A Comparison of Four Office Chairs Using Biomechanical Measures

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Objective: The authors sought to use biomechanical measures, including motion and pressure, to compare four office chairs. **Background:** The fit of a person to a chair is related to the geometric and kinematic compatibility between the two. This geometric compatibility influences the motions that are allowed or prohibited and the support pressures at the body-chair interface. Thus, during evaluation, it is necessary to treat the chair and user as a system. **Method:** Four dynamic test conditions were evaluated with 14 participants of varying anthropometries. Test conditions were selected to compare the ability to accommodate primary and secondary motions (recline and spinal articulation) of seated occupants. The ability of a chair to allow recline, yet maintain head and hand positions, was compared across chairs. Also, the ability of each chair to allow and support spinal articulation was evaluated. Motion data for the chair, head, thorax, pelvis, and extremities were collected along with chair back pressures. Upon completion of testing, subjective assessments were also conducted. **Results:** Statistically significant differences were found between chairs relative to head and hand motions. Also, significant differences were noted for the chairs' ability to move with the body during spinal articulation and the ability to provide support. Subjective assessments also yielded differences. **Conclusions:** Biomechanical analyses using motions and pressures can be conducted on office chairs with significant differences detected in their performance. **Application:** Biomechanical assessments can be used to compare and contrast office chairs in terms that are relatable to fatigue reduction as well as operator performance.

INTRODUCTION

When office seating is studied from a biomechanics viewpoint, the capability of a chair to support postural change is a function of the interaction of the seat pan, the back rest, the coarticulation of these two surfaces, and the geometry of each. In other words, the fit of a person to a chair is related to the geometric and kinematic compatibility between the chair and body.

This geometric compatibility influences the motions that are allowed or prohibited, as well as the support pressures at the body-chair interface. Furthermore, the mass of the user plays a role in the functionality (or lack of functionality) of these components (i.e., petite women unable to recline a chair). Thus, the evaluation of an office chair should treat the chair and user as a system. Most current biomechanical literature does not address the functional attributes through a system approach but rather focuses on a single design feature of a chair.

In this study, we address the biomechanical measurement of three functional attributes: spinal articulation, support, and stability of hand and head/eye locations during postural change for four commercial office chairs. These attributes are directly related to fatigue reduction (spinal articulation and support) as well as operator performance (hand and head/eye location).

An array of studies addresses some aspect of biomechanical measures. For example, the following researchers used pressure measures to assess seat compatibility: Goonetilleke (1998); Gyi and Porter (1999); Hobson (1992); Legg, Mackie, and Milicich (2002); Philippe (1995); Thakurta,

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Koester, Bush, and Bachle (1995); and Vos, Congleton, Moore, Amendola, and Ringer (2006). Furthermore, researchers such as Andersson and Ortengren (1974a, 1974b, 1974c); Andersson, Ortengren, Nachemson, and Elfstom, (1974); Makhsous, Lin, Hendrix, Helper, and Zhang (2003); and van Deursen, Goossens, Evers, van der Helm, and van Deursen (2000) have assessed objective measures such as disk pressure, electromyography (EMG), force, and spinal length differences. However, little biomechanical work has been done to study the chair as a functional system of components in conjunction with the user.

The movement of the body, movement of the chair, and interface pressures between the chair back and body were studied here for two different types of dynamic activities: postural change (spinal articulation) and chair back recline. These two activities make up the primary and secondary movements associated with sitting in an office chair. More so, these two activities have been shown to have effects related to overall body health. Research has documented that movement or, more specifically, spinal articulation plays an important role in the flow of nutrients to the intervertebral disks, as well as the removal of waste products (Adams & Dolan, 2005; Pope, Goh, & Magnusson, 2002). In turn, the flow of nutrients and waste removal are related to maintaining the vitality of the intervertebral disks, which is an integral part of overall spinal health. Thus, to facilitate a healthy spine, one should allow spinal articulation during office work.

Equally important to spinal articulation is the support provided to the user. Both motion and support are key seating factors, and it is necessary to study them in concert. For example, it could be argued that a straight-back kitchen chair allows a user to change his or her posture from lordosis to kyphosis, but in the lordotic position, a gap exists behind the lumbar region, resulting in a lack of support. If only the body motions were measured (without a mechanism to monitor the support), key pieces of information would be missing.

In addition to support and spinal articulation, the reclined working posture has advantages. Benefits such as reduced loading on the intervertebral disks and decreased muscle activity are associated with recline (Andersson & Ortengren, 1974a, 1974b, 1974c; Andersson et al., 1974; Bashir, Torio, Smith, Takahashi, & Pope, 2006). This finding seems intuitive because during recline, the seated occupant is decreasing the loading on the buttocks and thighs by increasing the loading on the thorax (Bush & Hubbard, 2007), and thus the load through the disks is reduced. Also, seated occupants naturally and continuously weight shift through recline and other means, such as side-to-side weight shifting; it is this natural weight shifting that helps prevent the occlusion of blood flow (Bansal, Scott, Stewart, & Cockerell, 2005). However, as one reclines, it is common to have to make adjustments to continue working. For example, occupants may find it necessary to slide their bodies forward in the seat or move the entire chair forward to prevent their hands from being pulled away from the keyboard and/or to keep their heads positioned at appropriate distances from the monitor.

As a result, methodologies were developed to use objective measures to compare the functional attributes of four commercially available office chairs. Comparisons between chairs included the capability to allow spinal articulation, provision of support along chair backs, and the effects of recline on head and hand positions.

METHODS AND ANALYSIS

This work complied with all requirements for use of human subjects by the Michigan State University Institutional Review Board.

Participants were sampled based on height and weight criteria. Six categories were developed, including short, light women (range, 152–154 cm, 48 kg); short, heavy women (range, 155–158 cm, 75–95 kg); midsized women (range, 163–166 cm, 57–58 kg); midsized men (range, 173–177 cm, 71–81 kg); tall, light men (range, 188–189 cm, 62–73 kg); and tall, heavy men (range, 188–194 cm, 100 kg). These categories were based around Natick Data (Gordon, Churchill, Clauser, Bradtmiller, & McConville, 1989) to ensure that the upper and lower ranges of height and weight had representation in the participant sample. Two participants within each of the anthropometric categories were desired. A total of 14 participants ranging in age from 20 to 51 were tested, but 2 of the 14 participants did not acceptably fit the midsized height and weight category (woman: 163 cm, 69 kg; man: 171 cm, 85 kg). All of the subjects had significant keyboarding experience.

Test Chairs

The four test chairs will be referred to as follows:

rigid back (RB), slightly flexible back (SF), mesh chair (MC), and double-pivot (DP) chair. All four chairs allowed for vertical adjustment of the armrests. The RB permitted lateral translation of the armrests, whereas the MC armrests rotated about a pivot located near the chair back. The DP had the most arm support adjustment, allowing vertical, translational (in the medial/lateral direction), and rotational motions.

In terms of the chair backs, the RB had a solid chair back covered with foam and fabric, whereas the SF incorporated a slightly flexible plastic grid covered by a layer of foam and fabric. The MC had a solid outer rim with mesh fabric for the entire back surface. The DP had a solid back with horizontal slits cut in the support across the lower region of the shell, and the upper thoracic region was solid. This back pivoted about two locations, one in the thoracic region and one at the base of the chair back. The entire back support (side in contact with the user) was covered by foam and fabric.

Both the RB and DP contained seat pan depth adjustments to accommodate different-sized users, whereas the MC offered three different-sized chairs for different anthropometries. Based on manufacturer's recommendations, the medium-sized MC was used by all of the participants except the short, light women, who used the small size, and the tall, heavy men, who used the large size. The SF offered a side-to-side rocking motion, but that feature was locked out, as the test conditions were primarily sagittal plane motions. Like the side-to-side rocking of the SF, the forward tilt mechanism of the MC (which allows the chair back to tilt forward) was not used for this study.

Equipment

The equipment used in the study included two systems: a motion system and a pressure-mapping system. Data collection from both systems was synchronized and occurred for 8 s with 12 samples per second (12 Hz).

Motion system. The positions and motions of the participants and the chairs were measured using a five-camera Qualisys (Gothenburg, Sweden) video system. This type of commercially available motion measurement technology has been proven to provide accurate human kinematic data. Work by Richards (1999) showed the Qualisys system to be accurate, on average, within 1 to 2 mm of marker position and 1.5 deg for an angular measure.

Reflective markers were attached using a medical adhesive to skeletal landmarks, and when possible, the markers were affixed directly to the skin (see Figure 1). All participants wore snug-fitting spandex athletic attire, which reduced motion of any markers secured to clothing. Markers were placed on the head, thorax, pelvis, and extremities at standardized anatomical locations (see Table 1a). Markers were also glued to key reference points on the chairs and keyboard, as well as taped to the pressure mat (see Table 1b). The analysis of the body segments and chair motions was planar, and thus at least two markers were located on each body segment. Key anthropometric data were collected on each participant, including height, weight, and age.

Pressure-mapping system. Contact pressures between the chair backs and the participants' torsos were measured with a Tekscan Body Pressure Measuring System (Boston, Massachusetts). The mats were equilibrated and calibrated before testing each participant. Because of the possibility of mat fatigue and wrinkling, two pressure mats were used during the testing, with each mat used for about half of the participants. Also, after removal from the testing situation, the mats were evaluated; both were still in good working condition with no cells having been lost.

Pressure patterns of 96 still frames made up a dynamic pressure movie for each test (i.e., each participant in each chair in each recline). Numerical data, including contact area and center of

Figure 1. A participant with markers attached seated in a test chair.

TABLE 1: (a) Location of Anatomical Reference Points and (b) Location of Chair, Keyboard, and Pressure Mat Reference Points

(a)	(b)
Sternal Notch	Keyboard Upper Left Corner
Midpoint of Sternum	Keyboard Upper Right Corner
Seventh Cervical Vertebra	Forward Marker on Seat Pan
Left Anterior Superior Iliac Spine (ASIS)	Rearward Marker on Seat Pan
Right ASIS	Forward Armrest Marker
Laterally on the Mid-Thigh	Rearward Armrest Marker
Lateral Epicondyle of the Femur (Knee)	Top of Reclining Section
Lateral Malleolus (Ankle)	Bottom of Reclining Section
Acromion Process	Chair Back Top
Lateral Epicondyle of Humerus (Elbow)	Back of Chair—Upper
Medial Wrist	Back of Chair—Middle
Middle Finger	Back of Chair—Lower
Left Temple	Pressure Mat Left Corner
Right Temple	Pressure Mat Right Corner

pressure data, were obtained from the Tekscan system. The pressure maps were also independently reviewed by three individuals, and notes were recorded on changes in magnitude of pressure, location of support relative to the participant's anatomy, and overall shape of the contact region.

Testing Protocol

Considerable time was allotted for participant orientation, which included appropriate consent procedures and the introduction of terminology such as *recline, lumbar lordosis* (erect posture), and *kyphosis* (slouched posture). Each term was demonstrated and explained while the participant was seated on a stool. Chair stations, separate from the laboratory testing, were set up with instruction boards on the operation of each of the four test chairs. For testing and reference purposes, each chair was assigned a letter (A, B, C, D), and the manufacturer and chair name were not disclosed to the participant.

A qualified laboratory assistant helped the participant with the chair functions and demonstrated each of the chair adjustments. As the participant was rotated through chair stations (approximately every 10 min), he or she gained familiarity with each chair. After rotating through all four chairs, the assistant readjusted each chair to a neutral position, and the participant was asked to readjust the chair (without assistance) so he or she could perform a typing task at that specific workstation.

Two types of test conditions were developed. Because of the importance of spinal articulation to the health of the intervertebral disks, a set of tests was devised to evaluate the ability of each chair to allow and support spinal articulation. A second working posture, and one that has been shown to reduce loading on the intervertebral disks by shifting weight from the seat pan to the chair back, is the reclined position. Seated occupants should be able to recline a chair with minimal effort while maintaining keyboard contact and keeping within their visual work space. Thus, a second set of tests was developed to evaluate the movements of the body and the support provided by the chair during recline. Specifically, movements of the hands and head away from the workstation and pressures on the chair back were studied.

Evaluation of permitting and supporting spinal articulation. The ability of the chair to support spinal articulation was tested at three levels of recline. At each recline angle, the participant was asked to move to a slouched position (kyphotic) and then to an erect position (lordotic) and then back to a slouched position, continuing this movement pattern for the entire test trial. The upright recline was tested with the chair in the most upright position (locking out recline). For the mid-recline and full-recline conditions, the back was positioned at a recline angle that was half of the full range or at the full range of recline attainable by the participant. The participant was then instructed to hold that recline angle as well as possible and perform the movement. At all three reclines, the participants were asked to maintain contact with the keyboard and a focal point on the monitor during the activity.

The goal of this test condition was to exercise each chair and evaluate each chair's full range of capabilities in terms of allowing and supporting spinal articulation. In other words, this trial was used to evaluate whether each chair could follow the movement of people as they changed posture. Although each individual person may not move his or her spine through this entire range of motion during normal office activities, different users will use different subsets of this range, some falling in the middle and some at the extremes. The chair performed well if two criteria were met. First, the kinematics of the chair and the person moved together, and second, support was provided to the occupant throughout the movement.

Evaluation of head and hand motion during recline. For the dynamic recline condition, the chair back was unlocked and free to recline. The participant began with the back in the most upright position, then reclined to the maximum recline attainable, and then returned to the upright position. During this test, the hands were resting on the keyboard and the forearms on the armrests. The participant was instructed to maintain a forward focal point, adjusting his or her gaze angle as needed and to maintain torso contact with the seat back. Participants were also instructed to allow their hands to slide freely down the keyboard (which had a slight tilt) and across the desk as they reclined, while movement patterns of the hands and head were measured.

Range of recline was calculated as the difference between the reference position for each chair (initial upright position) and the maximum reclined position. The computation was based on displacements of targets. Specifically, a vector was computed in the initial position between two targets on the seat back and then again in the final position. The change in angle, using the initial and final vector, is what is reported as the range of recline.

Data collection. After the participant was fitted with markers, the test chair, desk, simulated computer monitor, and keyboard were brought into the calibrated space. The participant was seated in a test chair and was asked to adjust the chair for a keyboarding task.

During testing, the order of chairs was randomized, and test conditions were randomized within each chair. Each condition was performed two times. Most testing was completed between 2 and 2.5 hr.

Finally, at the completion of testing, each participant was asked to rank order the chairs for six categories and provide verbal commentary. The main focus of this study was not to gather subjective responses but rather to gather the objective measures described earlier. However, for completeness of the chair evaluation, it was desirable to determine if any preference existed with regard to the chairs. All chairs were grouped together, and for each question, the participant was allowed to sit in each and make adjustments before providing his or her response. Next, the participant was asked to rank the chairs from 1 to 4 in order of preference (1 being the most preferred and 4 being the least preferred) with regard to the question asked. The following questions were asked of all participants in this order and the answers recorded.

1. Rank the chairs (from 1 to 4) on your overall preference.
2. Rank the chairs on appearance.
3. Rank how well the armrests accommodated your arm position for a typing task.
4. Rank the chairs on ease of adjustments.
5. Rank the chairs on comfort.
6. Rank the chairs on how well they moved with you from lordosis to kyphosis.

The questions were posed in the same fashion to each participant.

Analysis of Motion Data in Terms of Flexion and Extension

Motion data via the retro-reflective markers recorded thorax and pelvic motions. Hubbard, Gedraitis, and Bush (1998) and Hubbard, Haas, Boughner, Canole, and Bush (1993) showed that in the seated position, movement of the thorax relative to the pelvis can be related to spinal articulation of the lumbar region. Thus, when one captures the positional changes of the thorax and pelvis, the articulation of the spine can be evaluated. Specifically, postural openness, the angle between a pelvic vector and a thoracic vector, was computed for each participant (see Figure 2) (Bush, Hubbard, & Ekern, 1998). The pelvic vector used an internally computed point, which is the estimated location of the hip joint center (HJC) (Bush & Gutowski, 2003).

Postural openness changed as the positions of the thorax and pelvis changed. So when the top of the thorax rotated rearward and upward, and the front of the pelvis rotated forward and downward, the lumbar spine moved into a lordotic configuration. When the top of the thorax rotated

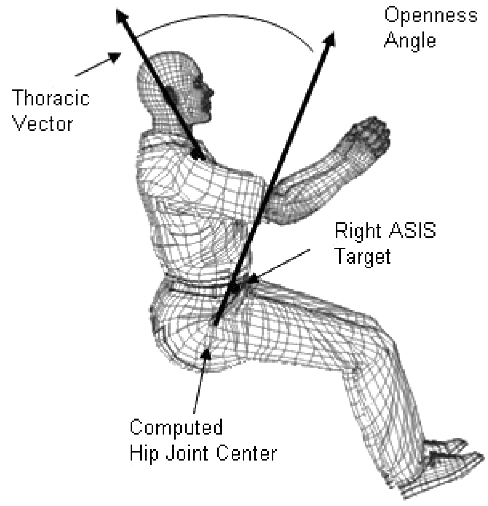

Figure 2. Computation of openness angle. As the lumbar spine moves into a lordotic curvature, the pelvic vector will tip downward while the thoracic vector will tip rearward, producing a larger openness angle. ASIS = anterior superior iliac spine.

forward and downward, and the front of the pelvis rocked rearward and upward, the lumbar spine moved into a kyphotic position.

A similar methodology was developed to gain an understanding of the ability of the chair back to respond to the participant's spinal articulation; this is referred to as chair back flexion. Chair back flexion was measured at the upper and lower regions of the chair back by four reflective markers spaced vertically along the back of the chair. Two vectors were computed for the upper portion of the chair, and two were computed for the lower portion of the chair. As the chair back changed shape, the angle between each pair of vectors changed. These two angles were summed to obtain the total chair flexion. As the vectors demonstrated increasing angles, the chair moved to support a lordotic spinal curvature. However, a smaller angle indicated a chair configuration that supported a kyphotic spinal curvature. (The SF chair exhibited flexibility in the upper region of the back while the base of the back was rigid. Thus, only the upper region of the back demonstrated motion.)

These two parameters, openness and chair back flexion, were measured and compared.

Analysis of Head and Hand Motions

Head motions were monitored by tracking two markers placed on each participant's temples. A center point between these markers was computed, and vertical and horizontal motions were compared for the different trials.

To monitor vertical and horizontal motions of the hand, a marker was placed on the wrist, just at the base of the hand. Movements of the marker were compared across trials.

Analysis of Pressure Data

In addition to the independent visual analysis made by three qualified individuals (each individual had at least 10 years' experience in the field of biomechanics, including intrepretation of pressure plots: Bush, Hubbard, and Reinecke), quantitative measures of contact between participants and chair backs were developed based on pressure readings. The pressure maps were analyzed relative to two criteria.

First, as the participant articulated his or her spine from lordosis to kyphosis, the range of movement of the center of pressure (COP) indicated the degree to which the chair back maintained contact with the participant's back. The center of pressure moved away from areas where support was lost. If the pressure patterns shifted large amounts, the COP had a larger travel path, whereas if the pressure patterns were consistent, there was little movement in the COP.

Second, the total area of the pressure distribution was measured and interpreted as a compatibility factor between the chair back shape and the participants' backs. In other words, the greater the contact area, the better the fit. As the participants changed their spinal curvature from lordosis to kyphosis, the change in the contact area indicated the ability of the chair back to provide distributed support for these changes of posture.

Much discussion surrounds the usage of pressure mapping and its accuracy, particularly when used to assess the forces found on the chair. However, for this study, the pressure system was not used to estimate the loading into the chair; rather, the system was used for within-subject comparisons across chairs for the amount of contact and shift in the COP.

Statistical Analysis

Five statistical evaluations were performed for this study.

1. The first involved the analysis of head and hand movements (dependent variable) across the different chairs (independent variable) during dynamic recline.

2. The second evaluation involved the r^2 values obtained from a cross-plot of openness and chair back flexion during spinal articulation. For this evaluation, the r^2 values for all three recline angles (mid-upright and full) were evaluated separately as well as together and compared across chairs.
3. The third evaluation was a comparison of vertical COP travel (dependent variable) during the movement from lordosis to kyphosis across chairs. Again, all three reclines were analyzed separately as well as as a combined data set.
4. The fourth analysis involved the minimum and maximum contact areas (dependent variables) evaluated across chairs. Separate analyses were performed for the maximum and minimum values for each recline angle. In addition, all reclines were combined as a single data set and an analysis was performed.

For all analyses stated above, statistical testing was performed using a one-way repeated-measures analysis of variance (ANOVA) with a 95% confidence level (an acceptable p value of $< .05$), followed by a Tukey post hoc test. In some instances, the data did not demonstrate a normal distribution, and a one-way repeated-measures ANOVA on ranks was used, followed by a Tukey post hoc test at a 95% confidence level.

5. The final statistical analysis was performed on the subjective data. Each question was analyzed for differences between chairs. Friedman's repeated-measures ANOVA on ranks was used, followed by a Tukey post hoc test.

RESULTS

Selecting participants from different anthropometric categories ensured that a wide range of individuals would be tested. However, because of the small number of participants in each category ($n = 2$), these test data were not analyzed by different anthropometric categories; rather, the data from all participants were pooled and trends reported as a function of the entire sample.

Results of Spinal Articulation During Upright, Mid-, and Full-Recline Positions

Because the RB had a stiff chair back, it did not provide a measurable amount of motion when the participants changed posture from lordosis to kyphosis.

The SF chair demonstrated a small amount of flexion in the upper chair back (movement seen in the upper set of markers and not the lower set), but this chair clearly did not achieve the motion ranges seen in the MC and DP.

The MC and DP demonstrated the ability of the chair back to move with the body during changes from lordosis to kyphosis. The data from the reflective markers on the body and those distributed vertically along the chair back were used to compare changes in postural openness with the response of the chair. A cross-plot between the two sets of kinematic data (participant and chair) was developed for each trial, and linear regression analysis was performed (see Figure 3). This analysis yielded a coefficient of determination (r^2), which provided an assessment of how well the participant and chair back motions correlated.

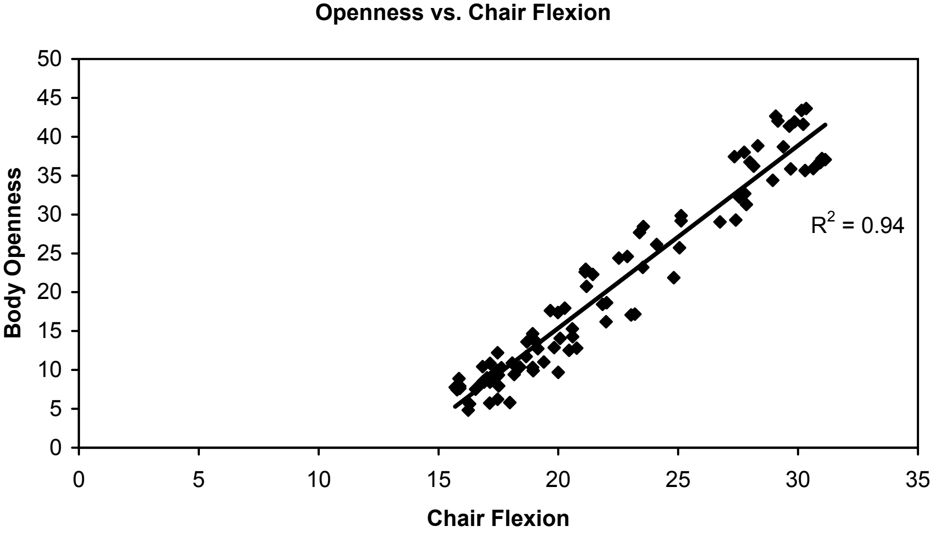

Figure 3. A cross-plot of the chair flexion data and the body openness data.

The average of the coefficients of determination for all three recline angles was 0.22 (*SEM* 0.04) for SF, 0.73 (0.05) for MC, and 0.86 (0.02) for DP. These data suggest that the DP chair was able to move with the body with a higher correlation than the MC or SF chair. The statistical analyses of these data are presented in Table 2. With regard to the pooled recline data, significant differences between all three comparisons were demonstrated. When the data across recline were compared, the MC and DP demonstrated differences in the ability to move with the body as compared with the SF, but comparisons between the MC and DP were significant only in the upright recline.

Pressure Results

The following describes the overall trends seen by the three reviewers in the pressure distributions. Example pressure plots (from a single participant) demonstrating some of these trends can be seen in Figure 4.

The RB chair had the least consistent pressure mappings and the most asymmetrical patterns for all test conditions. These readings typically did not exhibit uniform continuous contact with the chair; rather, they showed a "spotty" localized contact. When the participants were in kyphotic postures, there was a round contact zone in the lower region of the chair back, and when the participants moved into a lordotic posture, this contact zone shifted to the upper portion of the chair back. Thus, in an erect posture, there was little to no contact with the chair back in the lumbar region.

The SF chair consistently displayed high pressure zones at the top edge of the chair back along the participants' upper thoracic regions, specifically in the reclined condition and in the lordotic postures. Several participants showed high pressures horizontally across the lower thoracic/upper lumbar region of the chair at the contour break line. In the fully reclined condition and the dynamic recline condition, the petite participants showed contact only at the shoulder region, indicating their buttocks were pulled away from the chair back so they could maintain contact with the floor with their feet.

The MC showed a uniform pressure map in all test conditions. The participants were able to maintain contact over the thoracic and lumbar regions of the back. The MC showed symmetrical mappings laterally, although the pressures were primarily concentrated at the midline of the body with a narrow lateral distribution. Higher pressures were seen along the spine. The overall shape of the pressure map was a tall, thin rectangle. During the dynamic recline test condition in the MC, high pressures were seen in the shoulder region, especially for the lighter participants.

The DP chair demonstrated uniform, symmetrical pressure distributions across participants. The pressure data showed that participants were able to maintain contact between the chair and the upper and lower back during spinal articulation. The pressure mappings demonstrated a uniform, even distribution and generally did not show high localized pressure zones. DP patterns showed a wide, square-shaped pressure map stretching from the shoulders to the buttocks. The pressures were laterally similar with minimal pressures on the spinous processes. During the dynamic recline conditions, high pressure spots rarely appeared in the shoulder region across the participant sample.

The average vertical travel of the COP across all conditions was 292 mm (*SEM* 20 mm) for RB, 271 mm (17) for SF, 300 mm (19) for MC, and 217 mm (12) for DP. Indicated by visual observation, the DP demonstrated consistent contact across postural change and numerically had the smallest average vertical motion of the COP. Thus, these data support the conclusion that across participants and across postural change, the DP provided

TABLE 2: Statistical Analysis Comparing r^2 Values of Chair Flexion and Openness

Openness vs. Chair Flexion	SF vs. MC	SF vs. DP	MC vs. DP
Upright	**<0.001**	**<0.001**	**0.002**
Mid	**<0.001**	**<0.001**	0.558
Full	**<0.001**	**<0.001**	0.993
All reclines	**<0.001**	**<0.001**	**0.024**

Note. Bolded numbers are significant at alpha = 0.05, or 95% confidence level. SF = slightly flexible back; MC = mesh chair; DP = double-pivot chair.

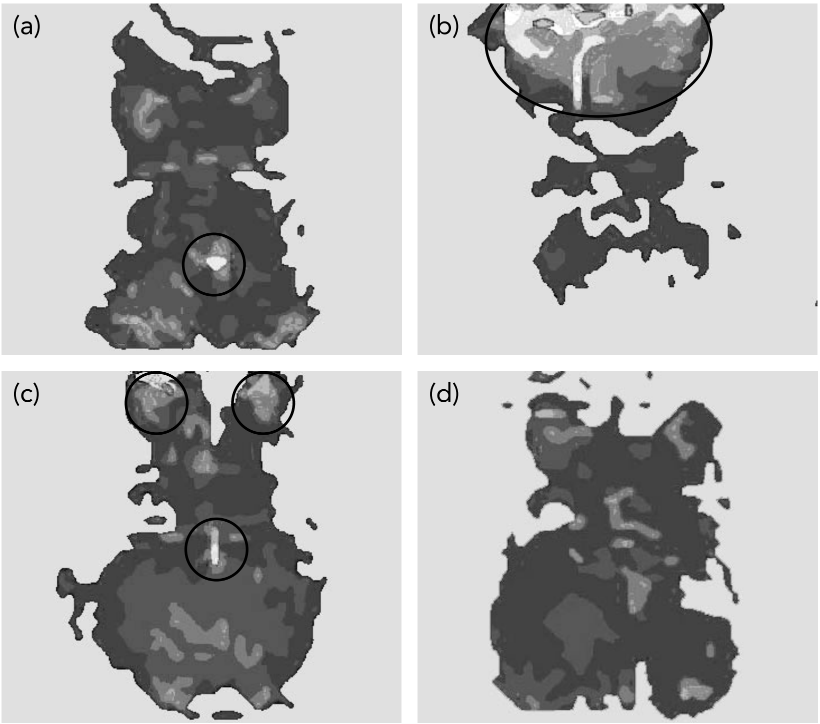

Figure 4. A sample of the pressure maps from a single participant demonstrating some of the described trends. Plots are one frame of midrecline in the lordotic posture: (a) rigid back (RB), (b) slightly flexible back (SF), (c) mesh chair (MC), and (d) double-pivot chair (DP). Circled areas highlight regions of higher pressure values for this participant.

consistent contact. Statistical testing showed significant differences in the vertical COP travel between the DP and MC, between the DP and RB, and between the DP and SF for the pooled data (see Table 3). With regard to the individual recline analyses (Table 3), only five of the comparisons demonstrated significance at the 95% level. However, several comparisons demonstrated low *p* values that with a larger sample size would likely yield significance.

The second method used to analyze the compatibility between chair back and the participant was the evaluation of the overall contact area. Table 4 displays the average maximum and minimum contact areas for all four chairs and all three reclines. All chair backs provided an increasing amount of contact area as the chair was reclined. The MC and DP provided the largest contact areas for both the maximum and minimum values, which was congruent with the comments from the reviewers. For the pooled recline data, statistically significant differences in the maximum contact areas, across all reclines, were found between all chairs except the RB and SF (see Table 5a). Differences between the minimums were detected between the DP and RB as well as the DP and SF

TABLE 3: Statistical Analysis Comparing the Vertical Travel of the Center of Pressure Between Chairs

Vertical COP	RB vs. SF	RB vs. MC	RB vs. DP	SF vs. MC	SF vs. DP	MC vs. DP
Upright	0.953	1.00	**0.040**	0.935	**0.012**	**0.040**
Mid	0.209	0.209	0.209	0.209	0.209	0.209
Full	0.123	0.962	0.107	**0.044**	1.00	**0.038**
Dynamic	0.426	0.426	0.426	0.426	0.426	0.426
All reclines	0.696	0.987	**<0.001**	0.485	**0.023**	**<0.001**

Note. Bolded numbers are significant at alpha = 0.05, or 95% confidence level. COP = center of pressure; SF = slightly flexible back; MC = mesh chair; DP = double-pivot chair; RB = rigid back.

TABLE 4: Average Maximum and Minimum Contact Area During Movement From Lordosis to Kyphosis (cm^2)

	RB		SF		MC		DP	
	Max	Min	Max	Min	Max	Min	Max	Min
Upright	690	380	658	393	710	426	722	464
Mid	716	535	761	535	819	613	806	581
Full	793	581	780	548	922	651	851	651
Dynamic	723	445	716	516	955	400	813	606

Note. SF = slightly flexible back; MC = mesh chair; DP = double-pivot chair; RB = rigid back.

(see Table 5b). Similar to the COP analysis, the individual recline comparisons did not yield significance, but many comparisons had low *p* values.

Dynamic Recline Test Conditions: Motion Results

The total recline range, which is the difference between the most upright position of the chair (unloaded) and the maximum reclined position, was measured for each participant and then averaged. The recline ranges are presented in Table 6. Note that the RB had the smallest range of recline, 6–7 deg less than that of the other chairs.

All statistical data were compared for the ability to reduce the motion of the head and hands during recline.

Differences obtained with the RB are a result of the fact that it had a 6–7 deg smaller overall range of recline as compared with the other three chairs and will be discussed first, followed by a comparison of the remaining three chairs.

The RB demonstrated significant differences for the horizontal and vertical hand movements when compared with the SF and MC chairs ($p < .05$) but not with the DP. Differences in the horizontal head motions were obtained for comparisons with the SF ($p < .002$) and MC ($p < .001$) but not with the DP. Finally, differences in the vertical motion of the head were found between the RB and all other chairs (RB vs. MC, RB vs. SF, $p < .001$; RB vs. DP, $p = .001$).

During dynamic recline, the DP on average

TABLE 5: Statistical Analysis Comparing (a) Maximum and (b) Minimum Contact Area Between Chairs

(a) Contact Area Maximum	RB vs. SF	RB vs. MC	RB vs. DP	SF vs. MC	SF vs. DP	MC vs. DP
Upright	0.800	0.800	0.800	0.800	0.800	0.800
Mid	0.502	**0.019**	**0.048**	0.322	0.546	0.978
Full	0.984	**0.007**	0.386	**0.003**	0.222	0.222
Dynamic[a]	—	<0.05	—	<0.05	—	—
All reclines	0.997	**<0.001**	**0.007**	**<0.001**	**0.015**	**0.034**

Note. Bolded numbers are significant at alpha = 0.05, or 95% confidence level.

[a] Data did not have a normal distribution; Friedman test on ranks was used. SF = slightly flexible back; MC = mesh chair; DP = double-pivot chair; RB = rigid back.

(b) Contact Area Minimum	RB vs. SF	RB vs. MC	RB vs. DP	SF vs. MC	SF vs. DP	MC vs. DP
Upright	0.259	0.259	0.259	0.259	0.259	0.259
Mid	0.172	0.172	0.172	0.172	0.172	0.172
Full	0.761	0.161	0.189	**0.020**	**0.025**	1.00
Dynamic	0.484	0.751	**0.015**	0.093	0.285	**0.001**
All reclines	0.899	0.379	**<0.001**	0.805	**0.006**	0.071

Note. Bolded numbers are significant at alpha = 0.05, or 95% confidence level. SF = slightly flexible back; MC = mesh chair; DP = double-pivot chair; RB = rigid back.

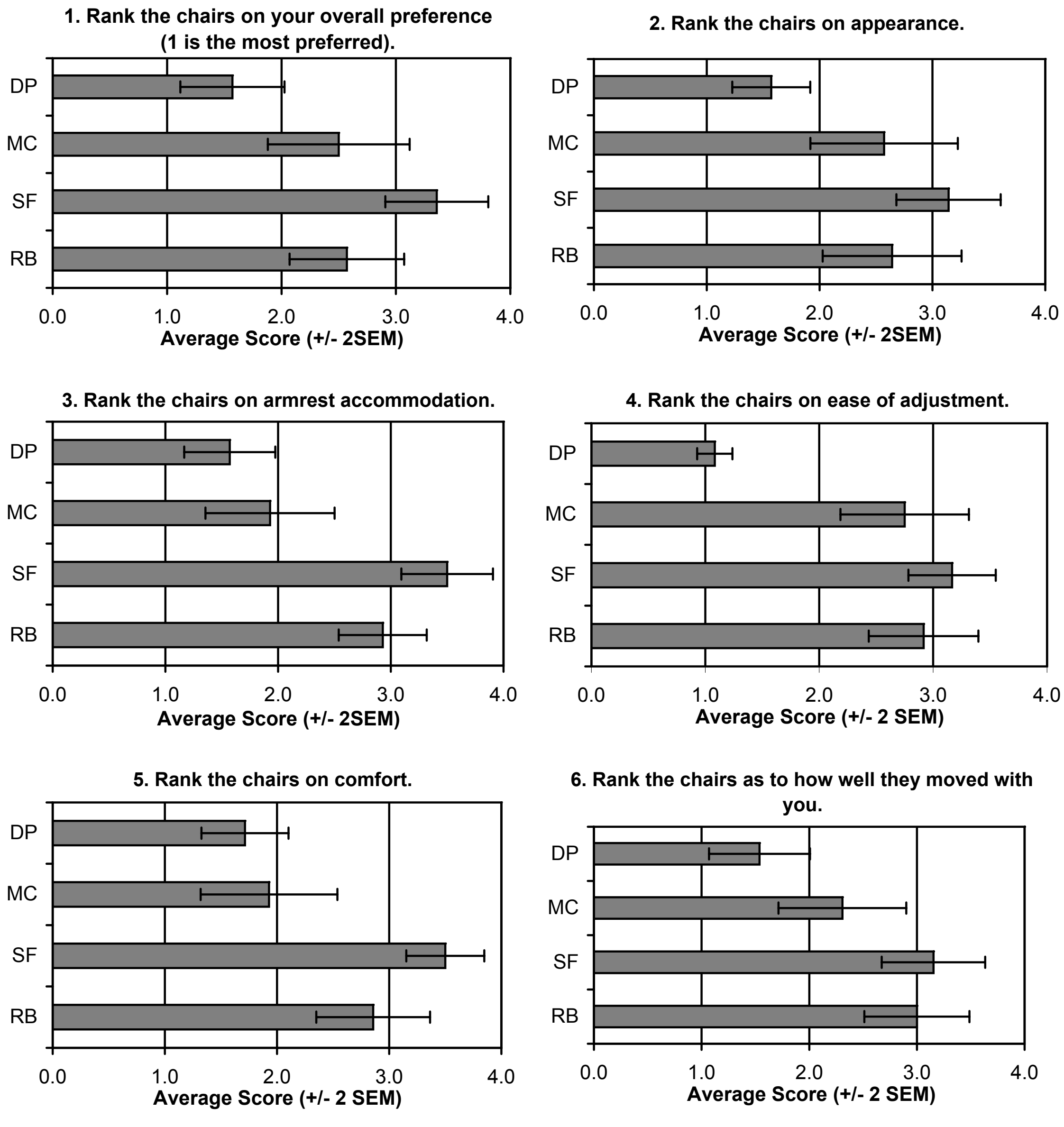

Figure 5. Average subjective ranking of each chair for each question. Plotted with plus and minus 2 standard errors of the mean. Lower rating means higher preference. SF = slightly flexible back; MC = mesh chair; DP = double-pivot chair; RB = rigid back.

reduced the horizontal travel of the hands by 78% as compared with the SF and MC (see Table 7). The DP also showed a reduction in the vertical motion of the hands (as compared with the SF and MC) by half, from 30 to 15 mm.

The horizontal motion of the head (see Table 7) was reduced in the DP, on average, by 15% to 25% compared with the SF and MC. The vertical motion of the head was reduced between 32% and 41%.

Statistical differences were produced for horizontal hand and head movements between the DP and MC ($p < .05$) and between the DP and SF ($p < .05$), but not between the SF and MC. The vertical motion of the head showed significant differences for all three comparisons: DP versus MC ($p < .001$), DP versus SF ($p < .001$), and SF versus MC ($p = .028$).

Results of Subjective Rating

For all questions, the average of the subjective

TABLE 6: Average Ranges of Chair Recline

	Recline (deg) Average (*SEM*)
RB	14 (0.4)
SF	21 (1.0)
MC	21 (1.2)
DP	20 (0.4)

Note. SF = slightly flexible back; MC = mesh chair; DP = double-pivot chair; RB = rigid back.

ratings showed the DP chair to have the most preferred rating, followed by the MC, the RB, and finally the SF chair. Figure 5 shows the average scores plotted with ±2 times the standard error of the mean (*SEM*). Clear differences in preference can be seen between the chairs – specifically, the DP is different from the RB and SF for all questions; possibilities for this preference are noted in the discussion.

Statistical testing ($p < .05$ for all evaluations) showed a difference in overall preference (Question 1) and appearance (Question 2) between the DP and SF. Question 3, which pertained to accommodation of the armrests, yielded differences between the DP and SF, the DP and RB, and the MC and SF. In terms of ease of adjustments (Question 4), differences were found between the DP and all other chairs. Question 5, which asked the participants to rank the chairs on overall comfort, yielded differences between the DP and SF, as well as the MC and SF. Finally, when asked about the ability of the chair to move with them (Question 6), participants indicated differences between the DP and SF, as well as the DP and RB.

DISCUSSION AND CONCLUSIONS

Results of this study demonstrate an ability to use biomechanical measures to evaluate office chairs in terms of three functional attributes: spinal articulation, support, and stability of hand and head locations. Thus, using these techniques, it is possible to determine if a newly designed chair meets design criteria set by a manufacturer. Also possible is the ability to compare and contrast chairs. Furthermore, early in prototype stages, evaluations of this nature can be performed on different concepts to determine which design has the best performance relative to specific design goals.

The primary focus of our work was a biomechanical analysis of office chairs. However, collection of the subjective assessments also provided insight for future work. Even with the small subjective survey in this study, a clear order of preference was observed: DP and MC chairs were preferred over SF and RB (see Figure 5). Furthermore, a commonality between the two preferred chairs was that they both allowed for and supported spinal articulation. Spinal research has shown that allowing and supporting natural spinal motion is better for the health of the spine, particularly for the intervertebral disks, as compared with a single static position (Adams & Dolan, 2005; Pope et al., 2002). Thus, from a biomechanics perspective, it seems reasonable that chairs that support and move with the back during spinal articulation are preferential to chairs with stiff backs.

Now that methods to use biomechanical measures have been developed for office seating, the next step is to design a comfort study (task oriented, longer sit time, and accounting for carryover effects between chairs) in conjunction with the measurement of the biomechanical measures. A study of this nature could be used to determine if specific objective measures can be linked to improved comfort or if health benefits can be documented. To some degree, Van Dieen, de Looze,

TABLE 7: Horizontal and Vertical Motions of the Hand and Head During Recline (in mm)

	Hand		Head	
	Average Horizontal Motion (*SEM*)	Average Vertical Motion (*SEM*)	Average Horizontal Motion (*SEM*)	Average Vertical Motion (*SEM*)
RB[a]	28 (4)	12 (2)	285 (19)	60 (5)
SF	175 (8)	30 (5)	365 (20)	130 (6)
MC	177 (11)	29 (3)	413 (23)	152 (9)
DP	38 (4)	15 (3)	309 (20)	89 (5)

Note. SF = slightly flexible back; MC = mesh chair; DP = double-pivot chair; RB = rigid back.

[a] RB has a reduced recline range.

and Hermans (2001) and van Deursen et al. (2000) have shown a health benefit related to dynamic seating by demonstrating a reduction in spinal shrinkage (less compression of the intervertebral disks) as compared with static seating. Also, work by Kolsch, Beall, and Turk (2003a, 2003b) and the study of a comfortable range of reach have led to conclusions that objective measures should be used in relation to subjective assessments.

A future goal of this research group is to establish a link between subjective assessments and objective measures, but it was necessary to first establish methods for capturing and analyzing objective data in a useful manner. The presentation of this study demonstrates that in a laboratory setting, objective data can be collected and used to provide a biomechanical assessment of office chairs.

Head and Hand Positions

As discussed in the Results section, participants achieved an average recline range of 20 deg in the SF, MC, and DP chairs. Therefore, the reduction in the head and hand motion found in the DP seems to be a result of chair design. One feature that differed from the other chairs and that is believed to contribute to this outcome was a small glide mechanism on the seat pan. This mechanism allowed the seat pan to glide forward slightly as the participant reclined, which kept the body over the base of the chair, resulting in reduced head and hand motion while still achieving the same recline range. Also, the armrests on the DP maintained their position during recline; they did not tip rearward as they did on the MC. Thus, of the three chairs with similar recline ranges, the DP produced the least amount of head and hand motion during recline, so movement away from the keyboard or desk was minimal, and disruption to the focal point was reduced.

Another point with regard to the vertical component of hand movement should be noted. Participants were asked to start with their hands on the keyboard and recline, allowing the hands to slide down the keyboard and onto the desk. This sliding motion, along with the instances where the forearms were pivoted up because of the upward movement of some armrests (SF and MC), was attributed to the vertical displacement.

Spinal Articulation

The RB chair back was stiff and thus did not move with the participant from kyphosis to lordosis. The SF showed a decrease in the average range of spinal articulation as the chair moved from an upright position to either a mid-recline or fully reclined position. This decrease in spinal motion range was caused, in part, by the difficulty that the petite participants had trying to maintain contact with the floor. However, even when ranges of spinal articulation were the same across chairs, the SF did not respond with movements near that of the body. Both the MC and DP performed well with regard to the ability to allow spinal articulation; the DP showed a slightly higher correlation between the chair and body motions than the MC.

Support During Spinal Articulation

The RB was unable to support spinal articulation because of its rigid back. The SF showed high pressures horizontally at the contour break line and at the shoulders during recline, indicating that the chair was difficult to maintain in a reclined position. The MC demonstrated a region of higher pressures vertically along the spine, with a thinner contact profile, which suggested that even though the participant was allowed to achieve postural change, a hammocking effect of the mesh fabric was occurring. The DP demonstrated a consistent square region of contact regardless of the posture; this was also supported by lowest overall vertical COP motion. The visual observations, along with the COP travel, indicate that support in DP was consistently and continuously being provided during postural changes.

Study Limitations

The individual and diverse behaviors of people using chairs for extended periods in real work settings are difficult to measure and interpret. Laboratory experiments with repeatable protocols and objective, instrumental measurements are required to document and understand the possibilities of posture and support that a chair user will experience in these extended-period settings. Thus, the study discussed here is a foundational step that included the development of protocols and methodologies that can be used to compare office chairs. Once these objective evaluators are well documented in laboratory studies, it will be possible to introduce such experimentation into an actual work setting.

Furthermore, effort was taken to include the middle and end ranges of the anthropometric spectrum with respect to height and weight. Although an analysis could have been conducted within each subgroup, we believe that it was more appropriate for this initial study to provide the trends that were consistent across our entire sample and thus related to the population as a whole rather than a specific subgroup. Future work should include larger sample sizes in each subgroup, so meaningful statistical analyses can be conducted on these groups.

CONCLUSION

Finally, understanding the movement and support parameters of a chair in conjunction with the user will not only increase our knowledge in the area of seating mechanics but also allow us to better understand how these two interact, leading to better chair designs and improved functionality.

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