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A biomechanical analysis of active vs static office chair designs

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ABSTRACT

The objective of this study was to provide a biomechanical comparison of two different types of active chairs (AC1 & AC2) versus a static chair (NAC). Thirty healthy participants were recruited: fifteen healthy females and fifteen healthy males. Participants worked at a computer workstation (1-h per chair). Equipment included: Pressure pads, Electromyography, Near–Infrared Spectroscopy, and Questionnaires (rate of perceived discomfort, seating discomfort questionnaire and exit survey). A significant increase in anterior–posterior postural sway was found on the seat pan with the use of the AC1. An increase in neuromuscular activity of the external obliques and an increase change in total oxygen index (%TOI) values in the gastrocnemius were also found using the AC1, however the difference was not much higher than the NAC and AC2. Lower discomfort scores in the gluteal area were found with the use of active chair AC1 compared to the NAC. Preliminary findings suggest that having an office chair with a split seat pan design shows potential to yield biomechanical and physiological benefits for the sitter, however further research is needed to better understand the ergonomic benefits of active sitting.

1. Introduction

The average office worker spends approximately 71–80% of their time at work in a sedentary seated position (Clemes et al., 2014), equating to over 6 h per day. Workplace sedentary sitting is exacerbated by outside of work hours, with most Canadians spending the majority (~90%) of their leisure time in a sedentary position watching TV or using computers (Chau et al., 2012; Jia and Nussbaum, 2018). Prolonged sitting has been linked to increased rates in reported musculoskeletal discomfort/pain, especially lower back pain (LBP) (Schinkel–Ivy et al., 2013), a debilitating condition that will affect approximately 80% of the North American population at some point during their lives (Rubin, 2007). Musculoskeletal pain/injury is not the only negative side effect related to sedentary sitting, it has also been linked to cardiovascular problems, reduction (even occlusion) of blood flow and decreases in concentration/productivity (Triglav et al., 2019; Holmes et al., 2015; Levin et al., 2009; Lind and Lithell, 1993) leading to increased rates of workplace absenteeism (Maniadakis and Gray, 2000).

As a means to reduce time spent in a static seated position, several strategies promoting body movement (while maintaining workplace productivity) have been proposed, including: stability balls, sit–to–stand workstations and active seating (Gregory et al., 2006, Kingma and van Dieën, 2009).

Gregory et al. (2006) were one of the first to evaluate and also discredit the use of stability balls at the workplace. According to Gregory et al. (2006) stability balls provided no differences in postural or muscular activation but resulted in higher reported values in low back discomfort. According to Kingma and van Dieën (2009), working while seated on a stability ball was associated with greater spinal shrinkage after sitting for 1 h, compared to a standard office chair with armrests. Kingma and van Dieën's (2009) findings were not surprising as stability balls lack back support. Without back support, the sitter will be more likely to adopt a kyphotic posture which leads to increased spinal shrinkage (Kingma and van Dieën, 2009). Sitting in a kyphotic posture places significant stress on the posterior region of the spine as the nucleus pulposus applies pressure on the annulus of the spinal disc, thereby increasing the risk for an injury to the spine and/or development of lower back pain (Harrison et al., 1999). Gregory et al. (2006) also highlighted the safety implications of using a stability ball due to its unstable nature, increasing the risk of trips and falls.

Sit–to–stand workstations have been found to decrease lower back discomfort (Chambers et al., 2019; Bao and Lin, 2018); although, the right sit–stand ratio must be determined: prolonged standing can be as detrimental as prolonged sitting (Karakolis and Callaghan, 2014). According to Karakolis and Callaghan (2014), a sit–stand ratio between 1:1 and 3:1 is best to reduce discomfort, which translates into standing

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between 30 and 45 min every hour. Sit–to–stand workstations coupled with active seating could be a means to help reduce discomfort and reduce the negative physiological effects of prolonged static seated posture, however active chairs are still not well researched.

Active/dynamic seating allows integration of more movement than a traditional chair. For the purpose of this study, it is important to identify the differences between dynamic and active chairs. Dynamic chairs are designed so that the user is required to be in constant motion, such as sitting on a rocking chair (Pynt, 2015). Active chairs are designed so that the sitter is providing the action to move the chair, while the mechanism of the chair accommodates that action (Pynt, 2015). Literature on the use of active and dynamic sitting at the workplace is currently minimal (especially active chairs) as they are relatively new to the market.

1.1. Dynamic chairs

Van Dieën et al. (2001) investigated the effect of two different dynamic chairs on trunk kinematics, trunk extensor electromyography (EMG) and spinal shrinkage. The chairs investigated by Van Dieën et al. (2001) were defined as dynamic as they permitted constant movement of the backrest independent of the seat pan while seated. No differences were related to chair design in trunk kinematics or trunk extensor musculature, however the dynamic chairs were found to promote stature increases; changes in trunk kinematics and changes in neuromuscular activity related to the computer task performed (but not the chair used). Ellegast et al. (2012) compared four dynamic chairs for their impact on trunk muscle activation, physical activity and posture. Limited detail was provided for each chair in their study, except that each chair had a different dynamic element in its design: 1– The first chair had an electronic motor that moved the seat pan from right to left 0.8°, five times per minute; 2– The second chair had a suspension system that allowed the seat pan to move horizontally; 3– The third chair allowed the seat pan to move in all directions on a pendulum, and 4– The fourth chair had a three–dimensional moveable joint, allowing the seat pan to move freely in all directions. Similar to van Dieën et al. (2001), no differences were found in the muscular activation, physical activity and posture between the four dynamic chairs and the standard office chair (Ellegast et al., 2012). In a companion paper, Groenesteijn et al. (2012) identified that posture and changes in neuromuscular activity were related to the task being performed and was not affected by the dynamic features of the chairs. These studies (Van Dieën et al., 2001; Ellegast et al., 2012; Groenesteijn et al., 2012) lacked details pertaining to the features of the chairs and the study designs did not discuss how the participants were to engage the dynamic features of the chairs.

1.2. Active chairs

Triglav et al. (2019) investigated the physiological and cognitive effects of using a multiaxial chair versus a traditional office chair. Triglav et al.'s (2019) most significant finding was that participants had more attention–task errors using a traditional chair, where there were no significant differences found with the multiaxial chair after the 4-h sitting task. Triglav et al.'s (2019) also found that after 4-h of sitting, there were no significant differences between both chairs in calf circumference, however there was a significant difference (between both chairs) after 2 and 3 h of sitting, in favour of the active chair. Triglav et al.'s (2019) calf circumference findings suggest that using an active seat can be beneficial for blood vasculature for up to 3 h, however it does not replace the importance of taking micro breaks to stand.

Kuster et al. (2018) investigated an inverted chair, an active stool and a standard office chair. The inverted chair had a seat pan that facilitated an upwards side–to–side motion with a backrest that was not movable in the frontal plane. The active stool had a convex seat pan that facilitated downwards side–to–side movement with also a backrest that was not movable in the frontal plane. The chair design that was the most preferred was the inverted chair. The inverted chair had the most stable upper body posture with the ability to perform a substantial range of lateral spine flexion (11.5°) and had lowest discomfort scores during the 4-h sitting task. It is important to note that only 8 healthy participants were investigated, and the authors recommended a larger sample size in future studies.

Synnott et al. (2017) evaluated an active forward–inclined saddle chair and a static office chair, where participants performed a 1-h movie–watching task. The saddle chair resulted in an increase in energy expenditure, however metabolic equivalents (METS) values were still below 1.5 (while using the saddle chair), indicative of sedentary behaviour. The key finding by Synnott et al. (2017) was that participants perceived less discomfort using the saddle chair: this was also supported by O'Keeffe et al. (2013) who tested the same chair. In 2019, Snarr et al. compared the same saddle chair to a stability ball and a standard wooden chair. Participants performed a reading and typing task in two separate sessions, each lasting 10-min per chair. Snarr et al. (2019) found that for both tasks, heart rate (HR), caloric expenditure per minute and METS values were all significantly greater while using the saddle chair compared to the other two sitting conditions; no significant findings were found between the stability ball and standard chair for any of the comparisons. Although the recorded time was small for each sitting condition in Snarr et al. (2019) study, it does complement Synnott et al. (2017)'s findings on the same saddle chair and did not find any significance in reported METS values. However, METS values reported in Snarr et al.'s (2019) study were still small but statistically significant (2.35 ± 0.49 while reading; 1.94 ± 0.40 while typing). Performing a task while using the saddle chair, instead of a passive task (such as watching a movie) would explain the slight differences in reported METS values between Snarr et al. (2019) and Synnott et al. (2017) studies.

Holmes et al. (2015) evaluated an active chair that simulated a stability ball (multiaxial chair), however this chair did provide some low back support. It was found that the active chair produced similar muscle activity and muscle recruitment patterns to that of performing selected exercises on a stability ball. The active chair was found to aid in promoting movement while seated, which could be beneficial to prevent spine loading (Callaghan and McGill, 2001), nourish spinal structures (Holm and Nachemson, 1983) and prevent muscle fatigue (Jonsson, 1978).

The objective of this study was to provide a biomechanical comparison of two different types of active chairs versus a static chair. It was hypothesized that an active seating design would reduce discomfort, increase blood oxygen levels to the lower legs and increase abdomen/trunk muscle activation.

2. Methodology

2.1. Participants

Fifteen healthy females (age: 23.9 ± 4.1 yrs, height: 160.3 ± 8.4 cm, weight: 58.8 ± 10.5 kg, desk height: 25 ± 0.9 inches) and fifteen healthy males (age: 26.3 ± 6.6 yrs, height: 176.1 ± 5.4 cm, weight: 82.8 ± 7.0 kg, desk height: 27 ± 0.7 inches) were recruited. Eligible participants were required to have no history of low back pain in the previous 3 months, and no known vasculature disorders in the lower limbs. Participants were provided detailed information on the experimental design and were explained the objectives of the study prior to commencing. Participants volunteered by signing an informed consent form approved by the university's research ethics board. Participants were remunerated for their participation in this study.

2.2. Chair design

The study compared three different office chair designs: 1– a static office chair (No Active Components: NAC); 2 – an active office chair with split seat pan (Active Chair 1: AC1); and 3 – an active office chair with a modified split seat pan (Active Chair 2: AC2). AC1 had a seat pan that was split longitudinally, which was designed to promote (lumbar, pelvic and hip) motion by alternating active ankle plantar/dorsiflexion and a 10–degree range of alternating hip flexion/extension similar to a walking action. AC2, was a modified version of the AC1, the seat pan was not split longitudinally, however, it had a pivot swivel at the front end of the seat pan to favour side–to–side swaying while seated. To activate the active component of the AC2, participants had to mimic the same ankle movements as they would for the AC1. See Fig. 1, for visual representation of the three chairs.

2.3. Experimental set up

Participants visited the Occupational Performance Laboratory (OPL) for a single experimental session. Participants worked at a computer workstation that was ergonomically configured for their specific anthropometrics using the Canadian Centre for Occupational Health and Safety (Canadian Centre for Occupational Health and Safety, 2018) ergonomic guidelines (see Fig. 2). Each office chair was set to a positive inclined seat pan angle (SPA) of 5° from the horizontal plane (Wang et al., 2019) and the seat back angle (SBA) in this study was reclined backwards to 10° from the vertical plane (Wang et al., 2019). Both SPA and SBA were configured using the FASTRAK electromagnetic motion tracking system (Polhemus Inc., VT, USA). This equipment has been verified by the manufacturer to have a static accuracy of 0.1 cm position and 0.15° orientation. Once the chairs were configured for the participants, they were not permitted to change any of the chair settings throughout the experimental collection.

2.4. Experimental design

During the experimental study, participants worked at a computer workstation for a 3-h period using each of the three chairs for a 1-h period. The study used a repeated measures study design with each presentation of the chairs randomized. Between each workstation, participants were given a 10-min unsupervised break to use the restroom and stretch their legs. Each participant was provided proper instructions on how to use each chair prior to collection (approximately 5-min per chair). To represent a more realistic workplace scenario, participants had the freedom to choose how they sat including "if" and "when" to pedal their feet, during data collection. It is also important to note that participants had no prior experience using active chairs and active sitting.

During the experimental design, participants were instructed to perform an unmonitored typing and web browsing task (to also simulate a realistic work environment); participants had the freedom to alternate between both tasks as they pleased. The only restriction was that while computing, participants were instructed to have at least one hand on the mouse or keyboard at all times and have both feet in contact with the ground while seated. This restriction was implemented as a means to avoid a movie watching position, such as arms crossed with no interaction with the computer.

Fig. 2. Illustration of the experimental set up.

2.5. Data collection: Equipment

2.5.1. Seated pressure

The chairs were instrumented with X3 Sensor (X3LX100, XSensor Technology Corporation, Calgary) pressure mapping system covering the seat pan. The pressure pad recorded engagement of the seat pan as well as leaning and sway patterns. The pressure pad had a dimension size of 45.7 cm × 45.7 cm with a 0.81 mm thickness when compressed. The accuracy of the pressure pad was based on a maximum standard deviation of 5 mmHg with less than 1.3% hysteresis and less than 5% creep over an hour–long use (www.xsensor.com). Pressure data was collected for a total of 60-min (the 60–min pressure data was recorded in 4 *x* 15-min blocks to help control for the size of the recorded data files). Pressure values were recorded at a frequency of 5 Hz with the units of pressure as force over area (N/cm^2).

2.5.2. Neuromuscular activity

Electromyography (EMG) was used to monitor muscle activation (Bortec biomedical Ltd. system). EMG electrodes were placed bilaterally

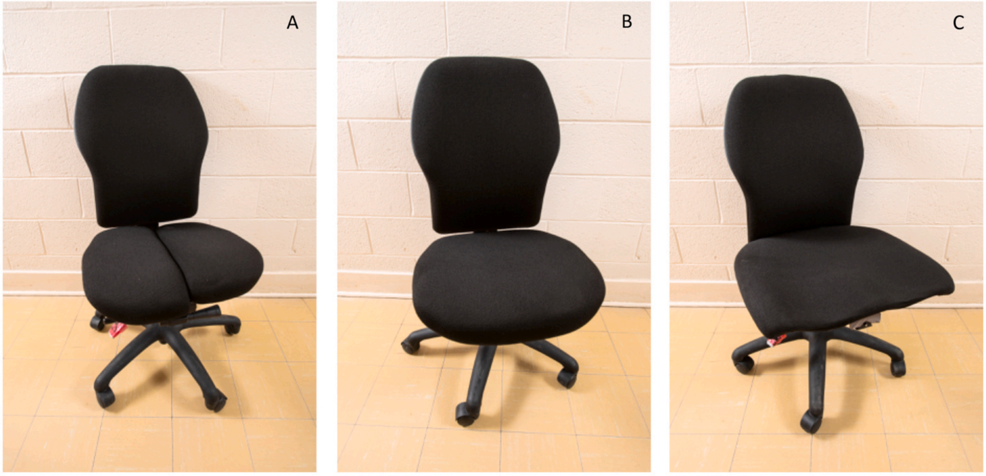

Fig. 1. The 3 experimental chairs that were investigated: AC1 (A), NAC (B), and AC2 (C).

on the splenius capitis, erector spinae at the thoracic (T9) and lumbar (L3) level as well on the external obliques. Relative scores from the participants maximal muscular contraction (MVC) were used to quantify the data. A maximal back extension was used for the MVC of the thoracolumbar extensors (TES, LES): participants were required to lie on a massage table with their torso suspended off the end and their legs secured to the table with heavy strapping. The participants were then required to extend their back as the primary investigators provided resistance. MVC for the neck (SC) required participants to extend their neck against resistance while their torso was secured to the massage table with heavy strapping. A chain bolted to the floor was attached from the floor to a robust head strap (height of the massage table). The participants were required to extend the neck, pulling up on the instrumented chain. MVCs for the trunk flexors (EO) included a series of maximum forward, left and right, trunk–flexion contractions. Participants were positioned on a table with their knees flexed to approximately 90° and the trunk positioned approximately 45° from horizontal while manual resistance was provided by one of the investigators, restricting flexion and twisting movements. During this procedure, the feet were secured to the table with heavy strapping. The myoelectric signal was collected at a frequency rate of 1024 Hz, recorded in 4 X 15-min increments, for a total 60-min.

2.5.3. Hemodynamic response

Near–infrared spectroscopy (NIRS) was used to assess changes in oxygenated blood flow to the lower limbs. The NIRO–200NX (NIRS spectroscopic oximeter, Hamamatsu Photonics KK, Hamamatsu City, Japan) uses two diodes (sensors), one to emit a light into the leg and the second to detect the refraction of light returned. The absorption of the light provides an indication of the oxygenation level of the blood in the area. The spectroscopic oximeter measurement principles, based on Beer–Lambert modified law, helps calculate oxygenated hemoglobin (O_2HB) and reduced non–oxygenated hemoglobin (HHB) which have divergent absorption spectrum (Herrmann et al., 2003). The sensors were placed on the lateral and medial head of the gastrocnemius. Hemodynamic data was also collected for a total of 60-min (the 60–min of hemodynamic data was recorded in 4 X 15-min blocks to help control for the size of the recorded data files) at a frequency rate of 5Hz.

2.5.4. Participant perceived discomfort

To acquire participants' perception of discomfort with each seating design, the rate of perceived discomfort questionnaire (RPD) and Seating Discomfort Questionnaire (SDQ) (Cardoso et al., 2018a,b) were used. The RPD questionnaire enabled the participants to report discomfort experienced at thirteen different body parts (head and bilateral: shoulders, upper back, low back, buttocks, upper and lower legs) using an electronic visual continuous 0 to 100 points (0 = no discomfort and 100 = extreme discomfort) sliding analogue scale, making the scale a total length of 130 mm. The SDQ questionnaire used the same electronic visual continuous sliding analogue scale as the RPD, the SDQ enabled the participants to report discomfort experienced relative to the chairs. The SDQ is a modified questionnaire of the Automotive Seating Discomfort Questionnaire (ASDQ); the difference between both questionnaires was the exclusion of questions that were specific to vehicle seats, questions can be found in Fig. 7. An exit survey was also administered at the end of the study to receive immediate feedback on all three office chairs. Questionnaires were given in 30-min intervals, resulting in three collections per chair: baseline, time at 30mins (T_{30}), and time at 60mins (T_{60}).

2.6. Data processing

2.6.1. Seated pressure

Center of pressure (CoP) was measured to assess postural movements. Previous work found large shifts in CoP to be an indicator of discomfort (Cardoso et al., 2018a,b). Peak pressure was also recorded to assess high pressured spots typically found under the ischial tuberosities (De Looze et al., 2003; Zemp et al., 2015) which is a concern for neuropathy, soft tissue damage and oxygenated blood occlusion (Makhsous et al., 2003; Orsted et al., 2010). The CoP and Peak pressure values were extracted using the XSensor software.

2.6.2. EMG

The raw signal was rectified (RMS converted) and Butterworth band pass filtered. Peak activity was found for each muscle during the MVC trials and used to normalize all subsequent EMG data. The EMG data was compiled into 1-min intervals to determine the level of muscle activity percentage change from MVCs during the computer tasks.

2.6.3. Hemodynamic response

Relative scores were compared to baseline, which consisted of 5-min of quiet sitting. The last minute of the 5-min of quiet sitting was used as the data set for baseline. The collected data during the computing task was compiled into 1-min intervals to determine the level of percent change from baseline during the computer tasks. Change percentage ratio of oxygenated hemoglobin to total hemoglobin (%TOI) were recorded. The %TOI equation was as follows: $TOI(t) = 100 \times k[O2Hb]/k[cHb]$, cHb represented, total hemoglobin from time = t_0 and k was an unknown constant.

2.6.4. Participant perceived discomfort

Relative values were subtracted from baseline values, representing changed scores from baseline, for both the RPD and SDQ questionnaires.

2.7. Statistics

The objective of this research project was to observe the effects of three different seating designs during a prolonged sitting task. A repeated measures ANOVA with two within factors (time and chairs) was performed to evaluate differences between neuromuscular activity, hemodynamic response, perceived discomfort and pressure distribution at T_{60}. Meaning the data comparisons made were on the last 15-min of the participants' 1 h sitting trials (T_{60}). Therefore, for the two variables of time and chairs: time had 1 factor (T_{60}) and chairs had three factors (AC1, AC2 and NAC); comparing the three chairs at T_{60}. The Alpha level was set at $p < .05$, and if any significant interactions were found, a Tukey correction was done as a post–hoc analysis.

3. Results

3.1. Pressure pads

3.1.1. CoP pressure

Seat Pan: To quantify posture, pressure pads were used to measure the shift in center of pressure (CoP) distribution. Fig. 3, compares the pressure distribution from the pressure pad on each of the seat pans. The shift in CoP in the y–axis, represents the movement found towards the front and back of the seat pan (front–to–back rocking movement). The shift in CoP in the x–axis, represents movement found side–to–side (lateral movement). Participants significantly shifted more in the front–to–back axis with the AC1 compared to the AC2 ($p < .001$) at T_{60}; however, participants shifted more in the front–to–back using the NAC compared to the AC1 ($p < .001$) and the AC2 ($p < .001$) at T_{60}. Participants showed significantly lower side–to–side movement in AC1 compared to the NAC ($p < .001$) and AC2 ($p < .001$) at T_{60}. Participants also had significantly higher movement side–to–side when using AC2 compared to AC1 ($p < .001$) and the NAC ($p < .001$) at T_{60}.

3.1.2. Peak pressure

Seat Pan: It was found that peak pressure values were higher in both AC1 (1.46 ± 0.46 N/cm^2) and AC2 (1.44 ± 0.39 N/cm^2) than the NAC (1.21 ± 0.26 N/cm^2) ($p < .001$ and; $p < .001$) at T_{60}.

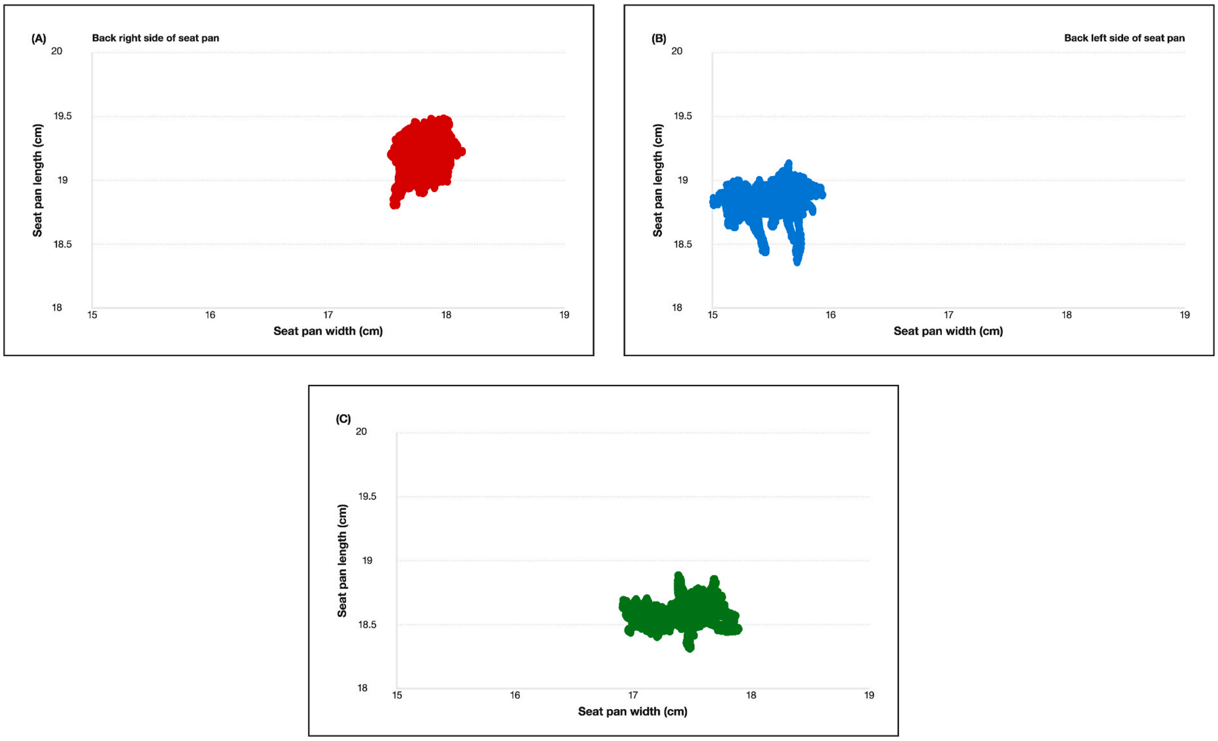

Fig. 3. Seat pan mean center of pressure for side–to–side (x–axis) and foreword–back (y–axis) displacement for all 30 participants between (A) ACI; (B) NAC; and AC2 (C) at T_{60}.

3.2. Neuromuscular activation

Fig. 4 illustrates the bilateral neuromuscular activity of the neck muscles (SC: splenius capitis), thoracic erector spinae (TES), lumbar erector spinae (LES) and abdominal muscles (EO: external obliques) for all three chairs.

During the last 15-min of the sitting task (T_{60}), it was found that the participants had significantly higher TES activation: *A–* The left TES neuromuscular activity using the AC1 (*4.9 ± 4.05* %MVC) versus AC2 (*3.88 ± 2.17* %MVC) ($p = .00$) and the NAC (*4.25 ± 2.48* %MVC) ($p = .00$). *B–* The right TES neuromuscular activity using the AC1 (*4.64 ± 2.44* %MVC) versus AC2 (3.91 ± 1.79%MVC) ($p = .00$) and the NAC (*4.41 ± 2.25*%MVC) ($p = .02$).

Greater neuromuscular activity was also found in the EO at T_{60}: *A–* The left EO in AC1 (*9.47 ± 10.79* %MVC) was significantly higher than AC2 (*8.14 ± 6.27* %MVC) ($p = .02$), however no difference was found between AC1 and the NAC (*8.88 ± 7.70* %MVC). *B–* The right EO in AC1 (*9.06 ± 6.99* %MVC) was significantly higher than the NAC (*8.55 ± 6.44* %MVC) ($p = .00$), however no difference was found between AC1 and AC2 (*8.99 ± 5.69* %MVC).

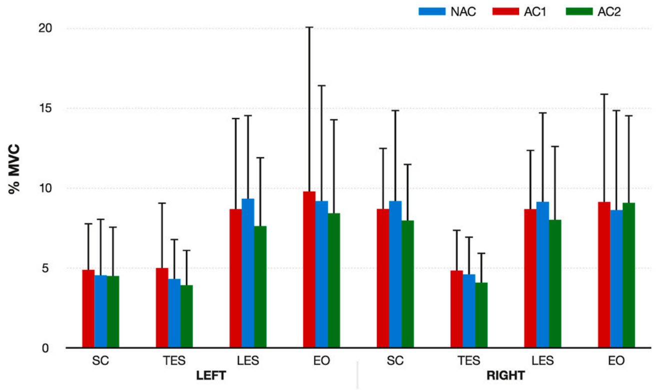

Fig. 4. Bilateral neuromuscular activity of the neck muscles (SC: splenius capitis), thoracic erector spinae (TES), lumbar erector spinae (LES) and abdominal muscles (EO: external obliques) for the AC1 (red), NAC (blue), and AC2 (green) at T_{60}. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Greater neuromuscular activity was found for the left (L) and right (R) LES at T_{60}: *A–* The left ES was greater in the NAC (*9.10 ± 5.10*% MVC) versus AC1 (*8.46 ± 5.56*%MVC) ($p = .00$) and AC2 (*7.42 ± 4.21*% MVC) ($p = .00$). *B–* The right ES was greater in the NAC (*8.84 ± 5.43* % MVC) versus AC1 (*8.40 ± 3.59* %MVC) ($p = .01$) and AC2 (*7.76 ± 4.47* % MVC) ($p = .00$).

Although statistically significant, these low activity levels found in the TES, EO and LES would have no effect to induce muscular fatigue.

3.3. Hemodynamic response

Fig. 5 (A & B) represents tissue % Oxygenation Index (%TOI) change from baseline. The figures depict oxygen saturation levels which is a representation of the ratio of oxygenated hemoglobin to total hemoglobin. A greater change in %TOI in both sensor 1 and 2 was found with the use of the AC1 (sensor 1: *4.67 ± 0.77*%, sensor 2: *2.76 ± 0.86*%) compared to the NAC (sensor 1: *2.71 ± 2.92*%, sensor 2: *1.79 ± 0.81*%) (sensor 1: $p = .00$, sensor 2: $p = .00$) and AC2 (sensor 1: *2.41 ± 0.11*%, sensor 2: *1.56 ± 0.76*%) (sensor 1: $p = .00$, sensor 2: $p = .00$) at T_{60}. Raw %TOI Values for the last 15-min of the sitting trials: AC1 (sensor 1: *68.94 ± 5.91*, sensor 2: *67.59 ± 5.48*) NAC (sensor 1: *66.78 ± 5.75*, sensor 2: *67.10 ± 5.03*) and AC2 (sensor 1: *66.83 ± 4.77*, sensor 2: *66.72 ± 4.87*). Although statistically significant, these are low changes in % TOI levels.

3.4. Questionnaire results

3.4.1. RPD

According to the RPD findings, participants experienced significantly more discomfort using the NAC (left buttocks: 10.68 ± 11.83 mm; right

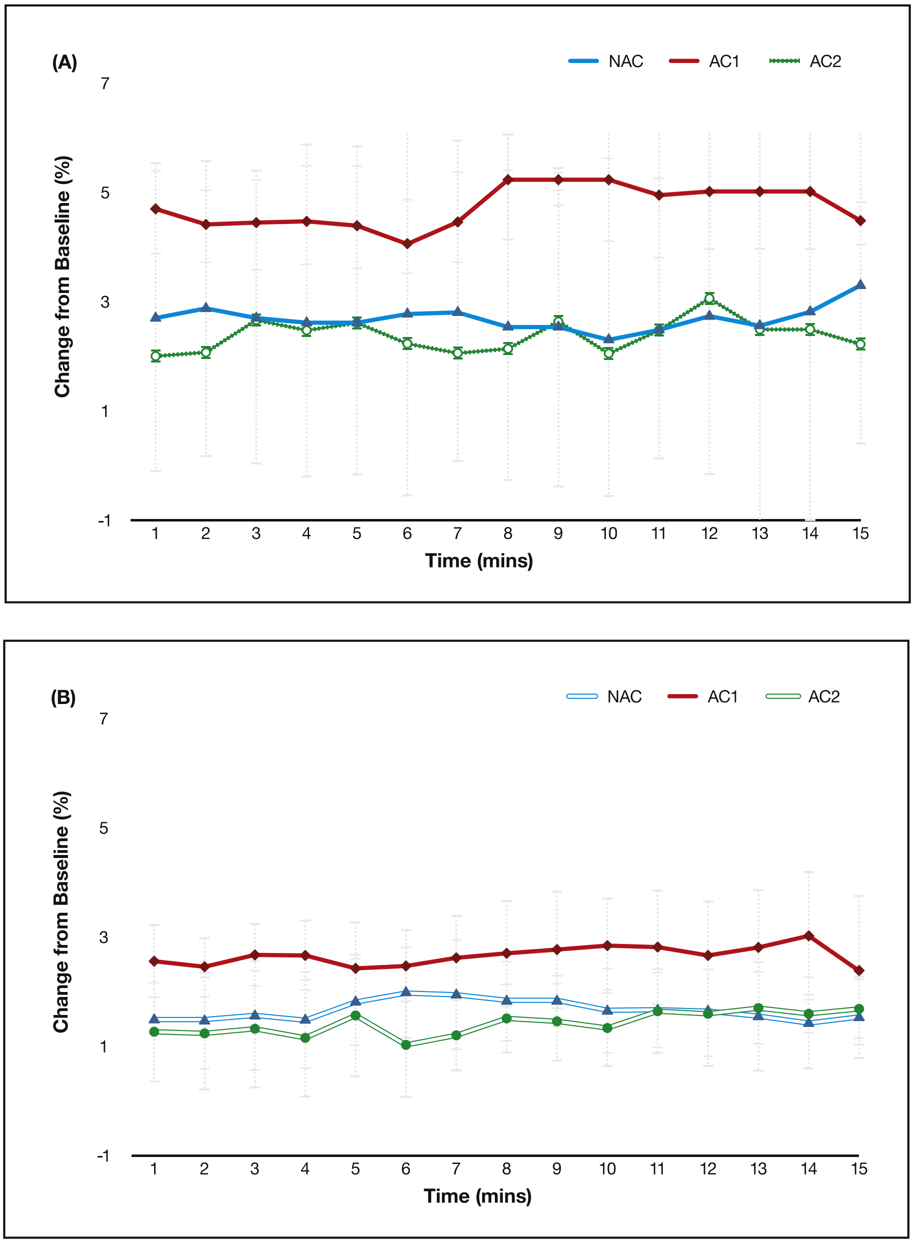

Fig. 5. Oxygenation Index (TOI) change from baseline for the lateral head of the gastrocnemius (sensor 1– Graph A) and the medial head of the gastrocnemius (sensor 2 – Graph B) for the left calf at T_{60}.

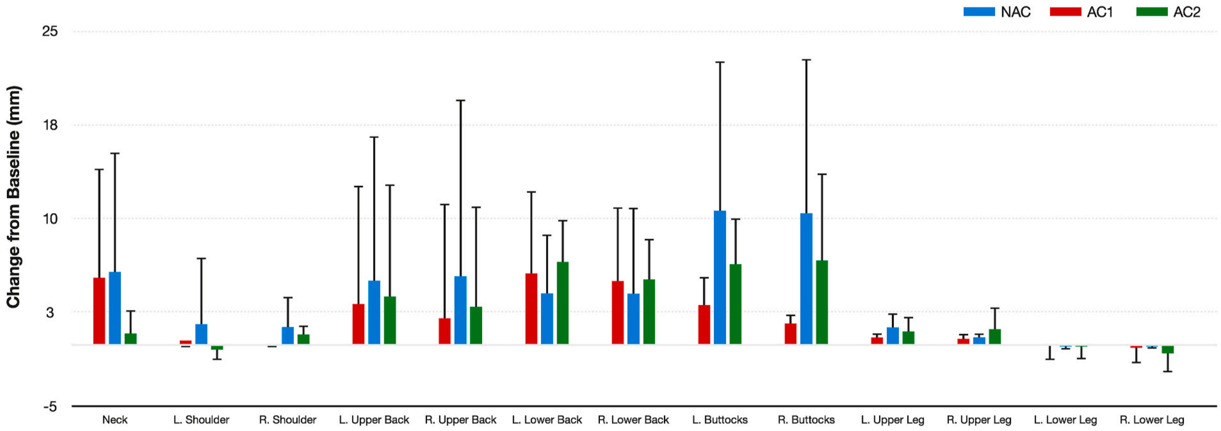

Fig. 6. Rate of perceived discomfort (RPD) questionnaire findings at T_{60}.

buttocks: 10.47 ± 12.25 mm) versus AC1 (left buttocks: 3.17 ± 2.14 mm; right buttocks:1.72 ± 0.68 mm) (left: $p = .01$; right: $p = .02$) in their left and right buttocks after 60-min (T60) of sitting (Fig. 6). There was no significant difference between RPD findings of AC1 and AC2.

3.4.2. *SDQ*

According to the SDQ questionnaire, participants experienced significantly more discomfort due to seat pan cushion firmness of the NAC (12.27 ± 15.93 mm) versus AC2 (3.65 ± 3.26) ($p = .01$) chair after 60-min of sitting (Fig. 7).

3.4.3. *Exit survey*

The exit survey revealed that the AC1 was most preferred (14 participants), AC2 was the second most popular choice (9 participants) followed by the NAC (7 participants).

4. Discussion

This study investigated the ergonomic performance of three different office chair designs to assess the beneficial claims associated with active seating. Specifically, the movement patterns, blood oxygen levels to the legs and upper extremity muscle activity were used for this assessment.

4.1. *Movement patterns and pressure distribution*

Participants significantly shifted more anteriorly–posteriorly (front–to–back) and less medially–laterally (side–to–side) with the AC1 compared to the AC2. The greater shift front–to–back with the AC1 (compared to AC2) is intuitive as the chair was designed to have users intentionally performing a walking movement while seated. According to Winter (1995), during quiet standing, anterior–posterior sway originates from the ankle and calf muscles whereas medial–lateral components of sway are controlled by the hip abd/adductor muscles. Winter (1995), describes sway as the "error signal in the balance control system" as it tries to correct itself to keep the body balanced. Notably, when comparing both active chairs, the greater anterior–posterior swaying pattern on the seat pan was found in the chair design (AC1) that favoured ankle plantar and dorsiflexion. However, when comparing the NAC to both active chairs, it is interesting to note that the greatest shift front–to–back was found using the NAC. As there was no active component to the NAC, the increase shift front–to–back could be a sign of discomfort, as we found scores to be the highest in the buttocks area using the NAC (compared to the AC1) after 60-min of sitting. Previous research has found that an increase in CoP (while using a static chair) is often indicative of an increase in perceived discomfort and participants compensate by readjusting their posture (Cardoso et al., 2018a,b).

As for medial–lateral movement, significantly greater side–to–side movement was found using AC2 (compared to both the AC1 and NAC) where the chair was designed to facilitate side–to–side (swaying). In hindsight it would have been interesting to place the EMG electrodes on the gastrocnemius and the hips abd/adductor muscles.

Further research could help inform which movement pattern is more favourable while seated, front–to–back sway, side–to–side sway, or a mix of both. Although both axes of movements were measured (front–to–back and side–to–side), the design of the AC1 and AC2 chairs influenced one of the two movement patterns and did not favour both. There were no significant differences in reported discomfort scores between the use of AC1 and AC2. Therefore, any type of movement could play a factor in reducing feelings of perceived discomfort and perhaps specific movement pattern has no effect. Another argument towards the effects of reported perceived discomfort and movement pattern, although not statistically significant between both active chairs, was that participants did report lower discomfort in the left and right buttocks using AC1 (compared to the NAC): this could be an indication that front–to–back movement is perhaps more favoured in reducing discomfort than a side–to–side sway and a longer sitting duration is necessary to see statistical significance. Evaluating a chair that influences a mix of both movement patterns during a prolonged sitting task would be interesting to evaluate in future studies.

Peak pressure while seated is predominantly generated by the ischial tuberosities (sit bones), as they are hard bones that contact the seated surface. High pressure generated by the sit–bones is concerning as it can lead to high pressure on the gluteal muscles, reduction of blood flow and potentially neuropathy (Makhsous et al., 2003; Orsted et al., 2010). It was found that both the AC1 and AC2 had higher peak pressure values than the NAC; this was surprising as participants subjectively reported that they found the seat pan cushion firmness caused more discomfort while seated in the NAC than AC2, and lower discomfort scores in the left and right buttocks using AC1 (compared to the NAC). As mentioned in the paragraph above, giving participants the ability to move while seated perhaps helps reduce reported subjective discomfort (even though peak pressure values are higher). Another factor to consider is that perhaps the peak pressures in active chairs are an artifact of movement (i.e., the increased movement down the vertical axis on the seat pan in AC1 and AC2 leads to higher values of peak pressure). Design modifications would be encouraged on both active chairs as a means to reduce peak pressure values while also facilitating movement while seated. Modifications such as shortening and adding more contour to the seat pan would help distribute seated pressure.

4.2. *Neuromuscular*

A slight increase in neuromuscular activity was found in the external obliques with the use of the AC1 versus the NAC and AC2; however, it is important to note that the difference between the 3 chairs was approximately 1% of the participant's MVCs. Having a split seat pan (AC1) helps engage muscle activity on the superficial muscles of the abdomen, but only slightly more than the NAC and AC2. The slight increase of muscle activity in the thorax could be the body's effort to stabilize the trunk (keeping the trunk upright while "peddling").

Signs of surface abdominal activity is a promising finding, however, to protect the spine it is important that deep core muscles such as the transvers abdominis and the deep multifidus muscles are engaged as well. Unfortunately, we could not measure the deep muscles of the abdominal wall/trunk, as it would require needle EMG. According to literature (Snijders et al., 2008; Pynt, 2013), the lack of a coordinated

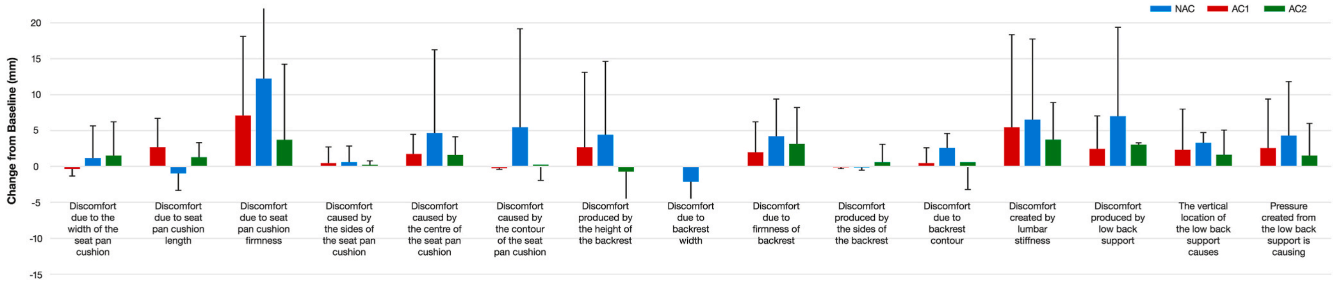

Fig. 7. Seating Discomfort Questionnaire (SDQ) findings at T_{60}.

contractile activity of the deep and superficial muscles of the abdominal wall/trunk, is concerning as it can provide strain on the iliolumbar ligaments (which could lead to triggering pain receptors in the sacro–iliac region). It is not suggested that there was a lack of muscle coordination contraction patterns between the deep and superficial muscles of the trunk in this study, however a realization that there might be training necessary to properly use AC1. As a precautionary measure to protect the spine, users of the ACI, should learn how to: 1–engage the deep core muscles prior to peddling their feet; 2– ensure that the user makes full use of the backrest when they are not peddling their feet, this would provide a rest to the superficial trunk muscles (Pynt, 2013).

Slightly greater neuromuscular activity was found for the lumbar erector spinae muscle for the NAC versus AC1 and 2. The increase of muscle activity found in the erector spinae in the lumbar region could be predominantly due to the length of the seat pan. The NAC was the only chair in which each of the participants could comfortably reach and make proper contact with the backrest. The increase of muscle activity could be a means to maintain lumbar lordosis (C–Curve in the low back) while maintaining contact with the backrest. It has been suggested by Callaghan and Dunk (2002), that a lack of muscle activity found on the lumbar erector spinae could be an indication that participants are relying more on the passive tissues surrounding the spine rather than on the muscles themselves; this is concerning for the development of low back pain as it increases the risk for activation of pain receptors in the passive tissues, tissue strain and herniated discs (Callaghan and Dunk, 2002; Rhalmi et al. 1993). Participants did perceive less discomfort using AC1 versus the NAC after 60-min of sitting, however, over a longer period of time, based on Callaghan and Dunk's (2002) findings, it would be hypothesized that reported discomfort scores would be reversed. Based on our findings, the AC1 design has significant potential, however, design changes (i.e. a shorter seat pan) should be made. A shorter seat pan would enable the sitter to utilize the backrest while they are not peddling, providing a rest to the paraspinal tissues.

Congruent with other researchers (Van Dieën et al., 2001; Ellegast et al., 2012; Groenesteijn et al., 2012) active sitting had little to no effect on neuromuscular activity. Groenesteijn et al. (2012) identified that changes in neuromuscular activity were related to the task being performed and was not affected by the dynamic features of the chairs. All participants in this study only performed computer work, while using all three chairs. The lack of change in neuromuscular activity found with the use of active chairs could be due to the absence of proper training on how to use the active chairs (in this present study and previous studies). In this study, approximately 5-min per chair was spent with each active chair prior to commencing data collection; more time on training is perhaps necessary. Future research designs should compare a trained group to a control group with the use of active chairs; this would provide insight as to whether proper training can better promote neuromuscular activity. Based on Pynt's (2013) research, proper training while using an active chair could also help protect the spine.

4.3. Muscle oxygenation

Near–Infrared Spectroscopy (NIRS) was used to assess changes in oxygenated and deoxygenated blood flow to the lateral and medial head of the gastrocnemius. %TOI depicts oxygen saturation levels which is a representation of the percent ratio of oxygenated hemoglobin to total hemoglobin. A slight change in %TOI with the use of the AC1 compared to the NAC and AC2 was found. Peddling the legs while seated was found as a means to promote slightly more oxygenated blood to the lower limbs; greater change was hypothesized. Participants had the freedom to choose to either pedal their feet or not, as a means to represent a realistic workplace. Implementing strict guidelines to promote more peddling while seated could further increase %TOI values. Why is it important to promote greater oxygenated blood flow changes in the lower limbs while seated? The average adult spends between 51 and 68% (71% for office workers) of their time in a seated position (Matthews et al., 2008; Healy et al., 2008; Dunstan et al., 2012; Clemes et al., 2014). Prolonged sitting has been associated with cardiovascular problems, reduction (even occlusion) of blood flow pathophysiology problems (ex: diabetes) (Triglav et al., 2019; Levin et al., 2009; Lind and Lithell, 1993).

While seated in a sedentary position, large postural muscles (ex: quadriceps, hamstrings and glutes) become inactive. A reduction of muscular demands leads to a reduction of blood circulation, meaning the metabolic system slows down and fewer calories are burned throughout the day. A slower metabolic system due to sedentary behaviour may lead to higher blood glucose and insulin levels (thereby increasing the risk of insulin resistance) (Czech, 2017). According to Dunstan et al. (2012), the implementation of light physical activity (2-min) every 20-min helps reduce insulin and blood glucose levels found in the blood stream. The light physical activity in Dunstan et al. (2012) study was simply a light treadmill walk. The increase in %TOI in this present study would be an indication that there was more oxygen in the sampled tissue site therefore, an increase in %TOI could be an indication that slight physical effort was occurring. According to Goodyear and Kahn (1998), exercise has been found to increase the rate of glucose uptake into contracting skeletal muscles (thus creating ATP/energy); although insulin and glucose have different signalling pathways, both lead to the activation of glucose transport. If someone is insulin resistant, exercise can increase muscle glucose transport (to create energy and lower blood glucose levels). The AC1 chair could potentially help lower key pathophysiology biomarkers that are linked to the development of Type 2 diabetes (due to the increase in %TOI), however further testing is needed to fully support this claim and determining specific guidelines on how much peddling would be needed to yield such health benefits. A big limitation of this study was the exclusion of energy expenditure measurement to help quantify the level of physical activity associated with the AC1 and AC2 chair designs and setting specific guidelines to promote more peddling while seated.

5. Study limitations

The biggest research limitation was the lack of control of the participants' engagement of the chairs' active elements. The experimental protocol was designed, as a means to help understand how the sitter would utilize the active chairs, representing a realistic workplace: this led to only slight changes found in neuromuscular activity as well as oxygenated blood flow to the lower limbs. However, as participants had the freedom to pedal their feet (or not); many participants chose not to pedal consecutively for the 60-min computing task. Participants choosing not to pedal their feet could be an indication of habit, as both active chairs served as a comfortable static chair if the legs remained stationary. To yield more health benefits from a chair design such as the AC1: perhaps a lengthy training process would be necessary to help change work habits. As for experimental designs, future studies should implement set protocol guidelines when it comes to investigating active sitting (meaning training would not be necessary), ex: setting a metronome on when the participants should pedal their feet. Another approach for future experimental designs would be to compare a trained group (where significant amount of time was spent on training, i.e. more than a few minutes) to a control group with the use of active chairs.

As highlighted above, the exclusion of energy expenditure (EE) measurement was also a limitation found in this research study design, this would help us provide more information on if active sitting would increase EE, by having values greater than 1.5 METS (indicative of sedentary behaviour). As an increase of 2–3 %TOI found in this research study (AC1 versus AC2 and NAC), it is difficult to quantify if these small percentage changes from sedentary behaviour are enough to provide any positive physiological changes.

Another limitation, was the investigation of only 1 h of work, studying the long–term effects of using an active versus static chair would be more realistic to a workplace setting. Future studies should also consider sex differences, as we have data on 15 males and 15 females, a spin off paper on this specific subject is included in our future plans.

6. What's next?

This paper serves as part one of a two–part project; Phase 2 is a comparison of three workstations: 1–NAC, 2– AC1 and 3– a standing desk. Equipment and the experimental design remained the same as phase 1, with the exception that participants were required to pedal their feet while using AC1. The participants were asked to simultaneously alternate their feet between plantar and dorsiflexion to the beat of a metronome, that was operating at 40 BPM, for the entire collection period. Combining Phase 1 and 2 will provide us information on the realistic use of using an active chair in the workplace versus setting specific guidelines. The results of phase 2 are currently under investigation. The AC2 design was excluded from phase 2, as results yielded from Phase 1 did not show as much potential biomechanically and physiologically, as the AC1 design. The biggest design flaw (in our opinion) of the AC2, was that the side–to–side sway feature did not require enough leg movement while seated, especially when compared to the AC1 design.

7. Conclusion

Three different office chair designs were investigated: NAC, AC1 and AC2. The predominant findings of this study, include: 1– Lower discomfort scores in the gluteal area was found with the use of active chair AC1 compared to the NAC, no significant differences were found between AC1 & AC2 in reported discomfort scores; 2– The increase in front–to–back sway using the NAC, is most likely due to participants readjusting their posture as a means to reduce perceived discomfort; 3– Slight increase blood oxygen levels to the lower legs were found with the use of the AC1 design (compared to NAC and AC2); 4– A slight increase in external obliques activity was also found with the use of the AC1 design (compared to NAC and AC2); 5– According to the exit survey, the majority of participants also preferred the AC1 chair. The use of an active chair (AC1) has potential, greater significant changes were hypothesized, however giving the participants the freedom to choose how to engage with the active chairs played a significant factor. To yield more health benefits from a chair design such as the AC1: perhaps a lengthy training process would be necessary to help change work habits (i.e. remembering to pedal the feet while working). As for experimental designs, future studies should implement set protocol guidelines (i.e. peddling the feet to the beat of a metronome) when it comes to investigating active sitting, meaning training would not be necessary. Overall our preliminary findings suggest that having an office chair with a split seat pan design shows potential to yield biomechanical and physiological benefits for the sitter, however further research is needed to better understand the ergonomics behind active sitting.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Bao, S., Lin, J.H., 2018. An investigation into four different sit–stand workstation use schedules. Ergonomics 61 (2), 243–254. https://doi.org/10.1080/00140139.2017.1353139.

Callaghan, J., Dunk, N., 2002. Examination of the flexion relaxation phenomenon in erector spinae muscles during short duration slumped sitting. Clin. BioMech. 353–360.

Callaghan, J.P., McGill, S.M., 2001. Low back joint loading and kinematics during standing and unsupported sitting. Ergonomics 44 (3), 280–294.

Canadian Centre for Occupational Health and Safety (2021-06-03), 2018. https://www.ccohs.ca/oshanswers/ergonomics/office/.

Cardoso, M., Fulton, F., McKinnon, C., Callaghan, J.P., Johnson, M.J., Albert, W.J., 2018a. Ergonomic evaluation of a new truck seat design: a field study. Int. J. Occup. Saf. Ergon. 1–13.

Cardoso, M., McKinnon, C., Viggiani, D., Johnson, M.J., Callaghan, J.P., Albert, W.J., 2018b. Biomechanical investigation of prolonged driving in an ergonomically designed truck seat prototype. Ergonomics 61 (3), 367–380.

Chambers, A.J., Robertson, M.M., Baker, N.A., 2019. The effect of sit–stand desks on office worker behavioral and health outcomes: a scoping review. Appl. Ergon. 78, 37–53. https://doi.org/10.1016/j.apergo.2019.01.015.

Chau, J.Y., Merom, D., Grunseit, A., Rissel, C., Bauman, A.E., van der Ploeg, H.P., 2012. Temporal trends in non–occupational sedentary behaviours from Australian Time Use Surveys 1992, 1997 and 2006. Int. J. Behav. Nutr. Phys. Activ. 9 (1), 76.

Clemes, S.A., O'connell, S.E., Edwardson, C.L., 2014. Office workers' objectively measured sedentary behavior and physical activity during and outside working hours. J. Occup. Environ. Med. 56 (3), 298–303.

Czech, M.P., 2017. Insulin action and resistance in obesity and type 2 diabetes. Nat. Med. 23 (7), 804.

De Looze, M.P., Kuijt–Evers, L.F., Van Dieen, J.A.A.P., 2003. Sitting comfort and discomfort and the relationships with objective measures. Ergonomics 46 (10), 985–997.

Dunstan, D., Howard, B., Healy, G., Owen, N., 2012. Review. Too much sitting – a health hazard. Diabetes Res. Clin. Pract. 97, 368–376.

Ellegast, R.P., Kraft, K., Groenesteijn, L., Krause, F., Berger, H., Vink, P., 2012. Comparison of four specific dynamic office chairs with a conventional office chair: impact upon muscle activation, physical activity and posture. Appl. Ergon. 43 (2), 296–307.

Goodyear, L.J., Kahn, B.B., 1998. Exercise, glucose transport, and insulin sensitivity. Annu. Rev. Med. 49 (1), 235–261.

Gregory, D.E., Dunk, N.M., Callaghan, J.P., 2006. Stability ball versus office chair: comparison of muscle activation and lumbar spine posture during prolonged sitting. Hum. Factors 48 (1), 142–153.

Groenesteijn, L., Ellegast, R.P., Keller, K., Krause, F., Berger, H., de Looze, M.P., 2012. Office task effects on comfort and body dynamics in five dynamic office chairs. Appl. Ergon. 43 (2), 320–328.

Harrison, D.D., Harrison, S.O., Croft, A.C., Harrison, D.E., Troyanovich, S.J., 1999. Sitting biomechanics part I: review of the literature. J. Manipulative Physiol. Therapeut. 22 (9), 594–609.

Healy, G.N., Wijndaele, K., Dunstan, D.W., Shaw, J.E., Salmon, J., Zimmet, P.Z., Owen, N., 2008. Objectively measured sedentary time, physical activity, and metabolic risk: the Australian Diabetes, Obesity and Lifestyle Study (AusDiab). Diabetes Care 31 (2), 369–371.

Herrmann, M.J., Ehlis, A.C., Fallgatter, A.J., 2003. Frontal activation during a verbal-fluency task as measured by near-infrared spectroscopy. Brain Res. Bullet. 61 (1), 51–56.

Holm, S., Nachemson, A., 1983. Variations in the nutrition of the canine intervertebral disc induced by motion. Spine 8 (8), 866–874.

Holmes, M.W., De Carvalho, D.E., Karakolis, T., Callaghan, J.P., 2015. Evaluating abdominal and lower–back muscle activity while performing core exercises on a stability ball and a dynamic office chair. Hum. Factors 57 (7), 1149–1161.

Jia, B., Nussbaum, M.A., 2018. Influences of continuous sitting and psychosocial stress on low back kinematics, kinetics, discomfort, and localized muscle fatigue during unsupported sitting activities. Ergonomics 61 (12), 1671–1684.

Jonsson, B., 1978. Kinesiology: with special reference to electromyographic kinesiology. Electroencephalogr. Clin. Neurophysiol. (34), 417–428.

Karakolis, T., Callaghan, J.P., 2014. The impact of sit–stand office workstations on worker discomfort and productivity: a review. Appl. Ergon. 45 (3), 799–806.

Kingma, I., van Dieën, J.H., 2009. Static and dynamic postural loadings during computer work in females: sitting on an office chair versus sitting on an exercise ball. Appl. Ergon. 40 (2), 199–205.

Kuster, R.P., Bauer, C.M., Gossweiler, L., Baumgartner, D., 2018. Active sitting with backrest support: is it feasible? Ergonomics 61 (12), 1685–1695.

Levin, E., MacIntosh, D., Baker, T., Weatherall, M., Beasley, R., 2009. Effect of sitting in ergonomic chairs on lower limb venous blood flow. Occup. Ergon. 8 (2–3), 125–132.

Lind, L., Lithell, H., 1993. Decreased peripheral blood flow in the pathogenesis of the metabolic syndrome comprising hypertension, hyperlipidemia, and hyperinsulinemia. Am. Heart J. 125 (5), 1494–1497.

Makhsous, M., Lin, F., Hendrix, R.W., Hepler, M., Zhang, L.Q., 2003. Sitting with adjustable ischial and back supports: biomechanical changes. Spine 28 (11), 1113–1121.

Maniadakis, N., Gray, A., 2000. The economic burden of back pain in the UK. Pain 84 (1), 95–103.

Matthews, C.E., Chen, K.Y., Freedson, P.S., Buchowski, M.S., Beech, B.M., Pate, R.R., Troiano, R.P., 2008. Amount of time spent in sedentary behaviors in the United States, 2003–2004. Am. J. Epidemiol. 167 (7), 875–881.

O'Keeffe, M., Dankaerts, W., O'Sullivan, P., O'Sullivan, L., O'Sullivan, K., 2013. Specific flexion–related low back pain and sitting: comparison of seated discomfort on two different chairs. Ergonomics 56 (4), 650–658.

Orsted, H., Ohura, T., Harding, K., 2010. Pressure ulcer prevention. Pressure, shear, friction and microclimate in context. Int. Rev. 1–25.

Pynt, 2013. Dynamic Sitting and the Core–Flex Office Chair. White Paper, Unpublished.

Pynt, J., 2015. Rethinking design parameters in the search for optimal dynamic seating. J. Bodyw. Mov. Ther. 19 (2), 291–303.

Rhalmi, E., Yahia, L., Newman, N., Isler, M., 1993. Immunohistochemical study of nerves in lumbar spine ligaments. Spine 18, 264–267.

Rubin, D.I., 2007. Epidemiology and risk factors for spine pain. Neurol. Clin. 25 (2), 353–371.

Schinkel–Ivy, A., Nairn, B.C., Drake, J.D., 2013. Investigation of trunk muscle co–contraction and its association with low back pain development during prolonged sitting. J. Electromyogr. Kinesiol. 23 (4), 778–786.

Snarr, R.L., Langford, E.L., Ryan, G.A., Wilhoite, S., 2019. Cardiovascular and metabolic responses of active sitting while performing work–related tasks. Ergonomics 62 (9), 1227–1233.

Snijders, C., Hermans, P., Niesing, R., Kleinrensink, G.J., Pool–Goudzwaard, A., 2008. Effects of slouching and muscle contraction on the strain of the iliolumbar ligament. Man. Ther. 13, 325–333.

Synnott, A., Dankaerts, W., Seghers, J., Purtill, H., O'Sullivan, K., 2017. The effect of a dynamic chair on seated energy expenditure. Ergonomics 60 (10), 1384–1392.

Triglav, J., Howe, E., Cheema, J., Dube, B., Fenske, M.J., Strzalkowski, N., Bent, L., 2019. Physiological and cognitive measures during prolonged sitting: comparisons between a standard and multi–axial office chair. Appl. Ergon. 78, 176–183.

Van Dieën, J.H.L., De Looze, M.P., Hermans, V., 2001. Effects of dynamic office chairs on trunk kinematics, trunk extensor EMG and spinal shrinkage. Ergonomics 44 (7), 739–750.

Wang, X., Cardoso, M., Theodorakos, I., Beurier, G., 2019. A parametric investigation on seat/occupant contact forces and their relationship with initially perceived discomfort using a configurable seat. Ergonomics 1–25.

Winter, D.A., 1995. Human balance and posture control during standing and walking. Gait Posture 3 (4), 193–214.

Zemp, R., Taylor, W.R., Lorenzetti, S., 2015. Are pressure measurements effective in the assessment of office chair comfort/discomfort? A review. Appl. Ergon. 48, 273–282.