, but because of the long periods spent motionless in a seated position with the back subjected to repeated jolts and vibrations.

Bonney[24] used a method entitled "shrinkage" to relate posture to disc pressure. Some people stay seated the entire work day and by the end of the day, they may shrink or shorten between 15 to 20 mm due to the changes in fluid absorption by the intervertebral discs[22, 24]. Bonney used the shrinkage method to measure the positions of spinous processes (in a sagittal plane) during an initial seated condition and again, after a period of time, in a second seated test position. If there was a decreased length between these spinous process measures, then this was considered to be spinal shrinkage. Bonney related measures of vertebral column shrinkage, or postural changes to disc pressures: increased shrinkage was linked to increased disc pressures.

Bonney[24] also found that a 90° (upright) back angle of the test seat caused and average of 1.3 mm spinal shrinkage, while a test seat with a 110° back angle (reclined 20 degrees from vertical) caused 0.8 mm of lengthening. Therefore, according to Bonney an increased recline angle caused a decrease in disc compression.

Andersson[25] evaluated the influence of physical characteristics of seats such as the magnitude of lumbar prominence, the height of lumbar prominence and the back rest angle also known as recline angle, on posture, specifically changes in lumbar lordosis. To monitor changes in spinal articulation, radiographs were taken subjects in the sagittal plane and were interpreted for changes in lumbar lordosis.

The first of the four tests evaluated differences in lumbar lordosis from standing to unsupported sitting. For these tests, Andersson[25] found an average decrease in total lumbar curvature of 38 degrees; 28 of the 38 degrees occurred due to the rearward rotation of the pelvis.

The second set of tests evaluated the effects of changes in the chair's recline angle. The largest effect, caused by changing the recline angle, was an increase in pelvis rotation relative to a standing position. The rotation was measured by drawing a line from the sacrum to a point on the acetabulum and comparing the angle of that line relative to a horizontal line[25]. The pelvis angle measured 63.8° in standing and rotated to 53° in the 80° recline and then to 22° in the 110° recline.

The third parameter Andersson[25] changed was the magnitude of the lumbar support. The lumbar support prominence was varied (Figure 9) from -2.0 cm (rearward from the back support) to +4.0 cm (protruding forward from the back support). The change in lumbar support magnitude had a significant effect on lumbar lordosis. The total lumbar angle increased 37 degrees from the -2.0 cm condition to the +4.0 cm condition; 20 of the 37 degrees was caused by pelvis derotation[25].

No significant change was found in lumbar lordosis with the change in lumbar height[25].

It should be noted that knee flexion was not a controlled variable in the study by Andersson[25], and knee flexion is known to have an affect on the ability of people to rotate their pelvis. As the knees extend, the hamstring muscles, which attach to the bottom of the pelvis become taut and do not allow the top of the pelvis to rotate forward, which inhibit rather than facilitate lumbar lordosis. As the knees flex, the opposite also becomes true. It should also be noted that the subject size was not a controlled variable either.

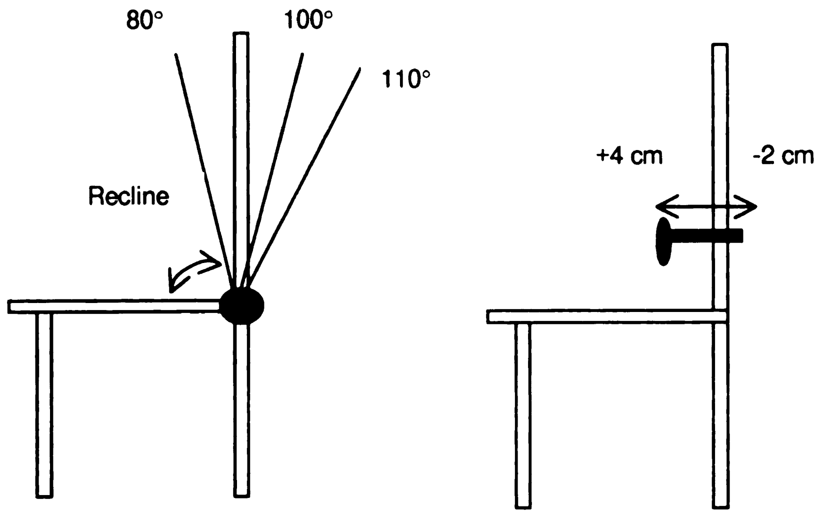


Figure 9: Experimental chair used by Andersson[25] for posture studies.

Physiological Effects from Postural Changes

Research has been conducted to examine the correlation of physiological changes in the body with posture, specifically muscle activity and fatigue. One study by Bush[11] examined the fatigue rate of back muscles for subjects seated in two different automotive seats. Subjects were tested at 80% maximal voluntary contraction and showed a slower rate of fatigue when seated in a firm automotive seat containing a prominent lumbar support, as compared to a faster fatigue rate in a soft seat with little lumbar prominence. The Bush[11] study showed a correlation between a change in posture and a change in the body's physiology defined as fatigue rate. It was concluded that the firm seat, with a prominent lumbar support, provided a mechanical advantage for the muscles, which exceeded that for the soft, flat seat. The seat with the prominent lumbar support placed the spine in a position of increasing lumbar lordosis, moving the spine closer to the natural amount of lumbar lordosis exhibited during standing.

According to another researcher[7], in an erect posture, the ribs, chest and diaphragm are raised, facilitating movements of the diaphragm and thus breathing is promoted. If breathing is promoted, the oxygen content in the blood is higher, thus, muscles fatigue at a slower rate. This correlates with the case for the firm seat with prominent lumbar support discussed in the Bush[11] study.

In additional studies by Andersson[26, 27], muscle activity and disc pressure data were collected as various adjustments were made to different seating apparatus. Using an experimental chair[26] the back rest, lumbar support, thoracic support angle, and seat pan angle were adjusted (Figure 10), while in the automotive seat[27] the recline angle, seat pan angle and the lumbar support were adjusted.

In the experimental chair, Andersson[26] tested four adults in eight different positions (Table 1).

Table 1: Conditions in an experimental chair tested by Andersson[26] while monitoring disc pressure and muscle activity.

1. Standing at ease.
2. Relaxed (no back support) sitting with arms at the sides of the body.
3. Relaxed sitting with the arms supported.
4. Relaxed sitting with the feet unsupported.
5. Straight (erect) sitting.
6. Relaxed anterior sitting.
7. Straight anterior sitting.
8. Relaxed posterior sitting.

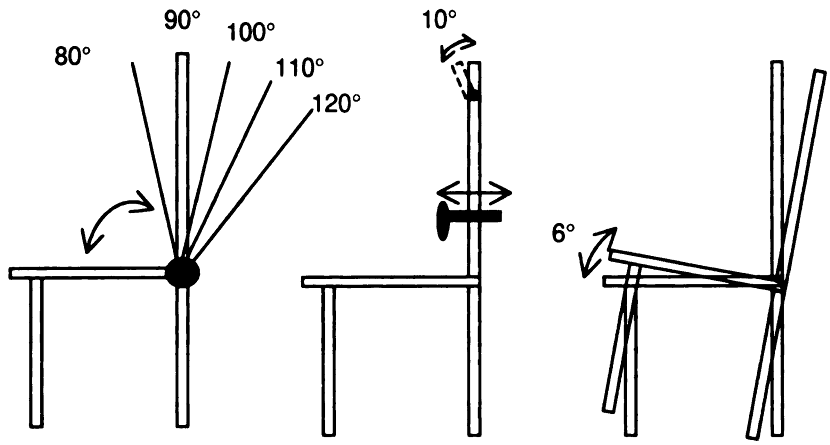


Figure 10: Experimental chair used by Andersson[26] allowing recline, thoracic support, lumbar adjustments from +4 to –2 cm and pan tilt.

The same four adults that were tested in Andersson's experimental chair[26] were also tested in an automotive seat[27]. The following seat parameters were evaluated in the automotive study: four recline angles, 90°,100°,110°,120°; two seat pan angles 10°, 14°; and five lumbar prominences, 0 to 5 cm, in 1 cm increments, Figure 11.

Needle electrodes were placed 3 centimeters lateral of the midline on both left and right sides at the C4, T5 and L1 vertebral levels and in the psoas muscles. Additional electrodes were placed at T8, T10 and L3 on the left side, for two of the subjects. The sensor for disc pressure was inserted into the center of the third lumbar disc, which was defined as the disc between the third and fourth lumbar vertebrae.

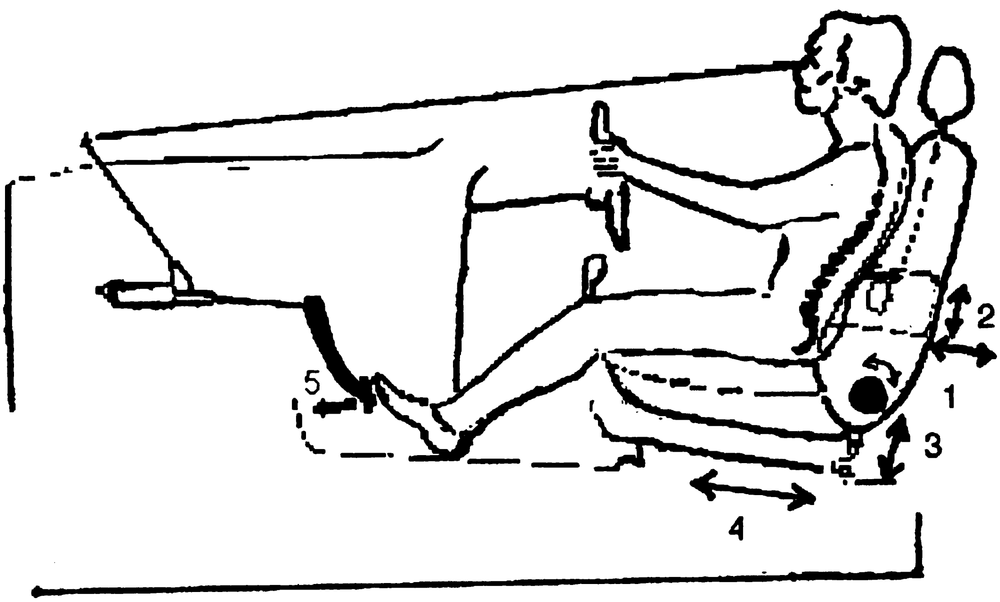


Figure 11: Automotive seat used by Andersson[27], where 1) seat back recline, 2) lumbar support adjustment, 3) seat inclination,4) distance to dashboard, and 5) clutch pedal force.

Andersson[26, 27] found that an increase in recline angle and an increase in the lumbar prominence reduced the pressure measured in the L3 disc for both the experimental chair and the automobile seat. The decrease in disc pressure was most pronounced when the lumbar support was adjusted from the 0 cm position to the +2 cm position in the experimental laboratory chair and +5 cm in the automotive seat. The lowest disc pressure was found with the automotive seat was reclined to 120° with the seat pan angle adjusted to 14°.

In the experimental chair[26], the rotation of the top of thorax support forward (Figure 10) increased disc pressure. The highest amount of disc pressure was observed when the subjects were in relaxed anterior sitting (condition 6 in Table 1) and the lowest overall disc pressure was when the subjects were standing.

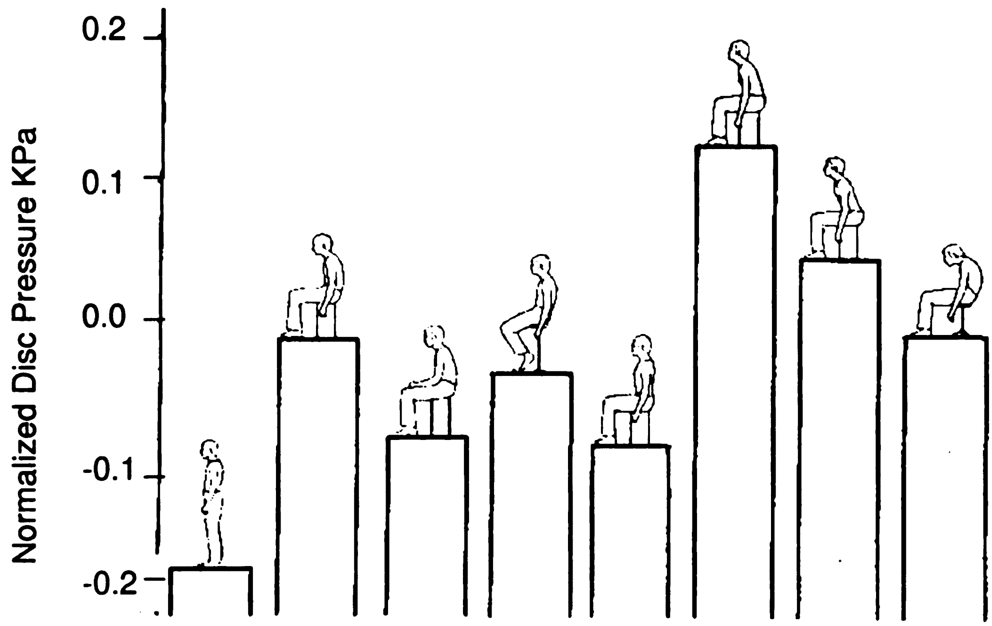


Figure 12: From Andersson [26], eight different postures with normalized disc pressure, refer to Table 1 for list of test conditions.

In the experimental chair[26] the largest decrease in muscle activity occurred in the lumbar region with the back rest reclined. Changes in lumbar support, thoracic support, and in the seat pan angle only had minor affects on muscle activity.

In Andersson's automotive seat[27], a decrease in muscle activity was found relative to an increased recline angle, increased pan angle and increased lumbar support prominence. In terms of muscle activity, not fatigue rate, low muscle activity was found with a recline angle of 120° and a pan angle at 14° and the lumbar prominence at 5 cm.

Literature Related to Support Force Data

Not only does posture affect what happens to the internal structures of the body such as diaphragm position, nutrient and blood flow, but the posture of a person also affects how the body interacts with the external environment. The postures of an individual affect their vision and reach zones, both important factors when designing for a work or driving environment. In any type of seated environment, a person's posture also affects how their body contacts the seat surface, and how support forces are transmitted between body and seat.

The findings of an extensive search in the area of seating revealed that little research has been performed on measuring or documenting the support forces of the body in the seated position. One paper by Faiks and Reinecke[10] discussed research that can be compared to a portion of the data collected for this dissertation. Otherwise, the most closely related research has been performed in the medical and automotive industries and involved the measurement of pressures under the buttocks and behind the torso.

Faiks [10] studied the movement patterns of people's spines during unsupported sitting tasks. He also evaluated the preferred lumbar forces (subject chosen force values) produced during movement from a reclined position to an upright position and the seat back support forces generated by "lifting" a person from a reclined position to an upright position.

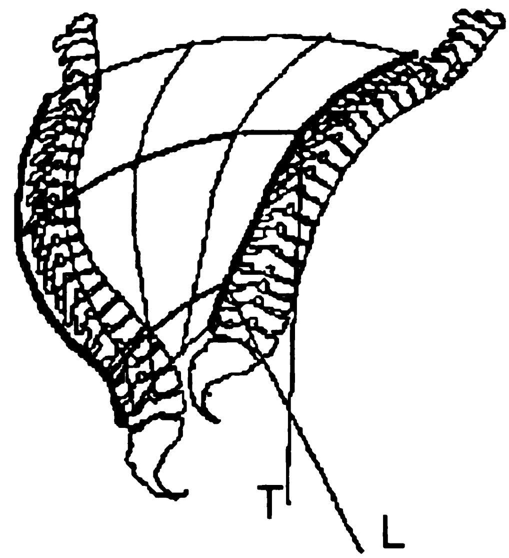


Figure 13: Movement patterns of the thoracic region of the spine differ from movement patterns of the lumbar spine[10].

Faiks concluded that the path and rate of motion of the lumbar spine was independent of the path and rate of motion of the thoracic spine, Figure 13. Faiks[10] also determined subjects preferred forces in the lumbar region, and the force necessary to lift the body from a reclined position to an upright position in the thoracic region, Figure 14. These data showed that the subjects (n=21) required an increasing amount of force on the thoracic region during a twenty degree recline, while the lumbar support force maintained a nearly constant level during recline. He found that as the amount of lumbar support was increased, the amount of force needed in the thoracic region was decreased and the opposite also held true.

Data broken down by gender showed that for men, the support levels for both the thoracic and lumbar region were at the same magnitude in the upright position and the thoracic force increased while lumbar stayed constant as they reclined. For the women subjects, the magnitude of thoracic support was lower than the lumbar support level in the upright position and increased during recline, but stayed below the desired level of the lumbar support.

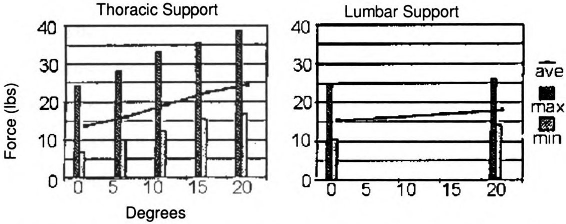


Figure 14: Preferred lumbar forces. Thoracic forces necessary to lift a person from a reclined position to an upright position[10].

In terms of force or pressure distribution, two philosophies exist for determining what is most comfortable or desirable for people. The first thought is that an even distribution is the best for the body; the second thought is that the forces should be distributed such that the higher loads are concentrated around the stronger structures of the body, for example under the ischial tuberosities when seated[28]. Goonetilleke[28] provided reasoning that supported each of these philosophies, but also offered a third suggestion, that higher localized forces, rather than an even distribution may be desirable, such as the pressures that would be induced by the use of a beaded seat cover. The beaded seat cover produced high localized pressures, above the recommended levels for the prevention of ischemia (less than 4.0-4.7 kPa) [28], yet was still found to be desirable by many people. As of yet, no single method for pressure distribution has been adopted by researchers or industry, the relationship of the pressure and force distribution to comfort is still determined on an individual basis.

Researchers[28, 29] have provided data on the amounts of pressure seen in regions of the body during sitting. Philippe[29], used pressure mapping to determine the contact area under the region of the thighs and buttocks and estimated the forces under the left and right side of the buttocks and thighs. Philippe's [29] research measured pressures in three different conditions for a man 1.75 m tall and having a mass of 85 kg: 1) in a seat with no vehicle controls (no steering wheel or accelerator pedal), 2) in a seat while using controls, and 3) in a moving automobile. Philippe[29] estimated the forces under the buttocks and thighs in the second condition and reported the approximate value of 196 N (20 kg) under the left buttock, 215 N (22 kg) under the right buttock, 88 N (9 kg) under the right thigh and 78 N (8 kg) under the left thigh, or terms of percent of body weight (%BW) 24-26 %BW under each buttock and 9-10 %BW under each thigh. Goonetilleke[28] listed the following measurements of pressures of a person in a seated position in terms of percent body weight; 18 %BW under the ischial tuberosities, 21 %BW under each thigh and 5 %BW under the sacrum. Large differences in %BW were given between Phillipe[29] and Goonetilleke[28], most likely because each had a different definition for the region used to convert pressure to force. Neither researcher provided these definitions.

The pressures at the body-seat interface are important for the disabled population, especially to those confined to a wheelchair. Without movement of the body, long periods of high pressures in localized regions can cause decubitus ulcers[3, 28], also known as pressure sores. Also affecting the development of pressure sores are temperature and humidity at the body-seat interface and the posture of the person. A study by Hobson[3] compared pressures produced on the seat pan by spinal cord injured (SCI) subjects to non-disabled (ND) subjects in different postures. These postural changes were induced by different configurations of a wheelchair. Hobson[3] found that the SCI subjects consistently produced higher pressures in all postures as compared to the ND subjects. Higher pressures would be expected because of the loss of muscle mass producing a more prominent skeleton in most SCI individuals.

From the Hobson[3] data, postures of a forward flexion of 50 degrees produced the lowest pressures on the seat pan for both subject groups. Forward flexion of 30 degrees also showed low pressures for the ND group. The ND subject group produced equally low pressures as in the 30 degree forward flexed condition in the full body tilt of 20 degrees with 100 degrees of back rest recline. SCI subjects also produced lower pressures in the full body tilt position.

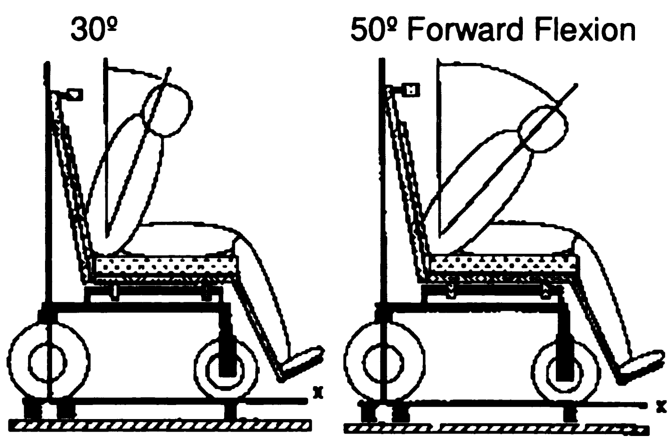


Figure 15: Forward Flexion from Hobson[3].

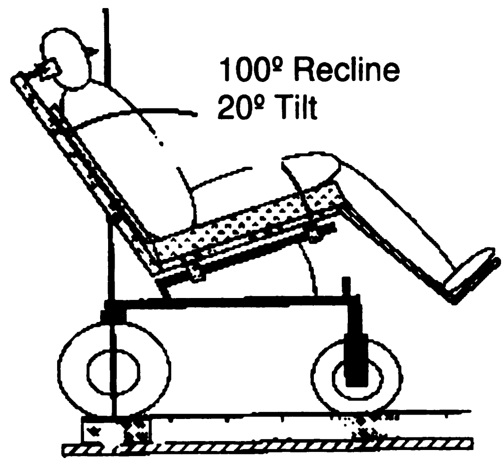


Figure 16: Full Body Tilt from Hobson[3].

In the Results section of this dissertation, discussions will include comparisons to the force measures reported by Faiks[10]. Discussions will also address dynamic data that shows possible methods of reducing or shifting the loading under the buttocks to decrease, or prevent, the occurrence of decubitus ulcers.

Comfort Related Literature

Since there is a wide variation in the human anthropometry, human body behavior and human preference, it has been difficult to interpret and define "comfort", or to define what makes a person comfortable and keeps them comfortable over time. Many researchers have tried to define what is comfortable for a person[2, 28, 30, 31]. However, difficulties arose in defining the term comfort. Some researchers stated that comfort was the absence of discomfort[28], or that comfort was associated with feelings of relaxation and well-being[28]. Judic[32] stated that in the automotive environment there were several factors which attributed to a person's comfort, including visual comfort, initial touch, postural comfort, dynamic comfort, sonic comfort and thermal comfort.

Designing a seat today requires that the seat pass several standards and tests, including fatigue tests, wear tests, and restraint testing; however a comfort test has not yet been developed. If a link could be established between the objective measures and the subjective ratings, or a series of links could be developed between several objective and subjective factors, a comfort test could be designed. This test would provide basic guidelines for designing comfortable seats and would address seat factors that affect a person's overall comfort.

Grandjean (1964)[2] established some basic seat positioning guidelines for reduced discomfort in seated postures, Table 2. Grandjean found seat inclination for minimum discomfort should be between 16 and 30 degrees. Backrest inclination should be between 125 and 138 degrees from horizontal, the seat height should be between 34 and 50 cm and the seat depth should be between 41 and 55 cm. Table 2 compares the comfort guidelines established by Grandjean to the chair positions that produced low intervertebral disc pressures as found by Andersson and Nachemson (1970 & 1974) [33,34].

Table 2: Comparison of seat orientation based on low disc pressure (Andersson[33] and Nachemson[34]) and minimum discomfort (Grandjean[2])

	Low Disc Pressure (Andersson and Nachemson)	Minimum Discomfort (Grandjean)
Seat Pan Inclination (with respect to horizontal)	14°	16-30°
Backrest Angle	110-130°	125-138°
Height of Seat	---	34-50 cm
Depth of Seat	---	41-55 cm

Table 3: Recommended body angle ranges to avoid discomfort[32].

Definition	Figure Ref. (Figure 17)	Minimum (degrees)	Maximum (degrees)
Torso Axis – vertical	a1	20	30
Torso axis – Thigh axis	a2	95	120
Thigh axis – Lower leg axis	a3	95	135
Leg axis – Pedal plane	a4	78	105
Torso axis – Upper arm axis	a5	0	50
Upper arm – Forearm axis	a6	80	170
Forearm axis – Hand axis	a7	170	190
Pedal plane – Floor pan	a8	40	70
Thigh axis – Horizontal	a9	12	25

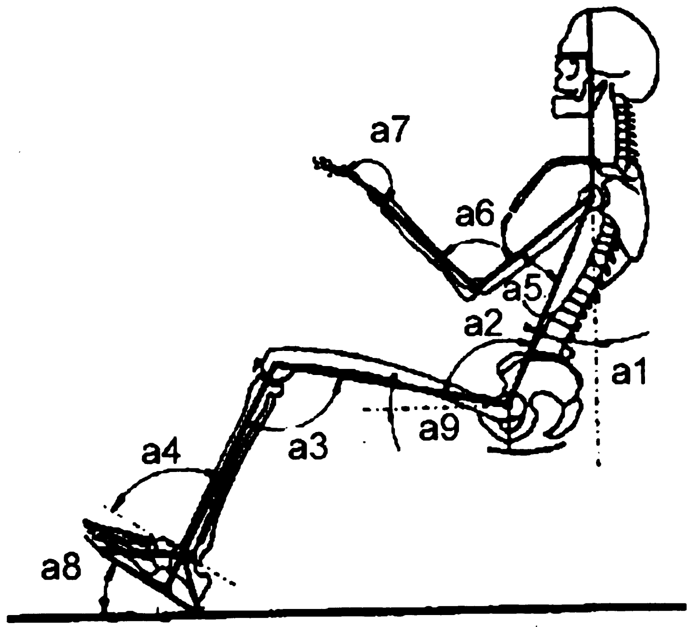


Figure 17: Identification of the comfort ranges by Judic[32]

Judic[32] also listed a set of data from Rebiffe's[35] research, Table 3, describing the ranges of body positions that should be assumed to avoid discomfort. Rebiffe developed an eight-segment body linkage system and used this system in conjunction with experimentation of subject preference in adjustable and unadjustable automotive seats to establish vision zones and steering wheel zones for subjects of the smaller (5th percentile) and larger stature (95th percentile).

Thakurta[31] performed research that evaluated short and long term comfort. Thakurta measured pressure distribution and collected subjective data on 36 subjects at the beginning and end of an 80 mile drive. Each subject was tested in five automobiles. The average distribution of pressure is displayed in Figure 18. The objective measures were broken into the following pressure zones: ischial, thigh, shoulder, tail burn on the cushion, tail burn on the back, lateral cushion, lateral back, and lumbar. The subjective questions also addressed these zones. Thakurta tried to establish a linear correlation between the subjective questions addressing discomfort of body zones with the objective pressure readings. Thakurta concluded that comfort was most likely a complex non-linear relationship of many measures.

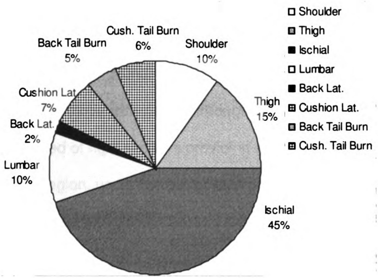


Figure 18: Pressure distribution from Thakurta's[31] work.

An overview of the primary literature relating to the anatomy and physiology of the spinal column, posture, the physiological effects of postural changes and comfort has been presented. The next section discusses the methods used to measure and define the posture of a seated person, the support forces and the estimation of internal joint forces.

Testing Methods

The following section discusses the equipment used for testing, the subject selection criteria, subject targeting and a description of the various test postures.

Equipment Description

Lab Chair

The specially built chair used in this study was termed the Biomechanically Articulating Chair (BAC) [36], it was an experimental apparatus that was designed to move with people through postural changes. The BAC (Figure 19) consisted of rigid sections providing support behind the thorax, behind the sacral region, under the buttocks and under the thighs. The rigid supports were covered with a foam-backed fabric of approximately 15 mm in thickness (13 mm of foam and 2 mm of fabric). The chair allowed two main movements, one being the recline of the body and the second being the increasing or decreasing of lordotic curvature in lumbar spine. Each of these movements was powered by a small motor (adapted from a powered automotive seat) which used a rotating screw to move the chair.

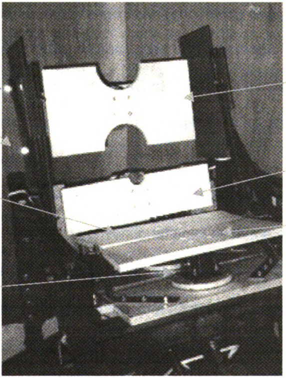
The chair was designed to move with the body and to recline about a point located (approximately) under the ischial tuberosities of a seated person. This recline point was chosen based on the assumption that the location of the person's ischial tuberosities did not change while in a seated position, therefore the person would rotate about the ischial tuberosities while reclining. Allowing the chair to pivot about this point, in theory, would reduce the shear forces on the back of the chair and the back of the person as the seat reclined.

The BAC also had a unique method for inducing lordotic postures, Figure 20. The chair did not have a typical lumbar support, such as bladder or paddle devices commonly found in automotive seats. Instead, the chair articulated the thoracic support and pelvic support in equal and opposite directions, thus a lordotic curve in the lumbar spine was induced without using a lumbar support. The buttocks section of the BAC cradled the pelvis, including the sacrum and the buttocks region, slightly forward of the ischial tuberosities. The thigh support did not move with the pelvis portion of the chair, rather it rotated about an axis just forward of the ischial tuberosities and was fixed at an angle 15° above horizontal.

Chair Targets

Buttocks Support

Force Transducer



Thorax Support

Pelvis Support

Thigh Support

Figure 19: Specially built laboratory chair used for testing.

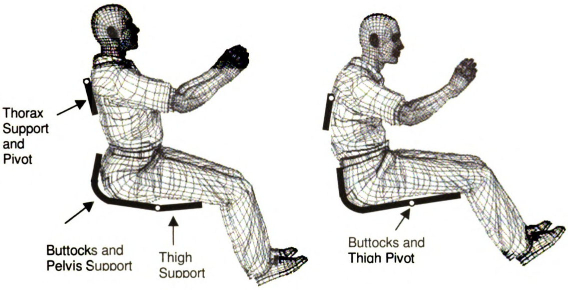


Figure 20: BAC chair articulation.

The BAC was used instead of an automotive seat because not only could the BAC accommodate a large range of anthropometry and provide a large range of movement, but it also could be positioned in a repeatable fashion with minimal effort. Another reason for using the BAC rather than a conventional automotive seat was the open seat back design that allowed easy access to different body landmarks during testing.

It is necessary to make a small note pertaining to the BAC design. Although this design was not a conventional practice in the automotive field, the idea of stabilizing the pelvis during sitting and inducing spinal articulation by moving the pelvis has been a common idea among the medical profession. Zacharkow[37] stated that a conventional lumbar support (such as a lumbar roll) did not assure the proper pelvic alignment relative to the spine and that without proper pelvic support continuous oscillations of the pelvis occurred. Zacharkow believed that rather than providing support to the spine as in a lumbar support, the pelvis, specifically the sacrum and posterior iliac crests, should be well supported and positioned to maintain lordosis in a seated posture.

Force Plates

A second type of equipment used in conjunction with the BAC was a set of multi-channel load cells (also termed force plates) located behind each of the support plates (shown in Figure 19) of the chair. The force transducers measured support forces in three directions, F_x, F_y and F_z and three moments M_x, M_y and M_z relative to the center of the force plate. Plates were mounted behind the thorax, pelvis, and steering wheel, and under the buttocks, thighs, and feet. The force plates were mounted between two rigid boards, one board was attached to the chair mechanism and the other board (which was foam covered) came into contact with the subject at the various anatomical regions. With this type of attachment, all the forces and moments from the seated subject were transmitted through the force plates.

The capacities of the force plates were 1112 N (250 lb) (behind the thorax and pelvis) and 4450 N (1000 lb) (buttocks, wheel, thigh, feet). The force plates were Advanced Mechanical Technology, Inc. (AMTI) MC3A series plates. The small size of the plates was the primary reason for the choice; these plates were 7.62 cm (3 inches) in height, width and depth.

The force plates were used in conjunction with AMTI amplifiers. The amplifiers were set to a gain of 1000 and a filter of 10.5 Hz. Each force plate came with factory measured sensitivities for each channel. These sensitivities were incorporated into the calibration file for data processing.

Motion Measurement System

A five camera 60 hertz Qualisys[38] motion measurement system was used to capture three dimensional positions of retro-reflective targets that were secured to both the articulating chair and the bony landmarks of the person. All five cameras contained high power, infra-red light rings mounted around each lens; the use of the infra-red system allowed testing to occur with ambient light in the laboratory. The camera speed was variable from 1Hz to a doubled-up camera system of 120Hz. All force and motion data were collected at 12 Hz. With pilot testing, 12 Hz was deemed acceptable to capture the static and dynamic seated movements.

The targets were made of lightweight spherical balls, covered with 3M high gain, 7610, retro-reflective tape[39]. The targets were 18 mm in diameter without the reflective tape and approximately 20 mm once covered. This reflective tape was used for special effects projection screens and provided at least 600 times more reflection than a white screen. Together the reflective tape and the spherical shape of the targets helped to maximize the visibility of the target. The targets were attached to a flexible material base and it was this base that was taped to the reference landmarks on the subjects.

Subject Recruitment and UCHRIS Approval (University Committee on Research Involving Human Subjects)

Since this research was supported in part by automotive companies, the work was structured around the automotive environment. Typically the automotive companies designed for accommodation from a small statured person (5th percentile female) to those of a large stature (95th percentile male), and the majority of the seat standards were tested with a manikin that represented a 50th percentile male by weight and stature. For the studies conducted for this research, 50th percentile men, or mid-sized males were selected as test subjects, Table 4 (UCHRIS IRB #96-054). The mid-size male requirements[40] were derived from the National Health and Nutritional Examination Survey of 1974 (NHANES II)[41] anthropometric study.

Table 4: Mid-Male Anthropometry

Height Range	1727-1778 mm (68-70 inches)
Weight Range	72.7-81.0 kg (160-180 lbs.)

The potential subjects were recruited and brought into the laboratory to verify their heights and weights prior to testing. At this time, the subjects were asked several lifestyle questions such as if they had any back injuries, back pain or back surgery. If the subject answered yes to any of the back pain or injury questions, he was excluded from the pool of test subjects.

For this investigation, it was desirable to develop a correlation between posture and force measures. Researchers have stated that people who have back pain or injury are more likely to produce atypical spinal motion patterns. Therefore, to decrease the measurement variability, only subjects without back injury or pain were tested. Before testing, the protocol was reviewed with the subject and he was asked to sign a consent form to grant permission to be tested, interviewed and photographed.

Two sets of subjects were tested the first set had a sample size of 10 while the second set had a sample size of 13. After the data were analyzed for the first 10 subjects it was determined that a larger sample size would be beneficial for statistical analysis. The only change made to the test protocol between the two subject sets was that the second set of subject had targets placed on either side of the head, while the first set of subjects did not have head targets.

Methods for Testing

Application of Targets

For all testing, subject positional data, chair positional data and force data were collected simultaneously. To collect these data, the subjects were targeted with light-weight, retro-reflective targets on various bony prominences. These target sites were surface body points that were easily palpated and could be located repeatedly.

The list of target locations can be found in Table 5 and the targets sites can be seen in Figure 21, Figure 22, and Figure 23. The articulating chair was also targeted to compare the position of the subject to the position of the chair; a list of chair targets is located in Table 6.

Table 5: Targeted Body Landmarks

Seventh Cervical Vertebra – C7
Sternal Notch
Mid-Sternum
Left Anterior Superior Iliac Spine (ASIS)
Right ASIS
First Sacral Vertebra (S1)
Right and left head at the center of gravity location
Right Acromion Process
Right Lateral Epiondyle on the Humerus-Elbow
Right Radial Epicondyle-Wrist
Right Mid-Thigh
Right Lateral Condyle (Knee)
Right Lateral Maleolous

Table 6: Chair Targets

Two targets on the Recline Bar
Two targets on the Thoracic Support
Two targets on the Pelvis Support
Two targets on the Steering Wheel Base
Two targets on the Base of the Chair

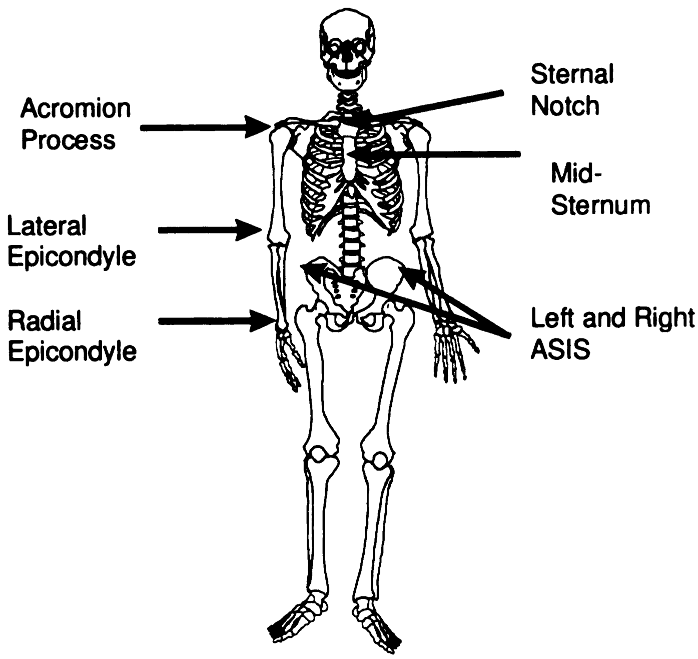


Figure 21: Anterior target sites.

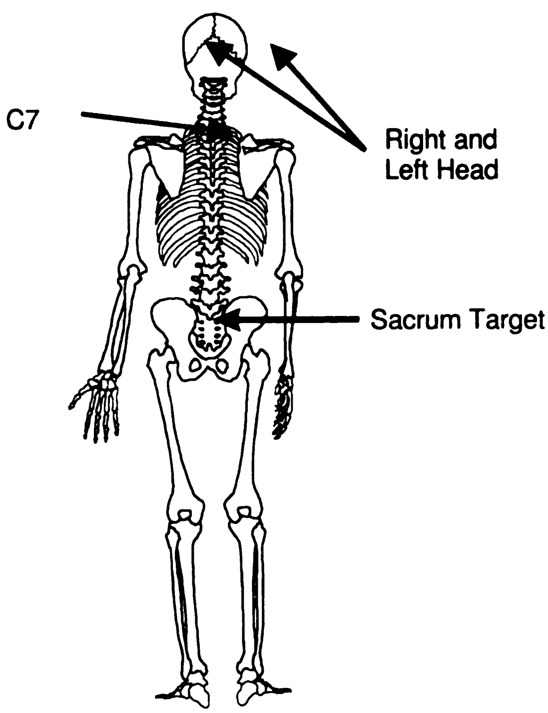


Figure 22: Posterior target sites.

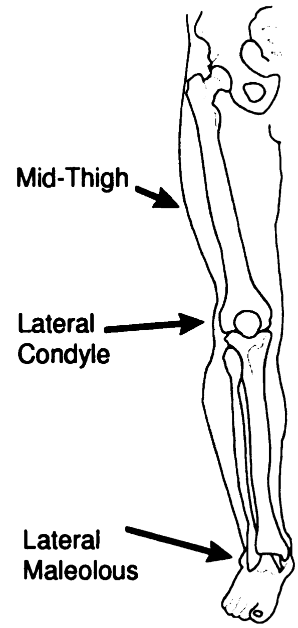


Figure 23: Leg targets.

The subjects were asked to wear tight fitting shorts and a tight fitting shirt, or no shirt; once the subject changed into this clothing his height and weight were measured and he was targeted. Using an alcohol pad, the target sites were wiped free of any oils; then with double sided medical tape, the targets were placed onto the landmarks listed in Table 5. In some cases, additional tape was used on the base of the target to keep it securely attached to the skin.

Test Conditions and Setup

The BAC was initially set in a mid-seat-height automotive package defined by an in-depth study performed at General Motors[42]. The seat height was located by placing the SAE manikin (not the new ASPECT manikin) in the chair and measuring the vertical distance from the manikin's H-point to the top of the foot plate surface. The H-pt, which is the manikin's representation of a human hip joint center, was measured in the middle recline angle, 24° and was set at 280 mm relative to the surface of the foot plate, Figure 24. The thigh support angle was adjusted to be approximately 14° as defined by the mid-thigh line on the SAE manikin (15° for actual thigh support angle); this angle was representative of a typical automotive seat pan angle. The angle of the foot rest was set at 61° based on the 280 mm seat height from the General Motors automobile interior package study[42].

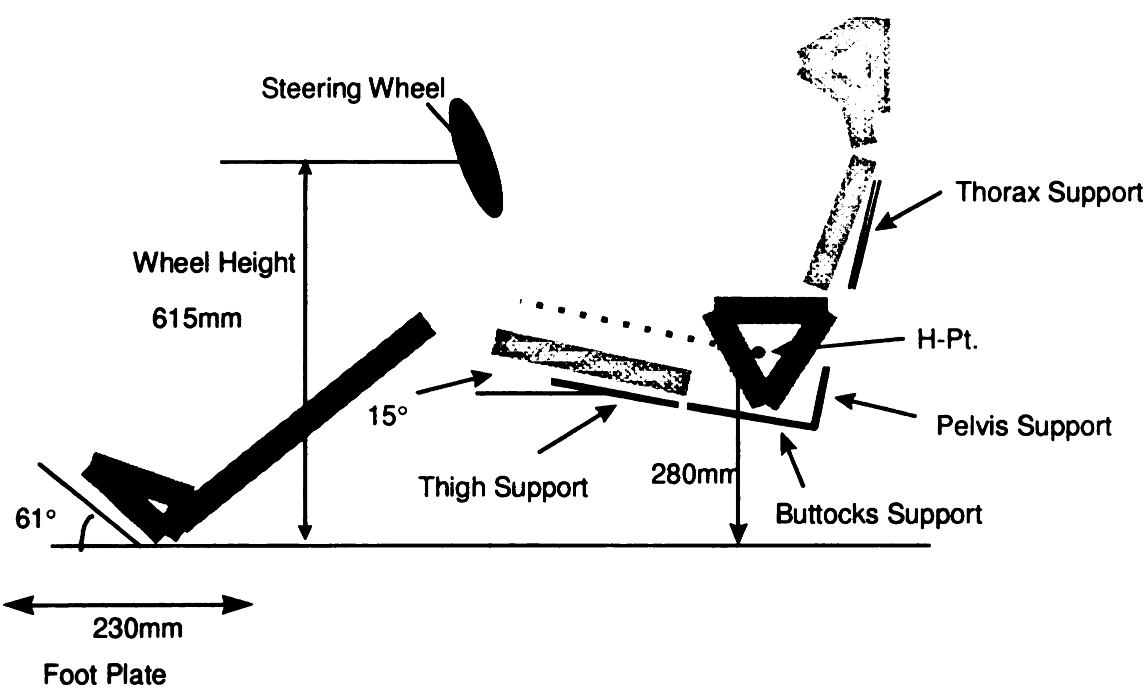


Figure 24: Set-up conditions for the BAC

The recline angles of the lab chair were set by placing the SAE manikin in the test seat while it was configured in the neutral lumbar position (neutral position: thorax support and pelvis support form a single plane) and measuring the back angle of the manikin. (See section entitled Test Descriptions for more detail). This technique, where the back angle of the manikin is also the seat recline angle, is currently used in the automotive industry to obtain a recline measurement. By using the SAE manikin, the test seat was adjusted to provide the same recline as an automotive seat. From the GM study[42], the average recline angle for a typical mid-sized automotive package was found to be 24°. For this study 20°, 24° and 28° recline angles were used, with the most upright angle being 20° rearward of vertical.

The center of the thoracic support surface was adjusted to be approximately at the ninth thoracic spinous process of the subjects and the pelvis support was adjusted so the top of the support was located in the sacrum region but did not interfere with the lumbar spine motion. Prior to testing, the subjects were brought in for a height and weight screening to be sure they met the requirements. At that time, measurements of the height of the ninth thoracic vertebra (T9) were taken relative to a horizontal seat surface. The thorax support and pelvis support were adjusted based on an average T9 height of the first ten subjects, and remained in the same location for the testing of all subjects.

For all tests, the arms were positioned on a steering wheel in front of the body with a load cell attached to the wheel. The subject was able to adjust the wheel fore and aft for comfort. The wheel height (center of wheel to foot support) was fixed at 615 mm. The subject was also allowed to adjust the foot plate fore and aft for comfort.

The entire test time per subject varied between 2.5 hours and 3 hours from start to finish. This included the informational session, targeting, and testing.

Test Descriptions

Reference File

First, an initial position of the chair (without the subjects) was taken with the back upright at 90 degrees relative to horizontal and the buttocks support at 0 degrees relative to horizontal and the thigh plate elevated 15 degrees relative to horizontal. This chair position was used as the reference data file for both the force plates and chair.

Static Tests

The chair was placed in three different recline angles (20°, 24°, 28°), based on the angles found in a typical mid-sized automotive interior package. For each recline angle, four amounts of lumbar curvature were selected. The order of the three recline angles was randomized, and within each recline, the four lumbar curvature angles were randomized. The various lumbar positions were created by adjusting the thorax and pelvis supports of the chair equal and opposite amounts. These four chair positions induced four different postures: slouched, neutral, erect and super-erect, Table 7. The neutral chair position, Figure 25 was determined by aligning the thorax support and pelvis support; in this condition if connected, the two supports would form a plane. For the slouched posture, the bottom of the thorax support was rotated away from the subject 5° from neutral and the top of the pelvis support was rotated away from the subject 5° from neutral, Figure 25.

Table 7: Static Test Postures

Static Postures - 5 second tests		
Recline 1	Recline 2	Recline 3
-10°TSA – slumped	-10° - slumped	-10° - slumped
0° - neutral	0° - neutral	0° - neutral
10° - erect	10° - erect	10° - erect
20° - super erect	20° - super erect	20° - super erect

For the erect and super-erect conditions the thorax and pelvic supports were rotated in the opposite direction from slouched. For the erect condition, the bottom of the thorax support was rotated toward the subject 5° from neutral and the top of the pelvis support was rotated toward the subject 5° from neutral, Figure 25. For the super-erect condition, each of the segments were rotated 10° in the same direction as the erect condition. For a descriptor of the test, the thorax and pelvis support movements were added together to describe the Total Support Angle (TSA): slouched -10°, neutral 0°, erect +10° and super-erect +20°, Table 7.

When entering the chair, the subject was instructed to make sure the back of their buttocks were in contact with the pelvis support, but not forcefully pushing on the support plate. After each chair movement, in the static tests, the subject was again asked to re-adjust and make sure their buttocks were in contact with the support. This instruction was given to each subject to provide consistency in how the pelvic support was loaded.

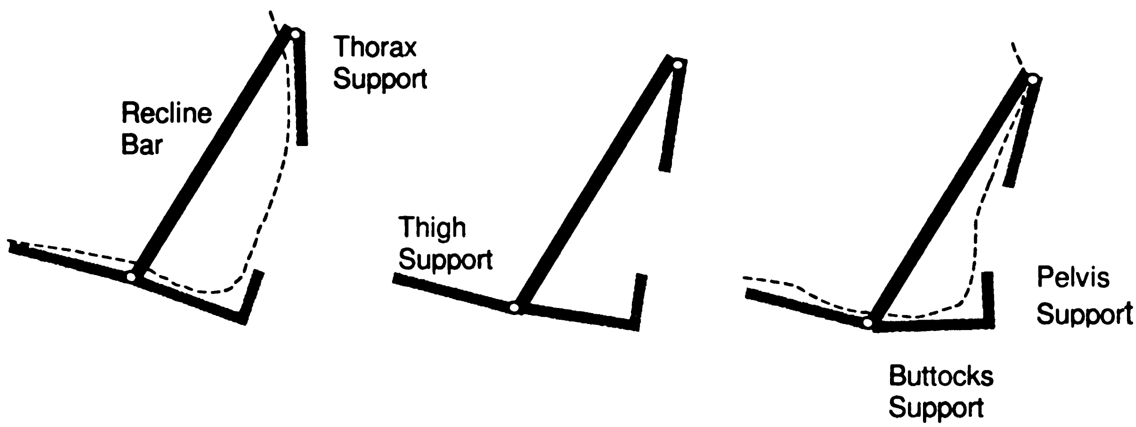


Figure 25: Slumped, neutral and erect positions of the test chair.

Preferred Postures

Included in the static tests were a set of preferred postures. At three different times during testing the subject was asked to choose two preferred postures (Table 8). For trial one of the preferred posture test, the chair was adjusted to an extreme upright position, then the subject was asked to adjust the recline and lumbar curvature and find a comfortable position. For trial 2, the chair was adjusted to an extreme reclined position, and again the subject was asked to find a comfortable position. Trials 3 and 4 and trials 5 and 6 were conducted in a similar fashion.

The method of moving the chair to extreme positions ensured that the subject would make chair adjustments and not choose the upright or reclined extremes as comfortable positions. For the preferred posture, the subject was asked to rest his hands in his lap, adjust the back of the chair until comfortable, then adjust the foot plate and finally pull the steering wheel to a comfortable position. The subjects were allowed to make changes after this sequence if necessary. The goal was to have the subject adjust for back comfort without the influence of the wheel or foot plate.

Table 8: Comfort Postures

Comfort Posture **Trial duration: 5 seconds**
Occurred before first set of static postures
Trial 1
Trial 2
Occurred after second set of static postures
Trial 3
Trial 4
Occurred after dynamic postures
Trial 5
Trial 6

Table 9: Dynamic Test Conditions

Dynamic Postures Occurred after the static test positions		**Trial duration: 10 seconds**
Recline 1	Recline 2	Recline 3
Trial 1 -10° to +20°	Trial 1 -10° to +20°	Trial 1 -10° to +20°
Trial 2 -10° to +20°	Trial 2 -10° to +20°	Trial 2 -10° to +20°

Due to the large volume of data generated for this dissertation, the preferred data will not be analyzed but will be considered work for the future.

Dynamic Tests

For the dynamic test conditions, the seat was adjusted to move through the full range of lumbar support positions in one continuous motion. The chair was operated by electric motors, which allowed the chair to move smoothly while the subject remained seated. For all of the dynamic tests, a test assistant, out of view of the cameras, operated the chair movement. Two trials were performed at each recline angle, one trial began in the neutral position and then moved to the slumped position and then to the super erect condition. The second trial also began in the neutral position but initially moved to the super erect position and then to the slumped position.

The subject was placed in the starting position and instructed to adjust the wheel and foot plate to a comfortable location. The subject was then moved through the entire chair motion to see if further adjustment was necessary. The subject was required to keep their hands on the wheel and their feet on the foot plate for the entire dynamic test.

During the dynamic testing, the subject was instructed to relax and let the seat move him through changes from lordosis to kyphosis. The dynamic tests were repeated two times for each recline angle and lasted ten seconds (Table 9).

Hard Seat

After testing in the Biomechanically Articulating Chair (BAC), additional targets were placed along the spine on the following spinous processes: C7, T6, T10, T12, L3 and S1, Figure 26. The hard seat data file was collected to establish a spinal reference position for comparison to the JOHN model. The JOHN model identified 0° TLC (Total Lumbar Curvature) as a straight lumbar spine without lordotic or kyphotic curvature. The hard seat was designed to position the spine in this straight position. The subject's openness angle was measured in the hard seat and could be calibrated to JOHN's 0° TLC position. (For further information regarding the definition of the JOHN model, see the Analysis Methods Section.)

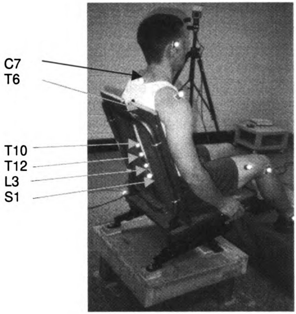


Figure 26: Hard seat reference file.

Analysis Methods

This section, Analysis Methods, discusses posture computations, the calculation of chair orientation, the processing of the force data and the methodology developed for the estimation of the internal joint forces of the lumbar region.

Motion Data

Prior to data collection, the motion system was calibrated using the procedure and calibration stand as described by the Qualisys[38] motion measurement system manual. Once calibrated, data collection could begin. The system was calibrated at the start of each day and usually two subjects were tested in one day.

After data collection, the motion data were tracked with a computer to obtain x, y and z coordinates for each target. Using the Qualisys[38] system to track the motion data, the targets were viewed on the computer screen, and each target was identified as either a specific chair target or a specific body landmark, Figure 27. Using the calibration file, the software[38] performed a direct linear transformation on each frame of data resulting in a set of three dimensional coordinates. After the targets were named and tracked, the data were exported for analysis.

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Custom Data Analysis

The orientations of the chair and body consisted of sagittal plane angles. The data was collected with the calibration identifying the Y axis as anterior to the seated subject and the Z axis as superior, but was converted to be similar to the buttock and thigh force plate orientations where the X axis of each plate was pointing anteriorly. To accomplish the conversion, the motion data was rotated 90° about the Z axis making the X axis anterior, Y left lateral, and Z superior, Equation 1.

$$\begin{Bmatrix} X' \\ Y' \\ Z' \end{Bmatrix} = \begin{bmatrix} \sin\theta & \cos\theta & 0 \\ \cos\theta & -\sin\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} \text{ where } \theta \text{ equaled } 90°$$

Equation 1: Rotation of the laboratory coordinate system about the Z axis.

Basic Vector Calculations

After the raw data coordinates were transformed, the calculation of the sagittal plane angles followed. First a vector was created between the two targets located on a chair segment or a portion of the body. To establish a vector C from target A (which is the position of point A relative to the laboratory) to target B (which is the position of point B relative to the laboratory), vector A was subtracted from vector B (Equation 2, a). To subtract vectors, the components of each vector were subtracted (Equation 2, b).

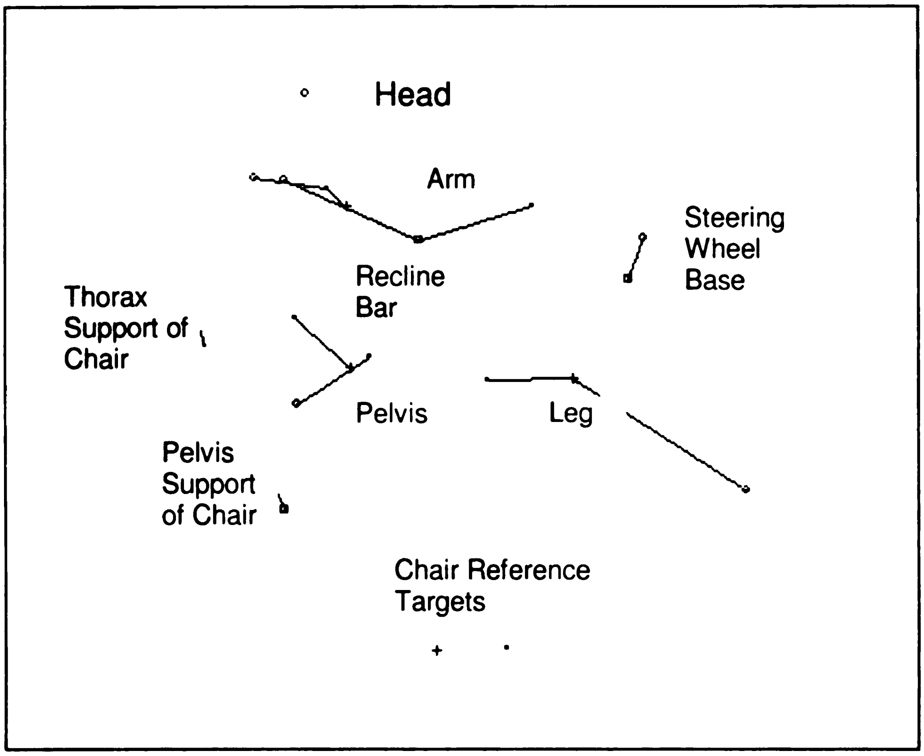

Figure 27: Computer image of subject being tracked, side view.

$$\vec{C} = \vec{B} - \vec{A}$$
$$\textit{where} \qquad \text{(a)}$$
$$\vec{A} = A_x\hat{i} + A_y\hat{j} + A_z\hat{k}$$

$$C_x = B_x - A_x \qquad \text{(b)}$$

Equation 2: Computing a vector C from target A to target B.

Computation of angles between vectors requires that the vector be first made into a unit vector, or a vector with a magnitude of one. To create a unit vector, first the magnitude of the vector must be computed. The magnitude of the vector was calculated using Equation 3.

$$\text{Magnitude of vector } \vec{C} = \left|\vec{C}\right| = \sqrt{C_x{}^2 + C_y{}^2 + C_z{}^2}$$

Equation 3: Computing the magnitude of a vector.

Then, to create a unit vector, each component of the vector was divided by the vector magnitude, Equation 3. This resulted in a unit, Equation 4, or directional vector with a magnitude of one.

$$\hat{C} = \frac{C_x, C_y, C_z}{\left|\vec{C}\right|}$$

Equation 4: Creating a unit vector.

Once a unit vector was developed, sagittal plane angles were found by computing the dot product between two unit vectors and then obtaining the angle by either computing the arccosine or the arcsine of the dot product. These angles were computed with the unit vector and a lab coordinate unit vector, such as lab Z (vertical), or two unit vectors calculated from the body or chair targets.

Posture Definitions - JOHN

The method of defining a subject's posture was based on a model of the body developed by Haas[43], Boughner[44], Bush[45] and Hubbard[46]. In the JOHN model, the thorax and pelvis were treated as rigid bodies with two joints (upper and lower lumbar) and a lumbar link connecting them (Figure 28). With this approach, the orientation of the torso was determined by: the position of the torso in space, the position of the thorax relative to the pelvis and the recline of the er

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entire body in space. For the JOHN model, the orientation of the thorax relative to the pelvis was termed Total Lumbar Curvature (TLC) and the recline of the body was termed Total Recline Angle (TRA). The TRA was measured by the angle of the lumbar link relative to a vertical, Figure 28. The TLC was measured by the amount of rotation of the thorax about the upper lumbar joint plus the amount of rotation of the pelvis about the lower lumbar joint. Since the thorax and pelvis were treated as rigid bodies, any two points picked consistently on the thorax and on the pelvis could be used to identify the rotation of each of the body segments, Figure 29. The initial reference position of the JOHN model was chosen to be when the joints in the lumbar spine formed a straight line. This was termed 0° TLC. Similar measures were developed for the subjects and are discussed in the following section.

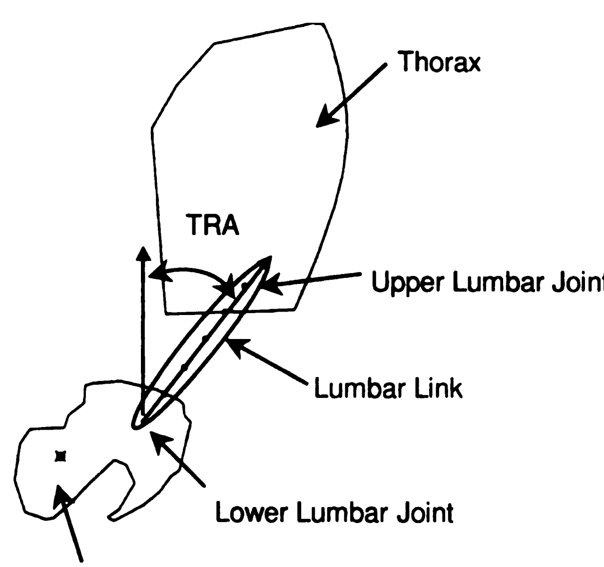


Figure 28: JOHN model with TRA measure.

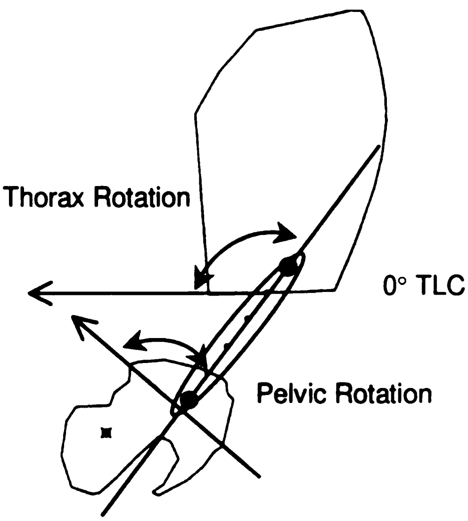


Figure 29: Pelvis and thorax rotation about the upper and lower lumbar joints.

Posture Measures - Subjects

The measurement of posture in the seated position is not a trivial issue. Currently a standard definition of seated posture does not exist, the methods and protocols developed for this dissertation were some of the first in the field of seating mechanics and were implemented with other methods developed for the ASPECT program (described in the literature survey section). These methods use exterior body landmarks, and treat the thorax and pelvis as rigid bodies to define posture.

A detailed discussion of the body measures is presented in the following sections, but in brief, the human openness angle measure was calculated as an angle between the thorax vector and the pelvis vector (similar to the JOHN model TLC). The human recline angle was calculated by establishing a vector from the midpoint of the ASIS targets to the sternal notch target. The angle of this vector with respect to the lab vertical vector was called the human recline angle.

However, this calculation may not be the optimum method for measuring the body recline and will be evaluated and discussed in the Results section.

Measurement of Pelvis Orientation

To compute the angle of the pelvis in the sagittal plane, it was necessary to calculate a point midway between the two Anterior Superior Iliac Spine (ASIS) targets on the pelvis. The midpoint was computed by first finding the magnitude of the vector between the left and right ASIS targets, then adding half of the magnitude to the vector identifying the right ASIS target, Equation 5. In cases where the right ASIS target was missing, the magnitude between the two ASIS targets could be determined from a reference file and the midpoint could be computed solely from the left ASIS or right ASIS target (described below).

One concern with using targets was the introduction of data artifact by the movement of targets due to skin motion. Since extra adipose tissue rests around the mid-section of the body, the area of most concern for artifactual target motion was the pelvis region. For this study, subjects were mid-sized males and of medium weight, so there was little adipose tissue on any of the subjects. Subjects also wore tight fitting clothing to reduce skin and clothing motion. When possible, the targets were attached directly to the skin. Calculating the midpoint of the two ASIS targets produced an average of the two target positions and was less sensitive to the skin motion than that of a calculation using one target.

$$\text{Right ASIS Vector} = \vec{R}$$
$$\text{Unit Vector from right ASIS to left ASIS} = \hat{A}$$
$$\text{Magnitude (between left and right ASIS)} = |LR|$$

$$\text{Midpoint} = \vec{R} + (\hat{A} * \frac{|LR|}{2})$$

Equation 5: Calculating the midpoint between two targets.

The orientation of the pelvis in the sagittal plane was determined by using the sacral target and the midpoint of the two ASIS targets, Figure 30. A vector from the sacrum to the midpoint of the ASIS targets was computed and the orientation of this vector relative to lab horizontal determined the pelvis orientation, Equation 6. Since the motion of the pelvis in the seated position was small, and did not exceed 180° of movement, singularities in the computation did not arise. However, since the vector from the sacrum to the mid-ASIS location could align with the lab X axis, an arcsine function was used in conjunction with the lab vertical axis rather than an arccosine function. This approach computes the angle with respect to the lab horizontal, using the laboratory Z axis (vertical) to perform the calculation, thus the two will never be parallel. To maintain the right hand rule convention, a negative sign was also used in the calculation, Figure 30.

$$\text{Pelvis Angle} = -1 * \arcsin(\hat{P} \bullet \hat{Z}) = -1 * \arcsin(P_Z)$$
$$P_Z = \text{Z component of the unit Pelvis vector from the Sacrum to the mid ASIS}$$
$$\hat{Z} = \text{Laboratory Z axis}$$

Equation 6: Calculation of pelvis orientation in the sagittal plane.

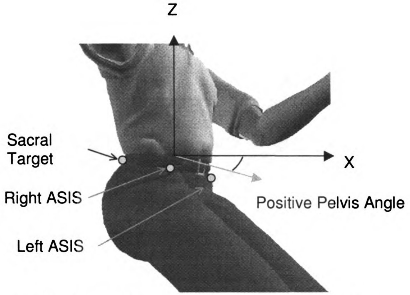


Figure 30: Vector used to determine pelvis orientation.

Measurement of Thorax Orientation

The mid-sternum and sternal notch targets were used to establish a vector to monitor thorax movement, Figure 32. The thorax and the pelvis vectors were used together to measure the amounts of torso flexion or extension, also termed as torso openness. The thorax orientation was determined by calculating the angle between the vector from the mid-sternum to the sternal notch and the lab vertical in the sagittal plane. The computation used an arcsine function to determine whether the thorax angle was anterior or posterior of lab vertical.

$$\text{Thorax Angle} = \arcsin(\hat{T} \bullet \hat{X}) = \arcsin(T_X)$$
$$T_X = \text{X component of the unit vector from the mid-sternum to the sternal notch}$$
$$\hat{X} = \text{Laboratory X axis}$$

Equation 7: Calculation of thorax orientation in the sagittal plane.

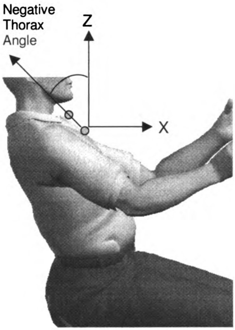


Figure 31: Sign convention of the thorax orientation.

Openness Angle

In the JOHN model, the motion of the thorax relative to the pelvis was defined by the rotation of each segment relative to the lumbar link, and was termed Total Lumbar Curvature. For the subjects, a similar measure that defined the rotation of the thorax relative to the pelvis was termed the Openness Angle. This angle was calculated by using the pelvis vector from the sacrum target to the mid-ASIS point and the thorax vector from the mid-sternum to the sternal notch. The angle between these two vectors was the openness angle, Figure 32, Equation 8. As lordosis increased, the pelvis vector tipped downward and the thorax vector rotated rearward causing the openness angle to increase. This was used as a within subject measure to compare the change of a person's posture in response to the chair.

When used in conjunction with a set of data collected in the hardseat, a calibration could be devised and comparisons could be made between the JOHN model TLC and the subject's openness angle. The subject was asked to sit with their pelvis and back flat along the hardseat. Thus, the subject's posture in the hardseat was considered to have a flat lumbar spine and was chosen to be equivalent to a TLC of 0° when represented by the JOHN model.

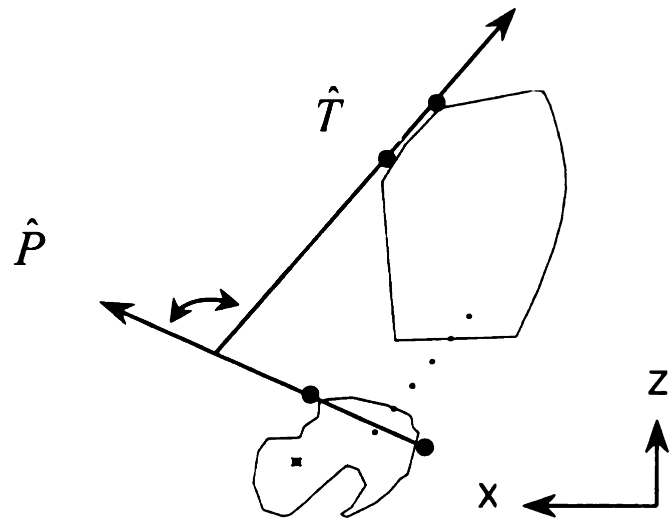


Figure 32: JOHN model used to display the openness angle.

$$\text{Openness Angle} = \arccos(\hat{T} \bullet \hat{P})$$
$$\hat{P} = \text{unit vector from the sacrum to the mid - ASIS point}$$
$$\hat{T} = \text{unit vector from the mid - sternum to the sternal notch}$$

Equation 8: Calculation of the Openness Angle.

Body Recline

If the body is moving with the BAC from lordosis to kyphosis at a given recline angle and the body recline measure was chosen so that it was independent of the openness angle, then ideally, the body recline measure should not vary, only the openness angle. However, it may be that with the human body these two parameters are linked and cannot be considered independently.

For this study, the body recline angle (BRA) was defined as a vector from the mid-ASIS location to the sternal notch target. This was an initial best guess at how to measure the body recline and proved to work well, with only a small amount of movement in the BRA when the subject changed the openness angle.

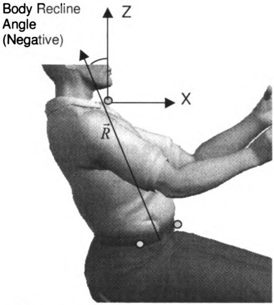


Figure 33: Body Recline Angle (BRA).

$$\text{Recline Angle} = \arcsin(\hat{R} \bullet \hat{X}) = \arcsin(R_x)$$
$$R_x = \text{X component of the unit vector from the mid-ASIS location to the sternal notch}$$
$$\hat{X} = \text{Laboratory X axis}$$

Equation 9: Calculation of the Body Recline Angle.

Head Position

The position of the head was measured by placing two targets at the approximate Center of Mass (CM), also known as the Center of Gravity, level on either side of the head. These targets were placed 10 mm (0.4 inch) forward and 20 mm (0.8 inch) above the Tragion[47]. The midpoint of these two targets was computed and was used as the head CM.

In many trials only one head target was visible by two cameras, this was due to hair partially covering the target or a slight turning of the head away from the cameras. An alternative method for computing the CM of the head was devised for the case where only one target was visible to the cameras. For the alternative method, a local coordinate system was developed on the thorax. A vector (A) was computed from the mid-sternum to the sternal notch and a vector (B) was computed from the sternal notch to the seventh cervical vertebra; a cross product was calculated to develop vector (C), which was perpendicular to the plane formed by (A) and (B). The plane formed by vectors (A) and (B) represented a sagittal plane through the thorax. Since the driving task was a sagittally symmetric task, if only one head target was available, the unit vector (C) was used as the directional vector for the computation of the head CM, Equation 10. The magnitude between the two head targets was determined from another file that contained the two targets, either a trial file or the hard seat reference file.

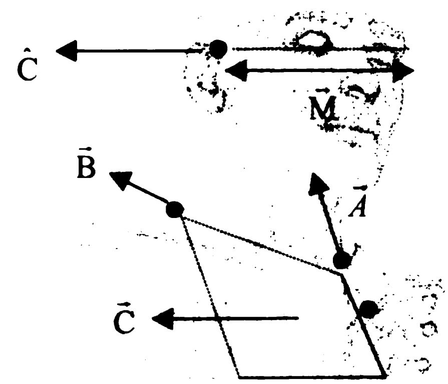


Figure 34: Calculation of Head CG when only one head target is visible.

$\vec{A}$ = vector from the mid - sternum to the sternal notch

$\vec{B}$ = vector from the sternal notch to C7

$\vec{C} = \vec{A} \times \vec{B}$

$\hat{C}$ = unit vecto r (direction al vector) of $\vec{C}$

$|\vec{M}|$ = magnitude between th e two head targets (from reference file)

$\vec{H}$ = Head Target Visible

$$\text{CM from one head target} = \vec{H} \pm (\hat{C} * \frac{|\vec{M}|}{2})$$

Equation 10: Calculation of head CM from only one head target.

Chair Position

The position of the chair was described by a recline angle, and the relationship of the thorax support to the pelvis support. A set of two targets were placed on the chair recline bar, on the thorax support, on the pelvis support and on the steering wheel base. By establishing a vector through each set of targets, the angle of each support plate could be determined in the sagittal plane, Figure 35 and Figure 36.

The buttocks support and the support behind the pelvis were attached and formed a ninety degree angle, only the pelvis support was targeted and its angle computed with respect to vertical. The buttocks support orientation had the same angle as the pelvis support, however the buttocks support angle was with respect to the laboratory horizontal axis. The thigh support and the foot support maintained a constant angle throughout the tests; these two support angles were measured prior to testing. All angles were deemed positive or negative by using the conventional right hand rule (X positive anterior and Z positive superior).

A chair total support angle (TSA) which is similar to the subject openness angle, was calculated by adding the angle of the thorax support relative to horizontal and the angle of the buttocks plate relative to horizontal, Figure 37. This identified a larger angle for an erect chair condition as compared to a slumped chair condition.

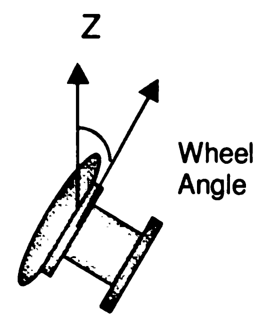


Figure 35: Measurement of wheel angle.

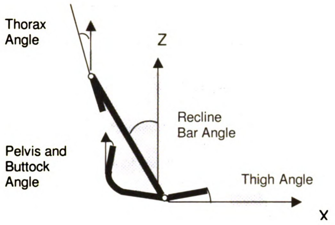


Figure 36: Angle measurements for the test chair, a larger angle is associated with a more erect chair position.

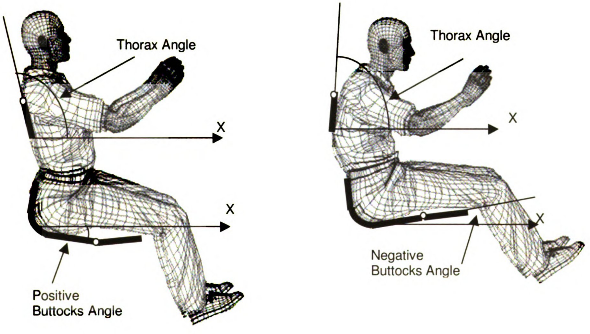


Figure 37: The Total Support Angle (TSA) of the test chair. A larger angle is associated with a more erect chair position.

Force Data

The force plates were mounted so that the X axis of the foot, thigh and buttocks plate pointed anteriorly relative to the subject, while on the thorax and pelvis force plates, the X axis pointed inferiorly, Figure 38. The Z axis of the plate was normal to the surface of the plate and the Y axis pointed left lateral. On the wheel, the X axis pointed superiorly and away from the subject.

To determine the support forces under the body, an initial reference trial (see *Test Descriptions* for details on reference position), with the chair unloaded, was collected. To zero the force plate data, for the reference test only, the force plate amplifiers were balanced. Because of the high capacity of the load cells, the readings were close to zero, but not exactly.

To account for this initial load measured on the force plates without a subject, the reference file forces were subtracted from each test. Since the chair changed orientation for each trial (Figure 39), a transformation matrix was developed to convert the components of the reference force values to the new plate orientation (Figure 40) and then subtracted from the force values obtained with the subject in the seat.

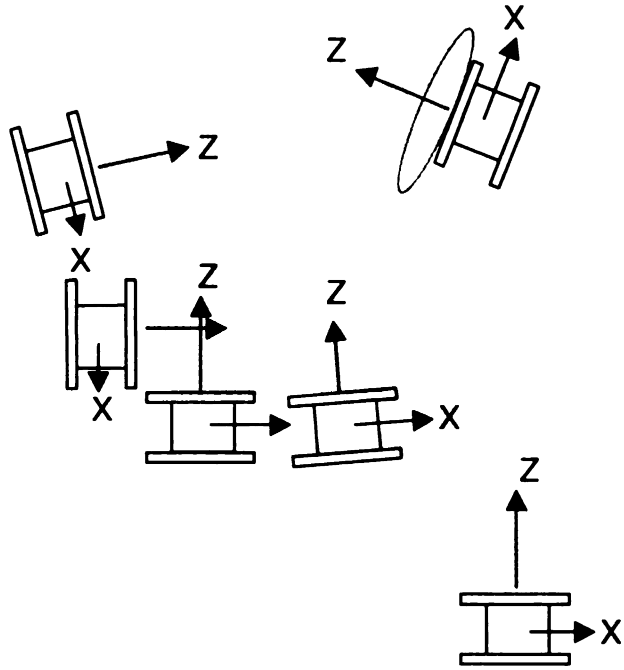


Figure 38: Force plate orientations.

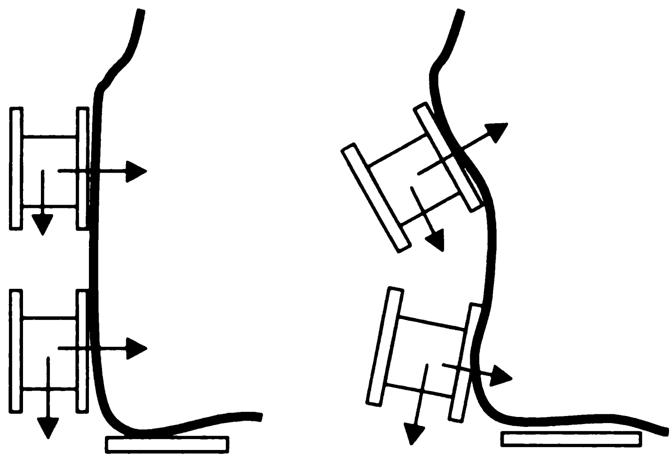


Figure 39: A comparison of the thorax and pelvis supports in a reference position and a trial position.

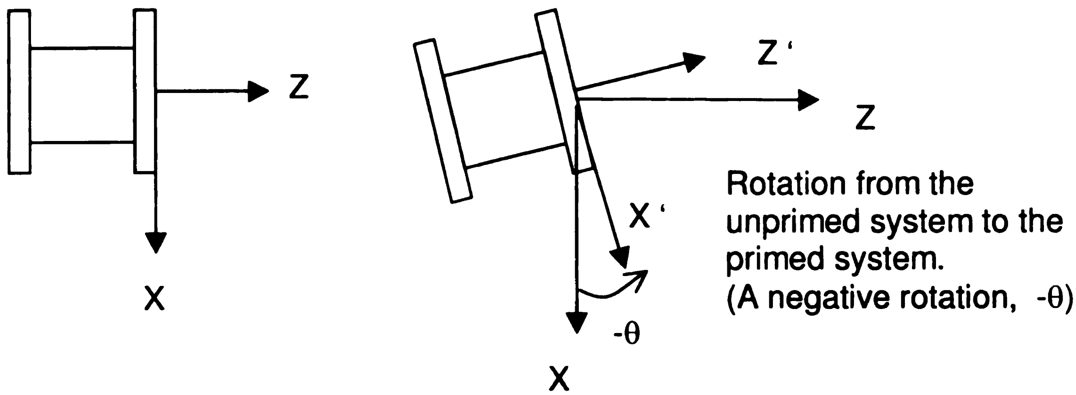


Figure 40: Rotation of the plate to recalculate the initial reference forces prior to subtraction from the trial data.

Figure 40 is an example of the change of the plate orientation from the reference file to a trial condition, (not including the recline angle of the entire chair). First the locations of the plates for the initial reference trial were computed, then the new positions of the plates from the trial data were computed. From these data, a transformation matrix was developed. This transformation matrix was then used to convert the force components of the reference forces (unprimed system) to the new orientation (primed system).

$$\begin{Bmatrix} F_x' \\ F_y' \\ F_z' \end{Bmatrix} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{Bmatrix} F_x \\ F_y \\ F_z \end{Bmatrix}$$

Equation 11: Rotation of the force plates from the reference position to the trial position.

Once the force data from the reference file was converted to the new plate orientation, these forces were either added to or subtracted from the forces measured for the trial data. The moments were computed with a separate set of strain gages in the load cells and the computation was performed about the center of the plate, thus a transformation was not necessary for the moments.

For all tests, the F_y values, or lateral shear forces were low relative to the other force components. The dominating forces were the normal forces, (F_z) and for some subjects there were substantial shear (F_x) forces primarily on the thorax and buttocks. The dominating moment value was the moment about the y axis, M_y.

Location of Resultant Forces

Another calculation performed with the force data was to determine the location of the resultant force in the plane of the support plate. This position was computed to evaluate how the location of the resultant force on the support surface varied as the posture of the subject varied. For this analysis, the dynamic files provided a continuous path of the resultant force, whereas the static files only provided one point per trial. With the trace path from the dynamic files, the distance of travel of the resultant force was easily identified. One application of this analysis would be in the medical industry, specifically wheelchair design. A test of this nature could determine if the chair movement is able to redistribute the forces, or provide a large enough movement of the resultant forces to reduce decubitus ulcers or pressure sores.

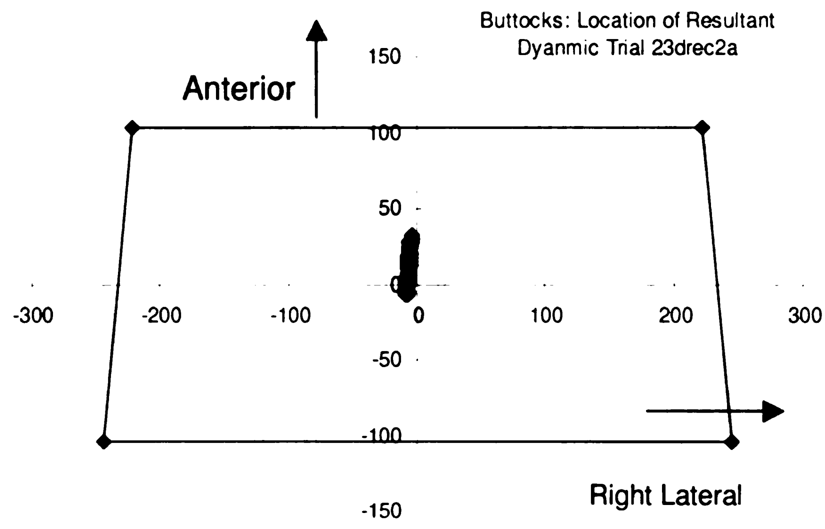


Figure 41: Example of resultant force travel on the buttock plate for a dynamic condition, top view.

To determine the position of the resultant force, the forces and moments were measured with the force plates, and then these values were used to compute the X and Y distances relative to the center of the force plate. Since the forces F_x, F_y, and F_z, and the moments, M_x, M_y and M_z were measured by the force plate, the only additional information needed to compute the location of the resultant force was the Z distance from the top of the plate to the center of the plate, which was provided by the manufacturer. The following equations were used:

$$M_x = (F_x * 0) + (-F_y * Z) + (F_z * Y) + T_x$$
$$M_y = (F_x * Z) + (F_y * 0) + (-F_z * X) + T_y$$

where Tx and Ty were the free surface torques

Equation 12: Equations used to determine the location of the resultant force.

The force plates were mounted behind or under the body for the seated tests, therefore it was not possible for the subject to generate a torque about the X or Y axis and T_x and T_y were considered to be zero. With this information, and rearranging the above equations, X and Y were determined. Once X and Y were computed, the distance the resultant force traveled in the X or Y direction could be computed, thus determining how much the movement of the chair shifted the resultant force in either direction, Figure 41.

$$Y = \frac{M_x}{F_z} + \frac{F_y * Z}{F_z}$$

$$X = \frac{F_x * Z}{F_z} - \frac{M_y}{F_z}$$

Equation 13: Determining X and Y location of the resultant force on the surface of the force plate.

Internal Joint Estimation

Lastly, the external support forces were used to estimate the internal forces at a specific point in the lumbar spine. To estimate the internal forces at a specific location, the seated subject must be in static equilibrium. To evaluate the equilibrium state of the subject, the Fx and Fz forces of each force plate were converted to the laboratory axis system and then the horizontal and vertical components were summed. If the subject was in equilibrium, both the horizontal and the vertical forces should sum to zero. As an example, subject 17 in the neutral condition of recline 1 measured horizontal forces with a residual value of -3.66 N (-0.82 lb), and the vertical forces summed to –727.46 N (163.47 lb).

Once the subject's weight was subtracted from the vertical forces the remaining force value was 2.34 N (0.5 lb). Note that neither the horizontal or vertical forces summed to zero (see Results Section for full data listing). However, these values were well within the measurement accuracy of the instrumentation and error was introduced during the calculations of the support plate angle and the transformation of the data into the laboratory axes system. Nevertheless, the overall equilibrium results were deemed reasonable and further internal joint analysis proceeded. Results of the force data in terms of an equilibrium analysis are discussed in the Results section.

Force data collected for this research measured support loads exerted by the body onto the chair, steering wheel or foot support. Equally as important as quantifying the external support loads was the ability to estimate internal joint loading from these external loads. For example, support force data could be used to determine how the internal reaction moments and loads change at the L5/S1 joint center as a person's posture changes. Having reference data of this nature could verify which postures reduce a specific type of loading on the intervertebral disc, useful information for those with back injuries. Also, these data are useful in the development of a kinetic model of a seated individual.

Andersson [48] estimated compressive loading of the discs in various seated postures based on the measurement of spinal disc pressure, however he did not measure or compute the shear forces or moments. Chaffin[49] also provided internal moment estimates on the lumbar spine based on general lifting tasks. To develop a perspective on the magnitude of the moments of a seated individual, moments estimated during a lifting task will be used for comparison when the results are presented.

From the external force data, it has been determined that the summation of the forces for the subjects produced a condition of equilibrium, or one that was within the measurement error of the instrumentation. Therefore, it was assumed the following approach would provide reasonable results.

For this dissertation, the methodology for the estimation of joint loads at the L5/S1 joint center were developed and tested on an individual subject. The analysis method for determining the internal joint loading is a tedious process and because a subject's specific anthropometry is used in the calculations, the analysis must be performed on an individual basis. As of yet, the analysis has not been optimized for automatic data analysis of multiple subjects. For these reasons, a sample set of data has been completed for this dissertation, but the analysis of the entire subject pool using these methods is considered a future step for this work.

Using an example subject throughout, the steps used to determine the joint loads are outlined in this section. The desired outcome of the internal joint load calculation was to estimate the forces and moments at the approximate L5/S1 joint center. The internal force results for Subject 17 in the most upright position (recline1) for all four torso articulations (slumped, neutral, erect and super erect) are listed in the Results section of this dissertation. Subject 17 was chosen because all of the target data were available for all four conditions and the equilibrium results were reasonable.

First, the body was divided into anatomical regions. These regions were based on common anatomical sections used by Dempster and Webb[49] and included the head, neck, thorax, lumbar (also called the abdomen), pelvis, upper arm, forearm and hand, Figure 42. For this analysis, the body segment masses of the torso, the center of masses (CM) of the torso, and the location of the L5/S1 joint center were necessary. However, knowing the segment mass and CM location for the legs was not necessary.

Several estimations were made to determine what type of loads were occurring in the body. Since the center of mass (also known as the center of gravity) and the mass of each body segment could not be measured easily on a living subject, these data were estimated based on cadaver work completed by other researchers[49]. Because these masses and locations of the CM were only estimates, the joint forces and moments were highly susceptible to errors in these estimations, particularly the moment calculations.

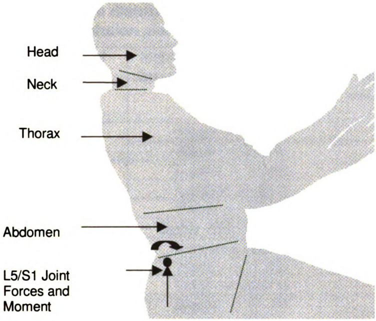


Figure 42: Sectioning of body to determine the center of masses of each section.

Calculation of Segment Mass as a Percent of Body Weight (%BW)

The mass for each of the body sections was defined based on data from Webb Associates [49], Table 10. The section masses were estimated as a percentage of the total body weight. For comparison, the results from Webb were also checked against those from Dempster, Clauser and Morris [49], Table 11.

Table 10: Percentage distribution of total body weight according to different segmentation plans (from Webb Associates, 1978) [49]

Grouped Segments, % of Total Body Weight	Individual Segments, % of Grouped Segments Weight	Example Subject (Subject 17) Weight 74.5 kg (164 lbs.)
Head and Neck = 8.4%	Head = 73.8%	4.62 kg
	Neck = 26.2%	1.64
Torso = 50.0%	Thorax = 43.8%	16.33
	Lumbar = 29.4	10.96
	Pelvis = 26.8%	9.99
Total Arm = 5.1%	Upper Arm = 54.9%	2.09
	Forearm 33.3%	1.26
	Hand = 11.8%	0.45
Total Leg = 15.7%	Thigh = 63.7 %	7.46
	Shank = 27.4%	3.21
	Foot = 8.9%	1.04

Table 11: Estimates of mass distributions (kg) for various male and female percentiles (a). [49]

	Male				Female		
	5%	50%	95%		5%	50%	95%
Hand	0.4	0.4	0.6		0.3	0.4	0.5
Forearm	0.9	1.2	1.6		0.7	1.0	1.4
Upper Arm	1.6	2.1	2.8		1.3	1.7	2.5
Head, Neck and Trunk	33.0	43.4	56.8		27.2	35.8	52.1
Arms, Head, and torso above L5/S1 disc (b)	27.2	35.8	46.8		22.4	29.5	42.9
Upper Leg	5.7	7.4	9.7		4.7	6.2	8.9
Lower Leg	2.6	3.4	4.5		2.2	2.8	4.2
Foot	0.7	1.0	1.4		0.7	0.9	1.3
Body Weight	57.1	75.2	98.3		47.1	62.1	90.1

(a) Estimates are from Dempster (1955) as corrected for fluid loss by Clauser et al. (1969).
(b) Based on Morris et al. (1961)
(c) Based on National Health Survey, Weight, Height and Selected Body Dimension of Adults, PHS Pub 1000, Series 11, No. 8 (1965).

Calculation of Location of Center of Mass within Each Segment

The calculation of the location of the center of mass within each body segment was determined by various methods. For the head, two targets were placed on either side of the head at the approximate location of the center of mass (10mm forward and 20 mm above the Tragion). As described earlier, the center point of these two targets was computed and used as the head CM.

For the upper arm, forearm and hand, the CM was determined as a percentage of link lengths, Figure 43 and Figure 44. The length of the vector between the shoulder (acromion) and elbow targets determined the link length of the upper arm. The length of a vector between the elbow and wrist targets determined the link length of the forearm. These link lengths were compared to the link lengths obtained by calculating the lengths as a percentage of standing height, Table 12. Since a target was not placed on the hand, this method could not be used to determine the link length of the hand. The comparisons from the upper arm and forearm were averaged to obtain a percentage of 104.5% and this percentage was multiplied by the link length obtained from using the Drillis[49] percentage of stature method. By combining the anthropometric measures made with the targets and the link lengths based on a percentage of stature, the link length of the hand was determined to be194.9 mm.

Table 12: Determining link lengths of arm[49].

	From Targets	% of Stature (Stature of Subject 17 =1727 mm)	Comparison
Shoulder to Elbow	324.6	321.25	108%
Elbow to Wrist	273.9	252.17	101%
Wrist to tip of middle finger	---	186.54	---

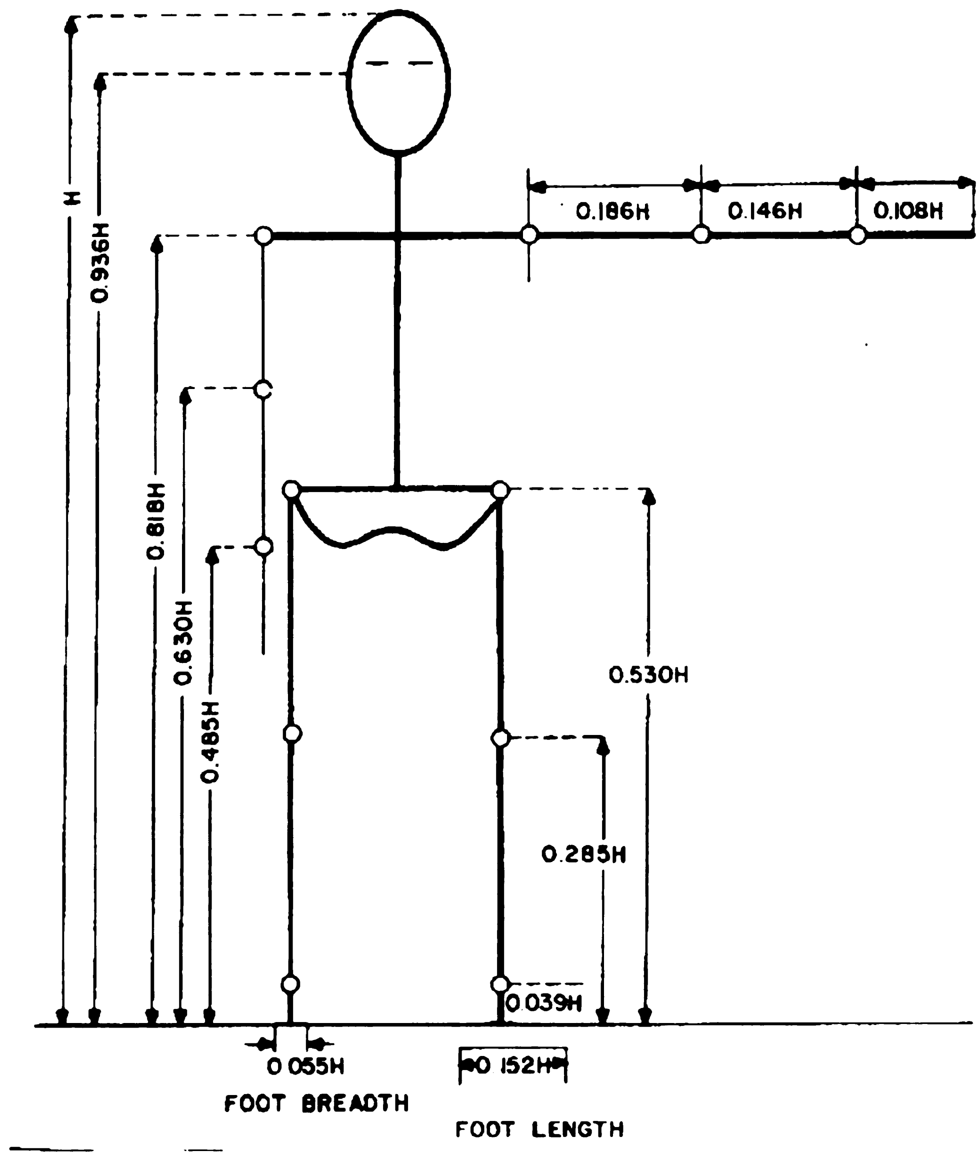


Figure 43: Body segment lengths expresses as a proportion of body stature by Drillis and Contini (Roebuck, Kroemer, and Thomson, 1975) [49]

After the link lengths of the arm were computed, the CM location could be identified as a percentage of the length of the link using the reference data listed in Figure 44 and Table 13.

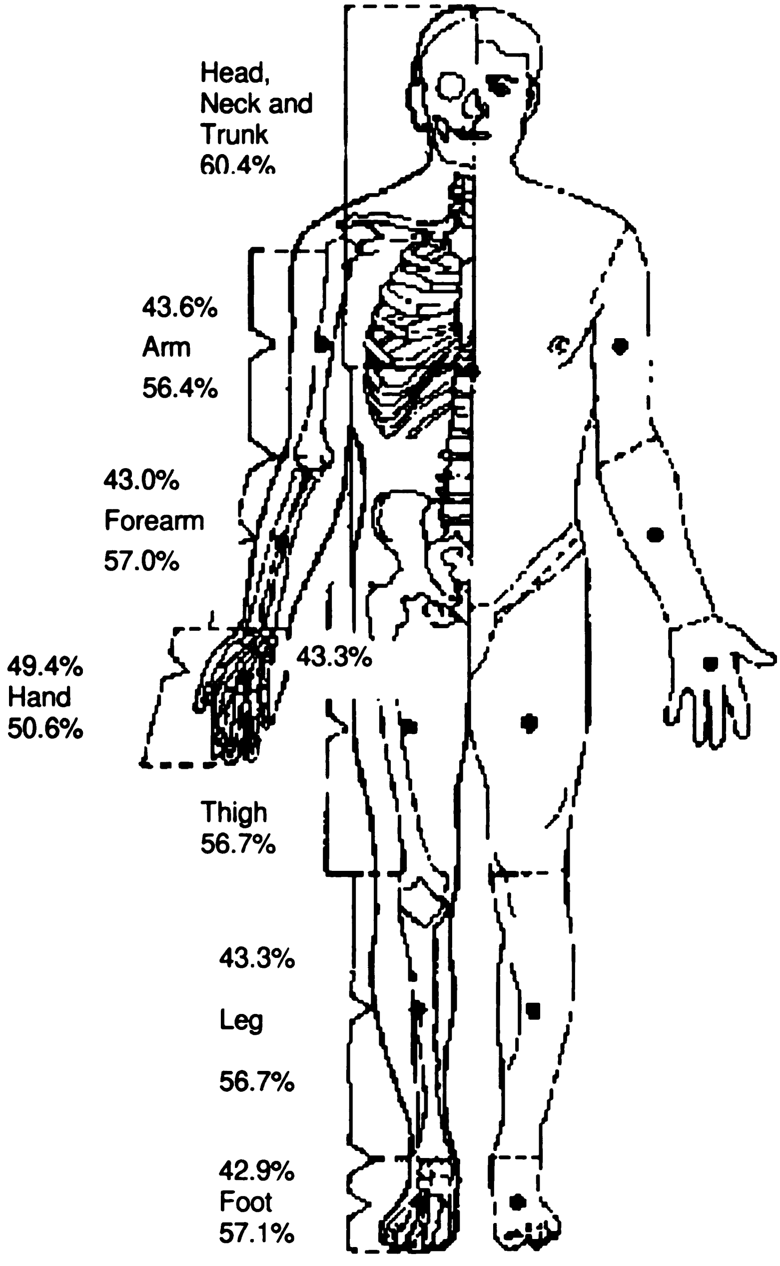


Figure 44: Link boundaries and mass center locations as a percentage of link lengths (Dempster, 1955) [49].

Table 13: Distances to segment center of mass in centimeters[49].

	Male			Female			Percent Link Length (a)
	5%	50%	95%	5%	50%	95%	
Wrist to hand CM	6.7	7.0	7.4	6.1	6.4	6.7	---
Elbow to forearm CM	11.0	11.7	12.3	9.9	10.4	11.0	43.0 %
Shoulder to upper arm CM	12.5	13.2	14.0	11.6	12.1	12.5	43.6 %
Hip to trunk, neck, head CM (b)	18.1	19.3	22.5	16.7	17.9	19.1	36.6 %
Knee to upper leg CM	23.0	24.8	26.1	22.2	23.2	24.2	56.7 %
Ankle to lower leg CM	23.0	23.2	24.9	19.3	20.6	22.1	56.7 %
Heel to foot CM	10.6	11.4	12.3	9.4	10.3	11.1	42.9 %

(a) All dimensions are based on the Dempster percentage of link length estimates (1955).
(b) When in erect posture. Measured from hip to top of head

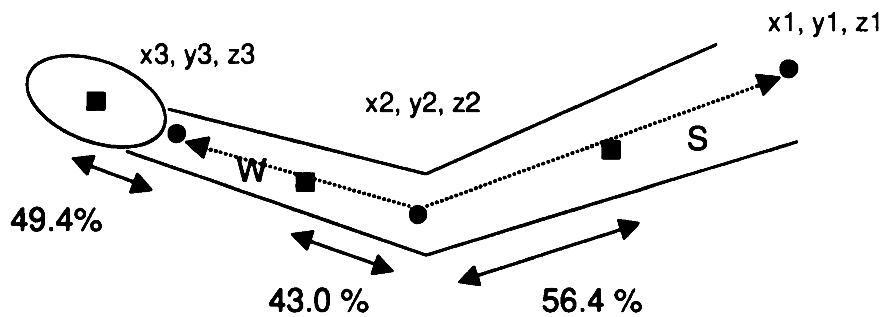


Figure 45: Calculation of CM for the upper arm, forearm and hand.

To locate the center of mass of the upper arm, first a vector was created from the elbow to the shoulder target, (S). The magnitude and the unit directional vector were computed for (S). According to the information from Dempster[49], Figure 44, the location of the center of mass (CM) was 56.4% of the link length of the upper arm from the elbow, Figure 45. A vector that had the direction of (S) with the magnitude of 0.564 * (S) was added to the vector identifying the elbow target, thus producing the CM location of the upper arm, Equation 14.

$\vec{S}$ = vector from the elbow target to the shoulder target

$\hat{S}$ = unit vector from the elbow target to the shoulder target, also defines the direction of $\vec{S}$

$|S|$ = magnitude of vector $\vec{S}$

$\vec{E}$ = vector from laboratory center to elbow target

$$CM\ of\ Upper\ Arm = \vec{E} + 0.564 * |S| * \hat{S}$$

Equation 14: Locating the Center of Mass for the upper arm.

To identify the location of the center of mass for the forearm, a vector from elbow to wrist (W) was created. The magnitude of (W) and the unit directional vectors were computed. The CM of the forearm was located 43% of the forearm link length from the elbow along the vector (W). Using the same methodology used to locate the CM of the upper arm, the CM of the forearm was determined.

Once the link length from the wrist to the tip of the middle finger was determined, the CM of the hand could be determined. Since a target was not placed on any of the fingers, an assumption had to be made that the hand was in line with the forearm therefore having the same direction. From this information, a vector that was 49.4% of the hand link length in the same direction as the forearm link was added to the vector defining the wrist target. This defined the CM of the hand. It was also assumed that the hand CM was the point of the steering wheel-body contact, and that the forces transmitted between the subject and the wheel occurred through this point.

The method of defining the CM location based solely on link lengths could not be used for the location of the neck, thorax, abdomen and pelvis CM. These body sections were not as clearly defined by targets as the extremities, and both inferior/superior and anterior/posterior coordinates were necessary to define each body section. To estimate the location of the CM for these body sections, the seated anthropometric mid-sized male dummy data[50] were used, Table 14.

First, data points from the dummy had to be matched to the target data from the subject. The target locations of C7 and S1 (from the subject) were adjusted to account for the 10 mm radius of the target and moved the target point to the skin. This was accounted for by creating a vector from C7 to the sternal notch target and moving the location of the C7 target 10 mm inward along this vector. The adjusted C7 target point was treated as the C7 skin point. The S1 target was also adjusted 10 mm inward along a vector from S1 to the mid-point between the two ASIS targets. These two points were used in conjunction with the dummy C7 and L5 points to calculate the translation coordinates.

The coordinates of the CM locations were translated from the mid-male dummy data to the subject data. These data were translated using the adjusted target landmarks (now skin points) as the original translation point. Translations were developed from both the adjusted C7 and S1 targets of subject 17. The translations developed in Table 15 were applied to the data points in Table 14, moving the dummy points into the subject coordinate system. No rotation was necessary since both the subject and the dummy data were positioned in a sagittal plane, thus only translation was necessary to convert between two. Note that in the dummy specifications, all of the centerline points had a zero coordinate for the Y axis. However actual subject data showed that the pelvis and thorax were not in the sagittal plane, there was a small rotation between the thorax and pelvis. This small rotation is common within human data and was ignored. Between targeting error, and the general human body composition, it is rare to find the thorax and pelvis in perfect alignment.

After the translation, the CM of the neck, thorax, abdomen and pelvis were plotted, Figure 46. Figure 46 shows that there is an anterior/posterior shift in the CM locations based on the two different methods (using either C7 or S1) for calculating the CM targets, and a slight vertical shift for the S1 data points. This vertical shift was due to the use of the L5 dummy point (S1 dummy point was not available) to translate the S1 target of the subject.

A translation of the dummy L5/S1 point could have been used to define the approximate L5/S1 joint center in the subject data. However, by using the measurement of the subject's pelvic width (ASIS to ASIS), a more accurate estimate of the location of the L5/S1 joint center was available. Based on work from Renyolds, 1981[51], the location of the L5/S1 joint center was estimated as 26.4% of the pelvic width (PW) rearward of the ASIS, along a line from the ASIS to S1 (pelvis x axis) and 12.6% of PW superior of the ASIS, along a line perpendicular to pelvis x axis.

Table 14: Locations of body landmarks from mid-male crash test dummy specifications[50].

(mm)	X	Z
C7 – Skin	-266	489
L5 – Skin	-174	13
Head CM	-179	646
Neck CM	-195	515
Thorax CM	-177	267
Abdomen CM	-85	110
Pelvis CM	-74	17
T12/L1 - Joint	-177	165
L5/S1 - Joint	-89	39
HJC	0	0

Table 15: Translation coordinates between the dummy points and the target points.

Target Locations	X (mm)	Y (mm)	Z (mm)
C7	-472.6	1.8	962.4
S1 treated as L5	-406.4	27.4	497.3
	Translation Points: Difference between Dummy Data and Subject Targets		
C7 Dummy to Target	-206.6	1.8	473.4
L5 Dummy to Target	-232.4	27.4	484.3

Research from Seidl and Marchinda[52] showed that the accuracy of defining internal pelvic points was increased by obtaining three anthropometric measures of the pelvis and using these measures to estimate interior pelvic points. For more accurate definitions of internal pelvic points, it is recommended that future studies use the following three measures: pelvic width (left ASIS to right ASIS), pelvic height (mid- ASIS to superior portion of pubic crest) and pelvic depth, ASIS to PSIS (posterior superior iliac spine).

After the masses of each body segment, the location of the center of mass and the location of L5/S1 were identified, the next step was the summation of the vertical and horizontal forces and the summation of the moments in the y direction about L5/S1, Equation 15 -Equation 17.

Finally, by taking the segment masses, the locations of the center of masses, and the force data, a free body diagram of the body superior to the L5/S1 estimated joint center was analyzed. Treating all of the body segments as rigid, and requiring equilibrium, the internal forces and moments could be determined.

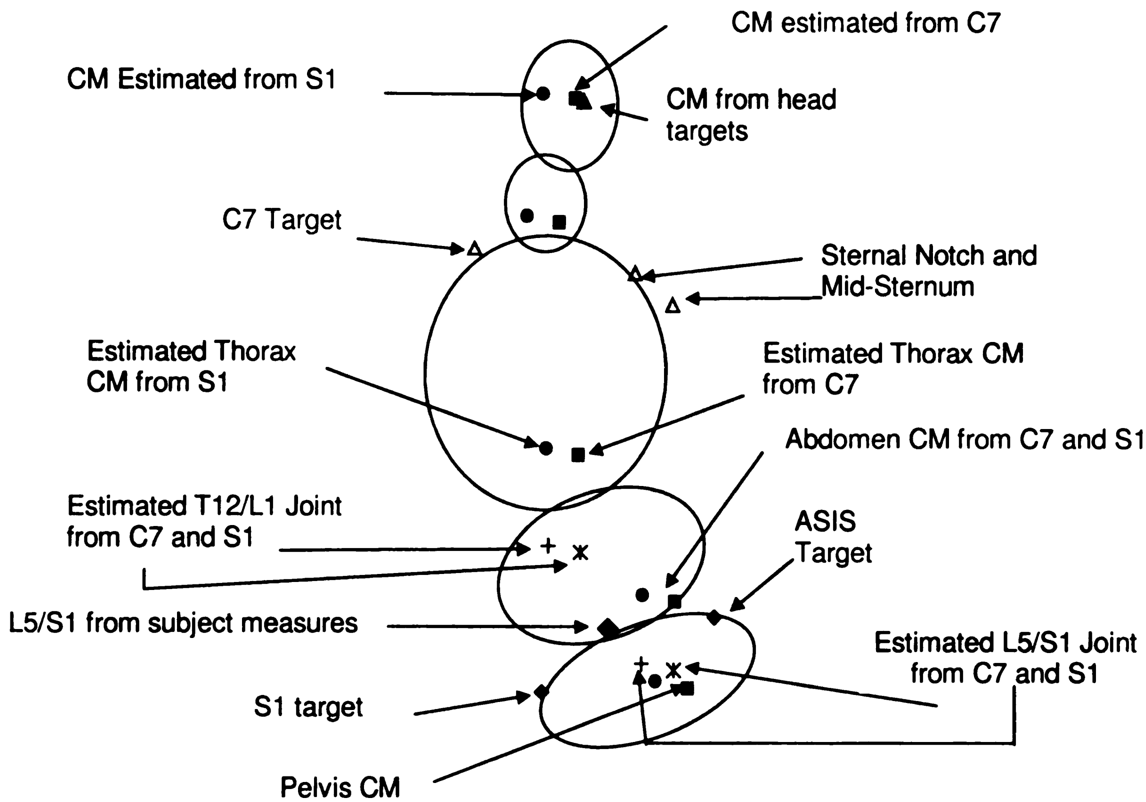


Figure 46: Subject 17, recline 1, neutral. Centers of Mass computed from the C7 skin point and from the S1 skin point.

$\sum F_x = 0$

Horizontal support through wheel + horizontal support through thorax support = horizontal (shear) loading at a plane between the abdomen and pelvis

Equation 15: Summation of the horizontal forces, according to the laboratory coordinate system.

$\sum F_z = 0$

Head Weight + Neck Weight + Thorax Weight + Abdomen Weight
+ 2 * Upper Arm Weight + 2 * Forearm Weight + vertical force on hands through wheel
+ vertical force on throax through thorax support =
vertical loading at plane between the abdomen and pelvis

Equation 16: Summation of the vertical forces, according to the laboratory coordinate system.

$$\sum M_{\text{y about L5/S1}} = 0$$

$$(F_z * x)_{Head} + (F_z * x)_{Neck} + (F_z * x)_{Thorax} + (F_z * x)_{Abdomen} + (2 * F_z * x)_{UpperArm}$$
$$+ (2 * F_z * x)_{Forearm} + (F_z * x)_{Wheel} + (F_x * z)_{Wheel} + (F_z * x)_{Thorax\ Support}$$
$$+ (F_x * z)_{Thorax\ Support} + M_{\text{y wheel}} + M_{\text{y thorax support}} = -M_{\text{y about L5/S1}}$$

Equation 17: Summation of the forces and moments about the L5/S1 estimated joint center.

Once the forces and moments were computed at the level of the estimated L5/S1 joint center, the final step was to transform these forces from the laboratory coordinate system to a more meaningful system. Since the subject was seated in a reclined position, the data at L5/S1 joint were rotated to match the orientation of the pelvis at each test position (slumped, neutral, erect and super erect). This rotation was assumed to match the angle of the lower lumbar spine and the sacrum region more accurately than the vertical and horizontal orientation of the laboratory coordinate system. The angle of the pelvis was measured as the angle of a vector from S1 to the mid-ASIS location with respect to lab horizontal.

The results of the internal joint analysis are discussed in the section titled Results and Analysis of Static Data.

Results, Analysis and Discussions of Static Data

At this time it is important to note that data similar to those presented in this dissertation are unavailable from any other source. A study examining the forces exerted on the seat back of an office chair[53], listed data comparable to those presented and discussed here. However, the study of the office chair[53] did not investigate forces supporting the buttocks, thighs, feet or hands during postural changes, and only the position of the spine in unsupported seated conditions was recorded. Further, an investigation measuring seated body forces and full body posture concurrently has never been performed; and results of the search done by this author indicate the data presented in this study are the first of their kind.

The following section discusses the data in terms of the static tests and analyzes the forces and body positions. The data in raw format are too numerous to present; rather the raw data have been reduced and summarized so meaningful conclusions can be made about the entire subject sample.

Test Chair Repeatability

Prior to comparing the force or motion data it was necessary to determine if the chair was consistently positioned for the various test conditions. The test assistants moved the chair to the various conditions (recline 1, 2, or 3 and slumped, neutral, erect or super erect) based on markings positioned on the chair. Because of inter-operator error, some variance was expected in the chair positioning.

The objective when positioning the recline of the chair was for each of these recline positions to be varied by four degrees: recline 1 was 20°, recline 2 was 24° and recline 3 was 28°. The thorax support was varied 5° between torso articulations (slumped, neutral, erect and super erect) and the range from slumped to super erect was 15°; the pelvis support also moved 5° between each condition and had a range of 15° between slumped and super erect. Since the thorax and pelvis movements were coupled, this resulted in a total chair movement of 30° from slumped to super erect.

Table 1 and Table 2 present the average chair position for all the test conditions and all of the subjects. The recline angle, on the average, reflected the desired location with a standard deviation ranging from 0.8 to 1.3 degrees between the three recline angles. The desired angles were 20°, 24°and 28° and the averaged measured angles were 20.0°, 24.2° and 28.4° with the negative value (seen in Table 1) indicating that the measurement was rearward of vertical, or reclined.

Table 16: Average recline measurement of the chair in degrees for each condition (n=92). The calibration of the recline angle relative to vertical was computed by subtracting the offset of the recline bar.

Repeatability of Chair (degrees)	Recline Bar Measure	Recline Bar Std*	Chair Recline subtract offset**
Recline 1	-41.0	1.3	-20.0
Recline 2	-45.2	1.2	-24.2
Recline 3	-49.4	0.8	-28.4

*Std = average standard deviation across slumped, neutral, erect and super erect conditions.

**21 degree offset between the recline bar and chair recline with respect to vertical.

Table 17: Average angle in degrees measurement of the thorax support and the pelvis support for each recline angle (negative sign means angle was rearward of lab vertical relative to a right-handed coordinate system with x anterior and z superior).

(degrees)	Thorax	Thorax Std	Pelvis	Pelvis Std
		Slumped		
Recline 1	-16.4	2.2	-23.4	1.2
Recline 2	-19.7	2.2	-28.0	1.0
Recline 3	-24.1	2.4	-32.7	1.4
		Neutral		
Recline 1	-20.6	0.9	-19.0	2.6
Recline 2	-24.7	0.7	-23.4	0.9
Recline 3	-28.8	0.8	-27.4	0.7
		Erect		
Recline 1	-26.2	1.2	-13.8	2.6
Recline 2	-30.6	0.9	-17.4	0.7
Recline 3	-35.0	2.8	-22.4	1.5
		Super Erect		
Recline 1	-31.0	1.2	-8.5	1.4
Recline 2	-35.6	2.2	-12.8	0.6
Recline 3	-39.5	2.2	-17.4	1.0

The data in Table 2 showed that on the average the thorax and pelvis supports were each adjusted approximately 5° degrees between torso articulations. However, the pelvis support angle showed a high standard deviation (>2.0) for recline 1, neutral and erect conditions. The thorax support angle also showed a high standard deviation for the slumped condition in all recline angles, the erect condition in recline 3, and in the super erect condition for recline 2 and 3. The data were re-examined and the single most extreme outlier was removed from these data, Table 3. In the majority of cases (5 of 8) the outlier came from subject 1 trials. Removing this one point reduced the standard deviations in all cases without drastically changing the average. These outlier measures could be due to partial target obstruction or data interpretation during sections of missing targets.

When examining the entire body of data, it showed that the chair was positioned in a repeatable fashion meeting the criteria that was outlined for testing: recline angles of 20°, 24°and 28° and 5° changes of the thorax and pelvis supports between the conditions designed to articulate the torso. Therefore the chair was consistently adjusted between subjects and within trials, allowing comparisons between the different conditions.

Table 18: Average angle measurement of the thorax support and the pelvis support for each recline angle after removal of one outlier in the shaded boxes.

(degrees)	Thorax	Thorax Std	Pelvis	Pelvis Std
		Slumped		
Recline 1	-16.0	1.1	-23.4	1.2
Recline 2	-20.1	1.0	-28.0	1.0
Recline 3	-23.7	1.5	-32.7	1.4
		Neutral		
Recline 1	-20.6	0.9	-18.5	1.2
Recline 2	-24.7	0.7	-23.4	0.9
Recline 3	-28.8	0.8	-27.4	0.7
		Erect		
Recline 1	-26.2	1.2	-13.3	1.4
Recline 2	-30.6	0.9	-17.4	0.7
Recline 3	-34.4	0.8	-22.4	1.5
		Super Erect		
Recline 1	-31.0	1.2	-8.5	1.4
Recline 2	-35.2	0.4	-12.8	0.6
Recline 3	-39.1	1.4	-17.4	1.0

Force Data for Static Tests

Recline Angle Comparison for Primary Forces

The forces discussed in this section are called the primary forces and are the maximum average support forces. These data include the normal forces (Fz) under the feet, thighs and buttocks and behind the pelvis and thorax, Figure 1. The shear force (Fx) was the largest force on the steering wheel and was the most likely to be affected by postural change, therefore it was tabulated with the normal forces from the other support plates.

Due to the body weight of the subject, all of the normal forces acted into the force plates and these data are reported with a negative sign. Since the force on the steering wheel was acting in a downward direction, due to the weight of the arms, this force is also reported as a negative force. Figure 47 depicts the positive directions of the primary forces acting on the force plates.

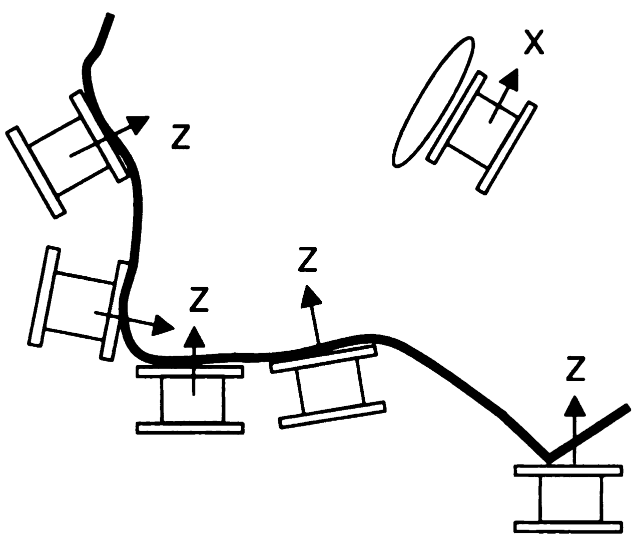


Figure 47: Primary forces represent the normal forces under all of the force plates except for the steering wheel where the shear force, Fx, was the maximum force.

Table 19: Primary forces for recline 1, 2 and 3 for each support plate. (Wheel is shear load, Fx, while all others are normal loads, Fz).

(Newtons)	Recline 1	Recline 2	Recline 3
Thigh	-135.1	-129.5	-117.6
Buttocks	-418.1	-405.3	-395.4
Pelvis	-24.8	-31.3	-34.1
Thorax	-184.3	-204.1	-225.8
Foot	-101.9	-97.2	-96.5
Wheel (Fx)	-32.7	-31.6	-33.1

Force data from all of the subjects were first analyzed in terms of the three recline angles, Table 4, where the data from the four conditions (slumped, neutral, erect and super erect) were averaged for each recline angle, the individual conditions are analyzed in a later section. Figure 48 through Figure 51 are graphical representations for each condition; within each graph, the force data for the three recline angles are represented.

When evaluating the force data between the various recline angles for statistically significant differences, the conditions (slumped, neutral, erect and super erect) were lumped together and compared as one set of data for each recline angle. A One Way Repeated Measures Analysis of Variance[54] statistical test was performed with these data. Both tests on data normality and variance equality were performed. These data failed the normality test but passed the equal variance testing, when this occurred, Friedman's Repeated Measures Analysis of Variance on Ranks was run. All statistical testing was performed at a 95% confidence level unless otherwise noted.

Table 20 shows that a significant difference exists between all recline angle combinations for the buttocks, pelvis and thorax when examining the primary support forces. The thigh and feet exhibited significant differences for two out of the three recline combinations and the wheel support loads (Fx) showed a significant difference only between reclines 2 and 3.

Table 20: Testing for a significant statistical difference between the primary support forces at given recline angles. Normal forces (Fz), except wheel force, which is (Fx).

Fz	Recline 1 vs. 2	Recline 2 vs. 3	Recline 1 vs. 3
Thigh	-	Y	Y
Buttocks	Y	Y	Y
Pelvis	Y	Y	Y
Thorax	Y	Y	Y
Feet	Y	-	Y
Wheel (Fx)	-	Y	-

These data support the conclusion that in the upright recline, the body weight was distributed between the seat pan (under buttocks and thighs), the footplate and the seat back (behind the thorax and pelvis). As the chair tipped rearward, or the recline angle increased, the loading was redistributed, with more of the load going into the seat back and less of the load into the seat pan and foot plate. This conclusion was best seen by the fact that the average load under the buttocks was reduced from -418.1 N in recline 1 to -395.4 N in recline 3 (negative sign indicated force into the plate) and the thorax support load was increased from -183.4 N in recline 1 to -225.8 N in recline 3. As the recline angle of the chair increased, the load under the thighs and feet also decreased by 17.5 N and 5.4 N respectively. Like the thorax, the load behind the pelvis also increased by 9.3 N. The loading supported by the wheel stayed constant as the recline angle changed and was confirmed by the lack of statistically significant results.

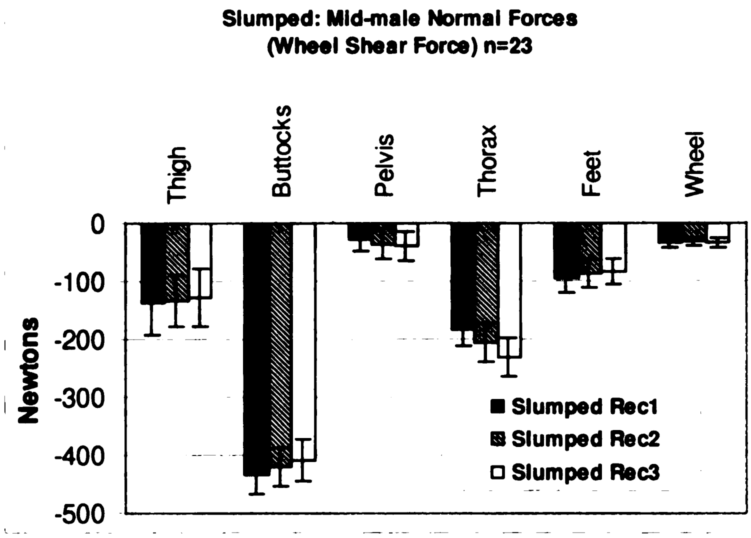


Figure 48: Primary support forces for the slumped condition at three recline angles.

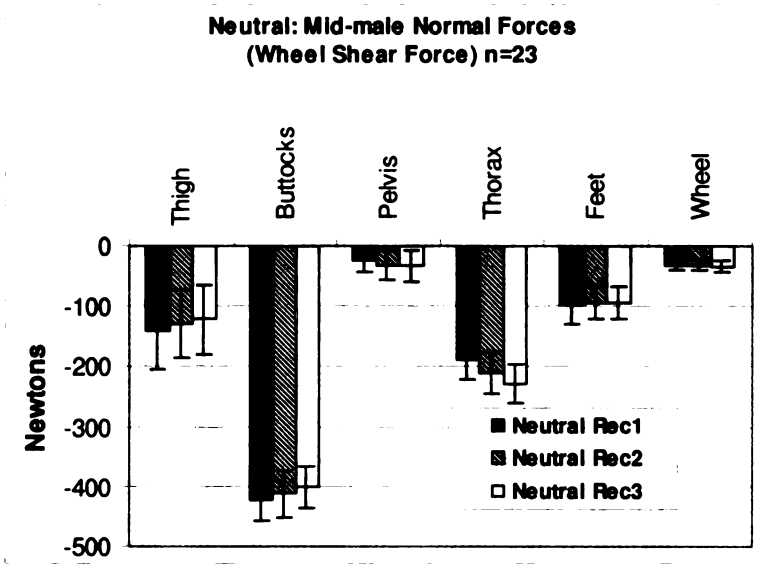


Figure 49: Primary support forces for the neutral condition at three recline angles.

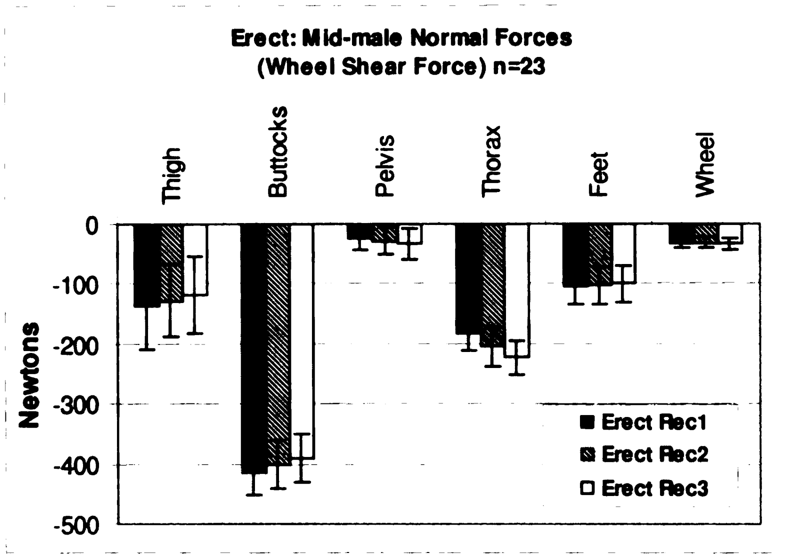


Figure 50: Primary support forces for the erect condition at three recline angles.

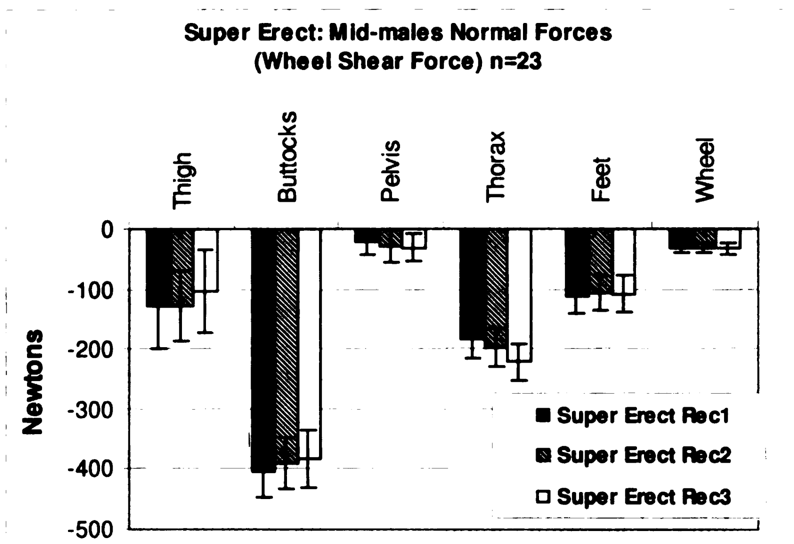


Figure 51: Primary support forces for the super erect condition at three recline angles.

Thus from these results, when determining the force distribution of a person on a seat, it is important to take into account the recline angle of the seat. The data from recline 3 (the most reclined position) would not be applicable to a subject seated in an upright position such as in an office chair. However, because the change in loading distribution is primarily affected by gravity, interpolations could be developed to estimate the loading for many recline angles.

The support data least affected by the recline angle is the steering wheel loading. Since the subject was allowed to pick both a wheel distance and a foot distance, this trend may be an artifact of the test protocol. In many automobiles, the foot to wheel distance is fixed and either the preferred elbow angle or knee angle must be compromised in the driving position. The newest generation of automobiles offers an adjustable pedal position, and this configuration more closely relates to the testing procedure implemented for these data.

The only published data pertaining to the measurement of seated support forces was that by Faiks[53] Faiks measured the forces behind the thorax, Figure 52, necessary to lift a relaxed person from a 20° reclined position to an upright (0°) position. This test was performed on 22 subjects ranging from 5th percentile stature to 95 th percentile stature. The data for this dissertation began at a recline angle of 20° and only involved subjects that were 50th percentile in stature. If we assume the average data reported in the Faiks study is a fair representation of the 50th percentile individual, then a direct comparison between the two data sets can occur at the 20° recline angle.

The Faiks[53] data reported an average of 25 pounds behind the thorax at the 20° recline angle, which converts to 111.3 N and compares to 184.3 N measured for this study. A difference of 73.0 N (16.4 lbs). Faiks also reported that the force data exhibited a slope of 0.554 (0.554 lbs of force per degree of recline), where the data for this dissertation had a slope of 5.1N or 1.12 lbs per degree of recline. It is clear that the two sets of thorax support data have differing slopes, and that the data for this dissertation is an average of four amounts of torso articulation while the Faiks data did not allow variations in torso articulation. It may be that these factors, along with the possibility that the anatomical regions supported in each study varied, cause the differences in the thoracic support forces.

However, if the thorax and lumbar forces were added together for the 20º recline of the Faiks[53] data, the total normal force would be 19.01 N, or 43.0 lbs. If the average thorax and pelvis normal forces from recline 1 (20º) of this study were added together, the total force would be 209.0 N, or 47.0 lbs. Therefore, in terms of total back support, the Faiks data and the data from this study are similar.

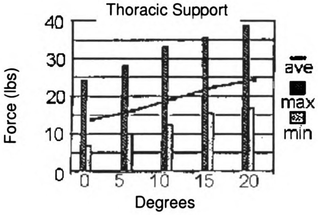


Figure 52: Thoracic forces necessary to lift a person from a reclined position to an upright position[53].

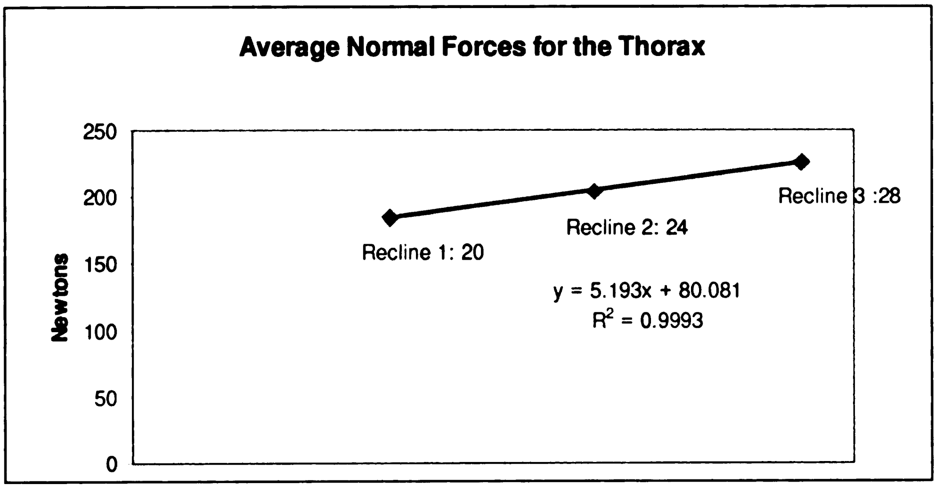


Figure 53: Subject data for thorax support at three recline angles. Recline 1: 20°, Recline 2: 24°, Recline 3: 28°.

Recline Angle Comparisons for Secondary Forces

The secondary forces (second largest in magnitude) are the shear forces (Fx) acting in the superior to inferior direction on the thorax and pelvis and acting in the posterior to anterior direction under the buttocks, thighs and feet, Figure 54. The secondary force for the wheel is the normal force Fz, this is the second largest force for the wheel and represents the pushing or pulling of the wheel. The shear forces summarized in Table 21 and Figure 56 through Figure 59 are the forces that were measured by the force plates. There are two sets of shear forces, there is a set that acts upon the chair, and then there is a set that is equal in magnitude and opposite in direction that acts upon the body, Figure 55. The shear forces discussed for this dissertation always refer to the forces acting upon the chair. Thus a positive shear force measured by the buttocks support plate is forward (anterior) as seen by the chair and rearward on the buttocks.

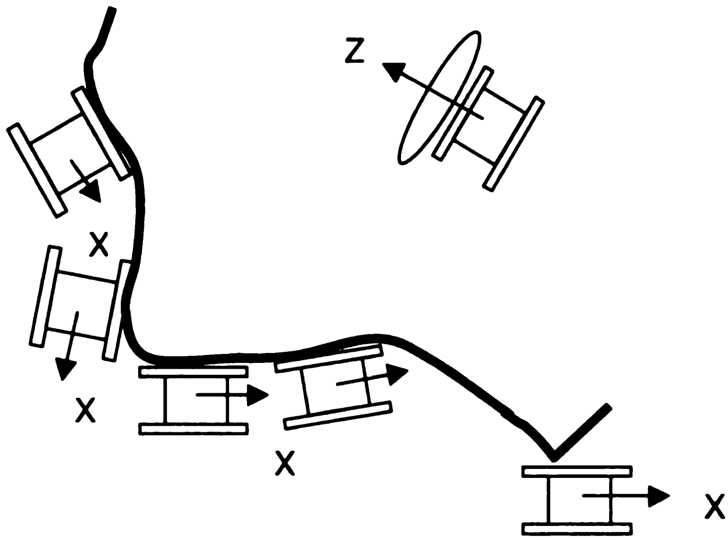


Figure 54: Secondary forces measured under the buttocks, thighs and feet and behind the thorax and pelvis Fx and the wheel Fz (positive is in the direction of the arrows).

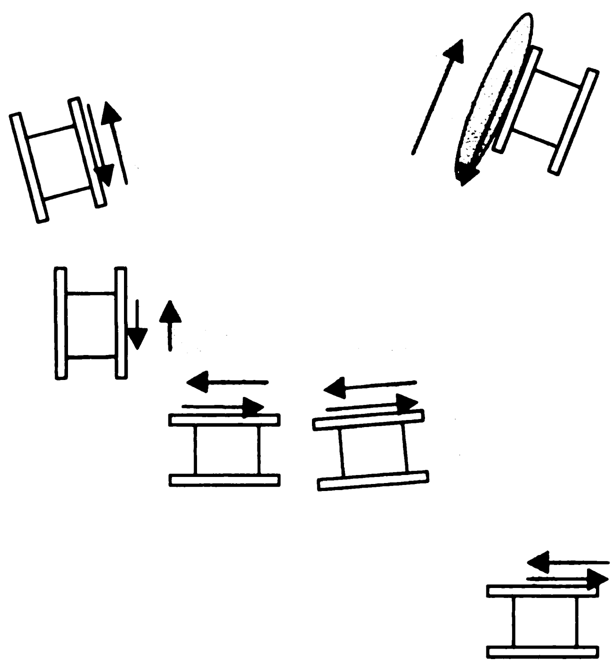


Figure 55: Shear forces measured were those acting on the support plates. The forces acting on the body were equal in magnitude, but opposite in direction.

Table 21: Secondary forces in Newtons. All support plates were the shear forces (Fx) except for the wheel, which was a normal force (Fz).

Shear Forces in Newtons: Averaged Conditions	Recline 1	Recline 2	Recline 3
Thigh	8.5	9.3	7.9
Buttocks	-10.5	-15.9	-21.7
Pelvis	14.3	19.2	20.3
Thorax	5.4	5.3	6.9
Foot	47.3	45.4	45.1
Wheel (Fz)	-5.9	-5.0	-3.0

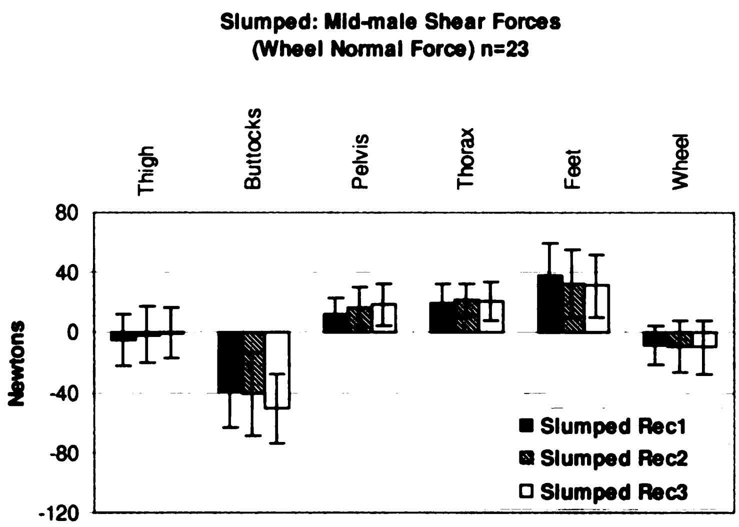


Figure 56: Secondary forces for the slumped condition comparing the three reclines.

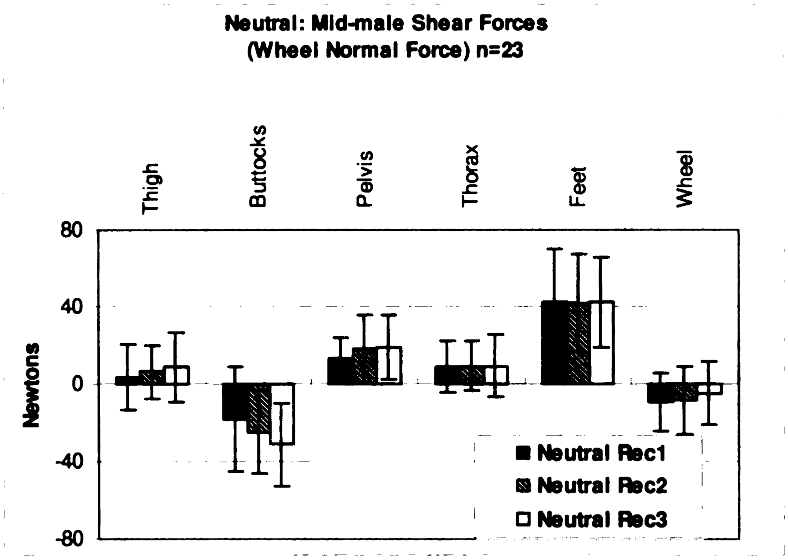


Figure 57: Secondary forces for the neutral condition comparing the three reclines.

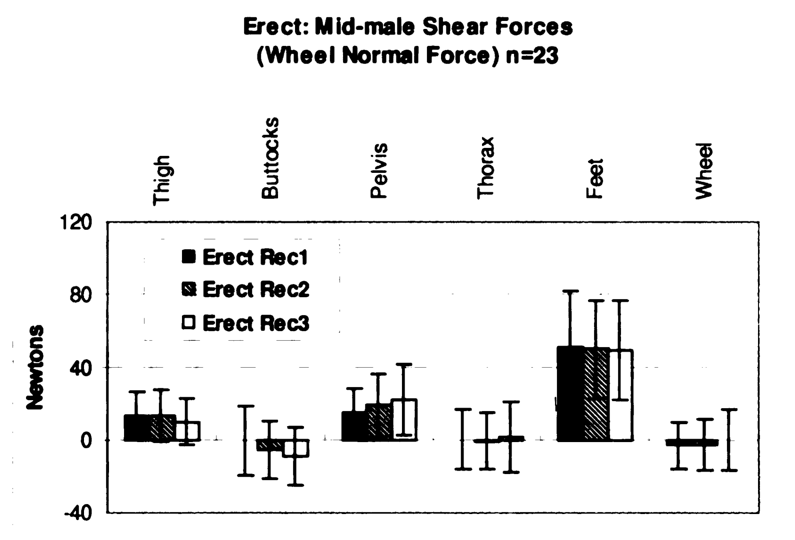


Figure 58: Secondary forces for the erect condition comparing the three reclines.

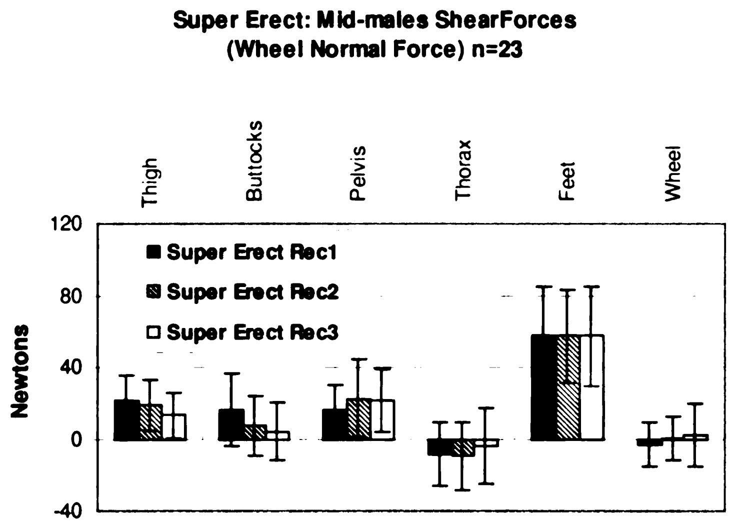


Figure 59: Secondary forces for the super erect condition comparing the three reclines.

Table 22: Testing for a significant statistical differences between secondary support forces at given recline angles. Shear forces (Fx), except wheel, (Fz).

Fx	Recline 1 vs. 2	Recline 2 vs. 3	Recline 1 vs. 3
Thigh	-	-	-
Buttocks	Y	Y	Y
Pelvis	Y	-	Y
Thorax	-	-	-
Feet	-	-	-
Wheel (Fz)	-	-	-

For the secondary forces, the posterior to anterior shear forces under the buttocks, thighs and feet showed statistically significant differences for the buttocks between all recline angles, Table 22, but not for the thighs or feet. The superior to inferior shear forces behind the thorax were not significantly different, however the shear forces behind the pelvis were significantly different for recline 1 vs. 2 and recline 1 vs. 3 but not recline 2 vs. 3. The normal forces for the wheel (push or pulling on the wheel) did not show any significant differences.

When the secondary force data were examined, Table 21, the average thigh forces were reported to be positive (forward on the chair) while the buttocks average forces were reported as being negative (rearward on the chair). However, this report may be misleading because the data were averaged across conditions. Upon examination, the forces, particularly the thigh forces, varied from positive to negative depending on the subject. Each condition showed high standard deviations which crossed the zero line for the thighs, Figure 57 and Figure 58 and for the buttocks and thorax Figure 58 and Figure 59.

Aside from the statistical analysis, trends were seen in the secondary forces under the buttocks, behind the pelvis and on the wheel. As the chair reclined, the shear force under the buttocks increased in magnitude and had a negative direction (rearward on the chair, forward on the buttocks) for the slumped, neutral and erect conditions, Figure 60. For the super erect condition, the forces on the buttocks were in the opposite direction and decreased in magnitude with increasing recline, Figure 61. The shear forces behind the pelvis were in the positive direction (downward on the chair, upward on the pelvis) and increased in magnitude as the recline increased for all test conditions. For the slumped, neutral and erect conditions the wheel force decreased as the recline angle increased, thus there was less pulling on the wheel as the chair reclined.

Overall, as the body reclined, the shear forces increased on the buttocks and pelvis region demonstrating that this region was sliding into the seat. A difference was seen in the super erect condition, most likely because the rotation of the buttocks and pelvis supports overcame the effect of the recline angle and created a “sliding out” effect.

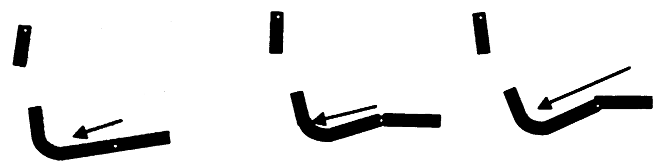


Figure 60: Shear forces on the buttocks and pelvis region increase in magnitude (negative direction) as the recline angle increases.

Figure 61: Shear forces on the buttocks and pelvis region for the super erect condition, decrease in magnitude (positive direction) as recline increases.

The thighs showed mixed responses to the varying recline angles. The shear forces under the thighs were in the negative direction (rearward on the chair, forward on the thigh) and decreased in magnitude for the slumped condition as recline increased. The thigh shear forces in the neutral condition had a positive direction and increased in magnitude from recline 1 to 3. The thigh shear forces were also in the positive direction for the erect and super erect condition, but decreased in magnitude from recline 1 to 3.

The shear forces for the thorax and feet did not show a trend between the recline angles, however it is worthy to note that the shear force behind the thorax was minimal, or the value closest to zero in the erect condition, for all three recline angles.

Recline Angle Comparison for Lateral Forces

The side-to-side shear forces (Fy) were small for all test conditions, Table 23. Small lateral forces were expected, since the subjects were performing a sagittally symmetric task and there was little to no lateral motion.

Table 23: Average lateral forces (Fy) and standard deviations. Each recline is the average of all test conditions (slumped, neutral, erect and super erect).

	Recline 1 (N)	STD (N)	Recline 2 (N)	STD (N)	Recline 3 (N)	STD (N)
Thigh	-0.4	3.6	-0.9	4.2	-0.7	5.0
Buttocks	-1.5	6.3	-1.5	6.8	-0.4	7.0
Pelvis	-1.1	2.2	-1.1	2.8	-0.8	2.1
Thorax	-1.6	5.8	-1.3	6.8	-2.5	5.2
Foot	-0.6	3.2	-0.8	3.2	-0.6	3.3
Wheel	1.7	1.5	1.7	1.5	1.8	1.4

For the lateral shear forces, which were small in value, only one significant difference (Table 24) was found and that was for the thorax forces between the second and third reclines.

Table 24: Testing for a significant statistical difference between the lateral support forces at given recline angles. Lateral shear forces, Fy.

Fy	Recline 1 vs. 2	Recline 2 vs. 3	Recline 1 vs. 3
Thigh	-	-	-
Buttocks	-	-	-
Pelvis	-	-	-
Thorax	-	Y	-
Feet	-	-	-
Wheel	-	-	-

Overall, significant differences were demonstrated for the primary forces (Fz) exerted under the subject's thighs, buttocks, and feet, and behind the pelvis and thorax for recline angles varying by four degrees or more. The primary force on the wheel (Fx) demonstrated a significant difference for only one recline comparison. The buttocks shear force (Fx), a secondary force, exhibited statistically significant differences between all recline angles while the pelvis showed significantly different secondary forces for two out of the three sets of recline comparisons (1 vs 2 and 1 vs 3).

The measurement of shear forces in this type of seat may not be realistic of the forces in a typical office or automotive seat, primarily because most office and automotive seats do not have such large ranges of motion. Other factors that could affect the shear forces are the amount of foam and fabric, and the type of fabric on the seat and on the subject. A typical seat has several millimeters of foam and suspension between the person and the seat structure, but for this test seat only a few millimeters of fabric and foam were between the subject and a rigid support. Also, frictional properties of fabric vary. Certain types of fabric have higher frictional properties than others, such as cloth seats verses leather seats. Thus, the type of fabric chosen for the subjects and for the seat would affect the shear forces. Along with the variation in frictional properties, a large seat pan angle could also cause the seat to grip a person's pants, continually placing an undesirable shear force on the buttocks. The shear forces measured for this study provide initial measurements and a starting point for further shear data analysis and gathering.

Chair Articulations: Primary Forces

The primary and secondary force data were also examined in terms of the various chair articulations, slumped, neutral, erect and super erect, Table 25, Table 26 and Figure 62. The forces on the buttocks, thighs, pelvis and feet indicated clear trends; as the subjects moved from slumped to super erect, the forces under the buttocks and thighs decreased, the forces behind the pelvis decreased, and the forces under the feet increased, Table 25. A clear trend was not seen in the support forces of the thorax. The forces into the wheel maintained a constant level for all conditions across all reclines. These trends confirmed that as a subject was moved into a more erect posture, there was an increased loading into the floor and a reduced loading into the seat and no change in wheel forces.

Table 25: Primary forces in Newtons for recline 1, 2 and 3 at all support plate locations.

	Slumped	Neutral	Erect	Super Erect
Recline 1				
Thigh	-136.8	-140.2	-135.9	-127.7
Buttocks	-432.4	-422.5	-414.1	-403.5
Pelvis	-27.9	-24.7	-24.1	-22.5
Thorax	-183.0	-187.4	-182.1	-184.6
Foot	-93.4	-97.9	-104.2	-112.1
Wheel (Fx)	-32.8	-32.3	-33.3	-32.3
Recline 2				
Thigh	-133.8	-129.5	-128.2	-126.6
Buttocks	-418.4	-411.7	-400.3	-390.7
Pelvis	-35.6	-31.7	-28.5	-29.5
Thorax	-204.8	-209.6	-204.3	-197.5
Foot	-86.3	-93.1	-102.4	-107.0
Wheel (Fx)	-31.9	-31.0	-31.8	-31.8
Recline 3				
Thigh	-127.5	-122.0	-118.0	-103.2
Buttocks	-408.6	-400.2	-390.2	-382.5
Pelvis	-39.1	-33.3	-33.4	-30.7
Thorax	-230.0	-229.0	-222.7	-221.6
Foot	-83.3	-94.1	-99.8	-108.9
Wheel (Fx)	-32.6	-33.7	-32.9	-33.1

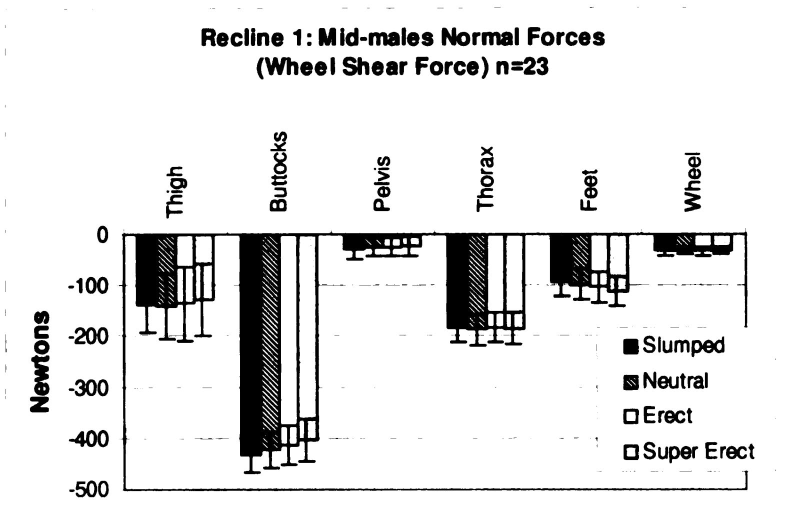
When evaluating these data for statistically significant differences, the conditions (slumped, neutral, erect and super erect) were compared to each other for a given recline angle, Table 26. A One Way Repeated Measures Analysis of Variance statistical test was performed with these data. Both a test on data normality and variance equality was performed. These data passed both the normality and the equal variance test.

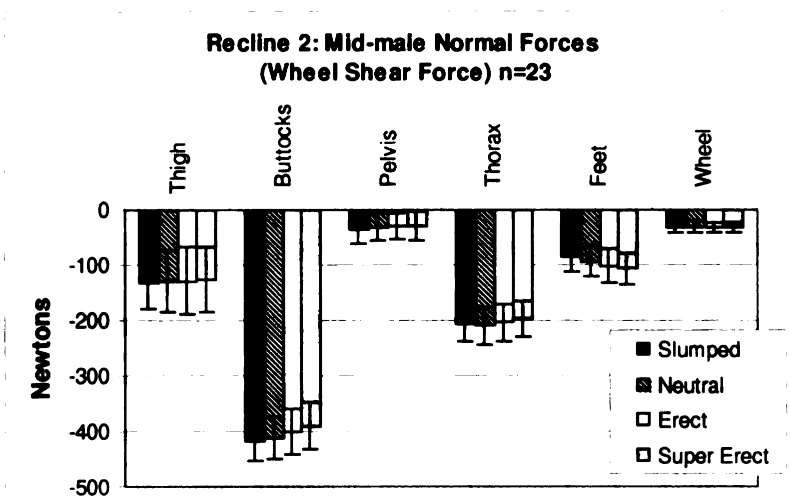
When evaluating primary forces, Table 26, for significant differences between chair articulations, one interesting conclusion was that the thorax and wheel support plates showed no significant differences between conditions. A consistent difference was seen between the slumped and super erect conditions for the buttocks, feet and pelvis for all recline angles. A significant difference was also seen between the neutral and super erect conditions for the buttocks and feet for all three recline angles. The statistical analysis confirmed the apparent trends reported. Forces shifted from the buttocks-thigh-pelvis region to the foot support as the chair moved from a slumped or neutral position to a super erect position.

In simple terms, a trade off occurred between the buttock - thigh - pelvis forces and the forces into the footplate. As the chair moved from a slumped position to a more erect position, more support was needed through the footplate and less through the buttocks, thighs and pelvis to support the body. A surprising conclusion was that the thorax support forces did not exhibit a clear trend during this chair movement. Intuitively one would hypothesize that as a person moves from a slouched position to an erect position, the support force behind the thorax would increase; however this trend was not seen in these data.

Table 26: Comparison of primary support forces between chair articulations. Slumped (S), Neutral (N), Erect (E), Super Erect (SE).

Normal Support Forces (Fz) except for Wheel (Fx - shear)						
			Recline 1			
	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Thigh	-	-	-	-	-	-
Buttocks	Y	Y	-	Y	-	-
Pelvis	Y	-	-	Y	-	-
Thorax	-	-	-	-	-	-
Feet	Y	Y	-	Y	-	-
Wheel (Fx)	-	-	-	-	-	-
			Recline 2			
	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Thigh	-	-	-	-	-	-
Buttocks	Y	Y	-	-	-	-
Pelvis	Y	-	-	-	-	-
Thorax	-	-	-	-	-	-
Feet	Y	Y	-	Y	Y	Y
Wheel (Fx)	-	-	-	-	-	-
			Recline 3			
	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Thigh	Y	Y	-	-	-	-
Buttocks	Y	Y	-	Y	-	-
Pelvis	Y	-	-	-	-	-
Thorax	-	-	-	-	-	-
Feet	Y	Y	-	Y	-	Y
Wheel (Fx)	-	-	-	-	-	-





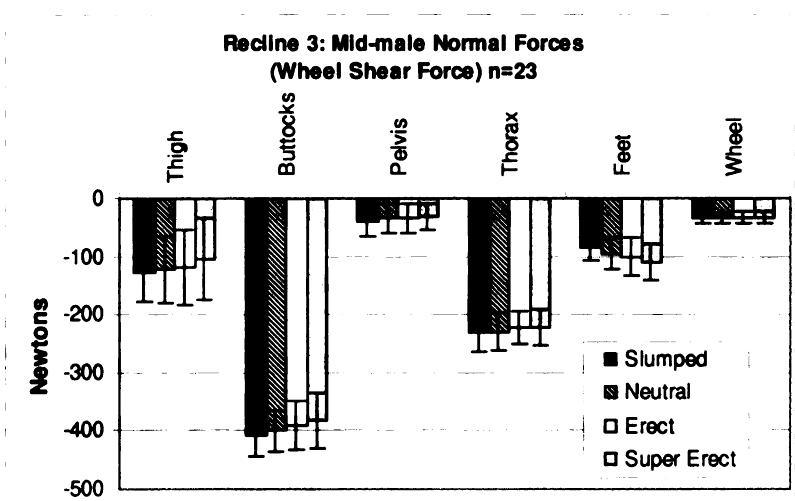


Figure 62: Primary seated support forces in Newtons. Comparison of chair articulations

In summary, the primary forces associated with torso articulation showed that statistical differences occurred if the chair's Total Support Angle (TSA) was at least 20°. Significant differences were not found between two contiguous chair positions, but rather between every other condition, i.e. slumped to erect. So, larger chair motions led to significant differences in the primary forces.

The support forces measured by the footplate were also found to be significant. Supporting the feet during tasks was important for the ability to change posture. Petite people most commonly have difficulty choosing their desired posture because of the inability to obtain support from the chair, or maintain contact with the floor. In the study of four office chairs by Bush[55], petite subjects were unable to maintain full contact with the seat back in one of the test chairs. As a result, to maintain floor contact, the buttocks and pelvis were pulled away from the seat back sacrificing support along the lower back. The demonstration of the significance of the support force from the floor, or foot rest showed that in future studies the forces under the feet should be measured to be assured important force information is not lost.

From a medical perspective, individuals in wheel chairs are at high risks of developing decubitis ulcers under the buttocks [56, 57]. A goal of a medical professional working with individuals in wheelchairs is to reduce the chances of the patient developing these ulcers. These data show that a shift in posture plays a significant roll in changing the loading under the buttocks. To reduce the loading, the person should be placed in an erect posture; from a slouched position to an erect position the loading under the buttocks is reduced by 4% of the subjects body weight. For a 170 lb (77 kg) subject this translates into approximately 6 lbs. (3 kg). An erect posture also has other physiological benefits, as discussed in the Literature Review Section, of increased ability to breathe, leading to increased oxygen content in the blood thus reducing muscle fatigue. Possibly a preferable solution would be to continuously articulate the individual so that the force distribution is not concentrated in one location but continuously shifting. Similar benefits exist for users of other chairs, such as office or automotive seating.

Chair Articulations: Secondary Forces

The secondary forces seen in Table 27, showed a change in direction for the forces under the buttocks and thighs (negative to positive, or rearward on chair to forward on chair) as the chair moved from a slumped condition to a more erect position, Figure 63. This trend was seen across all three recline angles. The secondary forces on the thorax exhibited a trend opposite to the buttocks and thighs; the thorax forces moved from a positive value (downward on seat back) to a negative value (upward on seat back) as the chair position became more erect, Figure 63. The pelvis and feet secondary forces were all in the positive direction (downward on the pelvis support and forward on the footplate) and increased in magnitude as the chair moved from a slumped to erect position. The wheel secondary forces all begin in the negative direction and decreased in magnitude; for reclines 2 and 3 the forces switched direction and became a positive value as the chair moved toward a more erect position. In general the secondary forces on the wheel indicated less pulling on the wheel as the chair moved to a more erect condition. This may be caused by the chair motion, since the subject's torso moved closer to the wheel as the chair moved from the slouched condition to the super erect condition.

Table 27: Secondary forces in Newtons (Fx) for the thigh, buttocks, pelvis, thorax and foot and Fz for the wheel.

		Recline 1		
Newtons	Slumped	Neutral	Erect	Super Erect
Thigh	-4.6	3.7	13.0	21.8
Buttocks	-39.9	-18.0	-0.7	16.5
Pelvis	12.7	13.4	15.0	16.0
Thorax	19.9	9.3	0.2	-8.0
Foot	38.1	42.5	51.4	57.3
Wheel (Fz)	-8.4	-9.0	-3.2	-3.0
		Recline 2		
Thigh	-1.3	6.3	13.4	18.9
Buttocks	-40.6	-24.6	-5.7	7.4
Pelvis	17.0	18.5	18.8	22.5
Thorax	22.2	9.3	-0.7	-9.4
Foot	32.6	41.9	49.9	57.3
Wheel (Fz)	-9.4	-8.4	-2.9	0.5
		Recline 3		
Thigh	-0.4	9.0	9.8	13.4
Buttocks	-50.6	-31.0	-9.2	4.2
Pelvis	18.9	19.2	21.8	21.1
Thorax	20.8	9.3	1.5	-4.1
Foot	31.5	42.3	49.6	57.1
Wheel	-9.6	-4.6	-0.1	2.3

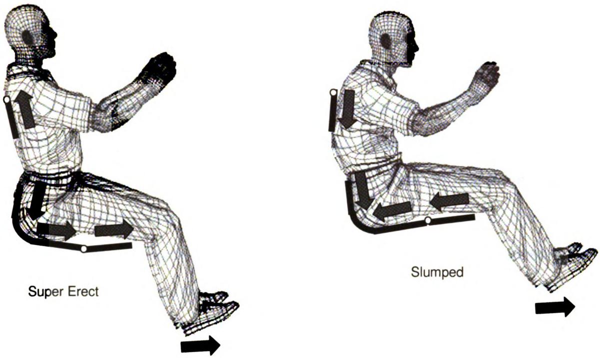


Figure 63: A comparison of the shear force directions between the Super Erect and Slumped chair positions.

A One Way Repeated Measures Analysis of Variance statistical test was performed with the secondary forces between chair articulations, Table 28. For this analysis each recline angle was analyzed separately. Both tests on data normality and variance equality were performed. All secondary force data passed the equal variance test and all of the support force data except that on the pelvis passed the normality test.

Significant differences were not found between any conditions for any recline angles when examining the pelvis shear force data.

All secondary support data, except for the pelvis, showed a significant difference for all three recline angles between the slumped and super erect chair positions. A significant difference was seen in Recline 1 and 2 for all support data (except for the pelvis) between the neutral and super erect conditions. Recline 3 also showed a significant difference except for the thigh and pelvis data between the neutral and super erect conditions. Reclines 1 and 3 showed a significant difference between the slumped and erect condition for all secondary support data except for the pelvis while Recline 2 showed a significant difference for all support data except for the wheel and pelvis. Table 27 lists these findings as can be seen by the shaded regions.

Again, as with the primary support force data, significant differences in the secondary force data were not found between two contiguous chair positions, but rather between every other condition, i.e. slumped to erect, or slumped to super erect, or neutral to super erect. The trends for the secondary forces as seen in Figure 63 showed that in the slumped chair position the body was being forced into the seat while the opposite was true for the super erect position. For the super erect condition the shear forces lifted the thorax, thus extending the lumbar region. From these data the one would expect that internal loading in the lumbar spine would have a higher compression force in the slumped condition. This will hypothesis will be compared in the during the internal joint analysis from this dissertation.

The next question to be answered is whether these types of shear forces are seen in other types of seats. When evaluating automotive seats, most likely the shear forces measured for this study would be larger than those in a typical automotive seat, primarily because today's auto seats do not have large ranges of motion. However, one current office seat (LEAP[55]) developed by Steelcase does exhibit ranges of motion comparable to the BAC, but shear force data were unavailable .

The seat pan on the test seat also contained separate thigh and buttocks plates that did not move together. Since the shear forces are strongly affected by the orientation of the support plate in space, and the fact that the buttocks and thigh plates do not move together most likely causes an increase in the shear forces. The thigh plate remains stationary while the buttocks plate rotates to accommodate the various postures.

Table 28: Comparison secondary support forces between chair articulations. Slumped (S), Neutral (N), Erect (E), Super Erect (SE).

	Shear Support Forces (Fx) except for Wheel (Fz - Normal)					
	Recline 1					
	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Thigh	Y	Y	Y	Y	Y	Y
Buttocks	Y	Y	Y	Y	Y	Y
Pelvis	-	-	-	-	-	-
Thorax	Y	Y	Y	Y	Y	Y
Feet	Y	Y	-	Y	-	-
Wheel (Fz)	Y	Y	-	Y	Y	-
Shear Support Forces (Fx) except for Wheel (Fz - Normal)						
	Recline 2					
	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Thigh	Y	Y	-	Y	-	Y
Buttocks	Y	Y	Y	Y	Y	Y
Pelvis	-	-	-	-	-	-
Thorax	Y	Y	-	Y	Y	-
Feet	Y	Y	-	Y	-	Y
Wheel (Fz)	Y	Y	-	-	-	-
	Recline 3					
	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Thigh	Y	-	-	Y	-	Y
Buttocks	Y	Y	Y	Y	Y	Y
Pelvis	-	-	-	-	-	-
Thorax	Y	Y	-	Y	Y	Y
Feet	Y	Y	-	Y	-	Y
Wheel (Fz)	Y	Y	-	Y	-	-

Support Forces Calculated as Percent Body Weight

The support forces were converted to percent body weight (%BW) for each subject and then averaged. Normalizing the data in terms of %BW could establish a method for estimating support loads for any size subject for any region of the body. By representing the support forces in terms %BW, and with further investigations of other sized individuals, a pattern may arise that allows the loading of a seat to be estimated with reasonable accuracy just by obtaining the subject's weight and applying a %BW distribution pattern. For the research reported in this dissertation, this prediction can only be validated for a mid-sized male subject.

Table 29 lists the average %BW (average of all subjects for all conditions: slumped, neutral, erect and super erect) for each recline angle with respect to each support plate. Table 30 and Figure 64 list in tabular and graphical forms the %BW for each condition within each recline angle. From a macroscopic viewpoint, a seated subject with the hands on a support device distributes approximately 70%BW on the seat pan, 30%BW on the seat back, 10%BW under the feet and 4%BW on the support under the hands. Note that the %BW distribution listed above does not add to 100% because it is not a list of the vertical force components but rather a combination of vertical and horizontal force components.

As seen in the statistics of these data, a significant difference between the postural changes (slumped to super erect, neutral to super erect and slumped to erect) exists, so the above macroscopic distribution is not universally applicable. Thus when considering primary and secondary support loads, posture must also be a factor in predicting the loading scenario specifically for the regions under the buttocks, behind the pelvis and under the feet.

Table 29: Primary forces represented in percent of total body weight (%BW) for each condition. All forces are normal forces (Fz), except for the wheel which is a shear force (Fx).

Average %BW: Average of all conditions.			
	Recline 1	Recline 2	Recline 3
Thigh	18	17	16
Buttocks	56	54	53
Pelvis	3	4	5
Thorax	25	27	30
Foot	14	13	13
Wheel	4	4	4

Representing the data in terms of %BW also mutes the differences seen in the numerical data. For example the primary pelvis forces show a statistically significant difference between slumped to super erect, yet the forces only vary by 1%BW. Similarly, when reported in terms of %BW the primary foot forces only vary 2 to 4%BW between conditions and the primary wheel support forces show no variation between conditions.

Table 30: Primary forces represented in percent of total body weight (%BW) for each condition. All forces are normal forces (Fz), except for the wheel, which is a shear force (Fx).

	Slumped (%BW)	Neutral	Erect	Super Erect
Recline 1				
Thigh	18	19	18	17
Buttocks	58	57	56	54
Pelvis	4	3	3	3
Thorax	25	25	24	25
Foot	13	13	14	15
Wheel (Fx)	4	4	4	4
Recline 2				
Thigh	18	17	17	17
Buttocks	56	55	54	52
Pelvis	5	4	4	4
Thorax	27	28	27	27
Foot	12	12	14	14
Wheel (Fx)	4	4	4	4
Recline 3				
Thigh	17	16	16	14
Buttocks	55	54	52	51
Pelvis	5	4	5	4
Thorax	31	31	30	30
Foot	11	13	13	15
Wheel (Fx)	4	4	4	4

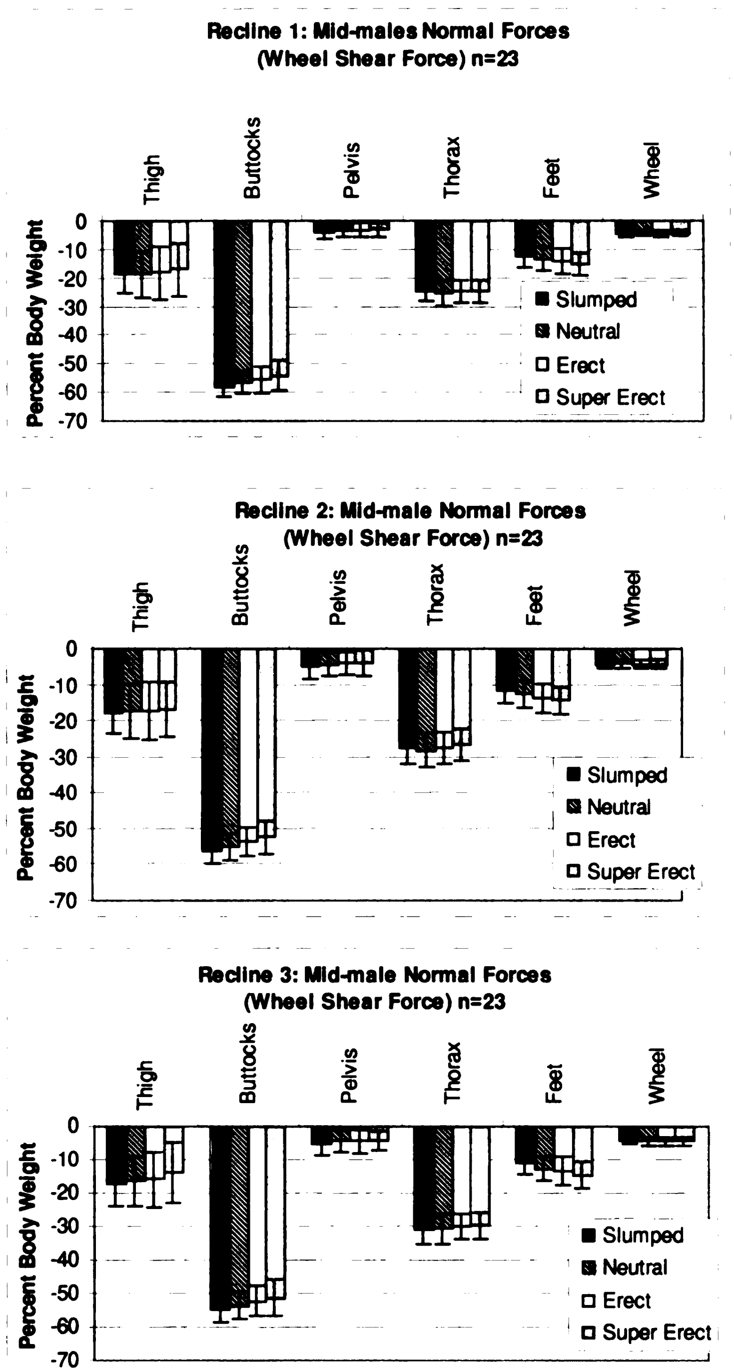


Figure 64: Primary support forces in terms of Percent Body Weight (%BW).

Static Equilibrium

Applying the principal of equilibrium to segments of the human body is not as simple as applying this principal to a non-living object, such as a pencil resting on a table. The body has several forces acting internally including abdominal pressure, passive tissue tension, and active muscular contraction along with fluid flow, and volume changes which affect mass distribution.

Examining the body from a micro-mechanics perspective produces an extremely complex model needing numerous measurements and model inputs, most of which are not easily measured in a living person nor are they available via published data. Backing away from the micro-mechanics perspective to a macro-mechanics viewpoint, the body can be treated as a rigid body, or series of rigid bodies resting in a seat. The macroscopic viewpoint ignores all of the internal happenings yet allows a reasonable analysis of the support forces. The support forces can be measured and summed to estimate if they balance in an equilibrium sense.

Therefore, if a subject was relaxed and was allowing the support plates to hold him in position, the forces measured by the load cells should produce results that are close to equilibrium. In other words, by breaking the forces into horizontal and vertical components relative to the lab space, the horizontal forces should sum to near zero and the vertical forces should sum to the subject's body weight. For the static trials, the force data were separated into components and summed to obtain the equilibrium data presented in Table 31 through Table 34.

As can be seen in Table 31, the summed horizontal forces for many of the subject trials were close to, but not exactly zero. It should be noted that there were several factors that affected these data and small errors could have been introduced into the system from any of the following: the identification of the chair position measured by the targets, the tracking of the targets, the calibration and zeroing of the force plates, the accuracy of the force plates and the conversion of these data into horizontal and vertical forces.

The biggest influence on the force data was the force plate accuracy. In the isolated case where there would be only vertical loading (Fz) the cross talk is minimized to ± 0.2% of full scale, or for a thousand pound plate the error would be approximately ± 2 pounds or ± 9 Newtons. This error would increase if there was a high shear loading or high moment on one of the other force plate channels that could increase the cross talk and affect the normal force reading.

Table 32 shows the average horizontal forces for all the subjects in each condition. On the average, the summed horizontal forces approached zero as the subject moved to a more erect posture. This finding was consistent across all three recline angles. The question arises, why would the equilibrium approach zero as the subject's posture is moved to a more erect condition, provided that all other errors are consistent? It may be that the subject felt most relaxed in the super erect condition; however from the testing experience and the judgement of this author this is probably not the case. The super erect chair position seemed to be the least tolerated by the subjects. One theory is that in this position, the body was approaching a position closer to an anatomical neutral position, causing the body segments to be “in balance” for this condition.

Table 31: Horizontal forces summed for recline 1, showing data for all subjects.

Recline 1: Horizontal Forces (Newtons)				
Subject	Slumped	Neutral	Erect	Super Erect
1	27.58	26.74	14.06	8.12
2	24.10	18.67	14.46	7.47
3	30.07	4.74	-0.12	-2.26
4	19.17	15.70	12.58	8.75
5	12.98	3.29	0.54	-0.03
6	12.28	1.85	0.32	-6.79
7	20.16	18.44	13.93	2.21
8	17.77	10.89	2.04	-0.85
9	4.12	4.85	4.53	0.43
10	3.26	19.61	10.78	-3.26
11	2.80	-2.28	-1.99	-9.11
12	3.87	10.30	1.66	-7.14
13	4.74	0.01	-12.26	-6.89
14	17.16	8.68	4.54	-7.93
15	3.95	-6.02	68.58	-12.57
16	-4.98	-10.13	-13.13	-14.92
17	-0.38	-3.66	-12.21	-14.80
18	-37.62	45.28	4.55	2.37
19	12.74	6.35	3.84	-0.65
20	2.48	3.61	-2.98	-0.48
21	14.14	0.50	-2.27	-4.09
22	8.30	7.51	-3.29	-13.24
23	26.55	21.51	9.45	0.45

Table 32: Average horizontal forces summed for recline 1, 2 and 3.

(Newtons)		Slumped	Neutral	Erect	Super Erect
Recline 1	**Ave**	9.79	8.97	5.11	-3.27
	Std	14.17	12.29	16.03	6.95
Recline 2	**Ave**	16.30	12.11	4.29	0.98
	Std	10.91	12.90	8.23	9.49
Recline 3	**Ave**	16.28	14.46	13.93	5.09
	Std	14.05	12.77	22.50	12.47

Table 33: Vertical forces summed for Recline 1, showing data for all subjects.

Recline 1 (Newtons)													
Subject	Weight (N)	**Slumped**	Differ w/ Weight	Differ w/ Neutral	**Neutral**	Differ w/ Weight	Differ w/ Neutral	**Erect**	Differ w/ Weight	Differ w/ Neutral	**Super Erect**	Differ w/ Weight	Differ w/ Neutral
1	716.5	-699.7	16.7	-2.3	-697.4	19.0	0.0	-700.0	16.4	-2.6	-697.5	19.0	0.0
2	743.2	-756.0	-12.8	1.3	-757.3	-14.1	0.0	-764.0	-20.9	-6.8	-766.2	-23.0	-8.9
3	720.9	-723.4	-2.5	3.2	-726.6	-5.7	0.0	-727.4	-6.5	-0.8	-732.6	-11.7	-5.9
4	774.3	-808.3	-34.0	6.7	-815.1	-40.8	0.0	-816.7	-42.4	-1.7	-821.7	-47.4	-6.6
5	821.0	-806.2	14.8	7.1	-813.3	7.7	0.0	-810.5	10.5	2.8	-811.6	9.4	1.7
6	738.7	-737.8	0.9	1.6	-739.4	-0.7	0.0	-743.3	-4.6	-3.9	-744.4	-5.7	-5.0
7	714.2	-739.4	-25.2	1.7	-741.1	-26.8	0.0	-744.0	-29.7	-2.9	-740.7	-26.4	0.4
8	725.4	-725.4	0.0	4.8	-730.2	-4.9	0.0	-730.8	-5.5	-0.6	-733.0	-7.6	-2.8
9	801.0	-819.2	-18.2	2.1	-821.3	-20.3	0.0	-822.2	-21.2	-0.9	-826.8	-25.8	-5.5
10	856.6	-840.7	15.9	1.7	-842.4	14.2	0.0	-841.3	15.3	1.1	-845.7	10.9	-3.3
11	743.2	-804.7	-61.6	8.1	-812.8	-69.7	0.0	-811.7	-68.5	1.1	-817.0	-73.9	-4.2
12	774.3	-868.2	-93.9	2.8	-871.1	-96.8	0.0	-865.7	-91.4	5.4	-774.9	-0.6	96.2
13	769.9	-819.3	-49.5	4.1	-823.4	-53.6	0.0	-822.0	-52.1	1.5	-826.8	-57.0	-3.4
14	725.4	-743.8	-18.5	0.0	-743.8	-18.5	0.0	-743.2	-17.9	0.6	-746.1	-20.8	-2.3
15	698.7	-736.7	-38.1	-1.7	-735.0	-36.4	0.0	-718.6	-20.0	16.4	-735.2	-36.6	-0.2
16	769.9	-803.1	-33.3	-0.1	-803.0	-33.2	0.0	-802.1	-32.3	0.9	-803.6	-33.8	-0.6
17	729.8	-731.5	-1.7	-4.0	-727.5	2.3	0.0	-733.2	-3.4	-5.8	-728.8	1.0	-1.4
18	734.3	-763.0	-28.7	-70.3	-692.6	41.6	0.0	-726.1	8.1	-33.5	-724.0	10.3	-31.3
19	774.3	-770.4	3.9	7.1	-777.4	-3.1	0.0	-774.1	0.2	3.3	-773.2	1.1	4.3
20	676.4	-760.8	-84.4	6.3	-767.1	-90.7	0.0	-762.0	-85.6	5.1	-759.9	-83.5	7.2
21	707.6	-727.9	-20.3	2.9	-730.8	-23.2	0.0	-730.0	-22.5	0.7	-728.0	-20.4	2.8
22	738.7	-726.5	12.2	2.4	-728.8	9.9	0.0	-728.7	10.0	0.1	-731.8	6.9	-2.9
23	712.0	-720.1	-8.1	2.9	-723.0	-11.0	0.0	-726.7	-14.7	-3.7	-727.6	-15.6	-4.5

Table 34: Average horizontal forces summed for Recline 1, 2 and 3.

(Newtons)		Slumped		Neutral		Erect		Super Erect	
		Differ w/ Weight	Differ w/ Neutral	Differ w/ Weight	Differ w/ Neutral	Differ w/ Weight	Differ w/ Neutral	Differ w/ Weight	Differ w/ Neutral
Recline 1	Ave	-20.27	-0.50	-19.77	0.00	-20.81	-1.04	-18.74	1.02
	Std	30.27	15.54	33.89	0.00	30.21	8.45	27.18	21.93
Recline 2	Ave	-12.50	2.35	-14.84	0.00	-20.73	-5.88	-22.43	-7.59
	Std	30.22	8.16	26.30	0.00	31.18	19.97	31.23	21.77
Recline 3	Ave	-15.07	-0.54	-16.04	0.00	-21.45	-5.98	-19.51	-3.89
	Std	25.85	10.68	26.65	0.00	30.36	21.29	23.84	8.80

Table 33 and Table 34 display the vertical forces (vertical relative to lab coordinates) of the subject trials. If the subject was in equilibrium, then the sum of the vertical forces should total the subject's weight. The subject's weight was subtracted from the totaled vertical force and listed in Table 33 and Table 34 under the column heading "Differ with Weight"; these remaining force values were termed the "residual forces". Even after the data from the reference file of the force plates (the unloaded condition of the plates) was subtracted from the trial data, some residual forces remained and for many subjects, the residual force was consistent across trials. An example of this residual force can be seen in the data from Subject 1 of Table 33. It should be noted that Subject 18 shows consistently high residual forces throughout all the conditions as well as Subject 12 in the super erect condition, but all of the other subjects show reasonable residual force data

Table 33 lists the difference of the vertical forces from the subject's weight, and also normalizes the data to the neutral condition. To accomplish the normalization, the force remaining after subtracting the vertical forces and the subject's weight in the neutral condition was subtracted from the other three test conditions ("Differ with Neutral"). On average, the data varied from the subjects' weights between -15 and -23 Newtons, with the negative sign meaning that the calculations produced more loading than the subject's weight. Again, in an ideal situation, the weight of the subject would be equal to the sum of the vertical forces, however as stated earlier some error was introduced through the measurement process, the accuracy of the system and the series of calculations.

So with this in mind, the difference of 15 to 23 Newtons (3.4 to 5.2 lbs) is within the typical 3% error seen in experimental data collection.

Estimation of Internal Joint Forces

The force data was broken down to vertical and horizontal components and was used to estimate the forces at a joint location in the lumbar spine. However, it should be noted again since the joint locations and the segment centers of gravity must be estimated, the joint forces computed must be considered only estimations. For subject 17, in recline 1, slumped, neutral, erect and super erect conditions, the joint forces and moments at the estimated L5/S1 were computed and are listed in Table 35 and visually displayed in Figure 65. (Subject 17 was chosen because the data set for this subject was complete and the residual vertical and horizontal forces for all four articulations were reasonable numbers.)

Table 35: Estimations of internal joint loads at the approximate L5/S1 joint center. Subject 17, recline 1. Forces are converted to orientation of pelvis. Fx is shear loading (positive anterior) and Fz is compressive loading (positive superior).

Condition	Fx (N)	Fz (N)	$M_{L5/S1}$ (N-m)
Slumped	84.7	515.4	20.39
Neutral	60.0	498.9	14.32
Erect	38.3	488.5	15.63
Super Erect	34.9	496.0	7.29

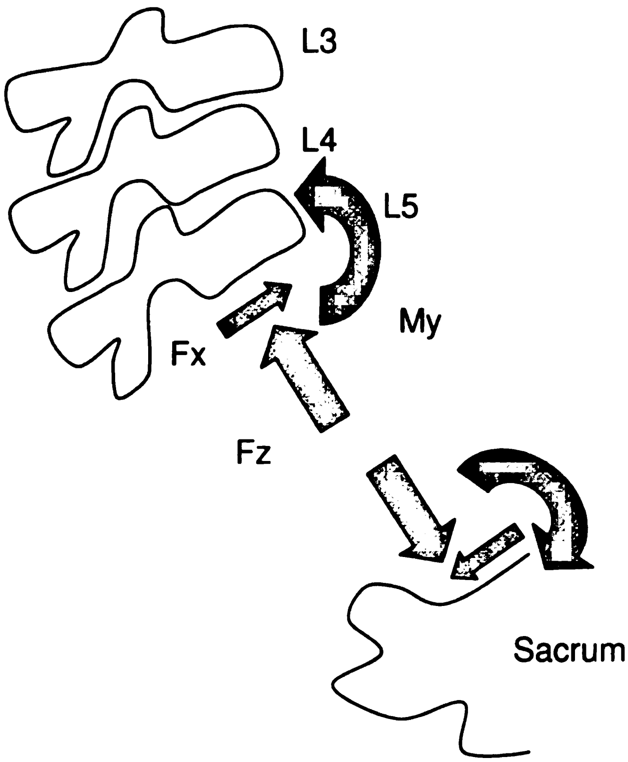


Figure 65: Visual display of the direction of loading on estimated L5/S1 joint center.

Table 36: Conditions tested by Andersson[58] while monitoring disc pressure and muscle activity.

9. Standing at ease.
10. Relaxed (no back support) sitting with arms at the sides of the body.
11. Relaxed sitting with the arms supported.
12. Relaxed sitting with the feet unsupported.
13. Straight (erect) sitting.
14. Relaxed anterior sitting.
15. Straight anterior sitting.
16. Relaxed posterior sitting.

Andersson[58] measured disc pressures in various seated positions and converted these data to force estimates, Figure 66 and Figure 67. Notice that many of the seated tasks exhibited force values (computed between L3 and L4) between 400 and 500 Newtons. These data are similar to the estimations made of the Fz forces from the external support forces gathered for this research. This comparison shows that using the external support forces to estimate internal loads provides reasonable results.

From the data listed in Table 35 it is clear that the compressive loads on the spine decreased as the subject moved from a slumped to a neutral to an erect posture. However, in the super erect position the loads increased to a value similar to that of the neutral condition. Andersson[58] presented postures that showed similar trends in Table 36, condition 8 could be considered similar to the slumped position, condition 2 could be considered similar to the neutral position and condition 5 could be considered similar to the erect position.

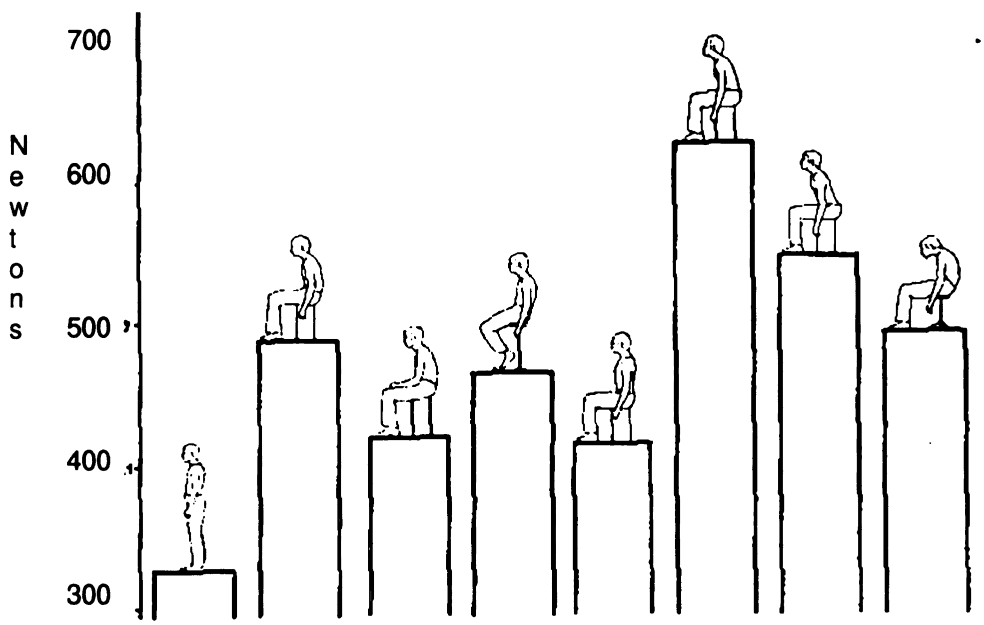


Figure 66: From Andersson [58], eight different postures with normalized disc pressure, refer to Table 36 for list of test conditions.

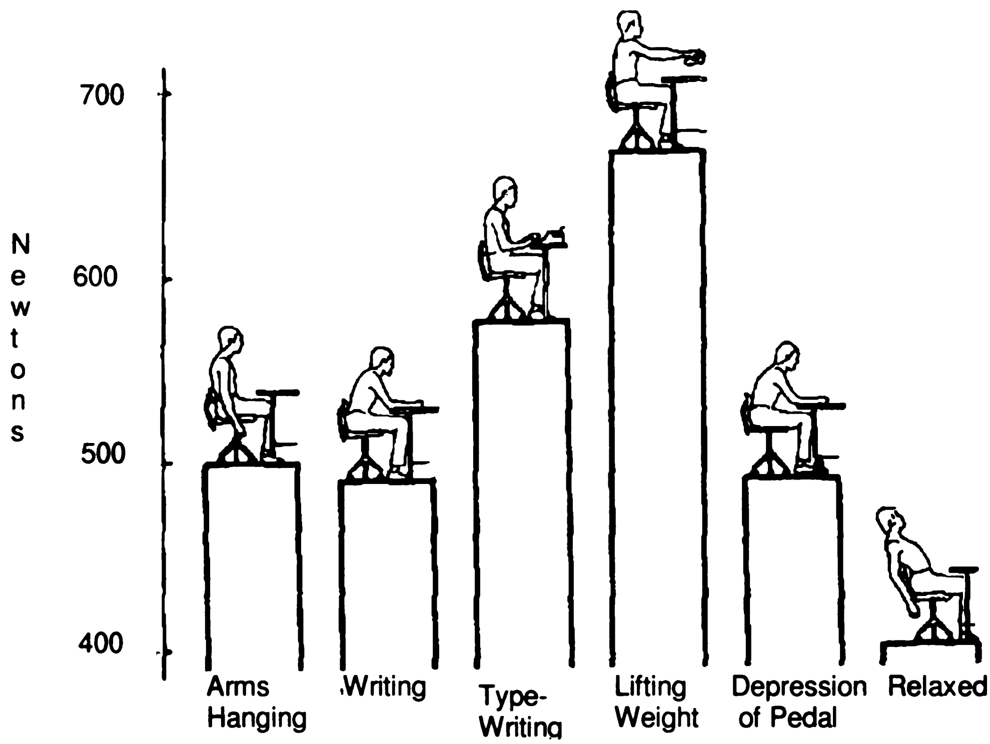


Figure 67: Disc pressure measured in an office chair during simulated work activities[58].

Table 37: Bush dissertation data compared to Andersson[58] data.

	Bush Compressive Forces (N) Driving postures	Andersson Compressive Forces (N) (estimated from graph) General Seated Posture
Slumped Andersson # 8 position	515.4	500
Neutral Andersson #2	498.9	480
Erect Andersson #5	488.5	430
Super Erect ---	496.0	---

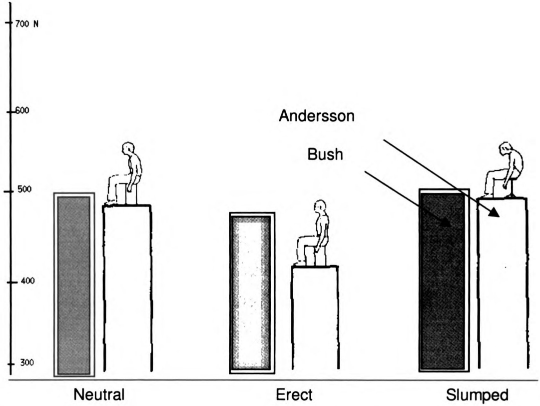


Figure 68: Comparison between Andersson[58] and Bush (shaded) data for loading of the lumbar spine.

From Table 37 and Figure 68 the differences between Bush and Andersson[58] data are numerically listed and visually represented. As stated above, a comparison of these data showed similar magnitudes. The difference between the two sets of data increased as the posture became more erect. This trend would be expected since Andersson measured the pressures in the intervertebral disc which is located between bodies of vertebrae (anterior portion of the vertebrae), and as a more erect posture is attained, loading from the bodies of the vertebrae is transferred to the posterior facets. Andersson could not measure this posterior loading; but the calculations using the external support forces treated the loading as a whole, not distinguishing between anterior or posterior regions. Therefore, the increasing differences between Bush and Andersson data were logical.

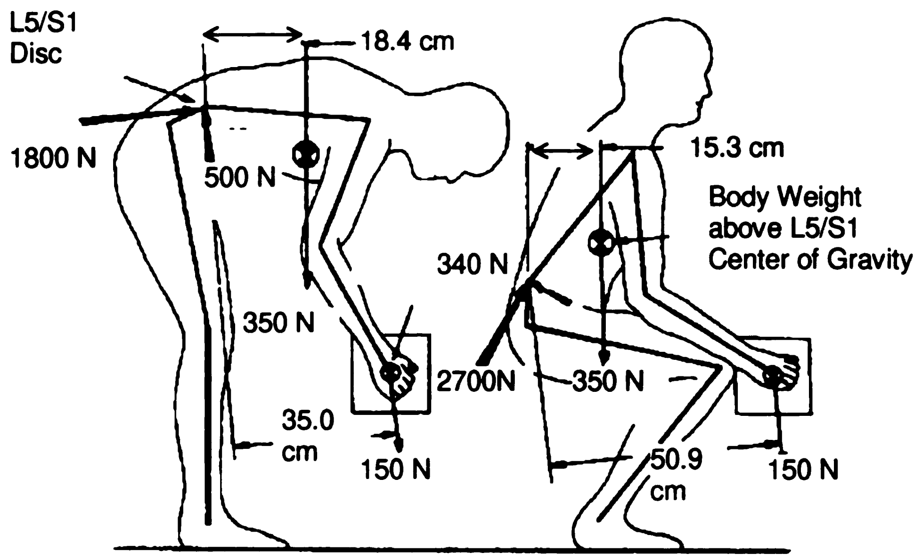


Figure 69: Comparison of predicted L5/S1 forces during lifting of a large object[59].

Data for comparison of the shear loading and the moments on the spine in seated postures is not available. However, data from Chaffin[59] an analysis of lifting tasks helps to put the magnitude of these forces and moments into perspective. From Figure 69, the lifting tasks list shear loads range from 340N to 500 N for different lifting techniques. Using the numbers provided in Figure 69, an estimate of the moments at the L5/S1 joint during lifting can be computed. These moments range from 117 N-m to 130 N-m. As expected, the lifting shear forces and moments are much larger in magnitude than those calculated for the general seated posture. This cannot confirm the accuracy of the calculations, but the numbers seem reasonable in terms of magnitude.

Segment Motions for Static Trials

Thorax and Pelvis Angles

In addition to the measurement of the support forces for the body at the various chair positions, the postures of the subjects were also measured. In this section, the total body openness (Figure 70) and chair Total Support Angle (TSA) (Figure 71) will be listed and compared, followed by the independent angular measurements of the thorax, pelvis, elbow and knee.

The posture of the torso was measured as a thorax angle, a pelvis angle and then the combination of the pelvis and thorax position, called openness, Figure 70. The position of the chair was also measured with the angle of the thorax support, the angle of the pelvic support and the Total Support Angle (TSA) which combined the thorax and pelvic support angles. In both openness and TSA, an increasingly erect position produced a larger angle.

Table 39 lists the average openness angle for all three recline positions and the four chair articulations. Table 41 lists the average chair positions for each condition across subjects. A 5° change of the thorax support plus a 5° change of the pelvis support should occur between chair articulations producing an overall 10° change between conditions.

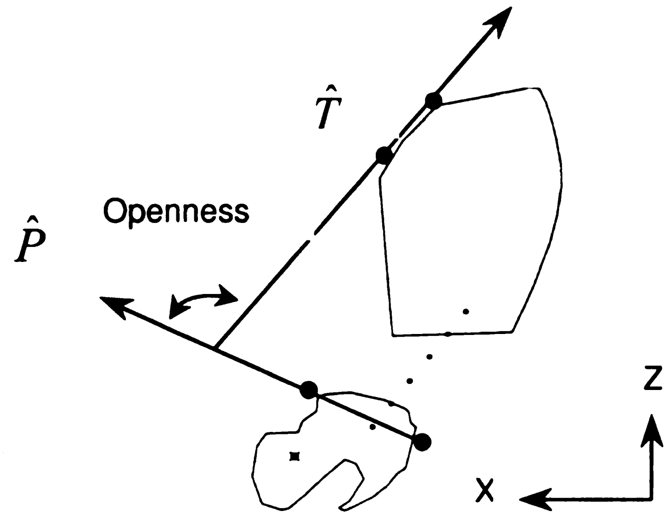


Figure 70: Openness as measured on the subjects.

Table 38: Average Openness of body (thorax plus pelvis orientation).

Body Openness								
Degrees	Slumped		Neutral		Erect		Super Erect	
	Angle	Std	Angle	Std	Angle	Std	Angle	Std
Recline 1	92.2	16.4	94.6	16.1	99.2	15.5	101.8	14.9
Recline 2	92.9	22.9	94.6	18.0	97.9	16.9	100.9	16.7
Recline 3	91.4	15.6	94.1	16.0	98.8	15.3	94.0	21.6

The data in Table 38 indicated that the subject moved to a more erect, or open posture as the chair was moved to a larger TSA. However, the movement of the body did not have the same magnitude as the chair. Table 39 indicated that the chair moved 30° between the slumped and super erect conditions while the subjects on average only moved 10° in reclines 1 and 2 from slumped to super erect and 7° from slumped to erect in recline 3. Further examination of the dynamic data in the next section will confirm the inconsistencies between the chair and body movement ranges.

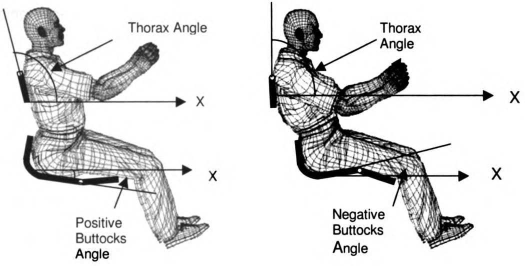


Figure 71: Total Support Angle, TSA is the thorax support angle plus the pelvic support angle.

Table 39: Average Total Support Angle (TSA) of test chair in degrees.

Degrees	Chair Total Support Angle: TSA							
	Slumped		Neutral		Erect		Super Erect	
	Angle	Std	Angle	Std	Angle	Std	Angle	Std
Recline 1	83.0	2.6	91.6	3.0	102.4	2.8	112.5	1.1
Recline 2	81.6	2.8	91.3	1.4	103.2	1.3	112.8	2.3
Recline 3	81.4	3.2	91.4	1.2	102.6	2.3	112.1	2.8

In terms of statistical analysis, a One Way Repeated Measures Analysis of Variance was performed on the openness data and the chair data. All data passed the equal variance testing, but the chair data did not pass the normal distribution test nor did recline 2 of the openness data. Recline 3 of the openness data could not be tested because the test matrix could not be inverted.

For all recline angles and all chair articulations, the data at each condition was significantly different from the data at all other chair positions, Table 40. These results confirm that the articulation conditions were consistently and sufficiently far enough apart from each other to detect a difference. If a difference in chair positions were undetectable, then it would not be reasonable to assume that a significant difference could be detected in the body position.

For the body openness angle, a significant difference was measured between all conditions in recline 1, and only between the slumped and super erect, and the neutral and super erect conditions for recline 2. An analysis of the pelvis angle separate from the thorax angle will explain why all conditions were found significantly different from one another in recline 1 and not in recline 2. Recline 3 could not be tested.

Table 40: Significant difference testing for body openness and chair TSA.

	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Recline 1						
Openness	Y	Y	Y	Y	Y	Y
TSA	Y	Y	Y	Y	Y	Y
Recline 2						
Openness	Y	Y	-	-	-	-
TSA	Y	Y	Y	Y	Y	Y
Recline 3						
Openness	Matrix not able to be tested					
TSA	Y	Y	Y	Y	Y	Y

Motion of Individual Segments: Thorax

Next, the individual motions of the body segments are presented. The angular data of the thorax for each subject in Recline 1 is listed in Table 41 and the average thorax position for each recline angle is listed in Table 42. These data showed that as the thorax support of the test chair was adjusted the subject's thorax also changed position. As the chair support rotated rearward to a more erect position, the thoracic cage, as measured by the sternal notch and mid-sternum targets, also rotated rearward. This was confirmed by the numerical data, which increased in magnitude as the thorax support was rotated rearward. The negative sign in Table 41 and Table 42 indicate that the thorax was rearward of lab vertical with the x axis pointing in the anterior direction.

Table 41: Subjects' thorax angles with respect to vertical (wrtv) for Recline 1.

Thorax Angle	(Degrees) (wrtv)		negative is rearward of vertical			
Subject	Recline 1 **Slumped**	**Neutral**	**Erect**	**Super Erect**	**Ave**	**Std**
1	-23.0	-23.3	-25.7	-25.8	-24.47	1.52
2	-29.7	-	-	-30.3	-30.04	0.42
3	-33.9	-32.1	-33.0	-39.6	-34.65	3.40
4	-34.9	-33.3	-37.4	-38.3	-35.98	2.27
5	-17.1	-17.3	-17.2	-18.5	-17.53	0.67
6	-31.1	-32.2	-37.8	-39.6	-35.17	4.16
7	-18.2	-17.4	-20.6	-21.7	-19.49	1.99
8	-19.9	-20.2	-23.0	-20.3	-20.86	1.45
9	-34.6	-34.0	-33.7	-34.6	-34.24	0.44
10	-28.2	-30.4	-	-.	-29.32	1.56
11	-31.7	-31.2	-30.8	-36.0	-32.42	2.41
12	-47.7	-49.7	-49.3	-49.7	-49.08	0.96
13	-43.1	-44.4	-46.2	-47.6	-45.33	1.99
14	-40.3	-40.0	-38.8	-41.0	-40.03	0.91
15	-36.0	-38.3	-41.3	-42.3	-39.46	2.89
16	-47.3	-46.4	-46.5	-50.3	-47.63	1.82
17	-41.8	-46.6	-47.2	-49.1	-46.18	3.11
18	-44.8	-37.3	-43.5	-47.2	-43.20	4.18
19	-39.2	-44.0	-45.5	-44.0	-43.17	2.72
20	-41.9	-43.7	-42.8	-41.4	-42.45	1.00
21	-34.8	-34.9	-39.4	-36.6	-36.41	2.16
22	-30.5	-35.2	-34.8	-36.9	-34.34	2.73
23	-43.2	-47.5	-51.4	-55.3	-49.33	5.22
Ave	-34.5	-35.4	-37.4	-38.5		
Std	9.0	9.6	9.7	10.1		
Range	30.6	32.3	34.2	36.8		

Table 42: Average thorax angles for all subjects across all three recline angles with respect to vertical. Negative angle is rearward of vertical.

Thorax Angle (Degrees) Subject	Slumped (wrtv)	Neutral	Erect	Super Erect
Recline 1				
Ave	-34.5	-35.4	-37.4	-38.5
Std	9.0	9.6	9.7	10.1
Range	30.6	32.3	34.2	36.8
Recline 2				
Ave	-36.4	-38.9	-40.0	-41.1
Std	9.8	10.5	11.1	10.9
Range	33.4	35.0	38.4	39.1
Recline 3				
Ave	-41.7	-42.1	-45.6	-45.4
Std	8.9	9.6	9.0	10.2
Range	32.5	33.3	35.2	37.4

Table 43: Average angle change of all subjects from the slumped to the super erect condition for the thorax and pelvis.

(Degrees)	Thorax	Pelvis
Recline1	3.7	-5.6
Recline 2	5.2	-6.3
Recline 3	4.8	-5.7

Table 44: Testing for significant differences between the thorax angles of the subjects.

Thorax Angle	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Recline 1	Y	Y	-	Y	Y	-
Recline 2	Y	Y	-	Y	-	-
Recline 3	Y	Y	-	Y	Y	-

For the thorax, pelvis and extremity data, a One Way Repeated Measures Analysis of Variance was performed to determine significant differences, Table 44. The statistical results for the thorax were consistent with what was found in the analysis of the force data. That is, significant differences were found between every other articulation position, i.e. slumped to erect or slumped to super erect or neutral to super erect. However for both recline 1 and recline 3, a statistically significant difference was found between the thorax angle in the neutral and erect conditions. This difference was not seen in recline 2. As with the force data, these data suggest that the chair thorax support must be moved 10° to consistently achieve statistically different thorax positions.

Notice that in recline 3 the average thorax angle change between the erect and super erect condition was small and opposite the trend. In this reclined position, it may be that the subjects have reached a physical limitation of the combination of the pelvis and thorax rotation; this, in combination with the requirement to maintain foot contact with the floor restricts the subject from additional movement. The same trend is seen with the pelvis in recline 3 which will be discussed shortly (Table 45). Following are some theories for what may cause the reduced movement in recline 3 for both the thorax and the pelvis segments. It may be that with combination of the large recline angle and the erect posture, the hamstring tension is at its maximum length and further rotation of the pelvis is not allowed. Likewise, the passive tissues along the back may be stretched to their maximum length and further coupled rotation of the pelvis and thorax is not possible.

Motion of Individual Segments: Pelvis

Table 45 lists the pelvis angles for all subjects at all chair articulations for recline 1, while Table 46 lists the average pelvis angles for all three recline angles. A trend was seen within and across the subjects: as the pelvis support moved from a slumped to an erect position, the pelvis angle became smaller. The negative sign of the pelvis angle denoted that the vector from the S1 target to the mid-ASIS location was above lab horizontal, or the front of the pelvis was tipped upward. As the subject became more erect, the front of the pelvis tipped downward bringing the pelvis angle closer to the horizontal reference line producing a smaller angle.

The statistical analysis of the pelvis angles shed some surprising results. For recline 1, all of the conditions were significantly different from one another. So, contiguous articulations moved the pelvis enough to demonstrate a difference from each other. In the more upright condition, recline 1, the chair appeared to have better command over how the pelvis moved and forced the pelvis to move with the chair.

Recline 2 did not show any significant differences between conditions and recline 3 showed differences between slumped and super erect and slumped and erect. If the theory that a more upright recline provides better control over the pelvis is true, then a higher number of statistically significant differences would be expected in recline 2 with the least amount of statistically significant differences found in recline 3. Thus data from reclines 1, 2 and 3 produce conflicting results toward this theory.

Table 45: Pelvis angles for each subject at each chair articulation in recline 1. The pelvis angle is measured with respect the horizontal lab (wrth) with the negative sign meaning the vector is above horizontal.

Pelvis Angle	(wrth)	negative is rearward of vertical				
(Degrees)						
	Recline 1					
Subject	**Slumped**	**Neutral**	**Erect**	**Super Erect**	**Ave**	**Std**
1	-34.4	-31.1	-29.4	-28.5	-30.9	2.6
2	-34.7	-33.6	-32.2	-31.3	-33.0	1.5
3	-41.0	-39.3	-34.9	-32.2	-36.9	4.0
4	-41.0	-38.8	-37.9	-35.5	-38.3	2.3
5	-43.1	-42.4	-38.2	-36.2	-40.0	3.3
6	.	-33.5	-30.5	-28.3	-30.8	2.6
7	-35.1	-31.9	-28.6	-27.5	-30.8	3.4
8	-34.1	-32.1	-29.1	-25.9	-30.3	3.6
9	-43.7	-41.8	-39.0	-36.0	-40.1	3.4
10	-49.4	-42.1	-38.9	-34.7	-41.3	6.2
11	-36.1	-35.1	-33.3	-32.7	-34.3	1.6
12	-12.6	-12.6	-11.4	-8.8	-11.4	1.8
13	-26.0	-23.3	-21.9	-19.6	-22.7	2.7
14	.	-39.3	-36.6	-34.3	-36.7	2.5
15	-24.5	-25.2	-25.2	-22.8	-24.4	1.1
16	-36.0	-34.4	-33.0	-26.7	-32.6	4.1
17	-28.3	-25.6	-22.4	-20.8	-24.3	3.4
18	-26.9	-27.7	-26.1	-23.9	-26.1	1.6
19	-23.0	-23.5	-22.0	-19.7	-22.1	1.7
20	-22.6	-22.4	-19.8	-19.4	-21.1	1.7
21	-32.8	-30.7	-27.5	-26.4	-29.4	3.0
22	-29.9	-28.9	-27.2	-25.1	-27.8	2.1
23	-17.7	-17.3	-14.4	-21.5	-17.7	2.9
Ave	-32.1	-31.0	-28.7	-26.9		
Std	9.1	8.0	7.6	6.8		
Range	36.7	29.7	27.5	27.4		

Table 46: Average pelvis angles for all subjects across all three recline angles, with respect to lab horizontal.

Pelvis Angle (Degrees) Subject	(wrth) Slumped	Neutral	Erect	Super Erect
Recline 1				
Ave	-32.1	-31.0	-28.7	-26.9
Std	9.1	8.0	7.6	6.8
Range	36.7	29.7	27.5	27.4
Recline 2				
Ave	-36.1	-35.0	-32.1	-30.2
Std	9.5	9.4	8.1	8.0
Range	35.5	33.0	29.5	30.5
Recline 3				
Ave	-40.3	-38.3	-36.6	-36.1
Std	9.2	8.4	8.2	7.6
Range	34.3	32.0	29.6	28.4

Table 47: Testing for significant differences between the subjects' pelvis angles.

Pelvis Angle	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Recline 1	Y	Y	Y	Y	Y	Y
Recline 2	-	-	-	-	-	-
Recline 3	Y	-	-	Y	-	-

Limb Angles: Elbow and Knee

Finally, to complete the evaluation of the posture of the body, the positions of the arms and legs will be discussed.

A unique aspect of the protocol used for this study was that the subjects were allowed to choose both the wheel position and the foot position. Allowing the subject to choose these positions helped to ensure that the torso posture and not the effect of the package (wheel and foot position) was the primary influence on the loading of the chair.

Table 48 lists the elbow angles for all the subjects in all chair articulations for recline 1, and Table 49 lists the average elbow angles for all three reclines. Upon examination of Table 48 it appeared as though each subject chose a preferred elbow angle and then maintained a similar elbow angle across chair articulations. Table 50, the statistical analysis of the elbow angle, confirms that there was not a significant change in the elbow angle between chair positions.

Table 48: Elbow Angles for all the subjects at all the chair articulations for recline 1. Note the small deviation within a subject across conditions.

Elbow Angle (Degrees) Subject	Recline 1 Slumped	Neutral	Erect	Super Erect	Ave	Std
1	101.4	106.4	107.7	104.0	104.9	2.8
2	91.3	86.1	90.2	97.9	91.4	4.9
3	126.8	123.9	118.9	122.6	123.1	3.3
4	102.3	101.3	102.8	101.0	101.8	0.9
5	102.2	105.0	105.8	102.4	103.9	1.8
6	106.6	100.7	110.1	115.6	108.3	6.3
7	101.7	96.3	102.6	102.9	100.9	3.1
8	88.3	86.7	88.8	96.0	90.0	4.2
9	106.9	104.3	103.1	108.9	105.8	2.6
10	91.8	93.7	96.5	111.1	98.3	8.8
11	133.0	131.1	131.1	134.1	132.3	1.5
12	117.6	119.9	104.4	100.5	110.6	9.6
13	113.9	117.4	119.0	118.7	117.3	2.3
14	123.8	127.5	122.1	117.6	122.7	4.1
15	102.7	114.8	109.8	112.4	109.9	5.2
16	80.1	79.0	87.4	76.8	80.8	4.6
17	112.9	116.6	114.0	107.1	112.7	4.0
18	117.1	111.7	116.6	121.0	116.6	3.8
19	92.0	103.6	104.7	100.5	100.2	5.7
20	118.1	133.3	127.1	114.1	123.1	8.7
21	122.6	119.3	116.8	116.3	118.8	2.9
22	82.0	94.8	86.7	96.6	90.0	6.9
23	118.2	120.2	119.1	129.6	121.8	5.3
ave	106.7	108.4	108.1	109.0		
std	14.6	14.9	12.5	12.6		
range	52.9	54.3	44.3	57.4		

Table 49: Summary of Elbow Angles for Recline 1, 2 and 3.

	Elbow Angle Summary (Degrees)			
Recline 1				
ave	106.7	108.4	108.1	109.0
std	14.6	14.9	12.5	12.6
Recline 2				
ave	109.8	110.7	111.3	109.6
std	16.1	16.3	15.0	15.1
Recline 3				
ave	108.2	110.7	109.7	112.0
std	13.5	12.3	12.1	13.3

Table 50: Testing for significant differences of the elbow angle between the various chair articulations.

Elbow Angles	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Recline 1	-	-	-	-	-	-
Recline 2	-	-	-	-	-	-
Recline 3	-	-	-	-	-	-

Table 51: Testing for significant differences of the elbow angle between the recline positions.

Elbow Angles Reclines	1 vs. 2	2 vs. 3	1 vs. 3
Significance	-	-	-

Since there were no significant differences exhibited between the slumped, neutral, erect and super erect groups, Table 50, these data were lumped together under each recline condition and an ANOVA used to test overall differences between reclines, Table 51, none were found.

Table 52, Table 53 and Table 54 show the knee angles of the subjects across conditions. Again, similar to the elbow angles, each subject picked a preferred knee angle and did not deviate from that position across chair articulations. Table 54 validates these trends by the lack of statistically significant results across the majority of chair articulations. Recline 2 showed a statistically significant difference between the slumped and super erect positions, but this was not supported by the data from the other two recline angles.

Table 52: Knee angles for all the subjects at all the chair articulations for recline 1. Note the small deviation within a subject across conditions.

Knee Angle (Degrees) Subject	Recline 1 **Slumped**	**Neutral**	**Erect**	**Super Erect**	**Ave**	**Std**
1	124.7	128.4	133.4	133.6	130.0	4.3
2	125.1	124.7	126.8	123.0	124.9	1.5
3	116.1	114.9	111.3	120.7	115.7	3.9
4	135.9	134.5	139.3	139.7	137.4	2.5
5	120.6	103.9	106.4	104.8	108.9	7.9
6	113.2	111.2	117.2	118.4	115.0	3.3
7	129.0	132.7	133.2	134.6	132.4	2.4
8	120.5	128.2	128.9	128.4	126.5	4.0
9	132.3	130.4	129.9	130.4	130.7	1.1
10	116.8	141.7	140.3	131.1	132.5	11.5
11	150.2	146.8	149.8	147.2	148.5	1.8
12	139.8	147.3	146.1	144.9	144.5	3.3
13	149.5	150.5	153.2	154.9	152.0	2.5
14	146.1	148.3	139.1	136.5	142.5	5.6
15	142.8	144.8	140.3	144.2	143.0	2.0
16	121.8	122.3	124.4	119.1	121.9	2.2
17	140.2	-	-	-	140.2	-
18	146.3	143.4	141.2	139.5	142.6	3.0
19	165.1	167.8	170.1	168.8	167.9	2.1
20	133.2	136.6	138.2	134.8	135.7	2.2
21	143.6	140.4	144.8	145.2	143.5	2.2
22	153.2	160.2	160.2	159.3	158.2	3.4
23	152.5	157.9	158.9	-	156.4	3.5
ave	135.6	137.1	137.9	136.1		
std	14.2	16.0	15.6	14.9		
range	51.8	63.8	63.7	63.9		

Table 53: Summary of knee angles for recline 1, 2 and 3.

Knee Angle Summary (Degrees)				
Recline 1				
ave	135.6	137.1	137.9	136.1
std	14.2	16.0	15.6	14.9
Recline 2				
ave	134.4	135.8	136.7	138.0
std	14.3	15.1	15.5	15.5
Recline 3				
ave	131.0	133.4	134.0	132.6
std	13.8	15.5	16.0	16.7

Table 54: Testing for significant differences of the knee angle between the various chair articulations.

Knee Angle	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Recline 1	-	-	-	-	-	-
Recline 2	Y	-	-	-	-	-
Recline 3	-	-	-	-	-	-

Table 55: Testing for significant differences of the elbow angle between the recline positions.

Knee Angles Reclines	1 vs. 2	2 vs. 3	1 vs. 3
Significance	-	-	-

Overall when examining the knee and elbow angles, the data shows that subjects chose a preferred knee or elbow angle and if they have the choice, they do not deviate from these angles regardless of the chair position, or the body posture. These data will be beneficial to the designers of the automobile interiors. Instead of fixing the horizontal distance between the steering wheel and pedals, a more desirable alternative may be to allow the driver to choose the position of each, and reduce the overall track motion of the seat. This approach would accommodate people with varying leg and arm lengths better than the current approach.

Results, Analysis and Discussion of Dynamic Data

In this section, data from the dynamic tests are analyzed and discussed. Since the dynamic tests were conducted by taking data continuously over a ten second time period, the data were in the form of traces rather than single points as generated from the static test data. When possible, comparisons between the static and dynamic tests were made. Also, new data that was only available from the dynamic tests were analyzed, such as the travel path of the resultant force vector.

Chair Motions

Prior to comparisons between the dynamic and static tests, the chair movement itself was analyzed.

Recline Angle

First, the recline angle of the chair was examined. Again in the dynamic condition, the three recline angles of 20, 24 and 28 were fixed while the torso articulation was adjusted in a continuous fashion through the full ranges of motion (slumped to super erect). Comparing the data in the shaded cells of Table 56, the recline angle between the dynamic and static tests were similar. The average dynamic recline angles as measured by the recline bar on the chair were -40.7°,- 45.4°, -49.4° for recline angles 1, 2, and 3, respectively, compared to -41.0°,-45.2° and -49.4° for the static chair positions. From these two sets of data and the statistical analysis, Table 57, it was clear that the recline angles could be considered the same between the dynamic and static testing.

The recline angle data for each subject in the static and dynamic conditions was statistically analyzed via a one way ANOVA test. However, this test showed that the data failed to be normally distributed so a Kruskal Wallis one way ANOVA on Ranks was performed, Table 57. The analysis found no statistically significant difference between the static and dynamic recline angles, however a statistically significant difference was shown within dynamic recline conditions. This demonstrated that the chair was positioned in a repeatable fashion between recline conditions, that the recline angles were far enough apart to detect a difference between recline conditions in the dynamic tests, and that the recline positions were similar between static and dynamic testing.

Table 56: Total Recline Angle (TRA) for the chair during both dynamic and static testing. All angles in degrees.

Chair TRA for Dynamic Tests			
Degrees	Recline 1	Recline 2	Recline 3
Ave Max	-40.0	-45.1	-49.0
Max std	2.6	0.8	1.1
Ave Min	-41.3	-45.7	-49.7
Min std	2.6	0.9	1.1

TRA for Static Tests			
	Recline 1	Recline 2	Recline 3
Average	-41.0	-45.2	-49.4
Std	1.3	1.2	0.8

Table 57: Statistical analysis of Total Recline Angle during static and dynamic testing.

	Recline 1	Recline 2	Recline 3
Static vs. Dynamic	-	-	-

	Rec 1 vs 2	Rec 1 vs 3	Rec 2 vs 3
Dynamic	Y	Y	Y

Y= a statistically significant difference was found

Torso Articulations

For dynamic tests, the recline angle of the chair was held constant while a test assistant moved the chair through the full range of total support angles to articulate the torso. The Total Support Angle (TSA) was initially positioned in the neutral condition and then moved to slumped, back through neutral and to super erect. For the entire 10 second period, force and motion data were collected at a 12 Hz sample rate. The trials were alternated, so that one trial started toward the slumped position while the second trial started toward the super erect position first. Recall that the static tests were positioned at each of the four torso articulations, slumped, neutral and erect and super erect and data were collected at each point, not between articulations.

Table 58: Total Support Angle (TSA) for the chair during both dynamic and static testing. All angles in degrees.

TSA for Dynamic Tests			
Degrees	Recline 1	Recline 2	Recline 3
Super Erect	113.6	112.3	113.0
Slumped	78.7	80.5	81.4
Range	34.9	31.8	31.6

TSA for Static Tests			
	Recline 1	Recline 2	Recline 3
Super Erect	112.5	112.8	112.1
Slumped	83.0	81.6	81.4
Range	29.5	31.2	30.7

Again, comparing the shaded cell data from Table 58 the average ranges of chair movement between the maximum and minimum TSA slumped to super erect in the dynamic test conditions were 34.9°, 31.8° and 31.6° for reclines 1, 2, and 3 while the ranges of movement for the static conditions were similar in reclines 2 and 3 (31.2°, 30.7°) but 5° less for recline 1, (29.5°). For the dynamic tests the chair was moved in a smooth continuous fashion and once the end articulations were reached, the direction of motion was reversed. Since the chair did not have stops at each setting, but rather markings on the chair that were aligned for each TSA, it was not surprising that there was some variation in the ranges. From observation, Reclines 2 and 3 average movements were similar between the static and dynamic tests, however when examined statistically, differences between the static and dynamic tests were determined.

The number of trials between the static and dynamic test data for each recline had large variations between the number of samples for each condition (dynamic condition had more samples than the static condition). The statistical analysis was performed using separate tests for comparisons between each condition (slumped: static vs dynamic, super erect: static vs. dynamic) rather than an ANOVA. Again the data failed the normality test and a Mann-Whitney Rank Sum Test was performed on each set of data, Table 59. For each case, the minimum TSA's (slumped condition) of the static test was compared to the minimum TSA's of the dynamic tests for each recline angle. The maximum TSA's (super erect) were also compared. In each recline angle, significant differences were determined to exist at either the minimum or maximum TSA's, thus leading to the conclusion that the full ranges of movement of the chair were significantly different between the static and dynamic conditions.

When appropriate, comparisons will be made between the dynamic and static test results with regard to torso articulation. However, it is important to note that the dynamic conditions on average had a larger range of chair motion than the static conditions and that statistically significant differences existed for all recline angles either at the maximum or minimum TSA, Table 59.

Table 59: Statistical analysis of Total Support Angle during static and dynamic testing.

	Static vs. Dynamic	Static vs. Dynamic
	Slumped (Min)	Super Erect (Max)
Recline 1	Y	-
Recline 2	Y	-
Recline 3	-	Y

Y= a statistically significant difference was found

Force Data for Dynamic Tests

Primary Forces

Next, the primary forces exerted during the dynamic tests will be presented and compared to the primary forces seen in the static tests. Again, the primary forces were the normal forces on all of the support plates, except for the wheel where the load from the arms produced a downward shear force on the support plate and was considered a primary force, Figure 72. The normal forces were all loads into the support plate from the body, therefore they were all identified as negative support forces.

Table 60: Average primary forces for both the Static and Dynamic Tests (Newtons).

Newtons	Static Tests			Dynamic Tests			Range Difference
Recline 1	Min	Max	Range	Min	Max	Range	Dyn-Stat
Thigh	-127.7	-140.2	12.5	-95.8	-173.0	77.2	64.7
Buttocks	-403.5	-432.4	28.9	-406.9	-450.7	43.8	14.9
Pelvis	-22.5	-27.9	5.4	-19.6	-40.6	20.9	15.5
Thorax	-182.1	-187.4	5.3	-154.3	-193.5	39.2	33.9
Foot	-93.4	-112.1	18.7	-72.5	-127.1	54.6	35.9
Wheel (Fx)	-32.3	-33.3	1	-29.8	-37.4	7.6	6.6
Recline 2							
Thigh	-126.6	-133.8	7.2	-95.3	-183.0	87.6	80.4
Buttocks	-390.7	-418.4	27.7	-393.7	-439.4	45.7	18.0
Pelvis	-28.5	-35.6	7.1	-19.8	-42.9	23.1	16.0
Thorax	-197.5	-209.6	12.1	-169.4	-205.2	35.9	23.8
Foot	-86.3	-107	20.7	-65.6	-119.1	53.5	32.8
Wheel (Fx)	-31	-31.9	0.9	-32.4	-39.9	7.4	6.5
Recline 3							
Thigh	-103.2	-127.5	24.3	-92.6	-183.1	90.5	66.2
Buttocks	-382.5	-408.6	26.1	-383.3	-424.4	41.1	15.0
Pelvis	-30.7	-39.1	8.4	-22.4	-42.7	20.3	11.9
Thorax	-221.6	-230	8.4	-194.0	-224.7	30.7	22.3
Foot	-83.3	-108.9	25.6	-65.4	-116.4	51.1	25.5
Wheel (Fx)	-32.6	-33.7	1.1	-33.7	-40.4	6.8	5.7

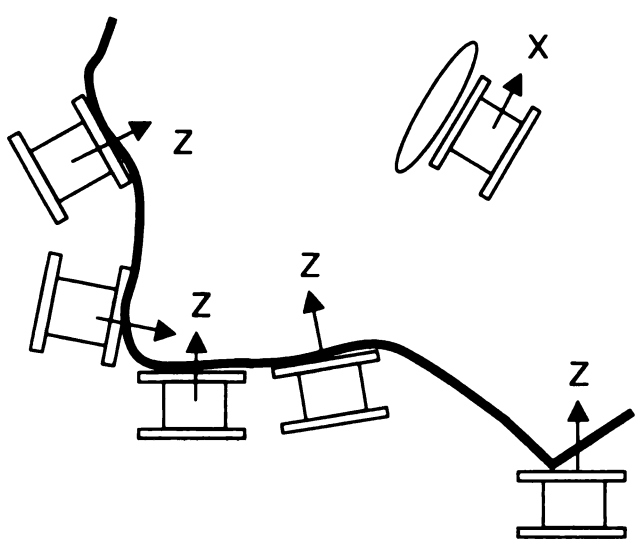


Figure 72: Primary forces represent the normal forces under all of the force plates except for the steering wheel where the shear force, Fx, was the maximum force.

Table 60 lists the average maximum, minimum and ranges for the primary support forces for both the static and dynamic tests. As can clearly be seen by the last column of data in Table 60, the primary forces exerted by the subject onto the chair were of a higher magnitude for all reclines and all support plates in the dynamic tests. The largest differences were seen in the thigh plate with an average of 70.4 N and the foot and thorax supports followed with average differences of 31.4 N and 26.7 N, respectively. Recall, the ranges of chair motion were larger for the dynamic test trials. However, the magnitude of difference between the static and dynamic forces was more than could solely be attributed to the larger range of motion of the chair in the dynamic movements. It is unclear as to what, aside from the different chair ranges, would cause these differences in loading, specifically why the dynamic conditions consistently produced higher loading patterns for all support plates.

In Table 60 the forces are represented as maximum and minimum values, in the static conditions, the location of the maximum and minimums were easily defined in terms of chair position, i.e. the maximum and minimums had to occur at one of the four torso positions. Table 61 identifies the position where the maximum and minimum forces occurred for the static tests. Identifying the location of the maximum and minimums for the dynamic tests was more difficult, but as can be seen in Figure 73 the maximum and minimum trends occurred in similar positions. However these points were slightly before or after the endpoints of the chair positions, but were in the same region (slumped or neutral vs erect or super erect). In order to determine the chair position at the maximum or minimum primary force, the points were selected from the graphs and matched to the same frame number for the graph of the chair position. This tedious procedure was completed for all the dynamic trials in the middle recline position (Recline 2) and a sample of these data are presented in Table 62. Thus, the chair position was determined for the maximum and minimum primary force value, Table 63.

As an example of the trend of the primary forces during dynamic movement, force data plots were developed for all subjects, and samples of these graphs are presented in Figure 73, Figure 74 and Figure 75. These figures show the chair movement in terms of openness (a larger angle means a more erect chair condition) and the forces (a more negative force means the force has a larger magnitude). Comparing Table 61, Table 63 and Figure 73 and it can be seen that the force trends of the thighs and feet are similar to the static tests for the majority of subjects. The minimum force magnitude of the thigh occurs near the super erect chair position and the maximum near the slumped condition. For the feet, the minimum force magnitude occurs near the slumped chair position and the maximum near the super erect position. Again, from a visual inspection, the primary force on the wheel does not appear to be affected by the torso articulation.

Table 61: TSA where the maximum and minimum average primary forces were exerted for static tests.

	Minimum Magnitude			Maximum Magnitude		
	Rec 1	Rec 2	Rec 3	Rec 1	Rec 2	Rec 3
Thigh	SE	SE	SE	N	S	S
Buttocks	SE	SE	SE	S	S	S
Pelvis	SE	E	SE	S	S	S
Thorax	E	SE	SE	N	N	S
Foot	S	S	S	SE	SE	SE
Wheel	No Change	---	---	---	---	---

S= Slumped, N= Neutral, E = Erect, SE = Super Erect

Table 62: Sample of data from which Table 63 data was obtained.

Trial	Force		Chair Position at Max Force	Chair Range		Estimated Location of S,N,E, SE Chair Positions based on Chair Range				Chair Position at Max Force
	Max or Min	Thigh Fz (N)	Degrees	Max (Deg)	Min (Deg)	S (Deg)	N (Deg)	E (Deg)	SE (Deg)	
11drec2a	Max	-134.9	109.0	110.3	79.4	79.9	89.9	99.9	109.9	SE
11drec2b	Max	-116.0	107.0	110.0	79.7	79.8	89.8	99.8	109.8	E-SE
12drec2a	Max	-103.9	112.0	112.7	78.4	80.5	90.5	100.5	110.5	SE+
12drec2b	Max	-113.4	108.0	114.1	79.6	81.8	91.8	101.8	111.8	E-SE
13drec2a	Max	-153.6	110.0	112.1	79.2	80.6	90.6	100.6	110.6	SE
13drec2b	Max	-153.6	106.0	113.8	82.6	83.2	93.2	103.2	113.2	E-SE

Table 63: The most common TSA position of the chair at the maximum and minimum primary force values for Recline 2 dynamic tests.

	Minimum Magnitude	Maximum Magnitude
	Rec 2	Rec 2
Thigh	E-SE	S-N
Buttocks	Mixed	Mixed
Pelvis	S-N	E-SE
Thorax	Mixed	Mixed
Foot	S	SE
Wheel	E-SE	S

S= Slumped, N= Neutral, E = Erect, SE = Super Erect, Mixed

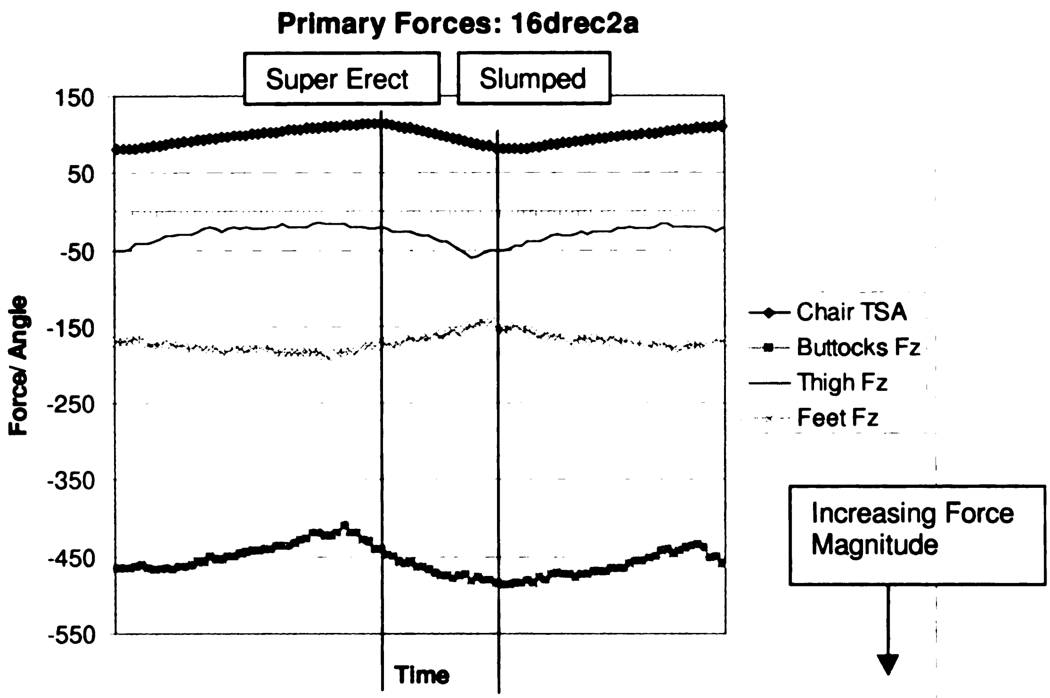
Table 64: Statistically significant difference in static tests between slumped and super erect conditions for the primary forces.

Statistically Significant Differences			
	Rec 1	Rec 2	Rec 3
Thigh	-	-	Y
Buttocks	Y	Y	Y
Pelvis	Y	Y	Y
Thorax	-	-	-
Foot	Y	Y	Y
Wheel	-	-	-

Table 65: Statistically significant differences of primary forces for the dynamic tests between the maximum and minimum values.

Statistically Significant Differences			
	Rec 1	Rec 2	Rec 3
Thigh	-	-	-
Buttocks	-	-	-
Pelvis	-	-	-
Thorax	-	-	-
Foot	-	-	-
Wheel (Fx)	-	-	-

Table 64 and Table 65 list the results for the statistical analysis of the primary force data for both the static and dynamic test trials. This analysis concluded that there was no statistically significant difference between the maximum and minimum primary force values for the dynamic test trials. A pair-wise comparison was completed using a one way repeated measures ANOVA on ranks at a 95% confidence level. The data was not normally distributed thus the ranks test was performed. These data contradict the findings of the statistical analysis of the static tests, Table 64, where the primary forces for the thigh, buttocks, pelvis and feet were found to have statistically significant differences between the slumped and super erect conditions.



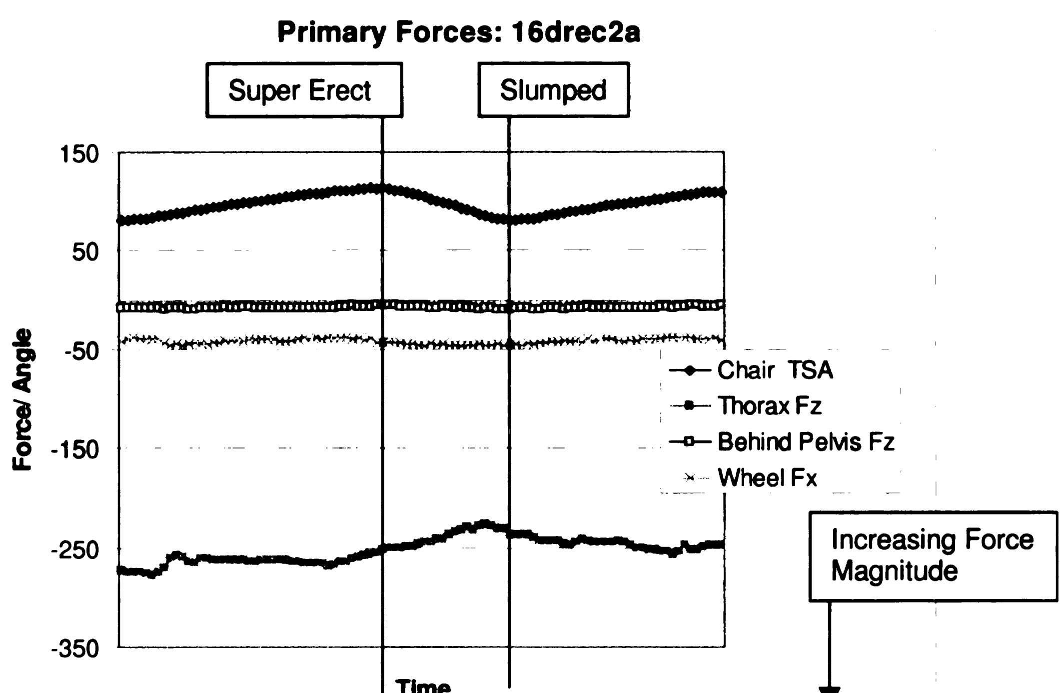
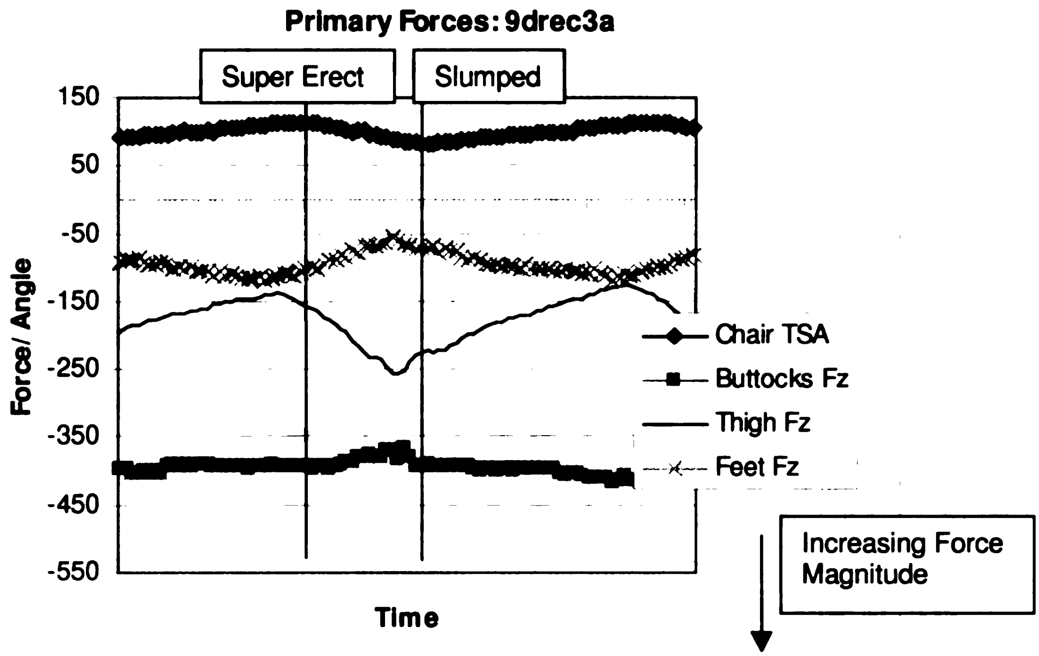


Figure 73: Primary forces (Newtons) from Subject 16, in recline 2, dynamic movement from neutral to super erect to slumped back toward super erect. All force data is displayed with respect to the chair TSA (degrees).



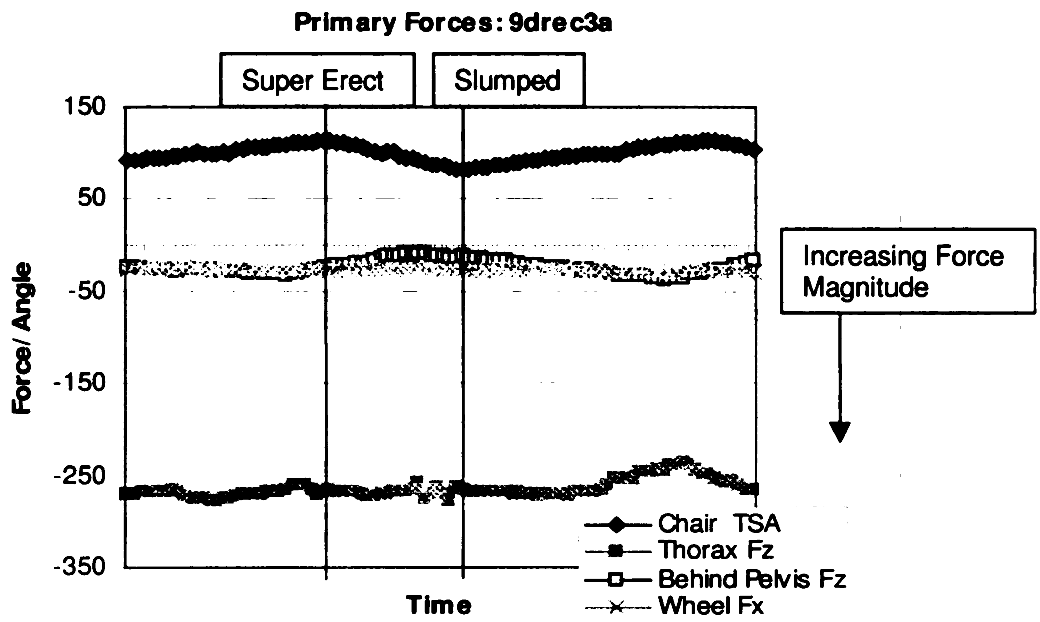
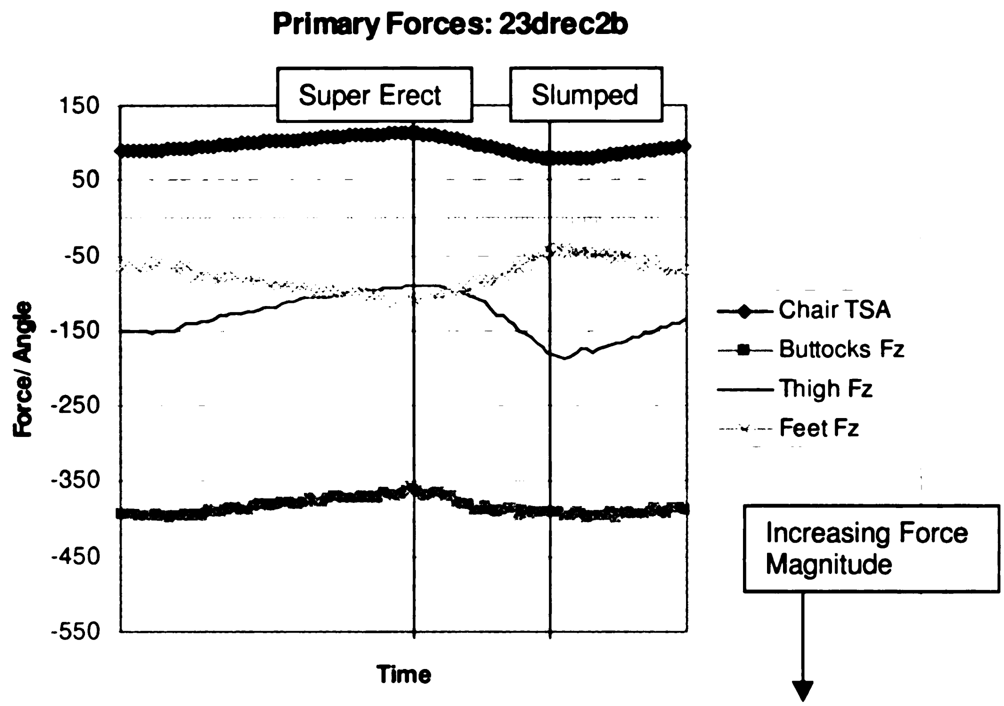


Figure 74: Primary forces from Subject 9, in recline 3, dynamic movement from neutral to super erect to slumped back toward super erect. All force data is displayed with respect to the chair TSA (degrees).



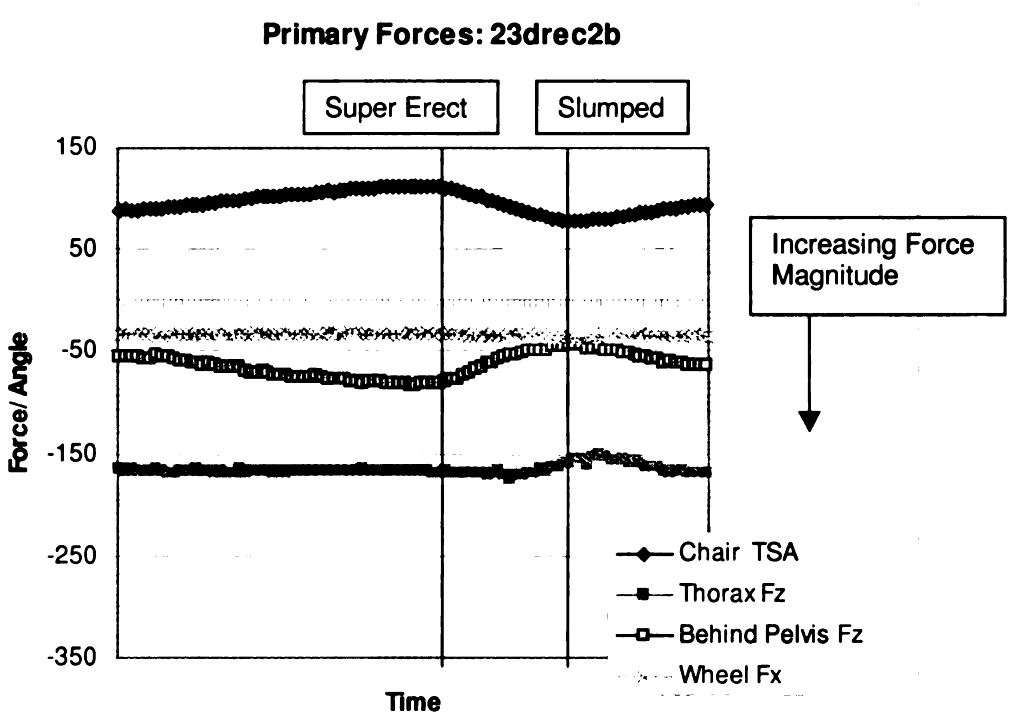


Figure 75: Primary forces from Subject 23, in recline 2, dynamic movement from neutral to super erect to slumped back toward super erect. All force data is displayed with respect to the chair TSA (degrees).

Secondary Forces

The secondary forces were also tabulated for the dynamic tests. As a reminder, the secondary forces were the anterior/posterior shear forces under the buttocks, thighs and feet and the superior/inferior forces behind the pelvis and thorax, Figure 76. The secondary forces on the steering wheel were perpendicular to the wheel and represented a pulling or pushing motion.

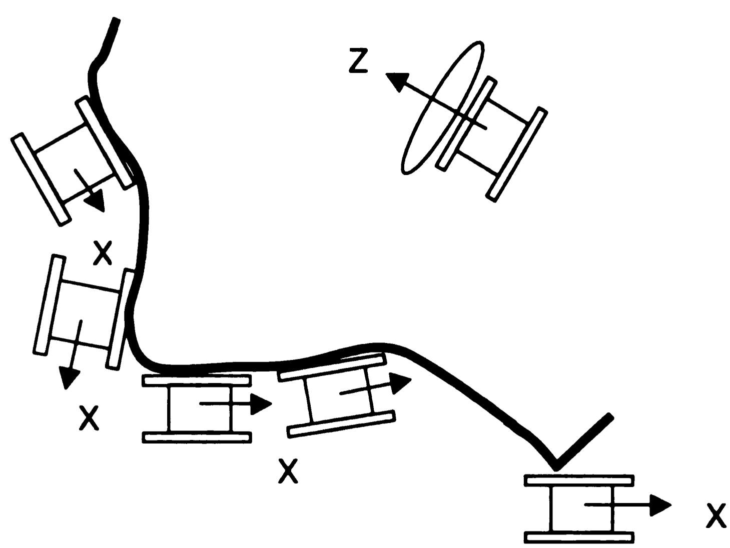


Figure 76: Secondary forces measured under the buttocks, thighs and feet and behind the thorax and pelvis Fx and the wheel Fz (positive is in the direction of the arrows).

When comparing the ranges of the shear forces in the static trials to those of the dynamic files, the dynamic files generally had a larger range of force distribution, Table 66. The buttocks plate was the only exception, where the range of shear motion for the dynamic trials was similar to the static trials. For all other support plates, the dynamic condition produced ranges two to four times larger than the static files, except behind the pelvis where the increase in range was as much as seven times greater than the static files.

Table 66: Secondary forces for both the static and dynamic tests in Newtons.

Newtons	Static Tests			Dynamic Tests			Range Difference
Recline 1	Max	Min	Range	Max	Min	Range	Dyn-Stat
Thigh	21.8	-4.6	26.4	37.1	-12.0	49.1	22.7
Buttocks	16.5	-39.9	56.4	7.6	-47.4	54.9	-1.5
Pelvis	16	12.7	3.3	29.6	5.5	24.1	20.8
Thorax	19.9	-8	27.9	36.4	-14.8	51.2	23.3
Foot	57.3	38.1	19.2	79.2	6.6	72.6	53.4
Wheel (Fz)	-3	-9	6	7.1	-15.1	22.1	16.1
Recline 2							
Thigh	18.9	-1.3	20.2	29.4	-13.2	42.7	22.5
Buttocks	7.4	-40.6	48	0.6	-54.1	54.6	6.6
Pelvis	22.5	17	5.5	29.1	5.9	23.2	17.7
Thorax	22.2	-9.4	31.6	32.7	-12.8	45.4	13.8
Foot	57.3	32.6	24.7	71.0	3.7	67.2	42.5
Wheel (Fz)	0.5	-9.4	9.9	14.3	-7.0	21.3	11.4
Recline 3							
Thigh	13.4	-0.4	13.8	27.4	-11.9	39.3	25.5
Buttocks	4.2	-50.6	54.8	-1.4	-47.9	46.5	-8.3
Pelvis	21.8	18.9	2.9	29.5	7.1	22.4	19.5
Thorax	20.8	-4.1	24.9	29.4	-15.0	44.4	19.5
Foot	57.1	31.5	25.6	71.5	3.3	68.2	42.6
Wheel (Fz)	2.3	-9.6	11.9	17.0	-6.1	23.0	11.1

Since these trials were dynamic, the subject was not able to readjust his body as the chair moved. For the static trials, after each chair motion, the subject was encouraged to lift his body off the seat and reposition it to reduce the shear loading and to make sure his body was positioned with the buttocks in contact with the pelvis support. Therefore, the higher shear forces would be expected in the dynamic conditions, since the subject was not able to adjust his body to reduce the shear forces as the seat was moving. Although slightly larger shear forces were expected, the magnitude of increase was higher than expected solely due to the inability of the subject to adjust his position. Another possibility for the higher shear forces, was that the chair did not move exactly with the body as will be shown later in this section, and this discontinuity added to the increase in the shear forces between the static and dynamic conditions.

Table 67: Statistically significant differences of secondary forces for the static tests between the slumped and super erect chair positions.

Statistically Significant Differences			
	Rec 1	Rec 2	Rec 3
Thigh	Y	Y	Y
Buttocks	Y	Y	Y
Pelvis	-	-	-
Thorax	Y	Y	Y
Foot	Y	Y	Y
Wheel (Fz)	Y	Y	Y

Table 68: Statistically significant differences of secondary forces for the dynamic tests between the maximum and minimum values.

Statistically Significant Differences			
	Rec 1	Rec 2	Rec 3
Thigh	Y	Y	Y
Buttocks	Y	Y	Y
Pelvis	Y	Y	Y
Thorax	Y	Y	Y
Foot	Y	Y	Y
Wheel (Fz)	Y	Y	Y

Table 67 and Table 68 list the statistically significant results for the secondary forces in both the static and dynamic test conditions. The statistical analysis showed a significant difference between the maximum and minimum values of the secondary forces in the dynamic tests for all support plates, Table

68. These findings were consistent with the statistical analysis of the static test trials, except for the case of the support behind the pelvis, where a statistically significant difference was not found in the static tests, Table 67.

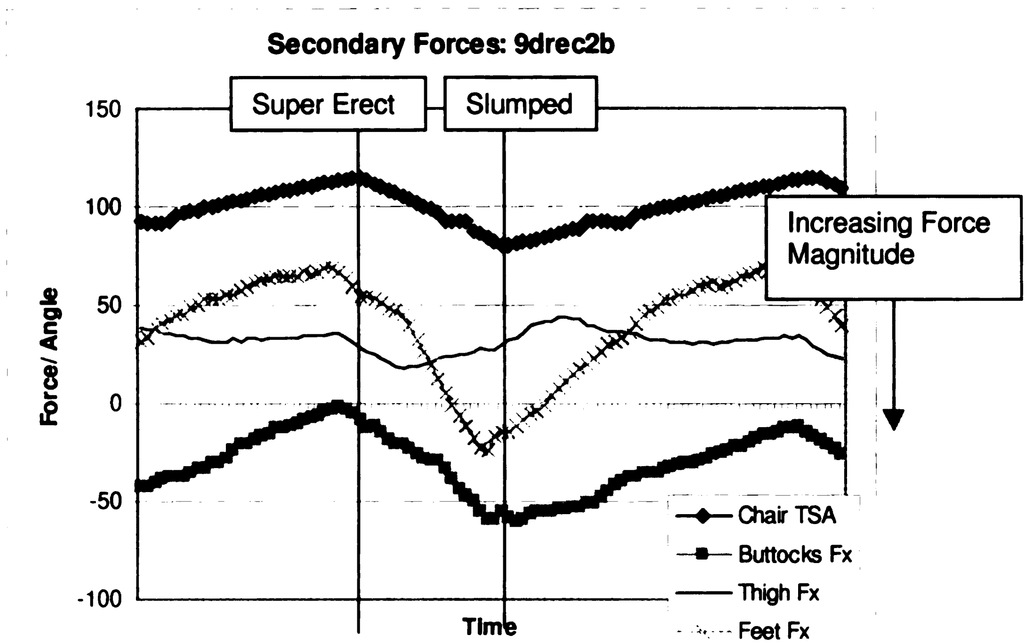
Figure 77, Figure 78 and Figure 79 are sample graphs (subjects randomly chosen) depicting the trends seen in the secondary force data for the dynamic test conditions.

For the majority of the subjects, the visual analysis of the trends in the secondary data showed that the pelvis, thighs and feet had positive shear forces (anterior in direction when acting on the chair) while the chair was in a maximum openness (SE) position. The shear forces reversed direction to a posterior force on the chair while in the slumped position.

The wheel forces also followed the movement of the chair. A pulling action of the wheel toward the body occurred in the super erect position and this pulling force decreased as the chair moved into a slumped position. This effect would seem reasonable since the shoulders were further away from the wheel in the super erect position as compared to the slumped position.

The changes of the thorax shear forces occurred with the majority of the subjects having a negative shear force in the super erect chair position (force on the chair pointed in the superior direction) and a positive shear force in the slumped chair position.

The shear force on the buttocks varied and was difficult to identify a consistent trend in the force data relative to the chair position. However, the data showed a statistically significant difference between the maximum and minimum shear forces, but the location of those forces with respect to chair position varied.



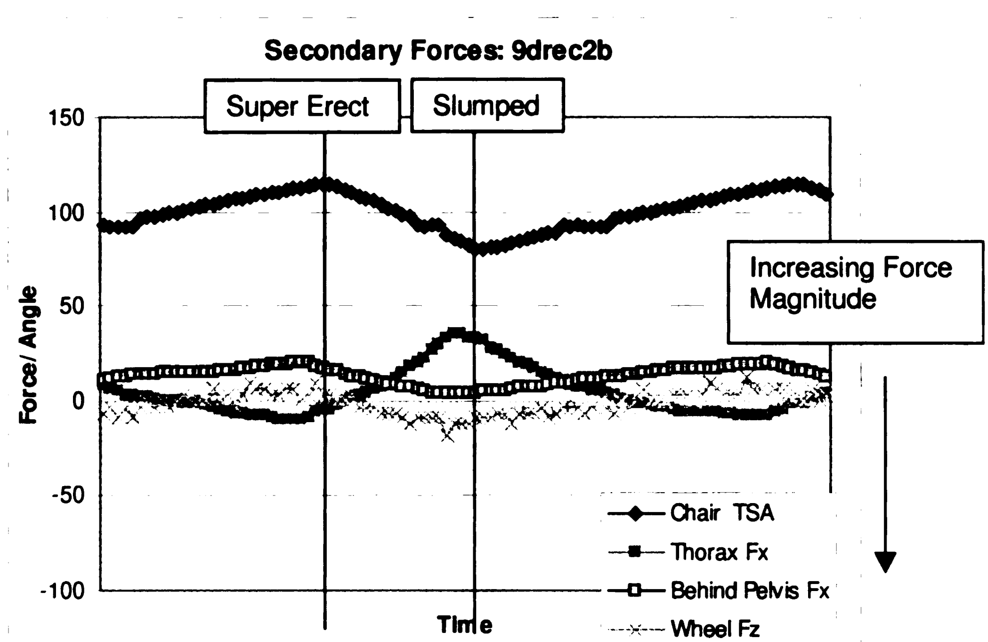
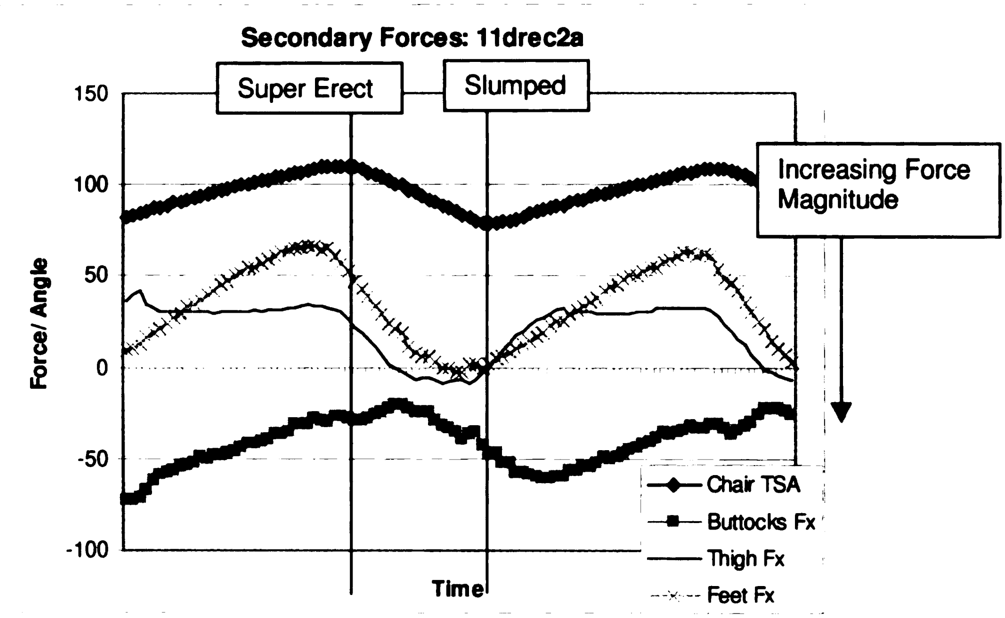


Figure 77: Secondary forces from Subject 9, in recline 2, dynamic movement from neutral to super erect to slumped back toward super erect. All force data is displayed with respect to the chair TSA (degrees).



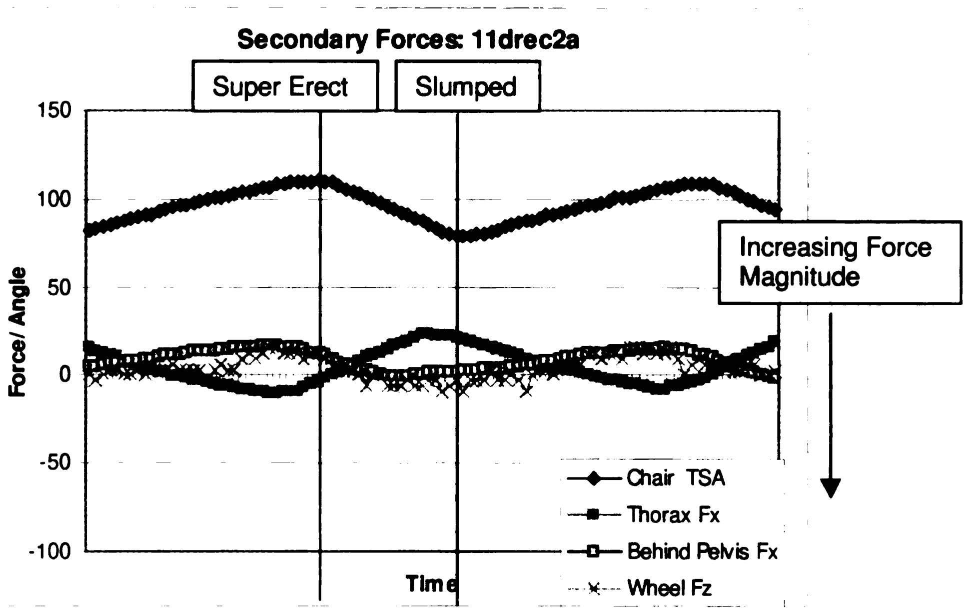


Figure 78: Secondary forces from Subject 11, in recline 2, dynamic movement from neutral to super erect to slumped back toward super erect. All force data is displayed with respect to the chair TSA (degrees).

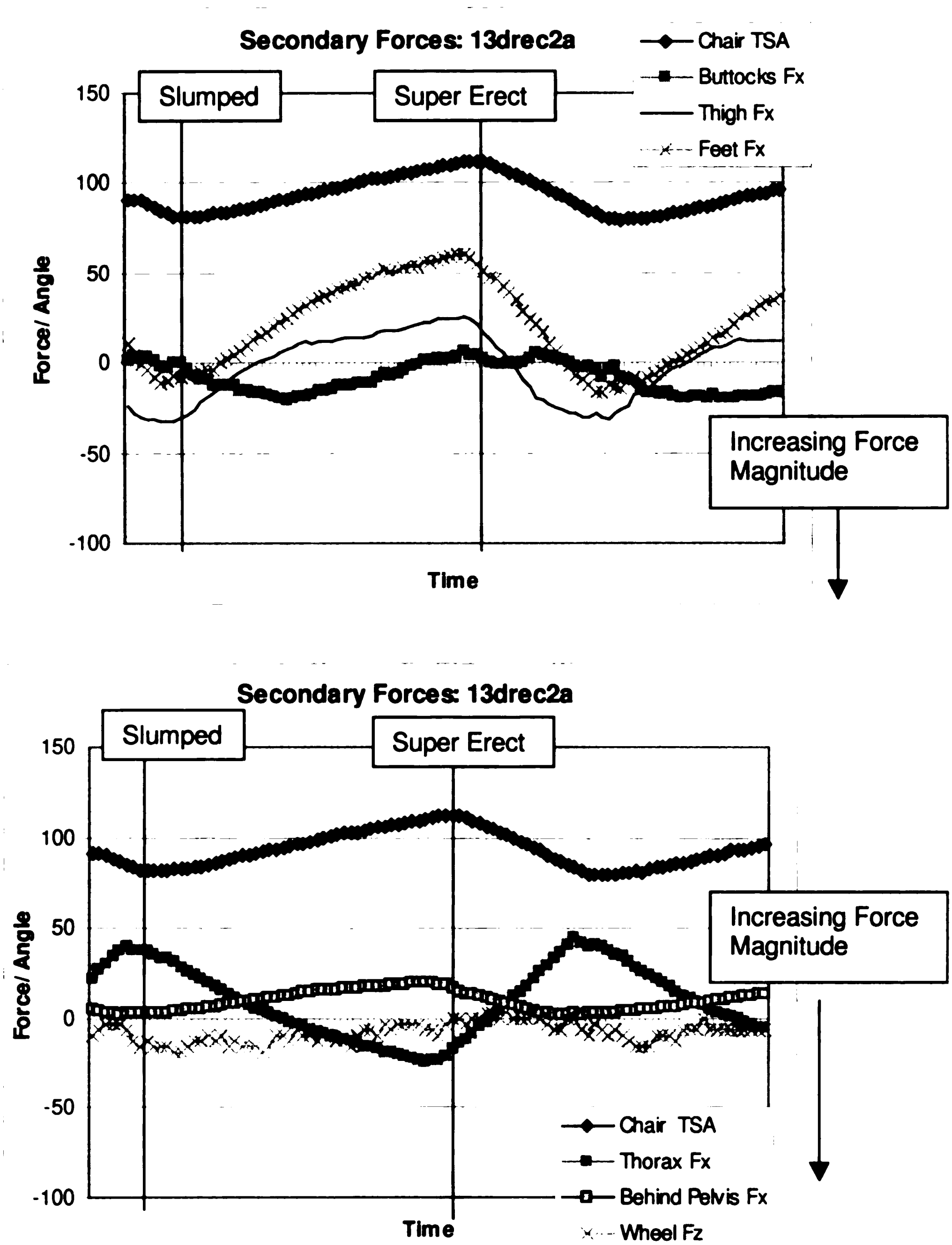


Figure 79: Secondary forces from Subject 13, in recline 2, dynamic movement from neutral to slumped to super erect back toward slumped. All force data is displayed with respect to the chair TSA (degrees).

Lateral Forces

The lateral forces were the side to side forces on the support plates. Since the motion of the chair and the subject occurred in the sagittal plane, these forces were expected to be small and not have significantly different results between torso articulations. The average maximum and minimum force data for both the static and dynamic tests are presented in Table 69.

Table 69: Lateral Forces for both the static and dynamic tests in Newtons.

Newtons	Static Tests			Dynamic Tests			Range Difference
Recline 1	Max	Min	Range	Max	Min	Range	Dyn-Stat
Thigh	0.4	-1.3	1.7	1.9	-3.8	5.7	4.1
Buttocks	-0.9	-2.0	1.0	3.6	-4.2	7.9	6.8
Pelvis	-1.0	-1.3	0.3	0.6	-2.2	2.9	2.5
Thorax	-0.5	-3.2	2.7	1.5	-5.9	7.4	4.8
Foot	-0.4	-0.8	0.4	1.6	-3.5	5.1	4.6
Wheel	1.9	1.6	0.3	3.8	-0.2	4.0	3.7
Thigh	-0.3	-1.9	1.6	3.0	-5.1	8.0	6.5
Buttocks	-0.4	-2.4	2.0	2.8	-6.1	8.9	7.0
Pelvis	-1.0	-1.3	0.3	0.8	-1.8	2.7	2.3
Thorax	-0.2	-1.7	1.5	1.8	-5.4	7.2	5.7
Foot	-0.4	-1.1	0.7	1.4	-3.7	5.1	4.4
Wheel	1.8	1.6	0.2	4.0	-0.1	4.1	3.9
Recline 3							
Thigh	0.8	-1.9	2.7	2.6	-5.1	7.6	4.9
Buttocks	0.9	-1.7	2.6	2.6	-6.0	8.6	6.0
Pelvis	-0.6	-1.0	0.5	0.8	-1.6	2.4	1.9
Thorax	-1.8	-3.0	1.2	1.9	-5.3	7.2	6.0
Foot	-0.3	-1.0	0.7	1.5	-3.5	5.0	4.3
Wheel	1.8	1.7	0.1	3.9	0.0	4.0	3.8

As demonstrated in Table 69, the dynamic tests consistently produced larger lateral forces than the static tests for all recline angles and all support plates. This was also the case when the primary and secondary forces were analyzed between the static and dynamic test conditions.

Table 70: Statistically significant differences of lateral forces for the static tests between all articulations. (Y) means statically significant differences found, (-) means no statistical difference found.

Lateral Support Forces (Fy)						
Recline 1						
	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Thigh	-	-	-	-	-	-
Buttocks	-	-	-	-	-	-
Pelvis	-	-	-	-	-	-
Thorax	Y	-	-	-	-	-
Feet	-	-	-	-	-	-
Wheel	-	-	-	-	-	-
Recline 2						
	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Thigh	-	-	-	-	-	-
Buttocks	-	-	-	Y	-	-
Pelvis	-	-	-	-	-	-
Thorax	-	-	-	-	-	-
Feet	-	-	-	-	-	-
Wheel	-	-	-	-	-	-
Recline 3						
	S vs. SE	N vs. SE	E vs. SE	S vs. E	N vs. E	S vs. N
Thigh	Y	-	-	-	-	-
Buttocks	-	-	-	-	-	-
Pelvis	-	-	-	-	-	-
Thorax	-	-	-	-	-	-
Feet	-	-	-	-	-	-
Wheel	-	-	-	-	-	-

Table 71: Statistically significant differences of lateral forces for the dynamic tests between the maximum and minimum values.

Statistically Significant Differences			
	Rec 1	Rec 2	Rec 3
Thigh	-	Y	-
Buttocks	-	-	-
Pelvis	Y	-	-
Thorax	-	Y	-
Foot	-	-	-
Wheel	Y	Y	-

Since the maximum and minimum lateral forces were not always found at the slumped or super erect chair position in the static tests, all chair articulations were listed and compared. For the static tests, there were no consistencies across recline angles that determined a statistically significant difference between lateral forces for any support plate. Only three cases, recline 1 for the thorax, recline 2 for the buttocks, and recline 3 for the thigh showed differences between lateral forces. The lack of statistically significant results across conditions and recline angles clearly demonstrated that the lateral forces did not change for the static tests.

For the dynamic tests, the only plate that showed a statistically significant difference for more than one recline angle was the support plate attached to the steering wheel. Since the subject was moving for the entire test it is reasonable that the wheel would see a change in lateral forces; the wheel would help stabilize the subject as the body was moved. For the pelvis, thigh and thorax support plates only one recline position showed a statistically significant difference in the lateral forces. Again, it was concluded that overall, the lateral forces did not vary significantly as the chair moved dynamically.

Overall Comments on Dynamic Force Data

In general the dynamic movement trials induced larger forces for the primary, secondary and lateral forces. The only exception were the secondary forces under the buttocks for recline 1 and recline 3 where the forces were larger in the static conditions by 1.5 N and 8.3 N.

The primary forces for the dynamic tests showed no statically significant differences between the maximum and minimum force values, unlike the static tests where the primary forces associated with the buttocks, pelvis and feet clearly showed statistically significant. From an examination of recline 2 data, the maximum and minimum primary forces occurred near the maximum or minimum chair articulations for the thighs, pelvis, feet and wheel, but had mixed locations for the buttocks and thorax plates. For the conditions where the chair position was mixed, it was difficult to make comparisons between the static and dynamic data. For the static tests, the maximum and minimum primary forces were located at the chair end points. Even though the dynamic primary forces did not show a statistically significant difference in magnitude, as discussed in the next section, a difference in the location of the resultant force on the support plates was related to changes in TSA.

The secondary force data produced similar results in terms of statistical significance between the static and dynamic tests. Statistically significant differences were shown to occur between the maximum and minimum secondary forces for all recline angles, and these forces primarily occurred at or near the extreme chair positions.

For the lateral forces, the majority of support plates in the various recline positions showed that there was no statistically significant difference between the maximum and minimum lateral forces. The lateral force maximum and minimum values occurred in various chair locations and were not consistently identified with slumped or super erect chair positions.

In general the primary forces were much larger than the secondary forces or the lateral forces. The secondary forces were typically only 9-14% of the magnitude of the primary forces, except for the pelvis and foot plates where the secondary forces were 60% of the primary force values.

Resultant Forces

Another point of interest when examining the support force data, aside from the magnitude of the forces, was path of travel of the resultant force. As stated earlier in this dissertation, one reason to look at the path of the resultant force was to examine the shift in the center of force. If a chair could be designed to shift the center of force, this chair design may be helpful in the prevention of decubitus ulcers. It is unclear as to how much of a shift in the distribution of the force is necessary to prevent the ulcers altogether, but it is known that postural change and force shifts reduce the occurrence and severity of the ulcers.

Figure 80 through Figure 83 show sample plots of the shift of the location of the resultant force in the XY plane, or the plane of the support plate. The graphs are labeled in terms of superior or anterior relative to the subject. Notice that the travel of the resultant force was primarily in the superior/inferior directions for the thorax and pelvis supports and in the anterior/posterior directions for the thigh and buttock supports. This type of movement coincided with the sagittaly symmetric task and the small lateral forces relative to the primary and secondary forces.

The location of the resultant force in the XY plane was computed using the moment equations, Equation 18, and solving for the X and Y distances to the forces.

$$X=(F_x * Z)/F_z - M_y/F_z$$
$$Y=(F_y * Z)/F_z + M_x/F_z$$

Equation 18: Calculation of the resultant force in the XY plane. Z values were between 54 and 55 mm which included 33 to 34 mm from surface of force plate to center of plate, 18 mm for board thickness and 3 mm for compressed foam thickness.

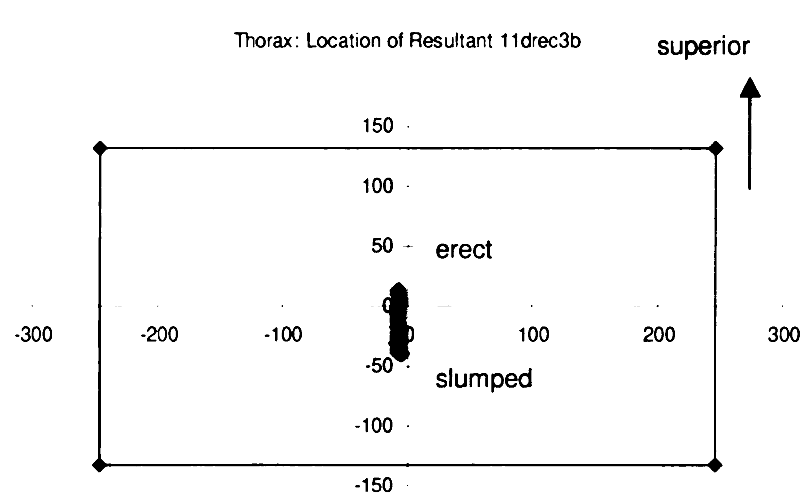


Figure 80: Location of resultant force for the thorax plate during dynamic chair movement from slumped to erect.

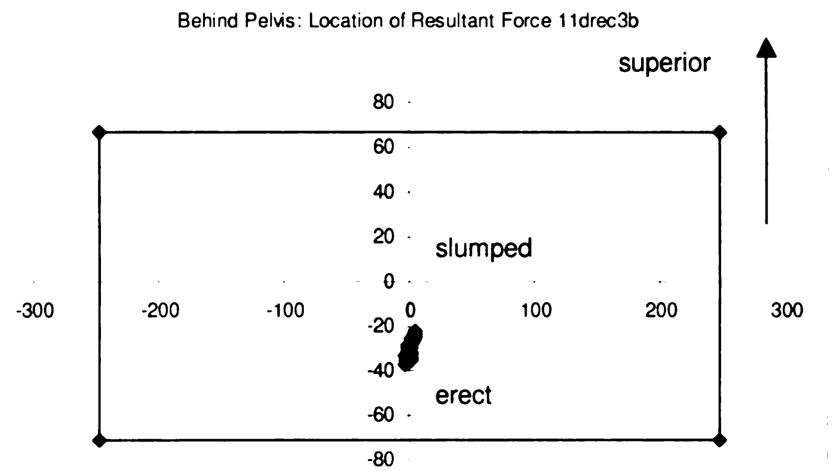


Figure 81: Location of resultant force for the pelvis plate during dynamic chair movement from slumped to erect.

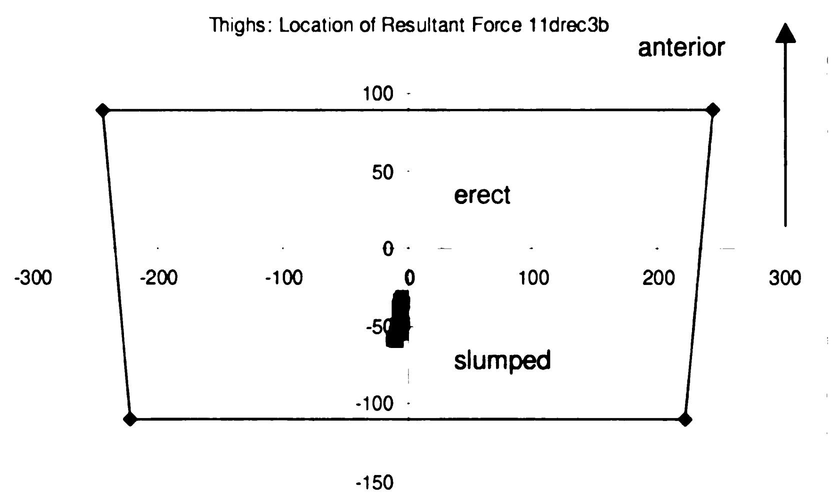


Figure 82: Location of resultant force for the thigh plate during dynamic chair movement from slumped to erect.

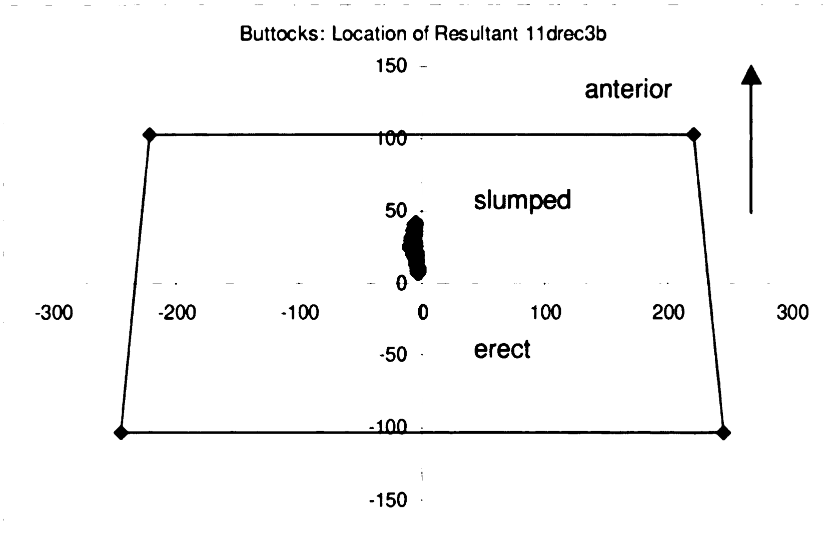


Figure 83: Location of resultant force for the buttocks plate during dynamic chair movement from slumped to erect.

Table 72: Location of the resultant force with respect to the center of the force plate in the X direction. X direction is positive inferior behind the thorax and pelvis, and positive anterior under the buttocks and thighs.

Location of Resultant in the X direction (mm)		Thorax	Pelvis	Buttocks	Thigh	Foot
Rec 1	Ave range	58.5	18.3	27.4	41.9	59.3
	Std	17.5	14.6	8.5	20.2	24.9
Rec 2	Ave range	50.1	17.6	28.2	36.4	57.1
	Std	16.9	11.9	8.6	14.0	31.8
Rec 3	Ave range	44.0	16.3	29.6	36.1	58.1
	Std	15.0	12.4	9.3	11.1	26.8
Average		51	17	28	38	58

Table 73: Location of the resultant force with respect to the center of the force plate in the Y direction. The Y direction is positive toward the left side of the body while seated in the chair.

Location of Resultant in the Y direction (mm)							
		Thorax	Pelvis	Buttocks	Thigh	Foot
Rec 1	Ave range	6.6	14.3	4.7	12.2	15.4
	Std	3.0	9.5	2.3	13.8	9.3
Rec 2	Ave range	7.3	14.9	5.5	13.4	18.8
	Std	3.4	10.9	2.8	7.6	16.9
Rec 3	Ave range	6.1	13.4	5.7	12.6	17.0
	Std	2.9	11.5	3.1	9.5	12.9

Table 72 and Table 73 list the average range of movement of the resultant force in the X and Y directions for a given recline through the full range of TSA's. When looking at the ranges of movement of the resultant force in terms of the Y direction (lateral), the ranges were consistent within a given support plate across all recline angles, meaning the distance of travel did not vary with the recline angle. The same observation was made with respect to the motion in the X direction (anterior/posterior or superior/inferior) for all support plates except the thorax. The thorax travel path decreased in length as the recline angle of the chair increased. This trend may be related to the requirement to maintain contact with the steering wheel. As the seat was reclined, the thorax could have been pulled slightly forward, away from the top of the support plate. An attempt was made to prevent this by allowing the subject to adjust the steering wheel position fore and aft for every trial.

For the location of the resultant force behind the pelvis, the lateral motion (Y direction) was similar in magnitude to the superior/inferior motion (X direction). Thus, the path produced for the pelvis looked more like a circle rather than a line trace. For all other support plates, the Y travel range was much smaller than the travel range of the force in the X direction. These data support that the Biomechanically Articulating Chair does change the location of the center of force under the thighs, buttocks and feet and behind the thorax with the change in torso articulation. The question now arises, is this beneficial to the body, and does the chair provide a large enough movement in the travel of the center of force to make a significant difference for a seated individual?

From earlier discussions of the physiology of the body, the answer to the first question has been addressed. It is clear that movement of the body has many beneficial aspects to the physiology of the body. It is unknown as to the degree of movement that is necessary to prevent decubitus ulcers, but it is known that any movement reduces the pooling of blood and waste products in the body which is desirable and beneficial.

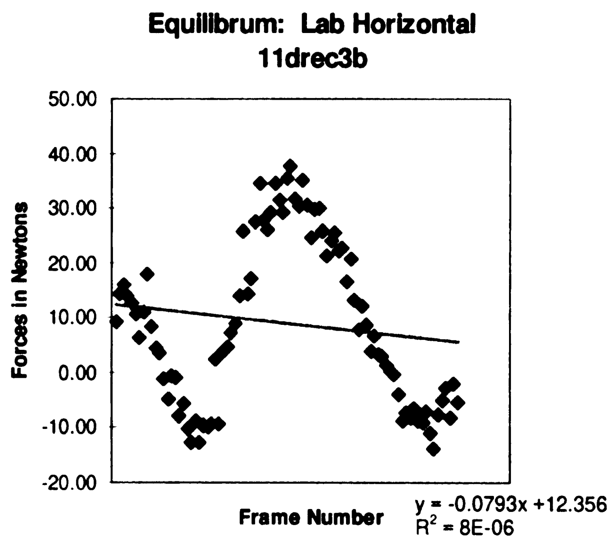
Equilibrium

The final analysis of the force data for the dynamic tests looks at the overall summation of the forces in the vertical and horizontal direction. Prior to performing the analysis of the internal joint force estimation, the static data were first examined to determine if the subject was in equilibrium. The dynamic data were not examined for internal joint estimations, however the initial step to evaluate the equilibrium conditions based on the measured data was completed.

To evaluate if the subject was in equilibrium, all of the support forces were converted to the laboratory horizontal and vertical components. The summation of the forces in the horizontal direction should result in a value near zero, while the summation of the vertical forces should result in a value close to that of the subject's weight.

Figure 84 and Figure 85 show sample data of the equilibrium plots for two subjects during dynamic tests. As seen in the sample data, similar trends were present for the other subjects: the horizontal force data was not equivalent to zero for the entire test, and the forces deviate from zero in a wave pattern, relating to the chair motion. When a best fit line analysis was performed, for the majority of the data, the y intercept of the line was near zero with a slope close to zero.

If the vertical force data were in equilibrium, then as stated above, these data should sum to that of the subject's weight. Subject 11 weighed 166 lbs, or 739 N while subject 16 weighed 173 lbs, or 770 N. Since the slope of the best fit line was near zero, the y intercept value of the best fit line was used as and average value of the vertical force summation. Subject 11's best fit line intercept data had a difference of 77 N or 17 lbs from the body weight, while subject 16 had a 39 N difference, or 8.8 lbs. As discussed with the static data these data are within reasonable measurement error of the system.



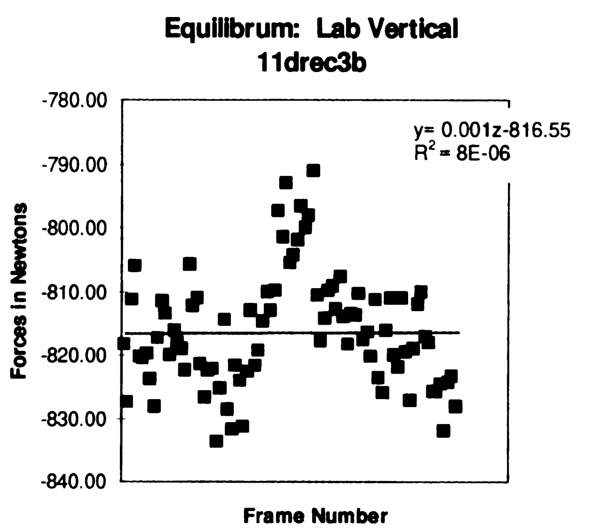


Figure 84: Equilibrium analysis of subject 11, recline 3 trial 2 depicting the vertical and horizontal summed force data, along with the information from a best fit line analysis.

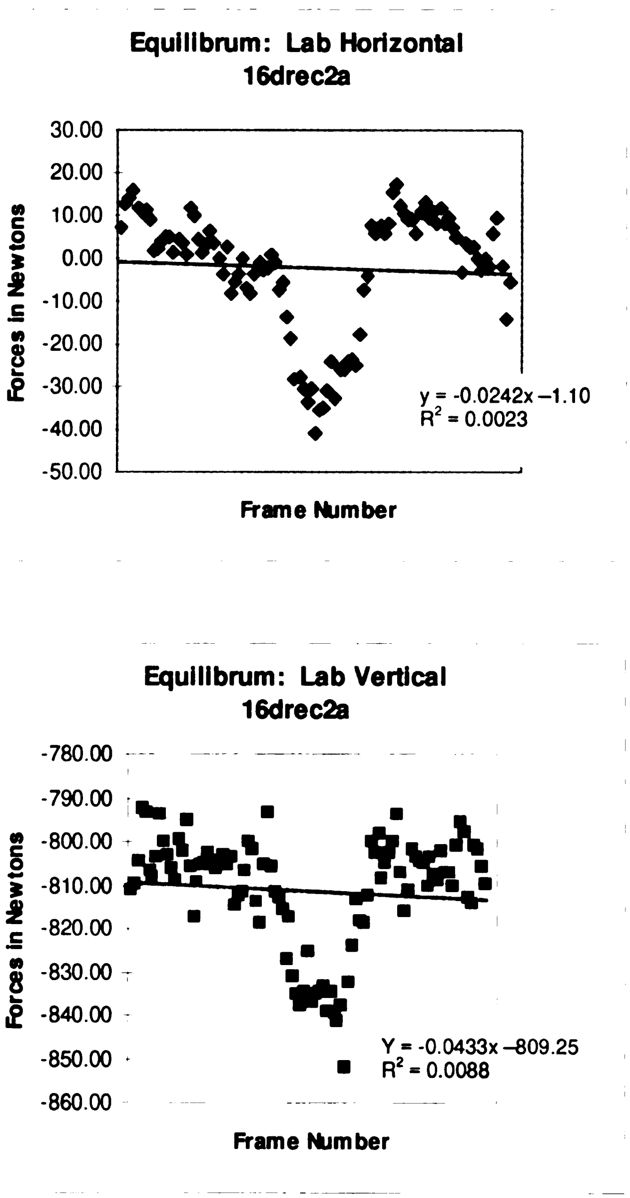


Figure 85: Equilibrium analysis of subject 16, recline 2 trial 1 depicting the vertical and horizontal summed force data, along with the information from a best fit line analysis.

Table 74 lists the average data from the best fit lines for all three recline angles. The slope of the best fit line through the data (for the horizontal forces) should be near zero, and on the average as seen in Table 74 the slope for all three reclines was near zero. The average intercept ranged from 7.6 N to 13.4 N (1.7 to 3.0 lbs); so on average the horizontal force data depicted subjects that were at or near equilibrium.

If in equilibrium, the vertical force data should have a slope near zero, with an intercept near the average weight of the subjects. The average weight of all subjects was 752 N or 169 lbs. The average vertical force data showed larger deviations from the desired averages, particularly in recline 2, (Table 74), but these data were near equilibrium requirements; close enough to make the assumption that the majority of the subjects were in equilibrium with regard to the vertical forces. If performing an analysis using the requirement of the forces being in equilibrium, such as that of the internal joint analysis, better results could be obtained by evaluating the information on an individual subject basis.

Table 74: Averages and standard deviations of best fit line slope and intercept for the equilibrium horizontal and vertical force data.

		Horizontal		Vertical	
		slope	intercept	slope	intercept
Recline 1	Ave	0.02	7.6	0.04	-749.2
	Std	0.20	10.8	0.26	141.5
Recline 2	Ave	0.04	9.5	0.36	-780.9
	Std	0.31	13.4	1.53	59.6
Recline 3	Ave	0.01	12.7	-0.03	-747.3
	Std	0.57	17.3	0.27	132.0

Torso and Chair Motion for Dynamic Tests

This section will evaluate the ranges of movement of the body, specifically the thorax and pelvis during the dynamic trials. First the thorax and pelvis motions will be analyzed, then the movement of the body will be compared and related to the movement of the test chair. The motions of the limbs (elbow angle and knee angle) were not analyzed for the dynamic data.

Thorax

The average maximum and minimum thoracic angles for each recline angle in the dynamic tests are presented in Table 75, along with the average maximum and minimum thoracic angles for the static tests. The thoracic angle was measured by forming a vector from the mid-sternum to the sternal notch and comparing the angle this vector made with laboratory vertical. Recall that in the static tests, the maximum angles, or the largest deviation from vertical occurred predominantly in the super erect postures and the minimum thoracic angles occurred in the slumped chair position. For the dynamic tests, as seen in the above section discussing forces, the maximum and minimum thoracic angles were not identified with an exact chair position, but rather a range of positions, usually near the end ranges of chair motion.

When examining the thoracic angular data, the angle increased as the recline angle of the chair increased, this was a function of the calculation and was expected. Overall, the averages between the static and dynamic tests were similar in terms of magnitude, with the ranges generated by the dynamic testing larger than those for the static testing (by 3.5 to 4.5 degrees) Again, the larger ranges were probably due to the fact that the chair movement for the dynamic testing was slightly larger than that of the static testing.

Table 75: Measure of Thoracic Angle in degrees during dynamic motion from a slumped position to a super erect position. All values are negative, meaning the thorax is rearward of laboratory vertical. (Maximum equals the maximum deviation from vertical.)

Thorax Dynamic (Degrees)				Thorax Static		
	Recline 1	Recline 2	Recline 3	Recline 1	Recline 2	Recline 3
Min	-32.3	-35.5	-39.6	-34.5	-36.4	-41.7
Min std	8.8	9.8	9.6			
Max	-39.8	-43.7	-48.0	-38.5	-41.1	-45.6
Max std	8.5	9.7	9.6			
Range	7.5	8.2	8.4	4.0	4.7	3.9
Rng std	3.0	3.6	3.0			

Pelvis

The average maximum and minimum pelvic angles for each recline angle in the dynamic tests are presented in Table 76 along with the average maximum and minimum pelvic angles for the static tests. Again, the pelvis angle was measured by forming a vector from the sacral target to a virtual point formed mid-way between the left and right ASIS targets. The angle between this vector and the laboratory x axis (horizontal pointing anteriorly) was the measure of the pelvic angle. Using the right hand rule, the angle was a negative angle if located above the horizontal plane. In the static tests, the maximum angles (largest deviation from horizontal) occurred in the slumped conditions and the minimum pelvic angles occurred in the erect and super erect chair positions.

Like the thorax angles, the pelvic angles increased as the recline angle of the chair increased. This was related to the pelvic angle calculation, which was based on the motion of the pelvis relative to the x axis of the laboratory.

As with the thoracic angular data, the static and dynamic tests produced average pelvic angles that were similar in terms of magnitude, however, the ranges generated by the dynamic testing were slightly larger than those for the static testing (by 3.1 to 3.9 degrees).

Table 76: Measure of Pelvic Angle in degrees during dynamic motion from a slumped position to a super erect position.

Pelvis Dynamic (Degrees)				Pelvis Static		
	Recline 1	Recline 2	Recline 3	Recline 1	Recline 2	Recline 3
Min	-24.6	-27.5	-33.5	-26.9	-30.2	-36.1
Min std	8.1	11.7	12.0			
Max	-33.7	-36.8	-40.9	-32.1	-36.1	-40.3
Max std	12.4	10.2	12.7			
Range	9.1	9.3	7.3	5.2	5.9	4.2
Rng std	7.0	10.1	3.1			

Chair vs. Body: Openness

One of the issues of interest during testing of the subjects was to evaluate how well the person moved with the chair. To accomplish this evaluation, the movement of the body or Openness was cross plotted with respect to the movement of the chair or Total Support Angle (TSA) during the dynamic tests, and a linear regression using a least squares method was applied to the data. The TSA and Openness were measures of articulation, one based on chair motions and the other based on body motions. If these two moved together, then the cross plot would be in the form of a straight line. If the body moved with the chair, the slope of the line would be near one. This would mean that as the TSA of the chair varied by five degrees, the body openness also varied by five degrees. Sample cross plots from two subjects can be seen in Figure 86 and Figure 87 while Table 77 lists the average slope and y intercept values across subjects. The averages and ranges of the chair and body motions are listed in Table 78.

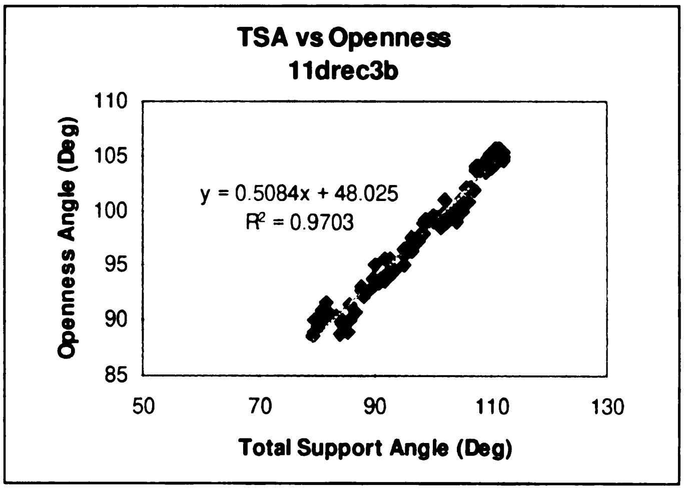


Figure 86: Chair TSA vs Body Openness for subject 11 in recline 3.

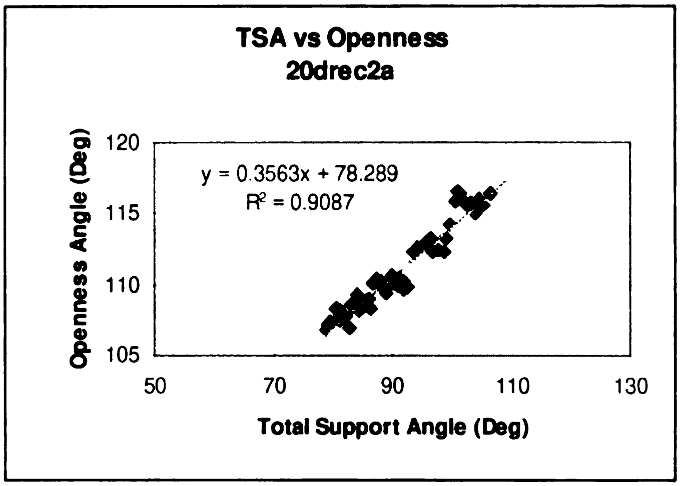


Figure 87: Chair TSA vs Body Openness for subject 20 in recline 2.

Table 77: Average data from best fit line through a cross plot of the chair Total Support Angle (TSA) vs the body Openness. r^2 (Pearson product moment correlation coefficient) is a measure of linear relationship between the two.

TSA vs Openness for all three reclines during Dynamic Tests	Recline 1	Recline 2	Recline 3
r^2	0.89	0.88	0.85
std	0.15	0.17	0.18
Slope	0.35	0.43	0.43
std	0.27	0.15	0.13

Table 78: Measure of body Openness and chair articulation (Total Support Angle, TSA) in degrees during dynamic motion from a slumped position to a super erect position.

	Openness			Chair TSA		
	Recline 1	Recline 2	Recline 3	Recline 1	Recline 2	Recline 3
Max	104.9	105.5	103.3	113.6	112.3	113.0
Max std	15.1	16.1	22.5	3.0	3.9	4.3
Min	88.6	90.9	88.7	78.7	80.5	81.4
Min std	21.0	18.4	22.3	4.2	5.2	5.8
Range	16.3	14.6	14.7	34.9	31.8	31.6
Rng std	12.5	5.5	5.1	6.1	6.5	6.8

As can be seen from the sample plots (Figure 86 and Figure 87), the data were linear, however when analyzing the best fit line, the slopes of these lines as seen in the sample plots were not one to one. This same trend was supported by the average of the subject data seen in Table 77, where the squared correlation coefficient (r^2) ranged from 0.85 to 0.89, showing a strong relationship between the subject's openness and the chair articulation. The average slope of the lines ranged from 0.35 to 0.43. These data supported the fact that the chair was moving the body, however it was not being moved at a ratio of 1:1, but rather at a ratio closer to 2:5. Meaning the subject moved only 40% of the amount the chair moved. From the range data listed in Table 78, the average movement of the subject relative to the chair was a little higher, 46% to 47%, or roughly a ratio of 1:2.

These numbers support the conclusions from the static data, that the chair motion had to be large, or greater than a 10 degree movement, in order to produce a statistically significant change in the openness of the subject.

Chair vs. Body: Recline

As presented in the methods section, the measurement of the Body Recline Angle (BRA) was accomplished by establishing a vector from the mid-point of the ASIS targets to the sternal notch target. It was thought that this measure would be stable during articulation of the body from a slumped to an erect posture. The vertical range on the cross plots in Figure 88 and Figure 89, the BRA measure was slightly affected by the torso articulation. The BRA had an average range of movement of 6.3 degrees in reclines 1 and 2, and 5.4 degrees in recline 3, (Table 79). The average range of the chair movement was much lower, 1.3 degrees in recline 1 and 0.7 degrees in reclines 2 and 3. The offset between the average chair recline and the average body recline remained consistent across the three recline angles, Table 80. The question now arises, does the method of measuring the body recline from these external landmarks provide a "good enough" method for establishing the recline angle of the body?

An alternative approach for establishing a body recline angle would be to estimate internal joint centers at two points in the spine and use that as a reference system for measuring the body recline. However, this method also has disadvantages, primarily that it is a more complex measurement, requiring more external targets. A second disadvantage would be that internal joint points have to be estimated from averaged cadaveric data, as in the internal joint analysis performed for this dissertation. Due to the fact that a body of averaged cadaveric data would be used on an individual with anthropometry that is similar, but most likely not identical to the averaged data would lead to errors. For example, a test subject might have a long torso for his stature, while the data applied to every subject would be that of a person with an average torso.

It is the feeling of this author that with the large variability of subject anthropometry and movement patterns, the external target method for defining the recline angle of the body in the types of movement patterns tested provided reasonable results, as reasonable as can be expected when dealing with the human body.

Table 79: Measurement of the Body Recline Angle and Chair Total Recline Angle in degrees for three recline angles. (Maximum angle equals the maximum deviation from vertical)

BRA	Recline 1	Recline 2	Recline 3	Chair TRA Recline 1	Recline 2	Recline 3
Min	12.2	16.4	20.8	-40.0	-45.1	-49.0
Min std	3.4	4.0	4.8	2.6	0.8	1.1
Max	18.4	22.8	26.3	-41.3	-45.7	-49.7
Max std	4.0	4.1	5.5	2.6	0.9	1.1
Range	6.3	6.3	5.4	1.3	0.7	0.7
Rng std	2.7	3.5	2.5	2.6	0.5	0.4

Table 80: Offset between the BRA and TRA average maximum and minimum measures.

(Degrees)	Recline 1	Recline 2	Recline 3
Min	-27.8	-28.7	-28.2
Max	-22.9	-22.9	-23.4

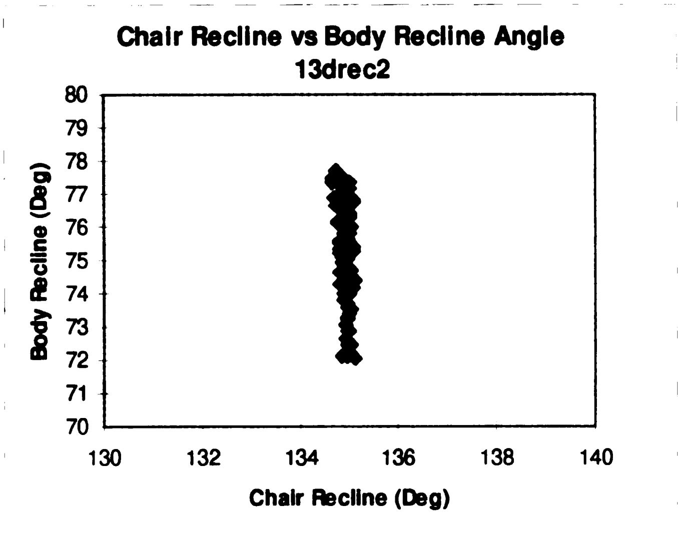


Figure 88: A cross plot of the body recline angle (BRA) vs. the chair recline angle. The chair recline was held constant while the subject was moved from a slumped to an erect position. Subject 13, recline 2.

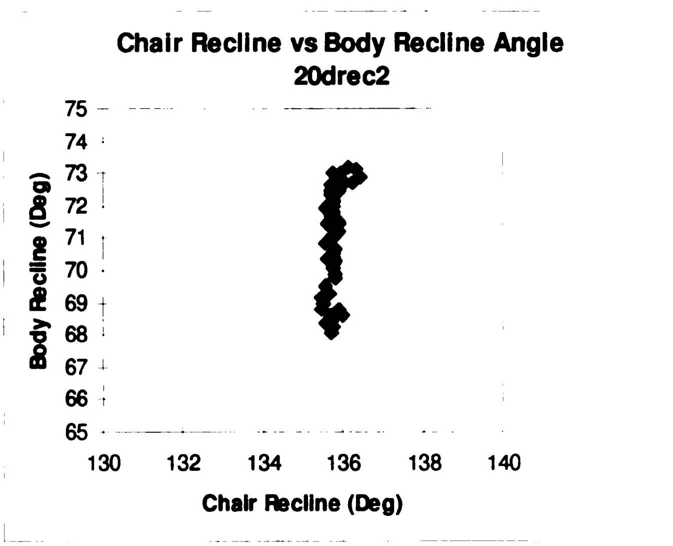


Figure 89: A cross plot of the body recline angle (BRA) vs. the chair recline angle. The chair recline was held constant while the subject was moved from a slumped to an erect position. Subject 20, recline 2.

Discussion:

From the previous analyses and discussions, it has been shown that the dynamic data trials have provided new information from the static trials and in some cases different conclusions. In the case of the primary force data, different conclusions were arrived upon as compared to those found in the static tests. For example, the primary force data from the dynamic tests did not show statistically significant differences between maximum and minimum force values as did the static tests; however, secondary and lateral force data produced similar results and conclusions as the static test data.

New information from the path analysis of the resultant forces provided insight as to how the loads were being distributed over time, and showed that the chair shifted the location of the resultant forces on the support plates as TSA was varied.

An equilibrium analysis of the forces was also performed and showed that the overall trial produced an average set of data that was near equilibrium. If only using a portion of the dynamic test, that region should be reevaluated for the equilibrium requirements.

The posture data was also analyzed in terms of dynamic motions and similar results were obtained in comparison to the static tests, keeping in mind that the dynamic test trials had slightly larger ranges of chair movement as compared to the endpoints of the static test trials.

The ability to compare the movement of the chair to the movement of the body was accomplished with the continuous data plots over the ten second trial period. These data showed than on average, the body did not move with the chair at an equal rate, but rather moved a portion of the chair motion, 40 to 47%.

Overall, the dynamic data were more complex than those of the static data, and only an initial analysis of these data have been performed for this dissertation. These data provide additional information and could be analyzed in more detail, as a future topic of study.

Conclusions

Throughout the results section of this dissertation, interpretations were presented regarding the meaning or usefulness of these data. The following section provides general conclusions pertaining to these data while the remaining two sections list major conclusions and findings from the static and dynamic tests, respectively.

I. General Conclusions:

Not only were new methodologies developed for the measurement of human posture, but also the body of data gathered for this dissertation was more comprehensive than any other work previously available. The ability to measure both static and dynamic conditions of body posture and support forces has been newly developed for this work. The methods to break down seated posture into primary and secondary motions (recline and torso articulation) as used by the JOHN model, were first applied to the movement of the human body in this research. Similarly, research measuring the support force data and developing correlations between body posture and force distributions has not been performed to this depth in any previous bodies of work. Until now, these unique aspects of seating have not been studied.

In terms of seat design, it was interesting that the data showed a combined movement of the thorax and pelvis supports (on the chair) be at least 20 degrees before statistically significant changes in a subject's posture occurred. This result will provide guidance to those interested in designing seats that allow people to truly change their posture. From this information, it is likely automotive seats that only have an adjustable lumbar support and do not allow other regions of the seat to move would not induce a significant change in a person's posture; primarily because the motion of the seat is too small.

In medical seating, particularly wheelchair design, these data showed that an articulating seat could induce changes in posture and shifts in the location of the resultant forces. A goal of a medical professional working with individuals who are wheelchair-bound is to reduce the chances of an individual developing decubitis ulcers under the buttocks. These data showed that a seat design which articulates the torso may be beneficial in shifting support forces and reducing these ulcers. The ability to change the posture of an individual who is wheelchair-bound also affects other physiological aspects of the body such as the ease of breathing and blood flow. There is no doubt that information of this nature will be useful for advancement of wheelchair design.

Another important discovery was that the loading into the floor was significantly changed as the posture was varied. This information is especially important in environments where the foot-to-floor contact is a necessity such as in the sewing industry or office industry. The change of loading into the floor also verifies that measurements occurring in the chair alone, independent of the environment in terms of support forces, do not provide a complete data set. Therefore, thoroughness necessitates the measurement of the forces from various surrounding contact zones.

As presented in the Literature Survey section, most researchers believe that for a single position, the erect seated posture is the optimal posture for your spine. This is based on many factors including increased ability to breath, reduced muscle fatigue, reduced intervertebral disc pressure, etc. One problem with the seated erect posture is that people find it difficult to maintain this position for a length of time. The static force data showed that in the erect seated posture, the shear behind the thorax support was at a minimum. This researcher theorizes it is this shear force that helps support the position of the torso, and with a reduced shear loading onto the seat, the individual has to do the majority of work to maintain the position.

Lastly, this study has developed a methodology for estimating internal joint loading, demonstrated the method, and obtained reasonable results without using invasive procedures. These results were then compared to published data from Andersson[58] that was gathered via an invasive procedure, and agreed well with his results. As discussed earlier, these data may be useful in the physical therapy of an individual with back injury. Studying a larger array of postures may show a series of body positions that have lower internal spinal loading than others.

The availability of these data, combining both posture and force, will be useful in seating design, including, but not limited to the office, automotive, aerospace and medical industries. It is also anticipated that these data will be incorporated into computer models that assist in the design of seats or environments that include seated individuals. These data provide a significant advancement in understanding seating mechanics.

II. Static Data Conclusions:

The following section lists the major conclusions found upon analysis of the static data.

1. The positioning of the Biomechanically Articulating Chair was repeatable in terms of the test conditions: three recline angles and four torso articulations.
2. When comparing the primary forces (normal forces except for the steering wheel which was a shear force) between the three recline angles, the forces were significantly different, as follows: The buttocks, pelvis and thorax showed significantly different forces between all three recline angles. Second, the thighs showed significantly different forces between reclines 2 and 3 and reclines 1 and 3. Third, the feet showed significantly different forces between reclines 1 and 2, and 1 and 3, and fourth, the steering wheel showed significantly different results between reclines 2 and 3.
3. When evaluating trends that occurred when moving from an upright posture to a reclined posture, it was clear that the body weight was transferred off the feet, buttocks and thighs and onto the back of the pelvis and thorax as the seat reclined.
4. When comparing secondary forces (shear forces except for the steering wheel which was a normal force) between the recline angles, significant differences occurred for forces under the buttocks between all three recline combinations. Trends were apparent behind the pelvis, but were not statistically significant.

5. The shear forces behind the thorax were nearest zero for the erect condition in all three recline angles.
6. When examining the primary forces between various torso articulations (slumped, neutral, erect and super erect) the thorax and wheel support plates showed no significant differences between conditions. A consistent significant difference was seen in recline 1 for the buttocks, pelvis and feet between the slumped and super erect condition. The buttocks and feet showed a difference between neutral and super erect for all recline conditions, and between the slumped and erect conditions for reclines 1 and 3 only.
7. With torso articulations, forces were shifted from the buttocks, thighs and pelvis onto the foot plate, when the subjects moved from a slumped to a more erect position.
8. When evaluating secondary forces in terms of torso articulations, there were no significant differences for the pelvis between any of the test conditions. The secondary forces showed significant differences for test trials that were not contiguous, however these differences were not always shown in all three recline angles. The following statistical differences were found for the secondary forces for all support plates except the pelvis: a) Slumped verses super erect all reclines, b) neutral verses super erect for reclines 1 and 2 c) slumped verses erect for reclines 1 and 3.
9. The support force data was analyzed in terms of percent body weight distribution (%BW). From a macroscopic viewpoint, lumping all recline angles

and torso articulations together resulted in the following distribution of forces: a) 70%BW on the seat pan (buttocks and thighs), b) 30%BW on the seat back (thorax and pelvis), c) 10%BW into the foot support and d) 4%BW into the steering wheel. (These forces included both vertical and horizontal components of the support forces, thus the %BW totaled more than 100%)

10. The movement of the chair in terms of Total Support Angle (TSA) was 30° from the slumped to the super erect position. However, on average, the subjects only exhibited a 10° change in torso openness from the slumped to the super erect position. In an articulating chair such as the BAC, the subjects exhibited a ratio of chair movement to body movement of approximately 3 to 1.

III. Dynamic Data Conclusions

The following section lists the major conclusions found upon analysis of the dynamic data.

11. The dynamic movement trials induced larger magnitudes than the static tests for the primary, secondary and lateral forces. The only exceptions were the secondary forces under the buttocks for recline 1 and recline 3 where the dynamic data had a larger magnitude than the static data by 1.5 N and 8.3 N. These values were approximately 2.7% and 16% of the total range of the secondary forces respectively.
12. The primary forces for the dynamic tests showed no statistically significant differences between maximum and minimum force values. These maximum

and minimum force values corresponded with the end ranges of chair movement, slumped verses super erect.

13. The secondary force data produced similar statistical results between the static and dynamic tests. These results occurred between the maximum and minimum secondary forces, at or near the extreme chair positions.

14. For the lateral forces, the majority of support plates in the various recline positions showed no statistically significant difference between maximum and minimum lateral forces (or no relationship to chair position). This agreed with the static data analysis.

15. The primary forces were larger than the secondary forces or the lateral forces. The secondary forces were typically only 9-14% of the magnitude of the primary forces, except for the pelvis and foot plate where the secondary forces were 60% of the primary force values.

16. The subjects moved with the chair, and had correlation coefficients (r^2) ranging from 0.85 to 0.89, showing a strong relationship between subjects' openness and the chair articulation.

17. In the dynamic tests, the chair did not move with the body at a ratio of 1:1, but from examination from the slope of a cross plot between chair motion and body motion, the ratio was closer to 2:5 (which differs from the 1:3 ratio seen in the static tests). This meant the subjects moved only 40% of the range the chair moved. Using the ranges of motion, rather than the slope of the line, the movement was shown to be 46 to 47% of chair motion, or an approximate ratio of 1:2.

18. Location of the resultant forces showed that the chair movement shifted the location of the resultant force on the majority of the support plates under or behind the body. Average travel of the resultant force in millimeters for each plate across reclines was: a) thorax: 51, b) pelvis: 17, c) buttocks: 28 d) thighs: 38 and e) foot support: 58.

Future Work

The study of seating mechanics has many aspects not yet investigated. Additional data were collected during this project but were not analyzed for this dissertation and will serve to be future work for this author. Subjective surveys were taken during the various test conditions and will be analyzed for correlations with the objective measures discussed here. Preferred seat and posture data were collected. For the preferred position, the force and positional data were measured and provide another body of data for future work.

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