Evaluation and design performance of a multi-axis office chair compared to a standard ergonomic office chair

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1.0 Executive Summary

Sitting has become the most common work posture in the developed world, with workers sitting for more than two thirds of their workday. Steadily, evidence has been accumulating highlighting that sedentary behaviours, which include prolonged sitting, increases the risk of cardiovascular disease, cancers and early death. Seated postures also involve significant amounts of spine and hip flexion: postures that are related to the development and aggravation of low back pain. The high prevalence of back pain, paired with the high prevalence of seated postures, highlight the importance of considering chair interventions that can address both the broader health implications of seated postures but also the impact on back pain itself: ideally with the goal of prevention, but definitely with the ability to better manage existing conditions. ***The ability of a chair to provide optimal occupant posture, stability AND whole body movement would theoretically have the potential to address both the posture and movement risk factors that affect both overall health and low back pain.*** The CoreChair has been developed with a novel multi-axis seat pan that allows the user to move in all directions without sacrificing stability, together with a unique low backrest design that supports spine posture. Studies conducted on the CoreChair have shown it to be stable while providing a large range of movement, comparable to a standard office chair in terms of seat pressure, and promote better spine postures. What is less understood is how well occupants utilize the movement capabilities of the seat pan, if the design affects pain group membership and/or whether it improves lower limb venous return in a healthy population. Therefore, this study exposed a population of healthy male participants to two-hours sitting while completing a standardized typing task in the CoreChair and a control chair. The study design utilized two separate data collections, in a randomized order, at the same time of day to control diurnal variation and separated by a 24-hour washout period. The following variables were compared between chair conditions: spine posture, seat pan pressure, seat pan movement, calf circumference, low back muscle activity, and perceived low back pain. Qualitative data capturing perceived back stiffness, physical tiredness, chair support, chair movement and beliefs surrounding the concept of a typical office chair were gathered via an Exit questionnaire at the end of each session. The results of this study provide evidence that the CoreChair design does facilitate improved spine posture, lower limb venous return and, while perhaps not to the degree it could be, increased seat pan movement in both the lateral and frontal planes compared to sitting in a control chair. Participants were less likely to be classified as a transient low back pain-developer and overwhelmingly perceived lower amounts of back stiffness and whole body fatigue compared to the control chair. While participants found both chairs could be more supportive, the CoreChair was rated as providing comparatively more support than the control. Nearly all participants reported that the CoreChair did not fit their belief of what a typical office chair should be. However, this may be a compliment in disguise, as the typical office chair design is probably more of a problem than solution in terms of improved health and wellbeing in sitting. ***Thus, the ability of the CoreChair to positively affect both general cardiovascular health and back pain appears to be realistic.*** However, larger field-based longitudinal studies would be needed to provide stronger support for these statements.

2.0 Introduction

According to the 2009 Statistics Canada Health Measures Survey Canadians are sedentary, defined as using 3 or less Metabolic Equivalents (METS), for an average of 68-69% of their day. The majority of this sedentary time is spent engaging in activities that predominantly involve seated postures. This finding is reflected in recent international research that has shown adults in developed countries spend approximately one-third of their workday seated (Clemes et al., 2014) and a large variety of workers such as commercial vehicle drivers, clerks, and business administrative workers spend almost the entirety of their workday seated (Jans et al., 2007). Therefore, sitting for extended periods of time is, in fact, a reality for a large portion of the population worldwide.

This sitting epidemic has serious implications for health and wellbeing, as mounting research shows that sedentary lifestyles are directly linked to increased risk of a number of serious adverse health events and diseases including a decreased life expectancy and increased risks of all-cause mortality (Dunstan, Howard, Healy, & Owen, 2012; Katzmarzyk, Church, Craig, & Bouchard, 2009), cardiovascular disease (Chomistek et al., 2013; Dunstan et al., 2012), type 2 diabetes and other metabolic diseases (Dunstan et al., 2012), certain cancers (Katzmarzyk et al., 2009) and low back pain (Gupta et al., 2015). While all of these conditions carry heavy burden for those affected, society often minimizes the impact of musculoskeletal disorders in comparison to systemic diseases. It is important to note that Low Back Pain (LBP) is now accepted as one of the major health care issues facing today's society (Hoy et al., 2012) and leads the burden of disease worldwide in terms of years lived with disease (Lancet, 2015).

LBP impacts a wide-variety of individuals with estimates of 70-85% lifetime chance of development (Andersson, 1999). However, the pathophysiology of this condition is poorly understood and in many cases it is thought to be linked to a combination of physical and psychological factors (Bosscher & Heavner, 2015) of which prolonged sitting is often implicated. Looking at the general epidemiological literature though, a direct link between prolonged sitting and low back pain has not been formally established. There are studies that have identified a significant correlation between prolonged sitting and LBP (Damkot et al., 1984, Frymoyer et al., 1980,Gupta et al., 2015 Pope and Magnusson 2002, Punnet et al. 2005) whereas this conclusion has not been reached in others (Picavet et al., 2016). This discrepancy could be related to the challenges presented by establishing relationships in two highly prevalent variables, as both sitting and low back pain are extremely common in the general population. It is important to note on a basic mechanistic level, numerous laboratory controlled studies have identified clinically relevant levels of transient low back pain are evoked in response to prolonged sitting in proportion of the general population (Nairn et al., 2013, Danquah et al., 2017, Weston et al., 2017, Li et al., 2017, Grondin et al., 2013, Gregory et al., 2006, Gage and Innes 2007, Dunk and Callaghan 2010, De Carvalho and Callaghan 2011, Beach et al., 2003, Aota et al., 2007) and the reversal of this transient pain with changes in posture (standing) and/or movement breaks (walking) (Danquah et al. 2017, Fewster et al. 2017, Gallagher et al. 2016, De Carvalho and Callaghan 2013, Foley et al., 2016, Karakolis et al., 2016, Chester et al., 2002).

What is it about sitting that can lead to back pain? Seated postures involve flexion at the hips, anterior rotation of the pelvis, and flexion of the lumbar spine (Andersson et al., 1979) resulting in relatively more spinal flexion compared to standing. These postural changes increase the stresses and strains on various tissues of the spine and low back and over prolonged time can increase injury risk. Thus, prolonged flexion of the spine, as during sitting, has been identified with local factors such as increased disc pressure, strain of posterior passive trunk tissues, static disc loading, and muscular fatigue (Andersson et al., 1974; Adams and Dolan 1986; McGill and Brown 1992).

Efforts to reduce the negative health effects associated with prolonged sitting have resulted in the development of numerous chair designs and features to address the problem. Many designs aim to support the lumbar spine in a more lordotic/neutral posture closer to that of upright standing. This can be achieved directly through lumbar support or indirectly with features that promote upper back extension and/or increase the hip angle such as modified thoracic backrests, forward-inclined seat pans and saddle-type seat pans (Annetts et al,; Colombini et al., 1985; Grondin et al., 2013; Kim et al., 2014; Stuart M. McGill & Chad M.J. Fenwick; Vaucher et al., 2015). However, most of these design features are unable to return low back spine angles to levels seen in standing postures (De Carvalho and Callaghan, 2016). This may be why Curran et al. (2015) concluded in a review of literature that interventions that decrease hip flexion are not able improve low back discomfort/pain or consistently alter trunk muscle activation. In fact, when these design features were assessed over a prolonged exposure in a laboratory controlled trial, even features known to reduce spine angle flexion still resulted in significant levels of transient back pain (De Carvalho thesis, 2015).

Instead of focusing on posture, it may be more effective to address the static nature of prolonged sitting: hence the recent focus on interventions allowing more movement during desk work such as height adjustable standing workstations, breaks, and dynamic chairs. Increasing movement at work would have the added benefit of increasing metabolic demand, reducing sedentary time, and potentially impacting the negative health effects on both the cardiovascular and musculoskeletal systems. A number of studies have shown that short activity breaks, typically consisting of walking, can improve metabolic and cardiovascular variables as well as short-term reductions in transient back pain. Bryan and Locke (2014) found that light intensity exercise breaks might decrease cardiovascular risk factors while standing breaks alone do not; emphasizing the importance of movement. Activity breaks have been further found to decrease fatigue, blood glucose, rested blood pressure, and insulin (Bailey and Locke, 2014; Chau et al., 2010; Gilson et al., 2013; Larsen et al., 2014; McCarthy et al., 2017; Wennberg et al., 2006). In a study examining the effect of 2-minute walking breaks at 40 minute intervals in a 2 hour exposure to prolonged sitting, De Carvalho and Callaghan (2013) showed a significant, but temporary, reduction in induced back pain. However, there are challenges with activity breaks. There are some occupations where out of chair activities are simply not possible (e.g. air traffic control, emergency dispatch) and many others where breaks are perceived to be a reflection of reduced productivity or a break in concentration. This makes the potential of increasing in-chair activity attractive. Passive dynamic chairs have been shown to reduce spinal shrinkage (van Deursen et al. 1999, van Dieen et al. 2001), which is promising, but these chairs have not been shown to increase spine movement or muscle activation (van Dieen et al. 2001, Gregory et al.

2006, McGill et al. 2006, O'Sullivan et al. 2006c, Kingma and van Dieen 2009). Further, while seats with decreased stability have been shown to increase center of pressure motion as the occupant continually adjusts their balance (Cholewicki et al., 2000), exercise ball-type seats have been shown to increase lumbar muscle activation, perceived discomfort and spinal shrinkage in females (Kingma and van Dieen, 2008). Clearly too much of a balance challenge, while helpful to increase movement, can create new problems for the occupant. Therefore, the ability of a chair to encourage in chair movement whist at the same time providing enough stability would be ideal.

This project has investigated just such a chair. The CoreChair is a novel "multi-axis" chair that, in theory, should encourage individuals to move more while they sit otherwise supported. This design would be expected to reduce prolonged static postures without the occupant having to get up from their workstation for a formal break. While past investigations of the CoreChair have found it to be comparable to a standard office chair in terms of stability and comfort, it is still not entirely clear whether individuals truly take advantage of its movement capabilities. Therefore, the purpose of this study was to compare spine posture, seat pan orientation, seat pan movement, back muscle activity, seat pressure variables and changes in calf circumference (as an indirect measure of venous pooling) between the CoreChair and a control chair (typical ergonomic office chair).

2.1 Investigative Purpose

The primary purpose of this project is to investigate the effects of an "active"/multi-axis office chair on spinal lumbar flexion angle during prolonged sitting in comparison to a standard office chair. Secondary purposes were to determine effects of the "active" chair on perceived pain, back muscle activation, seat pan orientation, seat pan movement, calf circumference and seat pressure variables during prolonged sitting in comparison to a standard (control) office chair.

2.2 Hypotheses

There are multiple hypotheses for this study. The main objective is a reduction of spinal flexion due to the fact that it appears to be a significant risk factor for the development of LBP. There is evidence that spine flexion can be reducing in sitting with certain office chair designs (De Carvalho Thesis, 2015). Therefore, this measure was used as the primary outcome upon which the most accurate sample size calculation could be made.

It is important to note that the secondary hypotheses explore valuable outcomes also important to understanding the relationship between sitting and back pain; however, since these secondary hypotheses are generated *a priori* and without an estimation of the required sample size, there is the potential that the ability to examine these differences may be underpowered. Thus, a failure to find a difference may be due to the size of the sample population and not due to the fact that a difference is lacking.

The hypotheses are as follows:

2.2.1 Primary Hypothesis

Participants will exhibit significantly less lumbar spinal flexion throughout a 2-hour standardized office task sitting in the CoreChair compared to the control office chair.

2.2.2. Secondary Hypotheses

a) Participants will exhibit significantly lower levels of low back muscle activity throughout a 2-hour standardized office task sitting in the CoreChair compared to the control office chair.

b) Participants will experience significantly less perceived pain throughout a 2-hour standardized office task sitting in the CoreChair compared to the control office chair.

c) Participants will exhibit significantly less peak pressure over a 2-hour standardized office task sitting in the CoreChair compared to the control office chair.

d) Participants will exhibit significantly less increase in calf circumference after the 2-hour standardized office task sitting in the CoreChair compared to the control office chair.

e) Participants will exhibit significantly more movement, as measured by tri-axial accelerometer, during the 2-hour standardized office task sitting in the CoreChair compared to the control office chair.

3.0 Methods

3.1 Participants

Thirty-one male participants from a university population were recruited for this study. Thirty participants completed both sessions of the study and were included in the final data analysis (average age 24.2 ± 6.5 years, height 180.3 ± 6.2 cm and weight 80.4 ± 14.3 kg). One participant did not return for the second session and was removed from the final analysis. Exclusion criteria included: a previous history of back pain linked to tumor, infection, fracture, or inflammatory arthropathy, and/or previous surgeries of the spine; inability to sit for two hours at a time; or an episode of low back pain resulting in a lost day of work or school, in the past six months.

The study focused on a university population because this group is used to long durations of seated deskwork or computer based tasks, therefore, it is expected they would not require additional time to acclimatize to the posture or task. All individuals were required to complete the informed consent process prior to participation. The Health Research Ethics Board of Newfoundland and Labrador approved the experimental protocol. Table 1 summarizes the anthropometric characteristics of the participants recruited and reflects a good range in the study population.

Table 1: The anthropometric characteristics of the 20 male participants that completed both sessions of the study.

	Mean (SD)	Range
Age (years)	24.2 (6.5)	19 - 56
Height (cm)	180.3 (6.2)	167.6 - 195.6
Mass (kg)	80.4 (14.3)	54.4 - 114.0
BMI (kg/m²)	24.6 (3.7)	16.8 - 35.9

3.2 Instrumentation

3.2.1 Questionnaires

Three qualitative questionnaires were included in this study design (Appendix A): a Health History Screening form, the Modified Oswestry Back Disability Questionnaire, and an Exit questionnaire. The Health Screening Form was developed by the research team specifically to screen for exclusion criteria and provide background information on low back pain experience and family history of back pain. The Modified Oswestry Disability Index was used to confirm that the study population was healthy and free of a clinical or subclinical low back disorder. Both of these questionnaires were administered at the start of the first study session. The Exit questionnaire, formulated in conjunction by representatives from CoreChair Inc., gathered feedback on how the chair was perceived by the participant. Responses to questions were collected using a 5-point Likert scale that focused on the participant's perception of the following aspects: the support provided by the chair to the occupant, the perceived ability of the occupant to move while seated, their perceived seated posture, their beliefs regarding what a chair should be, and their perceived fatigue and stiffness following the trial. The exit questionnaire was given following each session to capture responses to both chair conditions.

3.2.2 Workstation

When participants arrived at the laboratory, they were first familiarized with the workstation to be used during the prolonged typing trial of both sessions. This workstation consisted of the test chair (CoreChair, Core Chair Inc., Aurora, ON, Canada) or control chair (geocentric Mid Back, ergoCentric Seating Systems, Mississauga, ON, Canada) (Figure 1), a height adjustable office desk, and a desktop computer with a wired keyboard and mouse.

All components of the workstation were individually adjusted according to the anthropometrics of each participant according to the Canadian Standards Association guideline for office ergonomics (Canadian Standards Association, 2000). This includes having the workstation occupant sit with a 90° flexion angle at the knee, hip, and elbow and feet flat on the floor, neutral wrist posture, and relaxed shoulders. Participants were instructed that this original set-up provides a standardized starting position for office deskwork only. It was emphasized they were free to move/relax their body position as they wished throughout the prolonged sitting trial but

were not permitted to adjust any aspect of the workstation and/or stand up from the chair at any point during the trial.

Figure 1: The chairs used in this investigation: The CoreChair (left) and the control chair (right).

3.2.3 Surface Electromyography (sEMG) for Measuring Spine Muscle Activity

Following the workstation adjustment, participants were instrumented with six surface electromyography (EMG) surface electrodes to monitor the muscle activity of three back muscles bilaterally: right thoracic erector spinae (RTS), left thoracic erector spinae (LTS), right lumbar erector spinae (RLS), left lumbar erector spinae (LLS), right lumbar multifidus (RML), and left lumbar multifidus (LML). Before applying the electrodes, proper preparation techniques were used: the skin was lightly shaved, abraded with tissue, and cleaned with a diluted isopropyl alcohol cleansing solution. For each muscle, two disposable electrodes (Ag-AgCl, Blue Sensor, Medicotest Inc., Ølstykke, Denmark) were placed over the muscle belly in a bilateral orientation with a centre-to-centre inter-electrode distance of 2 cm (Figure 2). The raw EMG signals were differentially amplified, bandpass filtered from 10-1,000 Hz and then digitally sampled at 1500 Hz using a 16 bit A/D converter with a resolution of +/- 2V (Desktop DTS, Noraxon, Phoenix, AZ, USA; CMRR > 100dB, input impedance > 100 MΩ).

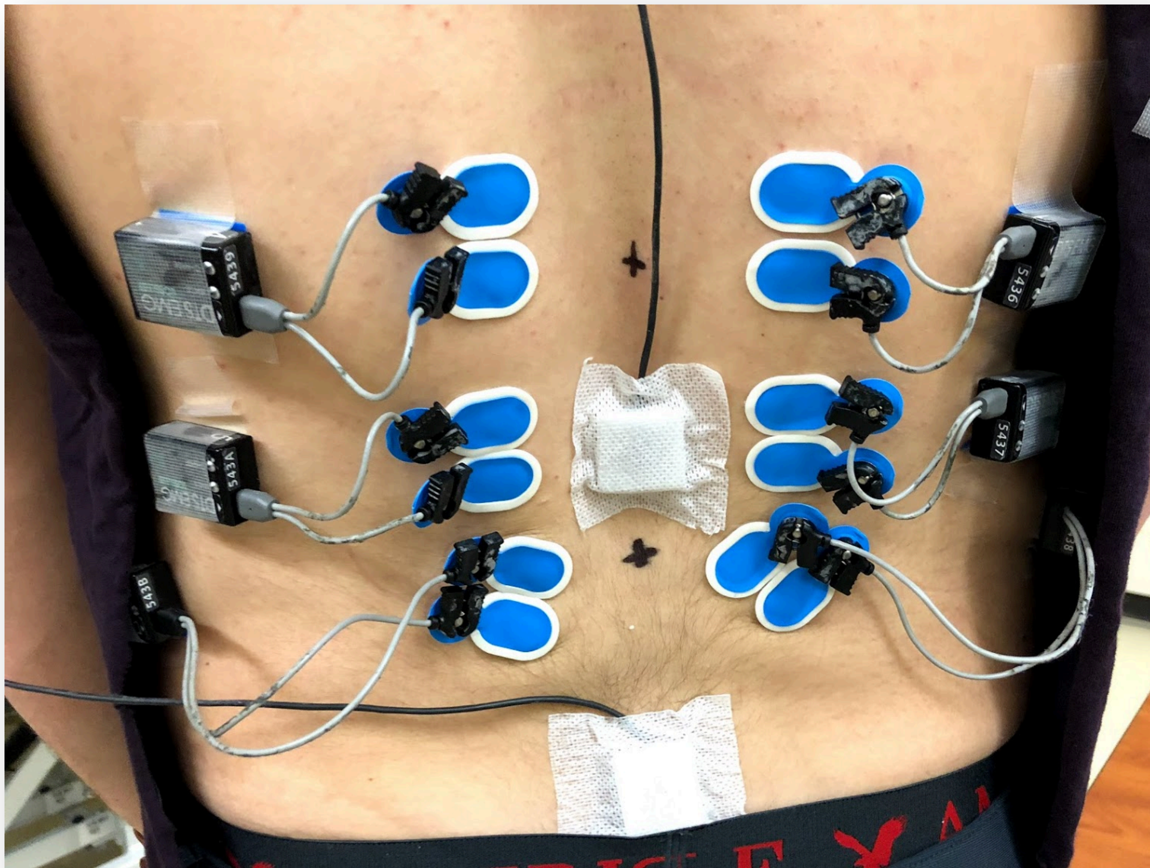


Figure 2: Experimental set-up for six channels of EMG (clockwise from top left: left thoracic erector spinae (LES), right thoracic erector spinae (RES), right lumbar erector spinae (RLS), right lumbar multifidus (RLM), left lumbar multifidus (LLM), left lumbar erector spinae (LLS) and left thoracic erector spinae (LES) and two tri-axial accelerometers (top mounted at L1 and bottom mounted at S2) used in all data collection trials.

Following the electrode placement, calibration trials were collected in order to normalize the data. A 5-second quiet trial was collected with the participant lying prone on a manual therapy plinth, relaxing all muscles. This trial was used as a baseline reference for zero activity when normalizing the EMG data. Next, three, 10-second, trials were collected in which the maximum muscle activity for each muscle was elicited. Maximum voluntary contractions (MVC) for the lumbar extensor muscles involved the participants extending their back isometrically against resistance by a researcher (Figure 3). During the MVC trial, the participant's torso was cantilevered at the hips (specifically the anterior superior iliac spines) at the end of a manual therapy table while their lower body was fixed in place by a researcher securing their lower body. The highest activity value (voltage) recorded for each muscle from all of the trials was later used as 100% when normalizing muscle activity levels to a percentage of maximum voluntary contraction (MVC).

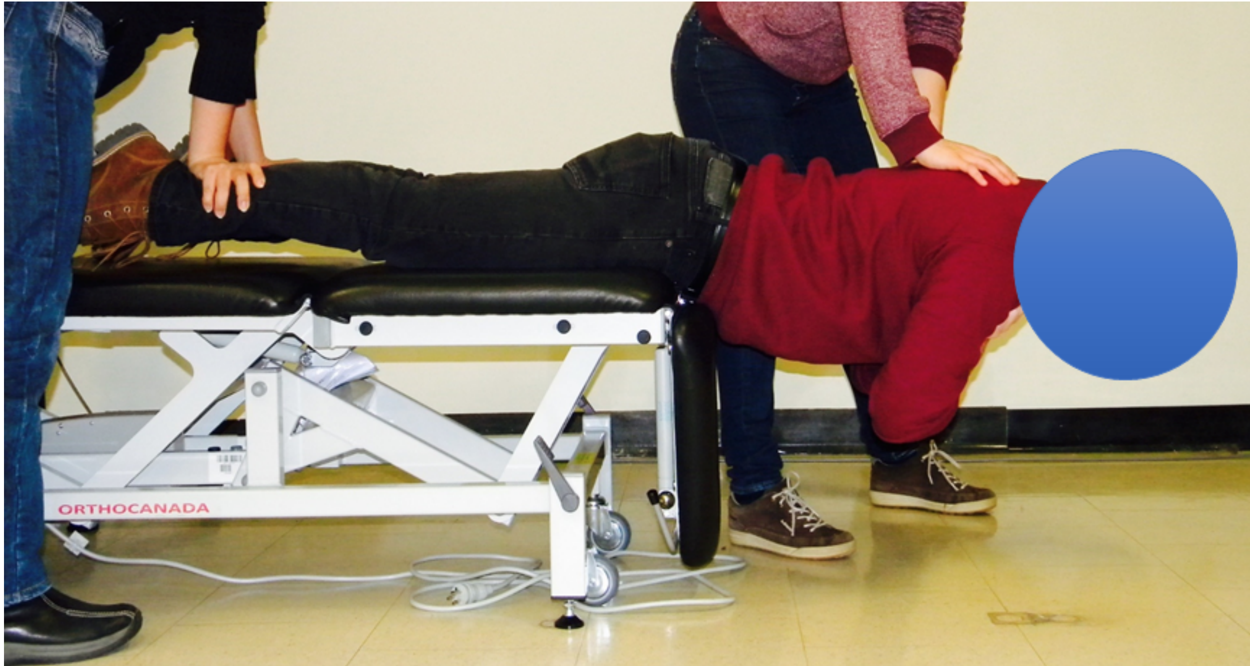


Figure 3: Example positioning for the maximum voluntary contraction trials. The participant ramps up and then provides a maximum isometric (no change in muscle length) effort by trying to extend his back as hard as possible towards the ceiling while research assistants provide counter resistance to the legs and torso. The highest voltage value of the three trials is picked by custom code during data processing to represent the maximum (100%) value of muscle activity for each muscle respectively.

2.3.4 Tri-Axial Accelerometers to Measure Spine Angle and Movements

Following this, two tri-axial accelerometers (ADXL335, Analog Devices, Norwood, MA, USA) were taped to the skin of the participant over the first lumbar and second sacral spinous processes in the +y down, +z anterior orientation using double-sided and medical fabric tape (Figure 2). These sensors were used to measure accelerations collected continuously throughout the prolonged sitting trials to provide time-varying data. Custom code used during data processing was then used to convert individual sensor accelerations due to gravity into angles using trigonometric equations. The individual orientations of the L1 and S2 sensors were then used to calculate the relative angle of the lumbar spine and the relative pelvic angle was presented in relation to the vertical gravity line.

Similar to muscle activity, it is helpful to normalize posture measures in order to provide a more functional interpretation of posture and stronger comparison between participants. With the accelerometers fixed in place, participants performed four posture calibration trials that were used to normalize lumbar and pelvic angles data to ranges of flexion motion of the spine (presented in a percentage of maximum range of flexion motion, % ROM). The trials are collected with the posture held for 5-seconds each and included: upright standing, maximum trunk flexion, maximum trunk extension, and maximum seated trunk flexion (Figure 4).

Throughout the experimental protocol, accelerometer data were low-pass filtered at 500 Hz, and A/D converted using a 16-bit board at a sampling frequency of 1500 Hz (Desktop DTS, Noraxon, Phoenix, AZ, USA). Normalized lumbar and pelvic angles, averaged throughout the prolonged sitting trials together with movement frequency parameters were compared between chair conditions.

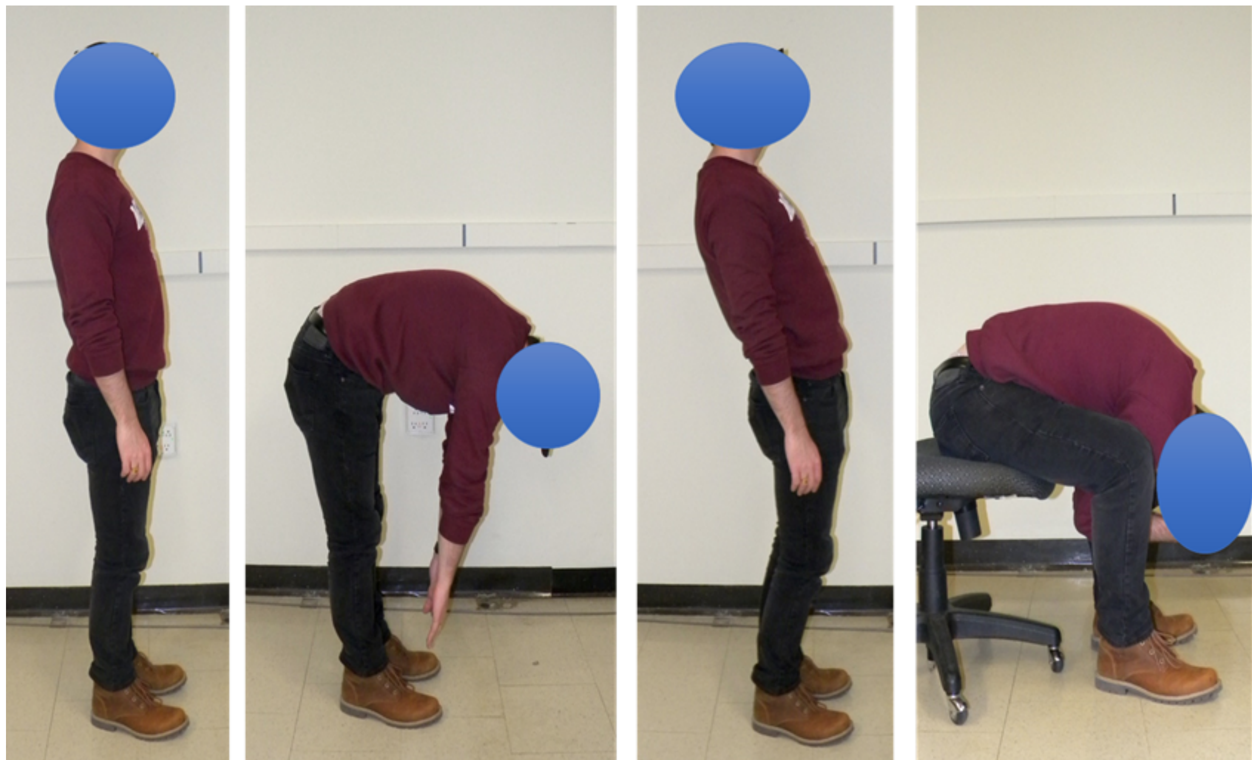


Figure 4: The four posture calibration trials used that were used for normalizing spine angles to %ROM. From left to right: upright standing, maximum trunk flexion, maximum trunk extension, and maximum seated trunk flexion.

2.3.5 Tri-Axial Accelerometer to Measure Seat Pan Position and Movement

A separate tri-axial accelerometer (ADXL335, Analog Devices, Norwood, MA, USA) was fixed to each chair in the +y down, +z anterior orientation using industrial grade tape. A vertical

location as similar as possible on each chair was identified for mounting the sensor: the rigid arm of the backrest at a point closest to the seat-pan. These sensors were affixed to a standardized location for each data collection (Figure 5).

Data from these accelerometers were used to track the orientation and movement of the seat pan during the prolonged sitting trials. Throughout the experimental protocol, this signal was low-pass filtered at 500 Hz, and A/D converted using a 16-bit board at a sampling frequency of 1500 Hz (Desktop DTS, Noraxon, Phoenix, AZ, USA). Average, max, range and standard deviation of seat orientation was compared between chairs.

Figure 5: Location of the accelerometer on the rigid arm of the seat pan for both the CoreChair (left) and the control chair (right) respectively.

2.3.6 Perceived Pain Ratings

Ratings of Perceived Pain (RPP) were measured using a 100 mm Visual Analogue Scale (VAS) with a custom desktop program (Matlab version 2015b The MathWorks, Natick, MA, USA, Figure 6). Participants were asked to rate their pain for 9 areas of the body (neck, right and left upper back, right and left lower back, right and left buttocks, right and left thighs) by sliding a bar along a continuous line with the following anchors: 0 mm = "no pain" and 100 mm = "worst pain imaginable". When saved, the rating bars reset to zero so that past scores would not influence subsequent scores. Ratings were collected every 7.5 minutes throughout prolonged sitting trials. A baseline pain rating was collected at the beginning of each session (immediately after adjusting the workstation to the participant) such that only the change in perceived pain response during each session was analyzed. This was done by subtracting baseline ratings from all subsequent data points.

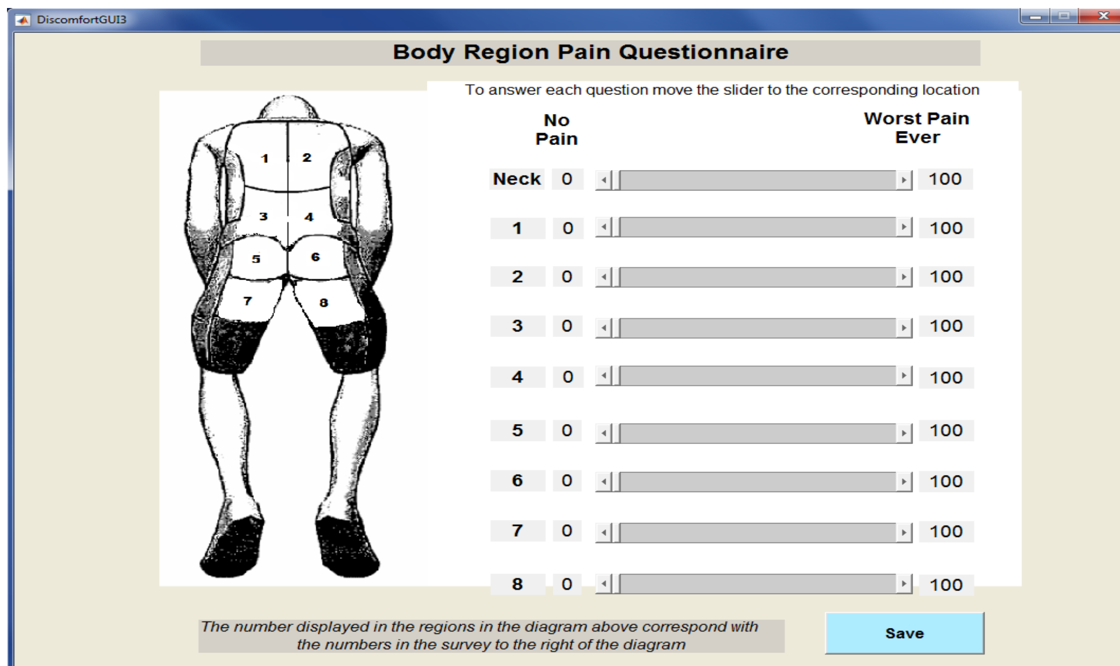


Figure 6: Screen capture of the digital Rating of Perceived Pain Visual Analog scale used to measure perceived pain for 9 body regions. Participants were instructed to slide the corresponding bar for each region to score their perceived pain between 0 m and 100 m then to click "save" which would reset all values to 0. The program auto-exports saved extracted pain ratings to the nearest mm.

2.3.7 Seat Pressure

A pressure sensor array mat (LX210:40.40.02 Sensor, XSensor Technology Corporation, Calgary, AB, Canada) was fixed to the seat pan of the test chair during each session using Velcro™ tape. The origin of the sensor surface was consistently placed at the back right of the seat pan. The X3 Pro Version 7.0 software was used to collect pressure data at a sample rate of 30 frames per second; synchronized to the rest of the signals with an external trigger. This program was also used for processing and analysis of the pressure data variables: peak pressure (N/cm^2), average pressure (N/cm^2), and contact area between the person and seat-pan (cm^2).

2.3.8 Calf Circumference

At the end of the instrumentation period, right before the start of the prolonged sitting trial, the experimenter measured and marked a point 10 cm distal to the patella on the participant's right calf with a pen. Baseline calf circumference was measured at this location to the nearest mm using a clinical measuring tape and taken as an indirect measure of venous pooling. The measure was taken three times. If one of the three measures was off by one or more centimeters from the other two measures it was discarded and a fourth was taken. The average of three measures was then used in the analysis. After the sitting trial this measure was re-taken for comparison. The

same experimenter performed all measures (pre/post) on all participants in this study. Differential changes were presented in centimeters and compared between chair conditions.

2.4 Data Collection Procedure

Two experimental sessions were booked for each participant: one using the CoreChair and one using a standard office chair (geoCentric Mid-Back Multi-tilt, ergoCentric Seating Systems, Mississauga, ON, Canada). These sessions were booked at the same time of day to control for diurnal variation, and at least one day apart to control for any carry over effects. The participants were randomized to start with either the intervention or control chair using a random number generator in Excel (Version 14.4, Microsoft Office, Redmond, WA, USA). The data collection procedure included a standardized typing task for 2 hours that was exactly the same for both conditions with the only difference being the chair that the individual was sitting on for the trial. The first session was divided in four phases: Pre-Collection (Informed Consent Procedure), Instrumentation, Sitting-Trial, and Exit Questionnaire. The second session only included the Instrumentation, Sitting-Trial, and Exit Questionnaire since informed consent was already completed (Figure 7). The only difference between sessions was the absence of the pre-collection phase during the second session and the use of the different chairs during the sitting-trial.

Figure 7: Schematic depicting the timeline for a data collection session including instrumentation, sitting trial, and the exit questionnaire. During the first experiment session the instrumentation block was preceded by a pre-collection session to complete the informed consent process and the first two questionnaires.

2.4.1 Pre-Collection

Subjects attended a brief pre-experiment session immediately preceding the first data collection. The purpose of this session was to give time for the participant to discuss, sign, and ask questions regarding the informed consent form with the research team. This procedure took approximately 10 minutes. The remaining time was used to complete the following questionnaires: the Modified Oswestry Low Back Disability Questionnaire and a Health History Screening Form (Appendix A). The pre-collection phase did not need to be repeated and therefore was only integrated into the first session. Immediately following the pre-collection session, or once the participant arrived at the lab for the second session, the participant was instrumented with the equipment outlined above and the EMG and posture calibration trials were completed.

2.4.2 Instrumentation

Both sessions began with instrumentation and calibrating the equipment as outlined in the methods section and depicted in Figure 2. This process took approximately 1 hour.

2.4.2 Sitting Trial

Prior to instrumentation participants were seated at the experimental workstation and the desk height, chair height, monitor height/depth and keyboard/mouse placement were adjusted according to the anthropometrics of the individual (Figure 8). A baseline rating of perceived pain was completed.

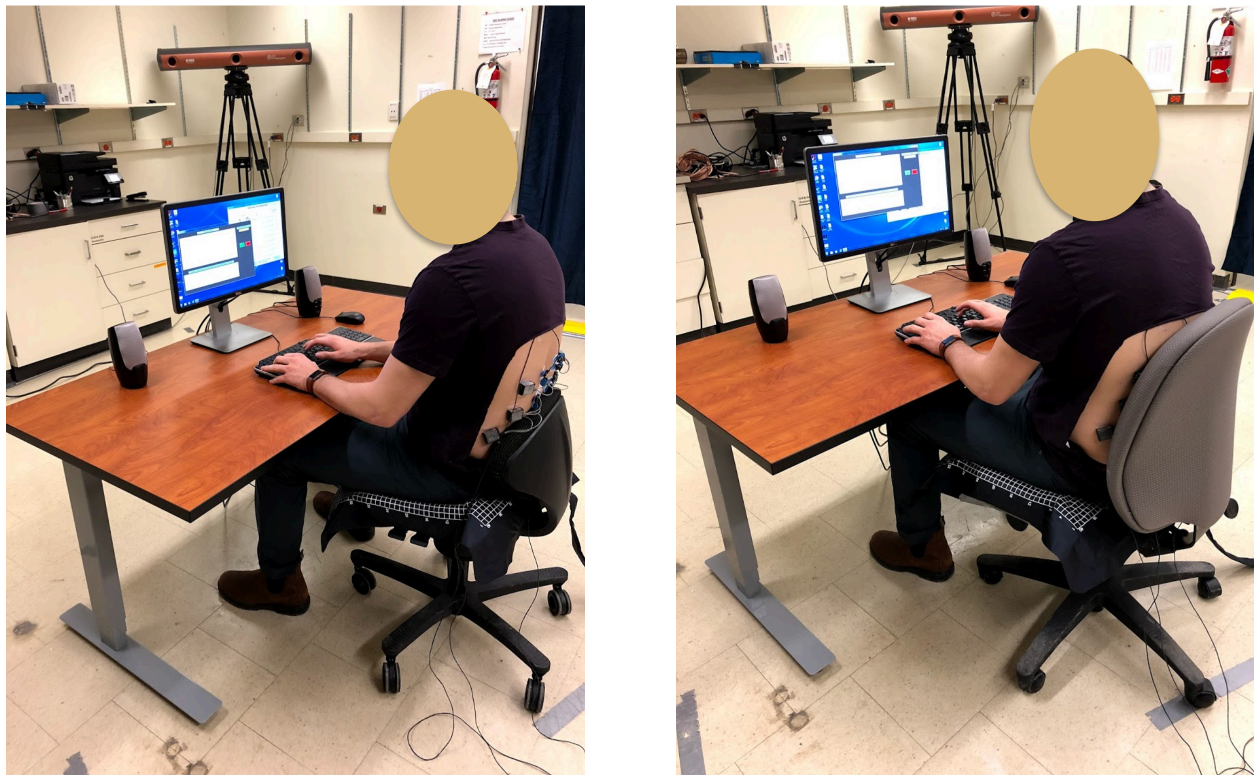


Figure 8: Set up at the workstation in the CoreChair (left) and control chair (right) respectively according to ergonomic guidelines with the pressure mat placed on the seat pan and the EMG and accelerometer sensors attached to the participant's back.

The participant then watched a short video, created by the research team, introducing the chair to be used in the session that day. A recent systematic review showed that ergonomic training is important for proper use of interventions (Van Eerd et al., 2010). Therefore, the purpose of these videos was to provide standardized information to all participants clearly explaining the features and normal use of both chairs involved in this study. Each video was approximately 30 seconds

long. The tone of the video purposely held little emotion to minimize a perceived bias of one chair over the other. A script for each video can be found in Appendix B.

The prolonged sitting trial began immediately after the video was shown. During this trial participant completed a standardized data entry task on a custom written software program (Matlab Version 2015b, The Mathworks, Natick, Massachusetts, USA) for two hours. This involved typing text appearing within the program window into the text box below. RPPs were completed every 7.5 minutes throughout the duration of the trial to measure changes in perceived pain in response to the seated exposure. A final RPP was completed at the end of the trial.

2.4.3 Exit Questionnaire and Session End

The Exit questionnaire was administered immediately at the end of the sitting trial. Participants completed this questionnaire while still sitting at the experimental workstation in the test chair. After this the participant was de-instrumented, received $10 as a thank you for their time and was free to leave the laboratory.

2.4.4 Collection Summary

First Collection

The data collection protocol commences by introducing the participant to the workstation and seating them in the test chair. Once adjustments are made in accordance to ergonomic guidelines (Canadian Standards Association 2000), a baseline rating of perceived pain rating was completed. The participant then watched the standardized video showing them how to use and sit in the chair that they were randomly selected to sit in for the session. Then, the participant was instrumented with EMG sensors and the MVC/quiet trials were completed. Then the participant was instrumented with accelerometers and four static end-range of motion trials were collected in order to normalize posture angles to a percent of the flexion range. The participant was then seated at the workstation and the baseline measure of calf circumference was taken 10 cm distal to the patella. This was followed by the start of the 2-hour standardized typing trial.

Second Collection

The collection procedure for the second session was almost identical to the first session, with the exception that the participant was seated in the second chair (according to the randomization scheme).

3.0 Data Processing and Analysis

3.1 Surface electromyography (sEMG)

EMG data were processed by custom software (Matlab version 2015b, The Mathworks Inc., Natick, Massachusetts, USA). This involved bias removal, band pass filtering of 30-500Hz, full wave rectification, low pass filtering using a 2nd order Butterworth filter with a cut off frequency of 2.5Hz, subtraction of resting EMG levels and then normalization to maximum voluntary contraction (% MVC) obtained for each muscle group using the quiet and maximum trials for each muscle respectively. In order to assess the degree to which muscle groups were similarly activated, which would provide information about motor control and a possible source of pain, cross-correlations of muscle channels were calculated using custom software (Matlab2015b, The Mathworks Inc., Natick, Massachusetts, USA) according to the method described by Nelson-Wong et al. (2009). Specifically, cross-correlations within a window of 500 ms were calculated for each minute of the sitting blocks throughout the study and the absolute maximum cross-correlation coefficient (R_{xy}) was calculated. After confirming no difference between these intervals, the average cross-correlation coefficient for all comparisons and average activity for all muscles were used to compare between chairs.

3.2 Accelerometers

Accelerometer data were processed using custom software (Matlab version 2015b, The Mathworks Inc., Natick, Massachusetts, USA). This includes calibrating the x, y and z axes with respect to gravity, converting voltages to accelerations, calculating absolute inclinations of each sensor from the tri-axial accelerations, smoothing the data using a dual-pass 2nd order Butterworth filter with a cut-off frequency of 1Hz and then adjusting the accelerometer inclination according to quadrant (based on the sign combination of the y and z axes). The inclination angle of each sensor was then used to calculate the relative low back and pelvic angles. Normalized versions of these angles were then calculated using the posture calibration trials to then express time-varying spine angles as a percentage of maximum flexion range of motion (% ROM). To analyze the frequency of spine and movements over each prolonged sitting trial the number of fidgets (small change in posture immediately followed by a return to the same position) were calculated according to methods established in the literature (Dunk and Callaghan, 2010). Average values for each outcome measure (normalized spine flexion, pelvic angle, spine fidgets and spine shifts) were then compared between chairs.

3.3 Perceived Pain Response

The Matlab program used to collect RPP's (Matlab version 2015b, The Mathworks Inc., Natick, Massachusetts, USA) is designed to report measures as the distance to the nearest mm from 0 mm (no pain) to 100 mm (worst pain imaginable). In order to investigate pain development

throughout the trial, the baseline rating was subtracted from each subsequent rating so that data throughout the sitting trial represented a change in perceived pain that would be in direct response to the sitting exposure. The peak pain rating for each body region at any point during the typing trial was also compared between chair types.

Additionally, baseline-removed RPPs of the back region were used to determine the pain group classification for each participant (Pain Developer, Sub-Clinical, Non-Pain Developer). Specifically, back pain developers (PD) were identified as reporting a RPP equal to or greater than 20 mm at any point in the session, Sub-Clinical (SC) were identified as reporting less than 20 mm but greater than 10 mm, and non-pain developers were identified as reporting RPP's less than 10 mm. Since the minimal clinically significant difference in pain response is a change of 20 mm or greater (Sokka, 2005), PD's are considered to experience clinically significant, but transient, amounts of pain in response to the seated exposure.

3.4 Seat Pressure

Seat pressure data was processed with the X3 Pro program (XSensor Technology Corporation, Calgary, AB, Canada) to calculate the peak pressure (N/cm^2), average pressure (N/cm^2), and contact area (cm^2), from the seat pressure distributions on each chair. Peak pressure, average pressure, and contact area values throughout the trial were compared between chair conditions.

3.5 Calf Circumference

Calf venous pooling was inferred by comparing the calf circumference 10 cm distal from the patella immediately before and after the prolonged sitting trials of each data session. The difference in centimeters was then compared between chair conditions.

4.0 Statistics

The outcome measures for this study include the following: normalized lumbar spine angles, lumbar spine movement variables (fidgets), muscle activity variables (average EMG and peak cross-correlation coefficients), peak ratings of perceived back pain, seat pressure variables (peak seat pressure and contact area) and differential calf circumference. The above variables were compared between chairs, using a one-way mixed general linear analysis of variance model. Statistical significance was set at p=0.05 and SPSS statistical software (Version 22.0, IBM Corporation, Armonk, NY, USA) was used to obtain results.

5.0 Results

Data tables for all outcome variables have been complied in Appendix C.

5.1 Accelerometers (Posture and Movement)

Participants sat with significantly less spine flexion on average in the Core Chair (62.25 % ROM +/- 18.22 SD) compared to the Control Chair 70.80 % ROM +/- 11.98 SD; p = 0.039) (Figure 9, Table 2).

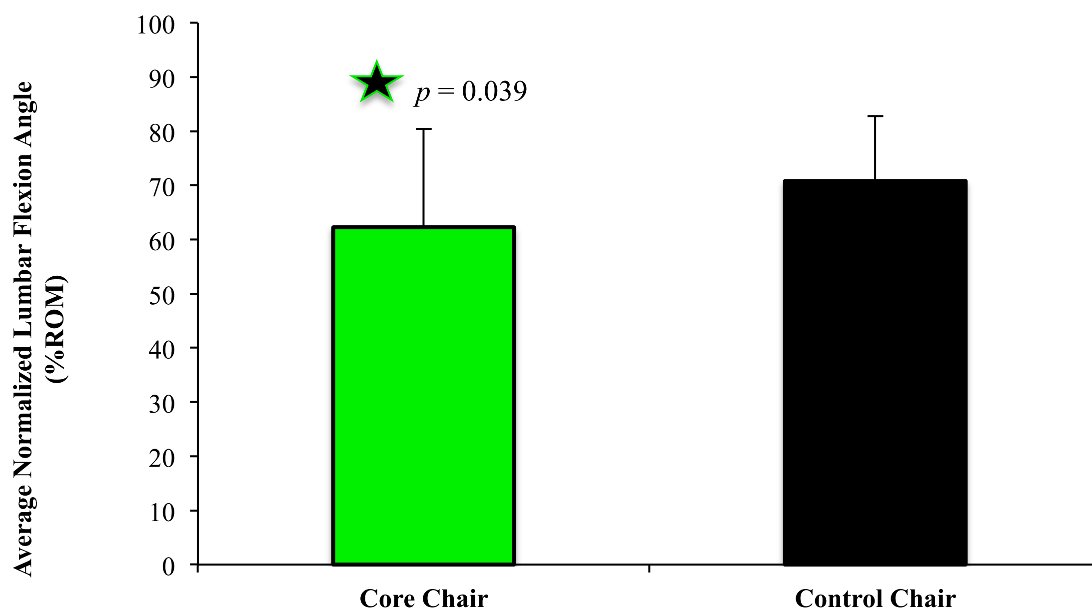


Figure 9: Average Normalized Lumbar Flexion Angle (% ROM) over the 2-hour typing trial for thirty participants in both the Core Chair and Control Chair conditions. Lumbar flexion angles were significantly lower (more extension) in the CoreChair compared to control (p = 0.039).

To determine the consistency of the lumbar spine angle throughout each prolonged sitting trial, average values of the flexion angle were calculated for each eight, 15-minute block throughout the two-hour trials (Figure 10). These were also compared between chair types and no differences were found between chair conditions at any time point throughout the two-hour sitting trial (significance ranging from: $p = 0.062$ - $p = 0.807$).

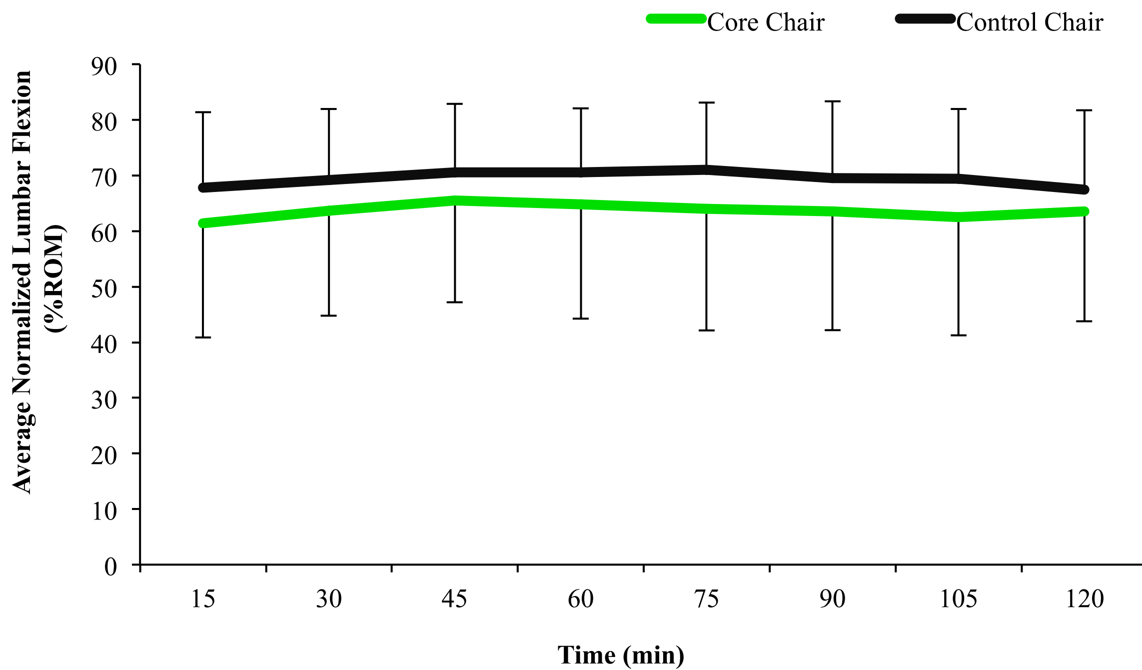


Figure 10: Average Normalized Lumbar Flexion (% ROM) at 15 minute intervals over the 2-hour typing trial for thirty participants in both the CoreChair and control conditions. There were no significant differences in flexion angle between chair conditions at any time point (significance ranging from $p = 0.062$ – $p = 0.807$).

Fidgets

The number of fidgets (movement of the angle that returns to approximately the same magnitude within a short period of time) of the lumbar angle throughout the experiment were calculated from the time-varying signal using established methods from the literature (Gallagher et al., 2015). Specifically, a 5 s window size with threshold +/- 3 SD was used to capture fidget events in the time varying signal and the number of events occurring throughout the 2 hour typing trial was counted for each participant. The average number of fidgets in the CoreChair was 9.8 +/- 3.1 and was 9.6 +/- 3.82 in the control chair. The average magnitude of the fidgets in the CoreChair was 2.6 +/- 1.73 and was 2.4 +/- 1.60 in the control chair. We found no significant difference in the number of fidgets (p=0.807) or the average magnitude of the fidgets (p=0.621) between chair conditions (Figure 11).

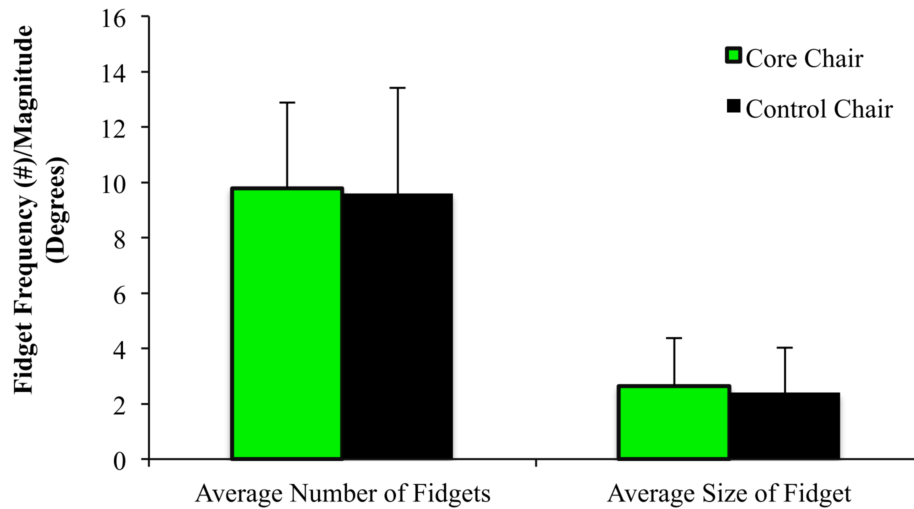


Figure 11: Average values for both the Average number of fidgets and the average magnitude (size in degrees) of the fidget over the 2-hour typing trial for thirty participants in both the CoreChair and control conditions.

5.2 Surface Electromyography (Muscle Activity)

Average Activity During the Prolonged Sitting Trials

The activity of all back muscles was very low for both chair conditions with no significant differences in average normalized activity between chairs (Figure 12, Table 3, RTS 2.94% MVC +/- 1.84% in the CoreChair and 3.74% MVC +/- 2.57% in the control (p = 0.173), RLS 2.39% MVC +/- 1.94% in the CoreChair and 3.47% MVC +/- 3.14% in the control (p = 0.115), RML 1.80% MVC +/- 1.70% in the CoreChair and 2.07% MVC +/- 1.80% in the control (p = 0.547), LTS 2.68% MVC +/- 2.08% in the CoreChair and 3.41% MVC +/- 2.76% in the control (p = 0.248), LLS 2.53% MVC +/- 1.99% in the CoreChair and 3.44% MVC +/- 3.32% in the control (p = 0.201), and LML 1.66% MVC +/- 1.01% in the CoreChair and 2.25% MVC +/- 1.62% in the control (p = 0.101).

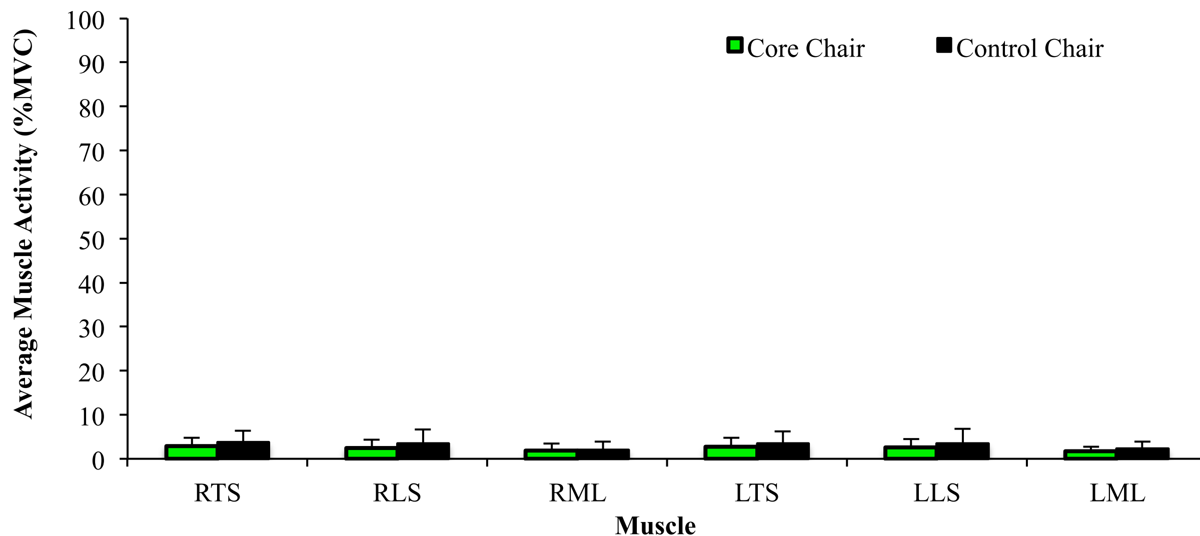


Figure 12: Average values for the muscle activity in six low back muscles of thirty participants after the 2-hour typing trial in both the CoreChair and control conditions. Muscle activity presented as a percent of maximal voluntary contraction. There were no significant differences in muscle activity for all six muscles tested between the CoreChair (Green) compared to control (Black).

Cross-Correlations of Muscle Channels Throughout the Prolonged Sitting Trials

The cross-correlation of muscle activity signals is a statistical technique that can be used to compare the degree to which muscle signal pairings are similar (similar activity "on/on", opposing activity "on/off", or some degree in between these extremes). This gives information comparable to muscle co-contraction indices where the peak cross-correlation index (peak R_{xy}) represents the correlation from +1 (maximally positively correlated: both muscles activated in a very similar way) to 0 (not correlated, as in one muscle on and the second muscle off). Peak cross-correlation coefficients (R_{xy}) for each muscle were compared between chair conditions. Of the erector spinae and multifidus combinations, a significant main effect for chair condition was found for the following combinations: right thoracic erector spinae and right lumbar erector spinae (p=0.005), right thoracic erector spinae and left lumbar erector spinae (p=0.029), right multifidus and left thoracic erector spinae (p=0.020) and right multifidus and left multifidus (p=0.040) (Figure 13).

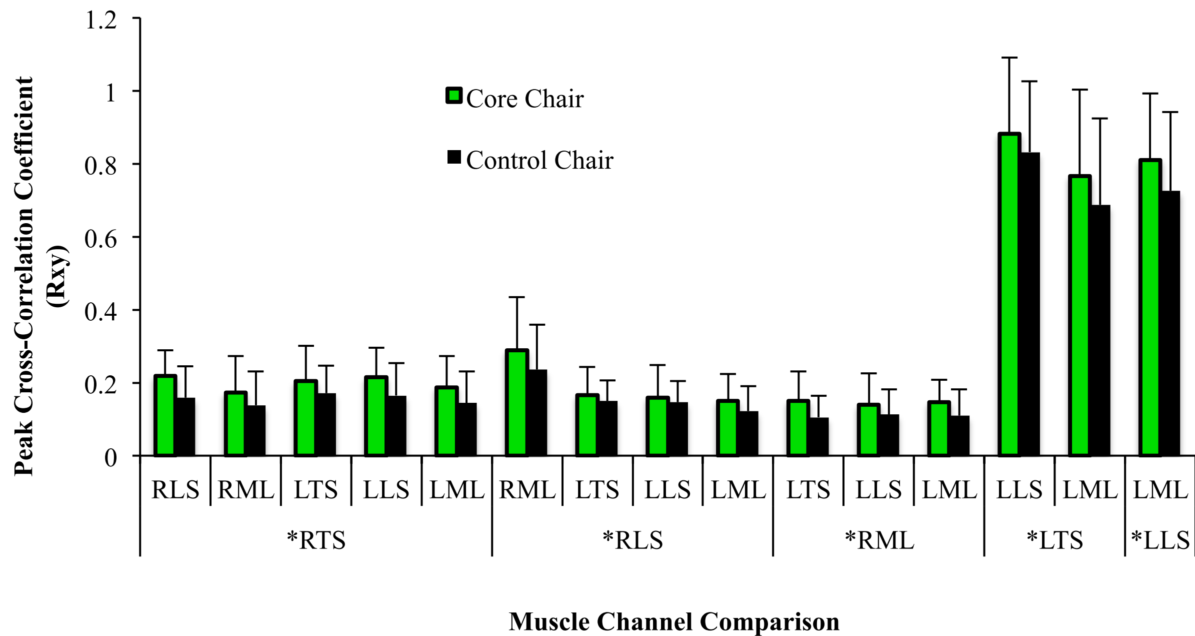


Figure 13: Peak Cross-Correlation coefficient (Rxy) for all muscle combinations in thirty participants over a 2-hour typing trial in both the CoreChair and control.

5.3 Perceived Pain Ratings and Classification of Pain Groups

In our analysis, the average peak perceived pain rating in the low back region was found to be significantly lower in the CoreChair compared to the control chair (*p*=0.025, Figure 14, Table 4). Analyzing the pain data over time (Figure 15) it is clear that perceived pain ratings for all regions continuously develop with time in both chair conditions, however, these increases appear to be much higher in the control chair.

The body region with the largest difference between the two conditions was the increase in the right and left upper and lower back sections in the control chair (Figure 15). These four body areas increased higher than the other five areas in the control chair, leading to the significance found in the two-hour peak averages.

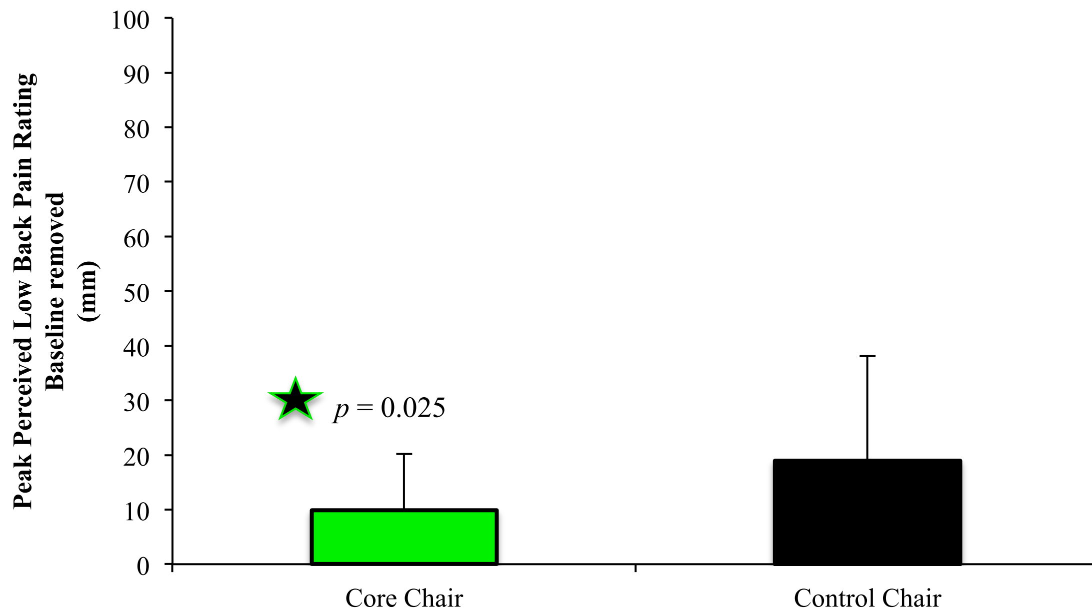
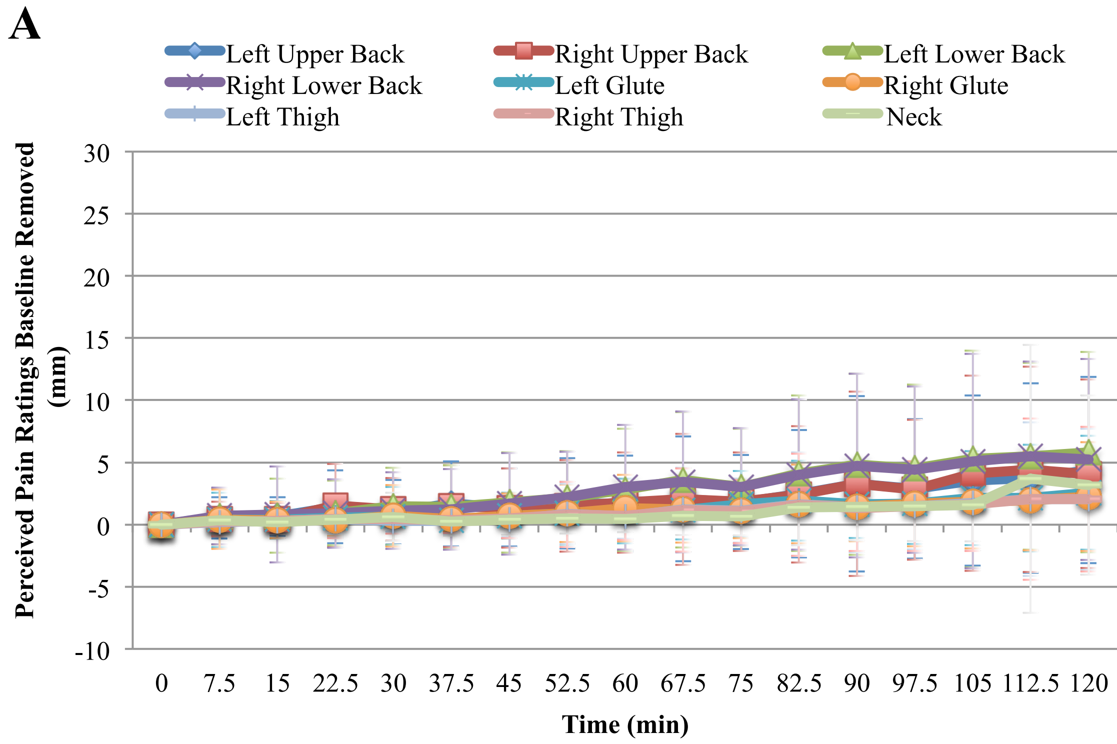


Figure 14: Average Peak Pain Ratings for the low back over the 2-hour typing trial for thirty participants in both the CoreChair and the control chair conditions. Average Peak Pain Ratings were significantly higher (worse) in the control chair compared to the CoreChair ($p= 0.025$).

Further, significantly fewer participants were classified as pain developers and sub-clinical pain developers in the sessions with the CoreChair (PD = 4, SC = 8, NPD = 18) compared to the control chair (PD = 10, SC = 4, NPD = 16, Figure 16, Table 5). These data shows an increase in individuals who developed a clinically relevant quantity of transient pain in response to a sitting exposure in control chair compared to the CoreChair.

A



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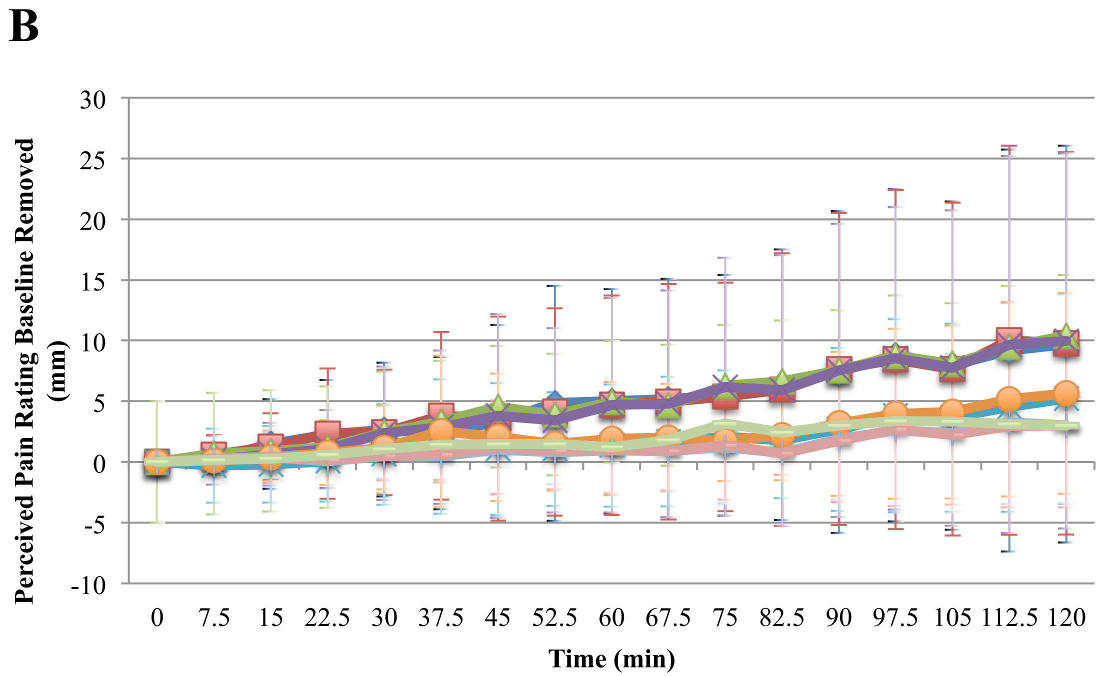

Figure 15: Average perceived pain with baseline removed for all 9 body regions as measured by a 100 mm visual analogue scale at 7.5 minute time intervals throughout the study for the (A) CoreChair and (B) control.

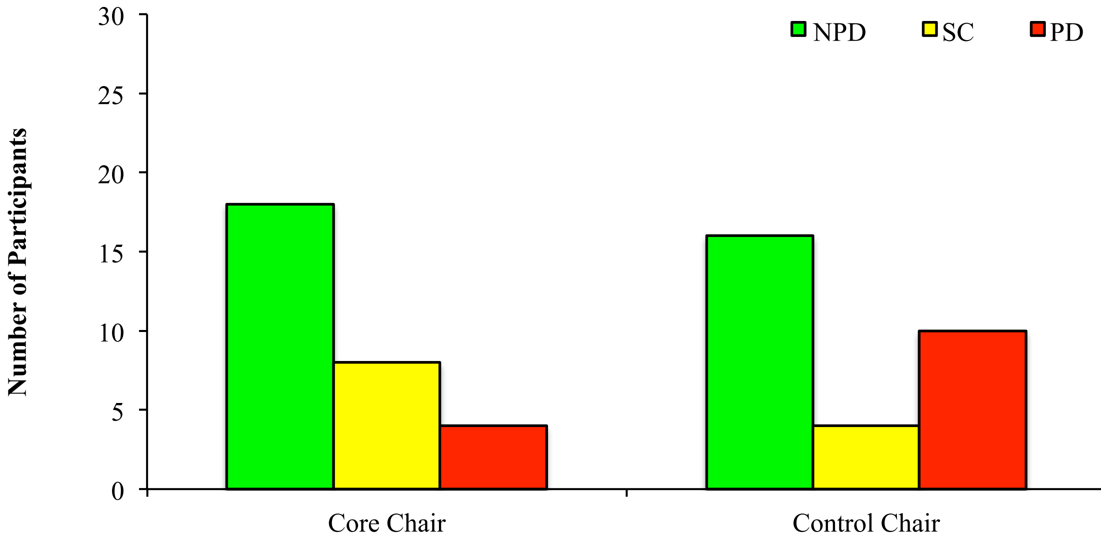

Figure 16: Breakdown of pain group classification for thirty participants in both the CoreChair and control conditions. Significantly more participants were classified as developing clinically meaningful levels of perceived back pain in the control chair compared to the CoreChair.

5.4 Seat Pressure

The average pressure was significantly lower on the CoreChair (0.50 N/cm^2 +/- 0.07 N/cm^2) compared to the control chair (0.61 N/cm^2 +/- 0.10 N/cm^2, p> 0.000, Figure 17, Table 6) and the contact area significantly greater on the CoreChair (1470.14 cm^2 +/- 199.34 cm^2) compared to the control chair (1332.54 cm^2 +/- 162.47 cm^2) (p = 0.03, Figure 18, Table 6). There was no difference in peak pressure between chairs (p =0.702).

Comparing the seat pressure data between the CoreChair and the control chair show a significant reduction in average pressure (p=0.000), and a significant increase in contact area (p=0.034). There was a trend towards a slight reduction in peak pressure in the CoreChair, however, the high standard deviation of this variable meant there was no statistical difference between chair conditions (p=0.702).

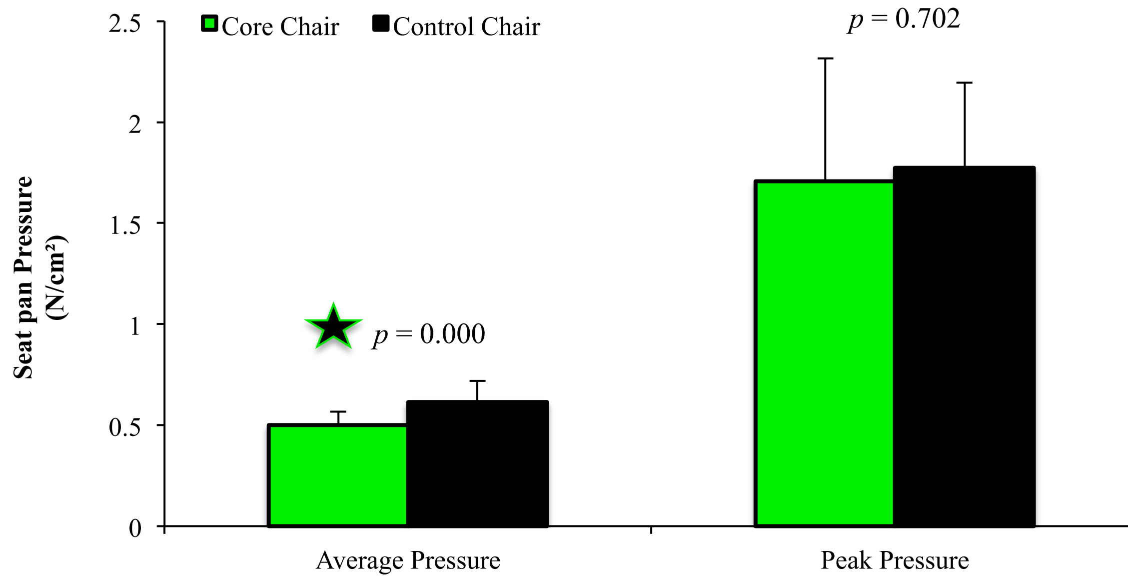

Figure 17: Average values for both average and peak pressure for thirty participants after the 2-hour typing trial in both the CoreChair and control conditions. There was significantly less average pressure in the CoreChair condition compared to the control (p=0.000), however, the difference in peak pressure was insignificant for the CoreChair compared to the control chair (p=0.702).

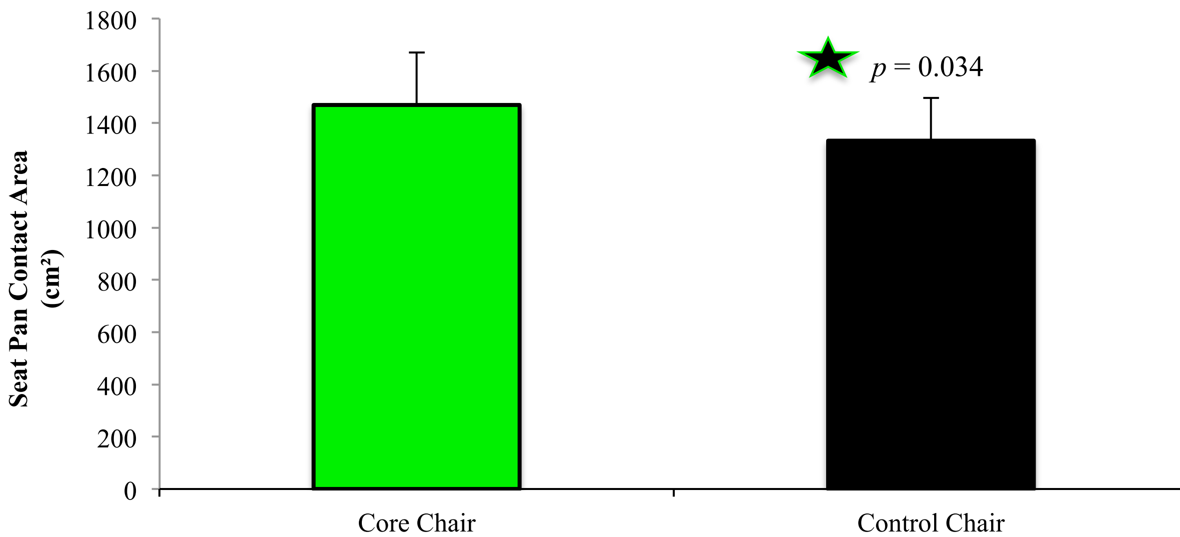

Figure 18: Average values for the contact area between the subject and chair for thirty participants after the 2-hour typing trial in both the Core Chair and control conditions. There was significantly more area of contact in the CoreChair condition compared to control (p = 0.034).

5.5 Calf Circumference Differential

Calf circumference increased significantly less in response to the prolonged sitting trial with the CoreChair (average circumference differential 0.021 cm +/- 0.73cm) compared to the control chair (average circumference differential 0.962 cm +/- 0.74, $p < 0.000$, Figure 19, Table 7).

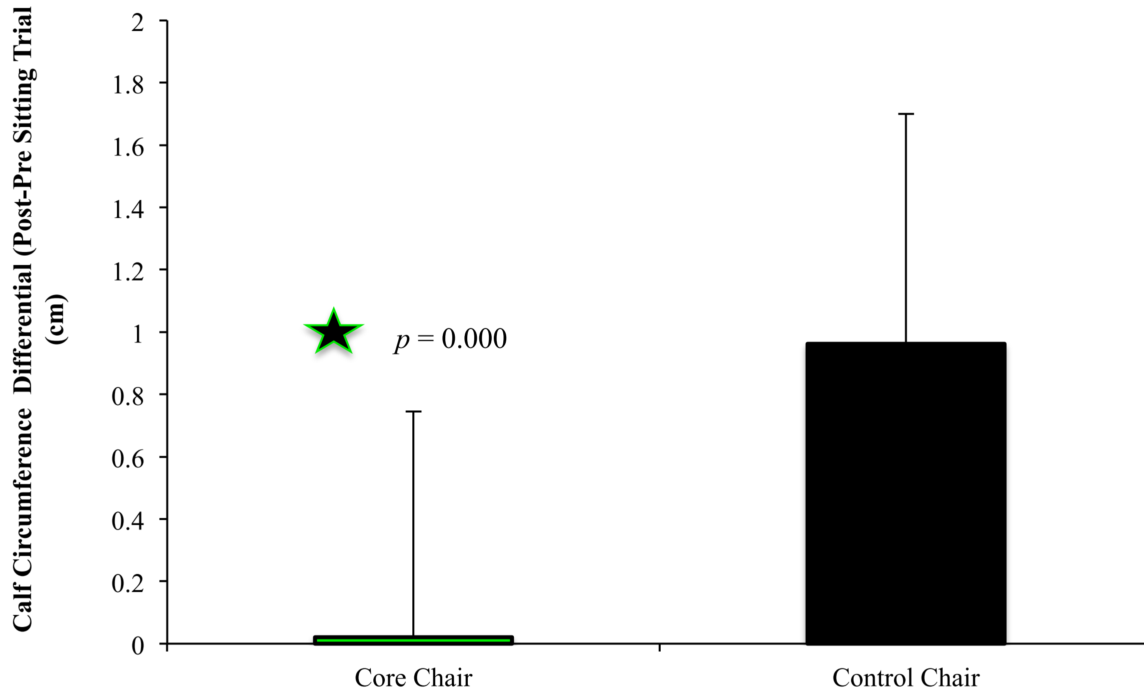

Figure 19: Average change in calf circumference (cm) for thirty participants after the 2-hour typing trial in both the CoreChair and control conditions. There was significantly less calf swelling in the CoreChair compared to control (p=0.000).

5.6 Seat Pan Orientation and Movement

One tri-axial accelerometer was placed on the seat pan for each chair for all thirty participants during the typing trials. Data shows there was a significant difference for the average angle of the seat pan tilt in the sagittal (forward-backwards) plane (p=0.00, Figure 20). This difference was driven by a forward tilting of the seat pan of an average magnitude of approximately 8° (SD 1.48°) when participants were seated in the CoreChair compared to the control chair (-1.47°, SD 0.51°).

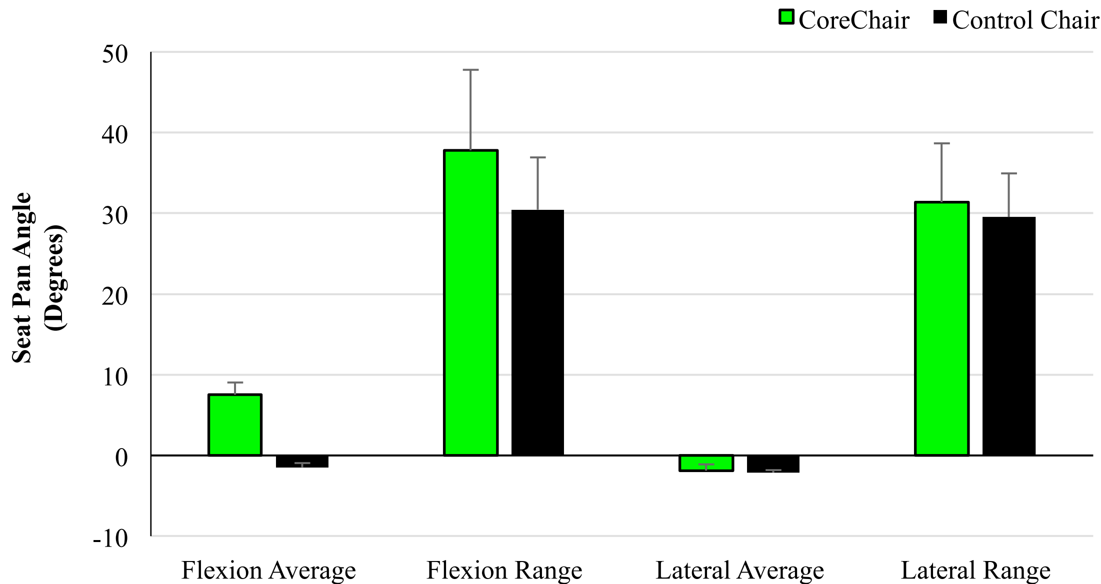

Figure 20: Average values for both the frontal (flexion) and sagittal (lateral) plane of the chair over the 2-hour typing trial for thirty participants in both the CoreChair and Control conditions.

Referring to the range and standard deviation of this angle we can infer the quantity of movement in the sagittal (forward-backwards plane (Figure 20). There was a significantly larger average range in the CoreChair compared to the control chair (p=0.004) suggesting that individuals took advantage of the increased range of motion provided by the CoreChair seat pan in this plane. Similarly, the average standard deviation was also significantly larger in the CoreChair (p=0.000) showing that people were moving in the forward-backward plane much more than in the control chair. In the lateral plane the results were different. The only significant difference was a larger average standard deviation observed in the CoreChair (p=0.000) compared to the control chair.

5.7 Exit, Health Screening, and Modified Oswestry Disability Questionnaires

The Health History Screening form of all thirty participants was unremarkable for conditions that would exclude them from our study. No participant indicated a previous severe back injury, and all indicated their current low back pain being less than 30 mm on a 100 mm continuous line.

The results of the Modified Oswestry Disability Index also support that we successfully recruited a healthy study population. All participants fell below the threshold for “minimal” disability in the context of low back pain.

Seven questions were asked regarding the person's experience in the chair following the 2-hour typing trial (Figure 21). Participants could answer on a 5-point Likert scale for each question. Question #1 asked participants if they felt supported in the chair. Higher average values were seen for the CoreChair (4.3 +/- 0.7) compared to the control chair (3.5 +/- 1.0). Question #2 asked participants if they would have wanted more support from the chair. Higher average values were seen for the control chair (3.5 +/- 1.3) compared to the CoreChair (2.8 +/- 1.2). Question #3 asked participants if the chair permitted them to move as much as they would have liked. Higher average scores were seen in the Core Chair (4.7 +/- 0.5) compared to the control chair (2.5 +/- 1.2). Question #4 asked participants if the chair allowed them to sit with an upright posture. Higher average scores were seen in the CoreChair (4.4 +/- 0.7) compared to the control chair (3.3+/- 1.2). Question #5 asked participants if the chair design matched their preconceived idea of an office chair. Higher average scores were seen for the control chair (4.2 +/- 0.8) compared to the CoreChair (2.7+/- 1.2). Questions #6 and #7 asked participants of there back felt physically stiff and tired in the chair. On both questions higher average results were seen in the control chair (3.9 +/- 1.1, 3.7 +/- 1.1) compared to the Core Chair (3 +/- 1.3, 2.6 +/- 1.2).

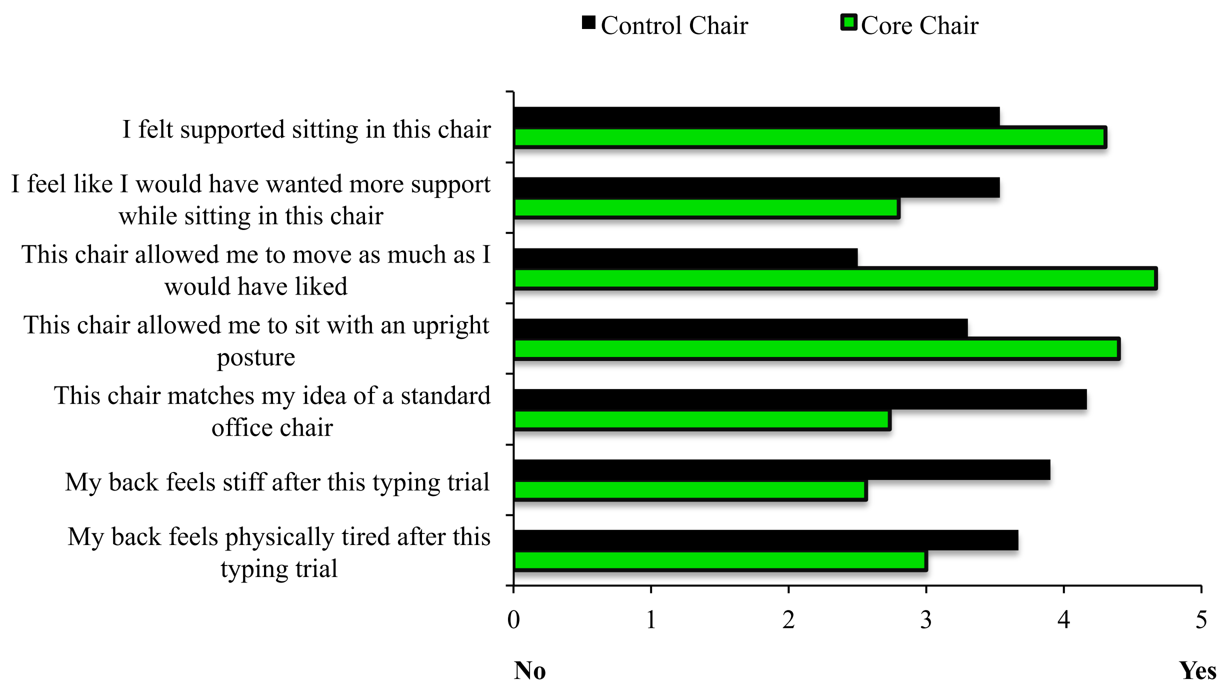

Figure 21: Average values for the Exit questionnaire responses on a 5-point Likert scale administered after the 2-hour typing trial for thirty participants in both the CoreChair and the control conditions.

6.0 Discussion

6.1 Summary of Findings

Overall, the results of this study allow the acceptance of the primary study hypotheses that participants would exhibit significantly less lumbar flexion throughout a 2-hour standardized office task sitting in the CoreChair compared to the control office chair. There were varying results in regards to the secondary hypotheses. The following hypotheses were accepted: there would be significantly less peak perceived pain in the CoreChair compared to control, less calf circumference increase in the CoreChair compared to control, and significantly increased seat pan movement in the CoreChair compared to the control. Whereas the following hypotheses were rejected: the CoreChair did not lead to a significant reduction in surface EMG, there was no difference in peak pressure between chairs.

6.2 Posture and Movement

Previous researchers have identified prolonged flexion of the spine with local factors such as increased disc pressure, strain of posterior passive trunk tissues, static disc loading, and muscular fatigue (Andersson et al., 1974; Adams and Dolan 1986; McGill and Brown 1992). The results of this study found that participants sat in significantly less flexed (more extended) spine posture in the CoreChair compared to the control chair. This finding reflects the previous investigations conducted on the CoreChair at the University of Waterloo (Callaghan et al., 2012) but differs from the literature on several other chair designs that have been tested: including one dynamic chair that permitted independent sagittal plane rotation of the backrest and seat (Van Dien et al., 2001), and another that allowed rotation in a fixed ratio of the seat-to-backrest rotation (Van Dien et al., 2001). Neither of these designs led to a reduction of lumbar flexion compared to a control chair.

It appears the multi-axis design of the seat-pan in the CoreChair allows individuals to open their hip angle by tilting their pelvis anteriorly, thus permitting a less flexed (more extended) lumbar posture. This is supported by the results of the accelerometer on the seat-pan of the chair, which found the seat pan tilted anteriorly in the CoreChair compared to the control. This posture also likely played a significant role in improving blood flow to/from the lower limbs as reflected in the calf circumference measure, which would appear to have important benefits for health. Further, the ability to reduce lumbar flexion angles may play a role in lowering LBP risk; however, this type of conclusion can only be drawn from larger epidemiological studies conducted on the general population.

While spine angles were different between chair conditions, those postures were found to vary minimally throughout the 2-hour testing period. It was hypothesized that the potential for seat pan movement in the CoreChair would translate into more varied occupant posture, however, this was not observed in the present study. The results instead support previous findings that spine posture tends to be remain fairly static during prolonged bouts of sitting in laboratory controlled studies (Beach et al., 2005a; Dunk and Callaghan, 2005; Dunk and Callaghan, 2010; Gregory et al., 2006). This is also reflected in the results for the fidget count variable: there was no significant difference in the number of time the spine flexion angle moved quickly away and

back between chair conditions. This was somewhat surprising as it was expected that individuals would be moving more frequently in the CoreChair leading to more fidgets and changes in posture over time. However, it is possible that individuals in fact moved to a different position (considered a shift) when they did make a movement, which would not be captured by this measure.

There is no existing literature investigating spine angle fidget frequency between chair types, however, fidget frequency and pain group status has been investigated. Overall we saw less participants classified as PDs in the CoreChair compared to control chair. A previous study by Vergara found that PDs fidget or have "micro-movements" less frequently but with larger amplitudes then NPDs (Vergara & Page, 2002). In another investigation Dunk & Callaghan compared healthy individuals to LBP patients. Their results showed no differences in the fidget pattern (on average 1 every 40 to 50 seconds) between pain groups. In this investigation there were a higher number of transient PDs in the control chair, however, no significant difference in fidgets number or amplitude. Our results seem to match the findings of Dunk & Callaghan, however, with the low number of people who actually achieved PD status in the CoreChair it could be that our findings were affected by the unequal group sizes. Therefore, future investigations, with a larger sample size, should study how healthy people move in the CoreChair relative to individuals with clinical LBP.

6.3 Muscle Activity

Prolonged sitting in the CoreChair during the standardized typing task did not result in any statistically significant differences in muscle activity when compared to the control chair. The average EMG levels for the thirty participants were very low, with magnitudes equal to or lower than 3% MVC for all six muscles in both chair conditions. Since it has been shown that prolonged levels of low muscle activity can lead to discomfort in other muscle groups due to continuous and increased activity of a fraction of the motor units in the muscle (Westgaard and De Luca., 1999) and continuous contraction levels of as low as 2% of maximum voluntary contraction can impair oxygenation of the musculature (McGill et al., 2000), there is always the potential that these low, but sustained muscle contractions are related to the increasing levels perceived pain observed in a portion of our study population in each chair conditions.

These low levels of muscle activity are consistent with seated torso EMG levels previously published on office chair seat pans in the literature (Callaghan et al., 2001; Gregory et al., 2006). This means that the demands of sitting in the CoreChair result in comparable muscle activation in traditional office chair designs. These results are also similar to other dynamic chairs that have been tested where no differences in torso EMG level were detected between chair conditions. However, when looking at different tasks (i.e. reading, data entry, mousing etc.) differences in muscle activity were observed (Van Dieen et al., 2001, Ellegast et al., 2012). Task was controlled in this study with a standardized typing scenario; therefore, the effect of task was not tested. Therefore, these results can only be directly applied to similar work scenarios in the field.

It may be of interest to consider evaluating whether differences exist in different office tasks such as reading, creative writing and/or meeting scenarios.

Even though the muscle activity levels were consistently low on both the right and left sides of the back, an interesting pattern of co-ordination was identified in the cross-correlation analysis. Our results indicate that muscle groups on the left side of the body were highly correlated (i.e. the muscles were either turned on or off at similar levels at the same time) compared to the right side of the body. While this pattern might make sense if the task studied involved heavy mousing, it is puzzling in the context of pure typing. Especially since the pattern was present in both chair types. Further, no such pattern has been identified in previous studies investigating prolonged sitting (De Carvalho Thesis, 2015). While this finding could be the result of some systematic error, it would be worthwhile to examine muscle co-ordination patterns further with a variety of tasks and chair types.

6.4 Perceived Pain

Steadily increasing perceived low back pain, as documented in many prolonged sitting studies (De Carvalho and Callaghan, 2011; Dunk and Callaghan, 2005), was also seen for both chair conditions in this study. However, participants reached significantly higher peak pain ratings in the control compared to the CoreChair. These results suggest participants had a less painful experience while seated in the CoreChair while completing the typing task. These results contrast the finds of one recent study investigating a dynamic chair on energy expenditure and discomfort while completing a DVD viewing task (Synnott et al., 2017). These investigators similarly found overall low levels of discomfort, however, they did find a significantly higher rating using a similar VAS in their dynamic chair. These results currently highlight one of the issues in comparing results between dynamic chairs: the chairs used in different studies often use very different designs to permit movement, meaning comparisons are difficult to draw. In their study, Synnott et al. used a forward inclined saddle chair adjusted to allow hip flexion in participants at 55°. A fixed ball under the seat-pan was adjusted to allow movement, and the chair did not include a backrest. It appears that this chair design does not provide the same type of support as the CoreChair, which potentially leads to the disparity in pain ratings seen between the studies. In an interesting comparison, the same saddle-type chair design was tested compared to a control chair using patients who already suffered from back pain related to prolonged sitting (O'Keefe et al., 2013). The results of this study found similar results to the current study, that the dynamic chair led to a significant decrease in discomfort compared to the control chair. These results further highlight the potential of the CoreChair as a therapeutic intervention for individuals suffering from back pain. Future studies involving the CoreChair should include a clinical group to see if this reduction in pain is similarly duplicated.

It is also important to note that although no participants in this study were identified as clinical LBP sufferers according to the Health Screening and Modified Oswestry Disability Questionnaires, clinically relevant, but transient, LBP development was still identified in a portion of the population in both chair types. As highlighted in previous literature, a change of ≥

20 mm on a 100 mm VAS is qualified as a “clinically relevant level of pain development” (Sokka, 2005). Using these parameters, four individuals were classified as pain developers in the CoreChair compared to 10 in the control chair. These results suggest the sitting in the CoreChair provides a preventative effect against pain development.

6.5 Seat Pressure

The pressure values in this investigation are very similar to a previous study done on the Core Chair. Callaghan et al. (2012) investigated seat pressure in previous investigation of the CoreChair over 15 minutes of typing and found an average pressure of 0.52 N/cm^2 which was almost identical to our results. In terms of our study there were no differences in peak pressures between the chair conditions. This is a beneficial finding as high peak pressures are associated with increased discomfort. It appears that the CoreChair is comparable to standard office chairs in this regard. The CoreChair had significantly lower average pressures and contact areas than the control chair, which could be directly related to the chair’s unique seat pan design. Specifically, the contoured seat pan design appears to provide a larger contact area, and thus a better distribution of weight, which is reflected in a lower average pressure compared to the control chair. Further, study participants, on average, sat with the seat pan rotated forward by 8° which would transfer the ground reaction force of the head/arms/trunk from the buttock to the feet also reducing pressure at the buttock.

6.6 Changes in Calf Circumference

Previous literature has shown that increased calf circumference due to leg swelling associated with venous pooling exists after periods of prolonged sitting (Seo et al., 1996, Chester et al., 2002). It is hypothesized these changes come from hemodynamic alterations with prolonged sitting in which there is a reduction in lower limb arterial Blood Flow (BF) (Thosar et al. 2015; Shvartz et al. 1983). The results of this investigation confirmed our hypothesis that sitting in the CoreChair would result in a lower calf circumference increase than in the control chair. This would suggest that the participants had less venous blood pooling in their calves while seated in the CoreChair compared to the control. Notably, this finding replicates that of an earlier CoreChair investigation: where a significant decrease in lower limb blood flow as well as significantly increased calf venous pooling during prolonged sitting was observed in a traditional office chair compared to the CoreChair (Cheema & Bent, 2016). These results could be explained by the fact that the CoreChair’s multi-axis seat pan allows individuals to move their lower limbs, thus promoting blood flow thereby reducing the pooling in the extremities. Movement breaks (specifically walking) during sitting have been shown to significantly reduce vascular impairments (Restaino et al., 2015) and improve leg blood flow (Thosar et al, 2015). In these studies, it is likely that the increased activity of the calf muscle pump promoted venous return, and therefore an increase in BF. Extrapolating from the seat pan movement analysis (discussion follows in the next section) in this current study, it does appear that the lower limbs must have been moving to drive the changes in seat pan orientation observed in both the frontal

and lateral planes and consequently must have played a role in improved calf circumference result. However, without measuring lower limb muscle activity in this study there is no confirmation that this was the case.

Differences in calf circumference can be further explained by the improved spine and hip posture that was facilitated by the CoreChair. With less spine flexion and a significantly more anteriorly rotated seat pan (which would translate into less flexion at the hips) it can be assumed that there was less compression impeding venous return from the lower limbs. Lower body kinematics and muscle activity were not measured in this study, but this may be a future area of interest for research involving the CoreChair, especially given the strength of these findings and the importance of blood flow to cardiovascular health.

6.7 Seat Pan Movement

The results from the seat pan movement analysis have allowed the acceptance of the hypotheses that more seat-pan movement would be observed in the CoreChair compared to the control chair. Accelerometer data indicate that, on average, participants sat with 8° of forward tilt in the frontal plane, had a larger range of movement and a larger standard deviation of movement (signifying increased variability of orientation) throughout the 2 hour typing trial while sitting on the CoreChair compared to the control. These results make sense given that the control chair seat pan was fixed in place on the control chair and therefore could not move. While the overall goal of the CoreChair seat pan design is obviously to encourage in chair movement, the freedom also introduces the ability for the occupant to "self-select" their preferred seat pan orientation. It is interesting to note that study participants overwhelmingly chose to sit in a forward inclined orientation in the CoreChair. Previous literature on anteriorly rotated seat pans have shown the feature to be associated with a decrease in LBP, thought to be due to the promotion of increased lumbar lordosis (Gale et al. 1989; Gadge and Innes 2007). In the current dataset, significantly less of the participants were classified as developing transient LBP during sitting. Perhaps adopting a more anteriorly tilted seat pan contributed to this differential pain response in a preventative way.

In terms of the lateral plane, the average result show participants sat quite neutrally, with little lateral tilt throughout the 2-hour typing trial, leading to no significant difference in average angle or range between chair types. However, there was a very significant difference in the standard deviation, indicating that participants were in fact actively moving in this plane, albeit continuously returning to a neutral position.

The increased CoreChair seat pan movement in both lateral and frontal planes is likely connected with other results observed in this study. Past research has shown increased seated movements for asymptomatic individuals have been identified as having the potential to reduce discomfort (Bhatnager, 1995; Jurgens, 1989), stiffness, or seat pressure (de Looze et al., 2003) and facilitate circulation (Winkel and Jorgensen, 1986). In this study we see comparatively fewer participants developing transient perceived LBP and significantly lower increases in calf circumference measures suggesting that the CoreChair had an effect on reducing discomfort and increasing

circulation. One point worth noting is that although we saw increased seat-pan movements in the CoreChair we did not see a corresponding increase in the number of spine fidgets. Therefore, tt is likely that seat pan movements were driven by the thigh and pelvis with relatively less movement of the spine above. Including lower limb kinematics (hip, knee and ankle angles) may be helpful in future studies to further understand how occupants are using the CoreChair.

6.8 Exit Questionnaire

The exit questionnaire responses were very favorable for the CoreChair (Figure 21). The first question asked about support: and participants indicated that they did feel more supported on the CoreChair compared to the control chair. This is important given that the obvious assumption from the public might be that the CoreChair would provide less support given that it does not have a traditional backrest.

Question two asked participants to consider whether they would have preferred the chair provided more support. Responses suggest that individuals would have liked more support from both of the chairs. However, the CoreChair received a lower score compared to the control chair, meaning that participants felt less added support was required in the CoreChair compared to the control chair. This is interesting given that the control chair, with the larger backrest, would appear to provide more support.

Question three asked if participants were permitted to move as much as they would have liked in the chair and CoreChair was rated much more favorably in this category compared to the control chair. This is not surprising given the CoreChair's active seat-pan.

The responses to Question four indicate individuals believe the CoreChair allowed them to sit with a taller posture compared to the control chair. This reflects the objectively measured spine posture, which was significantly more extended in the CoreChair compared to the control chair.

Perhaps not surprising, question five responses indicate that the participants did not believe the CoreChair fits their idea of a "standard office chair". This is likely due to the fact that the CoreChair, is a relatively new product does indeed look different than a regular office chair. The concept of the office chair has changed very little since its introduction as a stenographer chair 40 years ago so it is likely that changing attitudes in this domain may take a little time. Perhaps, though, this perception may be beneficial in that people may be looking for something different than the standard. This may become even more important if the CoreChair is able to show evidence of improved health benefits such as reduced risk of transient LBP and improved lower limb circulation.

The last two questions (6 and 7) asked participants to rate their perceived back stiffness and overall physical tiredness after sitting in each of the chairs. The responses suggest that participants in this study felt less back stiffness and less physically tired after sitting in the CoreChair compared to the control chair. These responses may also reflect the lower amounts of

peak perceived pain that were captured throughout the sitting trial in the CoreChair compared to the control.

In summary, from the exit questionnaire responses, it appears that participants had a very positive experience with the CoreChair. They felt both supported and free to move, which may have also translated into feelings of reduced back stiffness and physical tiredness after a prolonged exposure to sitting. It appears that even though individuals do not associate the design of the CoreChair to that of a standard office chair, after a two-hour exposure, they strongly identify with the potential benefits that the CoreChair design was intended to achieve.

6.9 Limitations

Despite the careful design of this study, there were several limitations that need to be considered together with the results.

The main limitation, which was unavoidable, is that there was no way to blind participants to the chair type due to the fact that the designs were quite obviously different. The fact that participants reflected the perception that the CoreChair did not fit their belief of a "standard office chair" must be considered to confirm this. There were a number of efforts taken to reduce this limitation including: covering up any identifying logos with fabric, using standardized language throughout the experiment to avoid emphasizing one chair over the other and showing participants standardized videos explaining the features of the chair in a balanced way. It is possible that participants may have been biased if they felt that the novel look of the CoreChair would mean it would be better for them; consequently leading to them perceive less pain, stiffness, sit and move differently etc. The reverse must also be considered, however, that the uniqueness of the chair would translate into being unfamiliar with how to best use the CoreChair design features; consequently participants would underutilize the benefits of the seat pan movement capabilities. The videos shown prior to each chair condition attempted to balance both of these potential scenarios: to normalize both chairs as much as possible and also provide enough education about chair features to prompt participants to use the chairs features as much as possible. The objective results of the study (spine posture, seat pan movements, calf circumference difference etc.) show that participants did sit differently between the chair conditions. Given the exposures were 2-hours in duration and participants were distracted with a standardized typing task, it is more likely that these differences were not voluntarily controlled by the participant and thus less susceptible to bias. The perceived ratings of pain throughout the study together with the exit questionnaire responses, being subjective in nature, must be considered in the context of increased risk of bias. In the future, minimizing the effect of this unavoidable limitation could be achieved by providing a run-in period with the CoreChair to increase its normalcy to the participants and/or a large field study of a fairly long duration (months).

A second limitation was the how the accelerometer was fixed to the seat pan to track movements. Due to differences in the design of each chair it was impossible to find a similar location on the

physical seat pan of both chairs, even with the best attempts to do so. Thus, the accelerometer was placed in the same orientation, fixed securely with double-sided tape, to the metal arm that rigidly connects the seat pan to the backrest. This location was chosen because it was the most similar region between chairs and moved together with the seat pan. However, in hindsight it was found that this location is extremely susceptible to artifact introduced when participants would interact with the seat back in the control chair. Therefore, while it provided a good measure of seat pan movement in the CoreChair, it is likely the position resulted in artificially high numbers of seat pan “fidgets” in the control chair. To minimize the effect of this limitation, the seat pan movement analysis was therefore concentrated on the total range of seat pan movement and the variability (standard deviation) of seat pan orientation in both the frontal and lateral planes as opposed to a count of signal fidgets as planned originally. Due to the extremely small magnitude of the movement artifacts picked up by the control chair accelerometer (which would have counted as a fidget but would not result in any meaningful change in seat pan orientation) this limitation should have been appropriately minimized such that it should not affect the interpretation of results in this study.

The sitting exposure tested in this study was 2-hours due to time constraints of the research team (the current design required 160 laboratory hours). Clearly, individuals sit for a much longer period of time then this in a typical workday. However, considering the average worker likely stands up for some sort of break (coffee, lunch, bathroom etc.) approximately after 2 hours of sitting, the duration tested in this study would at least would be generalizable to one of these blocks of sitting. This limitation could be overcome in the future by using a field study design where the entire day is studied.

In order to minimize the confounding effects of different office tasks, only a typing data-entry task was used in this investigation. This means the results of the study are not generalizable to other office tasks such as reading, meeting (phone and in person), thoughtful composition where creativity is required (both typing and writing) etc. Future studies should consider this.

Finally, in order to increase the statistical power, only healthy male participants were investigated in this study. This decision was made to accommodate time and resource limitations. Future work should replicate this study with the inclusion of both female and clinical populations.

7.0 Conclusion

In conclusion, this study has notably found that participants sitting in the CoreChair adopted a more upright posture (less spine flexion, 8° forward rotation of the seat pan), moved the seat pan more in both the frontal and lateral planes, experienced lower average seat pan pressures, calf circumference differences, perceived levels of LBP, perceived levels of back stiffness, perceived levels of physical tiredness and were happy with the amount of support and movement the chair design provided. Together, these results provide evidence that the CoreChair design is effective

at improving measures that logically would translate into positive health benefits of the occupant; however, larger, field-based studies are warranted to determine effectiveness at this level.

Future investigations should focus on reproducing these results in a female population and study the effect with a clinical population. For instance, it may be that individuals currently suffering from LBP may have a stronger response to the design features providing an opportunity to use the CoreChair as a therapeutic intervention in addition to one of prevention.

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Appendix A

Questionnaires

Exit Questionnaire

Participant: ___________________
Chair: _______________________

	Question	Strongly Disagree 1	Disagree 2	Niether Agree or Disagree 3	Agree 4	Strongly Agree 5
1	I Felt Supported Sitting In This Chair					
2	I Feel Like I Would Have Wanted More Support While Sitting In This Chair					
3	This Chair Allowed Me To Move As Much As I Would Have Liked					
4	This Chair Allowed Me To Sit With An Upright Posture					
5	This Chair Matches My Idea Of A Standard Office Chair					
6	My Back Feels Stiff After This Typing Trial					
7	My Back Feels Physically Tired After This Typing Trial					

Question 8: (Write as much as you would like)
Do you have anything else you would like to share about your experience in this chair?

Health Screening Form:

STUDY: Effect of an "Active" Office Chair on Spine Biomechanics And Perceived Pain During Prolonged Sitting

Subject Code: ______________________

This quesionnaire asks some questions about your health status. This information is used to guide us with your entry into the study as well as provide health data that will help us learn more about sitting-induced back pain.

Exclusion criteria to participating in this study include:

1. A history of back injury (such as a fracture or disc herniation), infection (such as osteomyelitis), arthritis (ie. osteoarthritis, rheumatoid arthrits or psoriatic arthritis) or spine surgery; inability to sit for 2 hours at a time; or an episode of low back pain resulting in a lost day of work or school, in the past 6 months

Past Relavent Health History (please check all that apply)

- [ ] Back Injury (soft tissue), please specifiy: ______________________
- [ ] Back Injury (fracture), please specificy: ______________________
- [ ] Low Back Pain
- [ ] Disc Herniation
- [ ] Disc Bulge
- [ ] Vertebral End Plate Fracture
- [ ] Scoliosis, known severity: ______________________
- [ ] Spondylolisthesis
- [ ] Pars Defect
- [ ] Scheuermann's Disease
- [ ] Transitional Vertebrae
- [ ] Congential Vertebral Abnormality
- [ ] Arthritis
- [ ] Cancer
- [ ] Leg Pain
- [ ] Surgeries, please specify: ______________________

Recent Health History (*within the past six months*, please check all that apply):

- [ ] Back Injury (soft tissue), please specifiy: ______________________
- [ ] Back Injury (fracture), please specificy: ______________________
- [ ] Low Back Pain
- [ ] Disc Herniation
- [ ] Disc Bulge
- [ ] Leg Pain

At This Moment, Rate The Level of Pain You Feel In Your Low Back (mark a vertical dash along the line)

no pain **0** ____ ***worst pain*** **100**

Participant ID: ____________________ **Date:** ____________________

Modified Oswestry Low Back Disability Questionnaire

This questionnaire is designed to enable us to understand how much your back pain has affected your ability to manage your everyday activities. Please answer each section by marking an "x" in the box that most applies to you for each section. We realize that you may feel that more than one statement may relate to you, but please **just mark the box that most closely describes your problem.**

Section 1 - Pain Intensity

☐ I do not have pain
☐ The pain comes and goes and it is very mild
☐ The pain is mild an does not vary much
☐ The pain comes and goes and is moderate
☐ The pain is moderate and does not vary much
☐ The pain comes and goes and is severe
☐ The pain is severe and does not vary much

Section 2 - Personal Care

☐ I do not have to change my way of washing or dressing to avoid pain
☐ I do not normally change my way of washing or dressing even though it causes me pain
☐ Washing and dressing increase the pain, but I manage not to change my way of doing it
☐ Washing and dressing increase the pain and I find it necessary to change my way of doing it
☐ Because of the pain I am unable to to do some washign and dressing without help
☐ Because of the pain I am unable to do any washing and dressing without help

Section 3 - Lifting (skip if you have not attempted lifting since the onset of your low back pain)

☐ I can lift heavy weights without extra low back pain
☐ I can lift heavy weights but it causes extra pain
☐ Pain prevents me lifting heavy weights off the floor
☐ Pain prevents me lifting heavy weights off the floor, but I can manage if they are conveniently positioned, e.g. on a table
☐ Pain prevents me lifting heavy weights but I can manage light to medium weights if they are conveniently positioned
☐ I can only lift light weights at the most

Section 4 - Walking

- [ ] I have no pain walking
- [ ] I have some pain on walking, but I can still walk my required normal distances
- [ ] Pain prevents me from walking long distances
- [ ] Pain prevents me from walking intermediate distances
- [ ] Pain prevents me from walking even short distances
- [ ] Pain prevents me from walking at all

Section 5 - Sitting

- [ ] Sitting does not cause me any pain
- [ ] I can sit as long as I need provided I have my choice of sitting surfaces
- [ ] Pain prevents me from sitting more than 1 hour
- [ ] Pain prevents me from sitting more than 1/2 hour
- [ ] Pain prevents me from sitting more than 10 minutes
- [ ] Pain prevents me from sitting at all

Section 6 - Standing

- [ ] I can stand as long as I want without pain
- [ ] I have some pain while standing, but it does not increase with time
- [ ] I cannot stand for longer than 1 hour without increasing pain
- [ ] I cannot stand for longer than 1/2 hour without increasing pain
- [ ] I cannot stand for longer than 10 minutes without increasing pain
- [ ] I avoid standing because it increases my pain immediately

Section 7 - Sleeping

- [ ] I have no pain while in bed
- [ ] I have pain in bed, but it does not prevent me from sleeping well
- [ ] Because of pain I sleep only 3/4 of normal time
- [ ] Because of pain I sleep only 1/2 of normal time
- [ ] Because of pain I sleep only 1/4 of normal time
- [ ] Pain prevents me from sleeping at all

Section 8 - Social Life

- [ ] My social life is normal and gives me no pain
- [ ] My social life is normal, but increases the degree of pain
- [ ] Pain prevents me from participating in more energetic activities e.g. sports, dancing
- [ ] Pain prevents me from going out very often
- [ ] Pain has restricted my social life to my home
- [ ] I hardly have any social life because of my pain

Section 9 - Travelling

- [ ] I get no pain while travelling
- [ ] I get some pain while travelling, but none of my usual forms of travel make it any worse
- [ ] I get some pain while travelling, but it does not compel me to seek alternative forms of travel
- [ ] I get extra pain while travelling that requires me to seek alternative forms of travel
- [ ] Pain restricts all forms of travel
- [ ] Pain prevents all forms of travel except that done lying down

Section 10 - Employment/Homemaking

- [ ] My normal job/homemaking duties do not cause pain
- [ ] My normal job/homemaking dutiescause me extra pain, but I can still perform all that is required of me
- [ ] I can perform most of my job/homemaking duties, but pain prevents me from performing more physically stressful activities e.g. lifting, vacuuming, etc.
- [ ] Pain prevents me from doing anything but light duties
- [ ] Pain prevents me from doing even light duties
- [ ] Pain prevents me from performing any job or homemaking chore

Appendix B

Chair Video Scripts

CoreChair Script

Chair A is an ergonomic office chair that allows you to move freely while seated. (*Rotate in chair*).When you sit in the chair, slide your bottom all the way to the back of the seat-pan so it is snug in the crevice of the seat-pan.(*Stand-up and then sit down, clearly showing how to slide bottom back into the chair*). Features of this chair include the ability to move the chair up and down to adjust height (*move chair up and down*), as well as moving the backrest in and out (*move the backrest in and out*) to match the requirements of your back. The research assistant will assist you with matching the chair to the recommended ergonomic guidelines. Proper height of the chair will allow you to bend knees slightly more then a right angle allowing you to keep the hip angle open (*Demonstrate this with proper knee/hip position*). Chair A allows 360° movement of your hips, pelvis, and spine through full rotation of the seat-pan and is permitted throughout the trial if you choose. (*Demonstrate full 360° movement)*

Standard Chair Script

Chair B is a standard ergonomic office chair. When you sit in the chair, slide your bottom all the way to the back of the seat-pan just so it is touching the back of the chair. (*Stand-up and then sit down, clearly showing how to slide bottom back into the chair)* Features of this chair include an adjustable seat-pan that moves in or out (*move chair in and out*), and a backrest that can move up or down (*move backrest up or down*) depending on the requirements of your back. The chair also features a lever that allows you to change the angle of the seat-pan (*change angle of the seat-pan*), as well as the option to move the seat up or down in relation to the ground (*move seat-pan up and down).* The research assistant will assist you with matching the chair to the recommended ergonomic guidelines. Proper height of the chair will allow you to bend your knees at a right angle and keep them in line with your hips (*Demonstrate knee angle when chair at optimal height*). Your feet should be approximately shoulder-width apart. Distribute your weight evenly through both hips. Movement is permitted throughout the trial if you choose (*Show that you can move, even if seatpan does not).*

Appendix C

Data Tables

Table 2: Average Normalized Lumbar Flexion Angle (% ROM) and standard deviation (in brackets) over a 2-hour typing trial for thirty participants on both a CoreChair and the control. Difference between chair conditions was statistically significant (p = 0.039).

	Core Chair	Control Chair
Average Normalized Flexion Angle (% ROM)	62.25 (18.22)	70.8 (11.98)

Table 3: Average values and standard deviations for the muscle activity in six low back muscles of thirty participants after the 2-hour typing trial in both the CoreChair and control conditions. Muscle activity presented as a percent of maximal voluntary contraction (%MVC). There were no significant differences in muscle activity for any of the six muscles tested between the CoreChair and control conditions (significance ranged from p = 0.101 – 0.547).

	Chair A		Chair B	
Muscle	**%MVC**	**SD**	**%MVC**	**SD**
Right Thoracic Erector Spinae	2.94	1.84	3.74	2.57
Right Lumbar Erector Spinae	2.39	1.94	3.47	3.14
Right Multifidus	1.8	1.7	2.07	1.8
Left Thoracic Erector Spinae	2.68	2.08	3.41	2.76
Left Lumbar Erector Spinae	2.53	1.99	3.44	3.32
Left Multifidus	1.66	1.01	2.25	1.62

Table 4: Average Peak Pain Ratings and Standard Deviations over the 2-hour typing trial for thirty participants in both the CoreChair and control conditions measured by Visual Analog Scale (VAS) in mm. Average Peak Pain Ratings were significantly higher (worse) in the control compared to the CoreChair (p= 0.025).

	Core Chair	Control Chair
Average Peak Pain Rating on VAS	9.84 (10.32)	18.93 (19.12)

Table 5: Breakdown of clinically relevant pain groups for thirty participants in both the CoreChair and control conditions. Participants were classified into groups using clinically relevant thresholds of pain development: non-pain developer (NPD) having peak scores less than 10 mm, sub-clinical pain developer (SC) having peak scores higher than 10 mm but less than 20 mm and pain developer (PD) having peak scores above 20 mm. Less people were classified as PDs in the CoreChair condition compared to the control.

	Core Chair	Control Chair
NPD	18	16
SC	8	4
PD	4	10

Table 6: Average values for the average pressure, peak pressure, and contact area between the subject and chair for thirty participants after the 2-hour typing trial in both the CoreChair and control conditions. Differences for Peak Pressure were not statistically significant (p=0.702), however, statistically significant differences were found for Average Pressure and Contact Area (p=0.000 and p=0.034 respectively).

	Core Chair	Control Chair
Average Pressure (N/cm², SD)	0.50 (0.07)	0.61 (0.1)
Peak Pressure (N/cm²)	1.71 (0.61)	1.77 (0.42)
Contact Area (cm²)	1470.14 (199.34)	1332.54 (162.47)

Table 7: Average change in calf circumference (cm) in thirty participants following the 2-hour typing trial in the CoreChair and control conditions. A statistically significant difference was found with calf circumference differentials being lower following exposure to the CoreChair than the control (p= 0.000).

	Core Chair	Control Chair
Change in Calf Circumference	0.02 (0.73)	0.96 (0.74)