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A biomechanical and physiological study of office seat and tablet device interaction

Eric Weston [a, b, *], Peter Le [a, b], William S. Marras [a, b]

[a] Spine Research Institute – Biodynamics Laboratory, The Ohio State University, Columbus, OH 43210, USA
[b] Department of Integrated Systems Engineering, The Ohio State University, Columbus, OH 43210, USA

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ABSTRACT

Twenty subjects performed typing tasks on a desktop computer and touch-screen tablet in two chairs for an hour each, and the effects of chair, device, and their interactions on each dependent measure were recorded. Biomechanical measures of muscle force, spinal load, and posture were examined, while discomfort was measured via heart rate variability (HRV) and subjective reports. HRV was sensitive enough to differentiate between chair and device interactions. Biomechanically, a lack of seat back mobility forced individuals to maintain an upright seating posture with increased extensor muscle forces and increased spinal compression. Effects were exacerbated by forward flexion upon interaction with a tablet device or by slouching. Office chairs should be designed with both the human and workplace task in mind and allow for reclined postures to off-load the spine. The degree of recline should be limited, however, to prevent decreased lumbar lordosis resulting from posterior hip rotation in highly reclined postures.

1. Introduction

Working adults tend to spend anywhere between about one half to 86% of the workday seated, depending on the occupation (Jans et al., 2007; Katzmarzyk et al., 2009; Toomingas et al., 2012). Prolonged seating has also been associated with musculoskeletal disorders related to low back pain (LBP), low-level static loading of the back muscles, disc degeneration, and spine stiffness (Beach et al., 2005; Callaghan and McGill, 2001; Frymoyer et al., 1980; Hales and Bernard, 1996; Holmes et al., 2015; Marras et al., 1995; Videman and Battié, 1999; Visser and van Dieen, 2006).

Trends relating to prolonged seating can be attributed to the increasing computer and deskwork associated with most jobs. In 2009, Sweden estimated that 70–75% of the workforce uses computers at work (SWEA, 2010). With the advancement of technology, computing devices have become more mobile, thereby resulting in heavier use of touch-screen tablets and smartphones (Dillon, 2014). Tablet devices originally gained popularity for personal use, but have increased in popularity within the workplace over recent years. It was estimated several years ago, that by 2017, nearly one in five tablets purchased in the United States will be used for business purposes (Dillon, 2014). Survey data has also shown that those employees that already own tablet devices spend 2.1 h daily on their tablet for work purposes, accounting for 26% of their total computing time (CDW, LLC. 2012).

It is well documented in the literature that extensive computer work serves as a risk factor for musculoskeletal disorders (Brandt et al., 2004; Ijmker et al., 2007; Lassen et al., 2004; Marcus et al., 2002; Waersted et al., 2010; Wigaeus Tornqvist et al., 2009). However, due to the sudden popularity and adoption of tablets in the workplace, little research has been performed to evaluate the risks associated with prolonged tablet use in an office setting. Sitting is the most common posture adopted during tablet computer use (Shan et al., 2013), and tablet use in a seated posture is often accompanied by forward flexion of the trunk and lack of armrest use, thereby leaving the weight of the upper body unsupported and risking back pain (Sttawarz and Benedyk, 2013).

While studies have examined how postures assumed during tablet use affect the head, neck, and upper limb over short time frames (Sttawarz and Benedyk, 2013; Vasavada et al., 2015; Young et al., 2012, 2013), none have examined how extended tablet use affects loading on the lumbar spine. Additionally, there are no studies to date that examine biomechanical measures associated with tablet use over an extended period. Thus, it remains unclear

* Corresponding author. 1971 Neil Avenue Rm 210, Columbus, OH 43210, USA.
E-mail address: weston.101@osu.edu (E. Weston).

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how the combined risks of prolonged seating and consistent use of both desktop computers and portable electronic devices such as touch-screen tablets might present over time.

Discomfort is also a common issue during long periods of sedentary work (Michel and Helander, 1994; Zhang et al., 1996) and is typically measured as a subjective factor in the ergonomics literature. However, subjective discomfort ratings have been shown to be subject to factors such as aesthetic bias (Helander, 2010). Moreover, a study in automotive seating by Le et al. (2014) showed high between and within subject variability in subjective ratings of discomfort, highlighting the need for more objective discomfort measures. The use of heart rate variability (HRV) as an objective measure of discomfort is new to the ergonomics literature and deserves further exploration. Under asymptomatic conditions, the heart is not a metronome; beat to beat variation in the signal exists during tonic flux between sympathetic and parasympathetic responses in the autonomic system. Under high stress conditions or pain, sympathetic responses may increase as parasympathetic responses decrease, thereby reducing the amount of variability between beats (Appelhans and Luecken, 2008; Cohen et al., 2000; Thayer and Brosschot, 2005; Thayer and Lane, 2000, 2009). Since pain and discomfort are believed to be interrelated, it is believed that interactions between discomfort and variability in heart rate will behave similarly.

It has been noted that individuals that are asymptomatic for LBP do not perceive disc pressure or proprioceptive information about body posture well enough to discriminate between chair design features (deLooze et al., 2003). Objective discomfort derived from HRV could capture information about physiological discomfort due to tissue loading that might not otherwise be perceived by the body. Additionally, HRV can be measured continuously as opposed to the need to rely on subjective reports from subjects at the end of the experimental condition. A recent study by Le and Marras (2016) explored heart rate variability (HRV) as an objective measure associated with discomfort in order to assess differences in discomfort as subjects interacted with different workstations (standing, perching, and seating) (Le and Marras, 2016). As findings showed that HRV could differentiate between standing (high discomfort) and seating (low discomfort) over time, it is postulated that the measure may also be sensitive enough to differentiate different seated/task conditions.

The overall aim of this study was to examine how physiological and biomechanical measures are influenced by different chair and device (desktop computer and touch-screen tablet) interactions. Our hypotheses for this study were two-fold. First, given that tablet use is likely accompanied by increased torso flexion angles that could increase moment exposure to the spine, we hypothesized that the use of a touch-screen tablet over the extended period of 1 h would be associated with higher spinal loads relative to traditional desktop computer use. Second, we hypothesized that the HRV measure would be sensitive enough to differentiate between chair and device interactions.

2. Methods

2.1. Approach

A laboratory study was conducted to evaluate biomechanical and discomfort measures in relation to varied chair and device interactions. Biomechanical measures were derived from motion capture and electromyography (EMG) data collected and processed together and used in a biologically-driven, EMG-assisted spine model; this model has been validated by over thirty years of peer-reviewed research and has been described extensively in the literature (Marras and Sommerich, 1991a, 1991b; Granata and Marras, 1993; Granata and Marras, 1995; Marras and Granata, 1997; Dufour et al., 2013). Discomfort was quantified both subjectively through survey and objectively as a function of physiological heart rate variability (HRV).

2.2. Study design

A 2 × 2 repeated measures design (Fig. 1) was implemented using two different chairs (a nearly right-angled wooden chair expected to be uncomfortable and denoted as the Control Chair and the Gesture chair; Steelcase, Grand Rapids, MI, USA) and two different devices (a desktop computer running a 64-bit Windows 7 Enterprise; Microsoft Corporation, Redmond, WA, USA and an iPad2; Apple, Cupertino, CA, USA). Subjects were assigned to complete typing tasks during each of the four conditions encountered. Each condition was tested for 1 h with a 20-min recovery period in between each level, consistent with the methodology presented by Le and Marras (2016). The order in which the conditions were encountered were randomized within a predetermined counterbalanced structure to control for potential order effects.

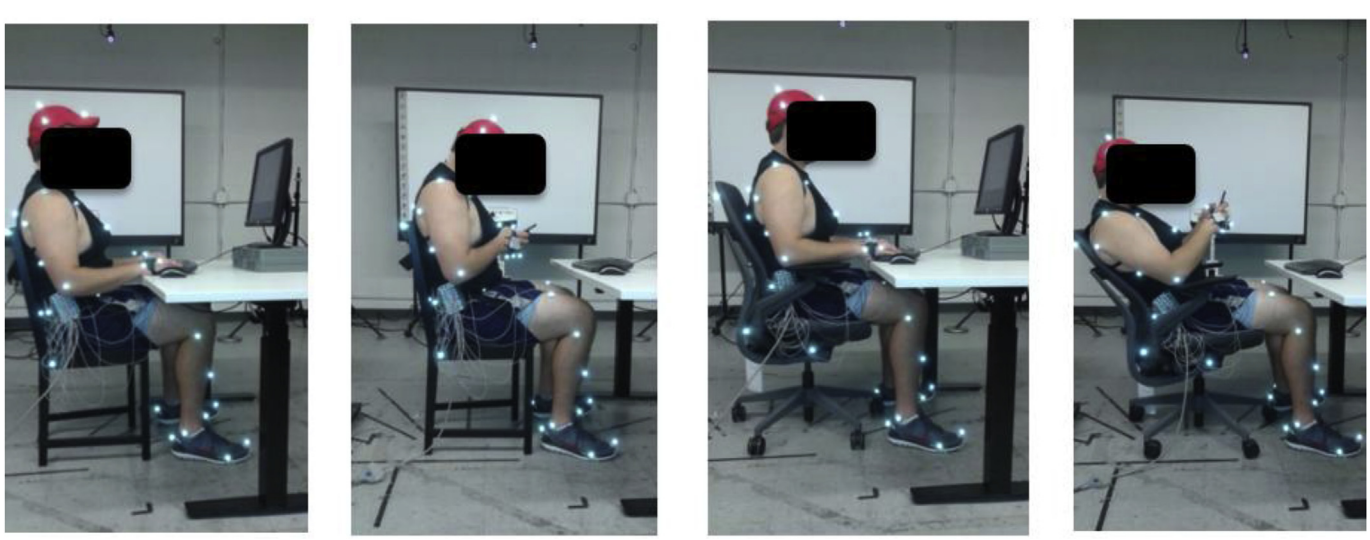

Fig. 1. Experimental setup (left to right) for the control chair/computer, control chair/tablet, Gesture chair/computer, and Gesture chair/tablet conditions.

2.2.1. Independent measures

Independent variables included chair, device, the chair*device interaction, and time as an ordinal variable. The order in which the conditions were encountered was also examined as an independent variable to determine the effectiveness of the counterbalancing measures taken.

2.2.2. Dependent measures

The data were analyzed with respect to three different areas of interest: biomechanical and physical loading, discomfort, and cognitive performance. The implemented spine model estimated peak muscle forces for the latissimus dorsi (LD), erector spinae (ES), rectus abdominis (RA), external oblique (EO), and internal oblique (IO) bilaterally for each trial via modulation of EMG activity with a gain ratio determined via model calibration, muscle location and area derived from MRI, and force-velocity and force-length relationships of muscle (Marras and Granata, 1997). The model also estimated peak spinal loads (compression, anterior/posterior shear, lateral shear) at both the superior and inferior endplate spinal levels extending from T12 to S1. Mean flexion and extension angles relative to each subject's upright standing posture were also calculated within the model for the neck, hips, and torso across the time interval of each trial collected; these kinematic calculations were driven by relative differences between body segment locations and orientations derived via motion capture.

Localized discomfort in 19 regions of the body was measured via the use of subjective VAS discomfort surveys on a 0–10 cm continuous scale (Hawker et al., 2011). Physiological discomfort was quantified via measurement of HRV in the frequency domain, in particular the ratio between the areas of power spectrum density for low and high frequency responses (LF/HF). Signal in the low frequency range (LF, 0.04–0.15 Hz) was influenced by both sympathetic and parasympathetic divisions of the autonomic nervous system, while the signal in the high frequency range (HF, 0.15–0.40 Hz) was predominantly influenced by parasympathetic response (Appelhans and Luecken, 2008). When the sympathetic and parasympathetic divisions were balanced LF/HF was expected to fluctuate at normal levels, but as discomfort set in LF/HF was expected to increase.

Cognitive performance was measured using typing speed and accuracy measures. On both devices, speed was measured using the gross words a minute (GWAM) typed by the subject. Accuracy was measured on the computer using an accuracy percentage calculated by software. The software chosen for typing on the iPad did not accept typing errors, so accuracy was instead measured by the total number of errors made for each assigned typing task.

2.3. Subjects

Twenty subjects (ten male, ten female) were recruited from the local population for this study. This sample size was found to be sufficient to detect effects in variables of interest with a power of 0.8 and significance level (α) = 0.05. All subjects were asymptomatic for LBP and had not encountered any musculoskeletal injury for at least one year prior to enrollment. Mean (±SD) age, body mass, stature, and body mass index (BMI) of the participants were 22.4 ± 2.4 years, 69.8 ± 10.6 kg, 173.5 ± 9.7 cm, and 23.3 ± 3.6, respectively. The study was approved by the University's Institutional Review Board.

2.4. Instrumentation

Kinematic data were captured at a sampling rate of 100 Hz using an OptiTrack optical motion capture system (NaturalPoint, Corvallis, OR, USA) with 24 infrared cameras, and kinetic data used during model calibration were recorded using a force plate (Bertec 4050A, Bertec, Worthington, OH, USA) sampling at 1000 Hz. Optical data were filtered using a fourth-order Butterworth filter with a cutoff frequency of 10 Hz. Electromyography (EMG) data was measured using a Model 12 Neuradata Acquisition System (Grass Technologies, West Warwick, RI, USA) at a sampling rate of 1000 Hz. Signals were band-pass filtered at 30–450 Hz and notch filtered at 60 Hz. The signals were then rectified, smoothed using a moving average filter, and normalized based on techniques presented by Dufour et al. (2013). Physiological discomfort was quantified via measurement of HRV using a FirstBeat Bodyguard 2™ heart rate monitor (FirstBeat Technologies, Jyväskylä, Finland).

2.5. Experimental procedure

Time of day effects were minimized by ensuring that testing sessions began in the mornings and concluded in the early evening. At the beginning of each testing session, subjects were given a brief description of the subject preparation process and experimental conditions that would be encountered. After providing informed consent, anthropometric measurements were recorded as inputs for the biologically-assisted dynamic spine model. Standard muscle site preparation guidelines were followed (Marras, 1990), and surface electrodes were applied to the ten muscles contributing to the lumbar spine model according to standard placement procedures (Mirka and Marras, 1993; Soderberg, 1992). Forty-six motion capture markers were placed on the body according to the 41 standard placement locations from OptiTrack's motion capture software with 5 extra markers placed onto the torso and hips for redundancy, and a heart rate monitor was also placed with electrodes located directly inferior to the clavicle on the right side of the body and on the inferior aspect of the rib cage on the left side. Once fitted with all of the sensors, subjects underwent a series of lifting motions on the force plate to calibrate the spine model according to a no-max calibration procedure (Dufour et al., 2013). Subjects were also asked to complete a baseline VAS discomfort survey at this time.

Before each seating condition encountered, the workstation was adjusted to fit each individual subject's anthropometry and in accordance with ANSI/HFES 100-2007 standards (ANSI/HFES, 2007). Subjects sat behind a standard table 74 cm high with basic workstation parameters aimed to keep torso-thigh angles $\geq 90^\circ$, elbow flexion aimed for 90°, and wrist flexion within 30 degrees of flexion or extension. Subjects were allowed to set the back tension in the Gesture chair according to what felt most comfortable. The monitor distance was set within 50–100 cm, and the viewing angle was set between 15 and 25° below horizontal eye level in experimental conditions using the desktop computer. Additionally, subjects were constrained to using the device in the landscape orientation only during tablet typing, as the spacing of the keyboard in this orientation better approximated that of a desktop computer.

Once settled, subjects were instructed to begin typing at a comfortable pace. Subjects reproduced text displayed on the screen in front of them on both of the devices; computer typing was performed using Typing Test TQ software (Giletech e.K, Munich, Germany) in which subjects reproduced paragraphs of text, while tablet typing was performed using MySpeed—Typing Speed Test v2.2 (Giuseppe Socci, accessed and downloaded for free on the iTunes Application Store) in which subjects reproduced single sentences. These typing tasks were assumed to be representative of actual workplace demands based on device, as desktop computer and tablet use are generally associated with heavy and light levels of content creation, respectively (Muller et al., 2012). Posture and typing technique were unconstrained, and subjects were instructed

Table 1
Summary of the statistically significant main effects and interactions for the dependent measures. (*p < 0.05, **p < 0.01, ***p < 0.001). Effects that were also deemed biologically significant have been shaded and include the directionality of the main effects. Directionality compares the Gesture chair relative to the control chair tablet typing relative to computer typing.

	Dependent Measure	Chair		Device		Chair * Device
Physiological Discomfort	LF/HF	↓	***	↓	***	
Subjective Discomfort Rating	Neck	↓	*			
	Upper Back	↓	**			
	Lower Back	↓	***			
	Buttocks	↓	***			
	Wrist/Hand					
Muscle Forces	R. Erector Spinae	↓	***			
	L. Erector Spinae	↓	***	↑	***	*
	R. Latissiumus Dorsi			↑	***	
	L. Latissimus Dorsi			↑	***	
	R. Rectus Abdominis					
	L. Rectus Abdominis					
	R. External Oblique					
	L External Oblique			***		
	R. Internal Oblique	***				
	L. Internal Oblique	**		***		
Spinal Load - Compression	T12/ L1 (Superior)	↓	***	↑	***	
	T12 / L1 (Inferior)	↓	***	↑	***	
	L1 / L2 (Superior)	↓	***	↑	***	
	L1 / L2 (Inferior)	↓	***	↑	***	
	L2 / L3 (Superior)	↓	***	↑	***	
	L2 / L3 (Inferior)	↓	***	↑	***	
	L3 / L4 (Superior)	↓	***	↑	***	
	L3 / L4 (Inferior)	↓	***	↑	***	
	L4 / L5 (Superior)	↓	***	↑	***	
	L4 / L5 (Inferior)	↓	***	↑	***	
	L5 / S1 (Superior)	***		↑	***	
	L5 / S1 (Inferior)	***		↑	***	
Spinal Load – A/P Shear	T12/ L1 (Superior)	**				
	T12 / L1 (Inferior)					
	L1 / L2 (Superior)					
	L1 / L2 (Inferior)					
	L2 / L3 (Superior)					
	L2 / L3 (Inferior)	↓[x]	***	*		**
	L3 / L4 (Superior)	↓[x]	***	*		**
	L3 / L4 (Inferior)	↓	***	***		***
	L4 / L5 (Superior)	↓	***	**		***
	L4 / L5 (Inferior)	↓	***	***		***
	L5 / S1 (Superior)	↓	***			***
	L5 / S1 (Inferior)	↓	***			**
Spinal Load – Lateral Shear	No significant effects					
Joint Angles	Neck Flexion			↑	***	
	Torso Flexion	↑	***	↑	***	
	Hip Extension	↑	***	↑	***	***

[x] Effect represents a shift from anterior to posterior shear, is actually an increase in the *magnitude* of shear loading.

to move naturally throughout each hour so as to be representative of an actual workplace sitting environment as possible; the only constraint was that subjects could not stand up out of the seat. At the end of each hour, subjects filled out a discomfort survey and were encouraged to walk around to recover before the next experimental condition.

2.6. Analysis procedure

Localized subjective discomfort ratings were collected via the VAS discomfort survey at baseline and then the end of each condition. Objective whole-body discomfort was measured using HRV data collected continuously throughout each hour and analyzed in 5 min windows using Kubios open-source software; this analysis software has been described in depth in Tarvainen et al. (2014). EMG and motion capture data were collected in 1 min increments every 5 min (0, 5, 10, 15 min, and so on) to compare time points between conditions and subjects. These data were input into the EMG-assisted spine model to calculate peak muscle forces and spinal loads and calculate mean joint angles throughout each minute. Cognitive performance on both the computer and tablet devices were also analyzed in 5 min windows.

Processed data were analyzed using JMP 11.0 software (SAS Institute Inc., Cary, NC, USA). A repeated-measures, two-way analysis of variance (ANOVA) was employed for all dependent measures with a significance level (α) of 0.05, and post-hoc analyses were performed using a Tukey HSD test where appropriate. LF/HF and cognitive performance measures for the tablet device were log-normalized before running the statistical analysis to reduce skew in the data. All data derived via outputs of the biomechanical model were also interpreted relative to assumed biological significance within the resolution of the model employed; only differences between mean muscle forces of 15 N or more and between mean peak spinal loads of 30 N or more between experimental condition types were assumed to be biologically significant. Finally, correlation analyses were run to determine potential relationships between postural and biomechanical measures.

3. Results

A summary of statistically significant differences observed for all dependent variables relative to the chair, device, and the chair*-device interaction is shown in Table 1. No time or order effects were observed in relation to the biomechanical results (muscle force, spinal load, joint angles) or the physiological or subjective discomfort measures; as such, the data subsequently presented are representative of all of the processed data obtained during each hour across subjects. Conversely, cognitive performance measures of typing speed and typing accuracy (not shown in Table 1) were not found to be significant for either of the main effects or the interaction, but time and order did significantly affect cognitive performance.

3.1. Biomechanical

3.1.1. Muscle forces

As shown in Fig. 2, consistent and statistically and biologically significant main effects were observed bilaterally in only two muscles: the latissimus dorsi and erector spinae. Latissimus dorsi muscle forces were increased bilaterally during tablet use ($p < 0.0001$). Erector spinae muscle forces were also increased bilaterally in the control chair compared to the Gesture chair ($p < 0.0001$). In the left erector spinae, muscle force was also increased during tablet use ($p = 0.0002$) and a chair*device interaction was observed to be significant in which the increase in muscle force between the computer and tablet devices was much more drastic in the control chair than in the Gesture chair ($p = 0.0258$). Other statistically significant results included: increased left internal oblique and right internal oblique force in the control chair relative to the Gesture chair ($p = 0.001$ and $p = 0.0001$, respectively) and increased left external oblique and left internal oblique force in tablet typing relative to computer typing ($p = 0.0002$). These differences were in the order of only several Newtons of difference and were not deemed to be biologically significant.

3.1.2. Spinal loads

Spinal compression and anterior/posterior shear saw significant effects, but lateral shear was not found to be significant. Spinal loads were driven by compression at all levels. Compression was higher for tablet typing ($p < 0.0002$) and higher in the control chair ($p < 0.0001$), with no significant chair*device effect. In terms of A/P shear, significant chair and device* chair interaction effects were observed at spinal endplate level L2/L3 (Inferior) and below in which shear forces were shifted towards posterior shear in the Gesture chair ($p < 0.0001$), with the greatest effect during the Gesture chair/tablet experimental condition ($p < 0.004$).

All spinal loads observed were consistently well below tissue tolerances of 3400 N compression and 700 N shear (Waters et al., 1994; Gallagher and Marras, 2012). The highest spinal loads in compression were observed at the L4/L5 Superior endplate, while the highest magnitude of A/P shear spinal loads were observed at L5/S1 Inferior. These spinal loads are represented in Fig. 3, though the effect sizes and directions noted in this figure are consistent across all other endplate levels mentioned to be significant in terms of the aforementioned main effects.

3.1.3. Joint flexion/extension

A summary of mean flexion/extension angles for the neck, hips, and torso is shown in Fig. 4. Mean neck flexion angles were increased for the tablet typing conditions as compared to computer typing ($p < 0.0001$). Mean hip extension angles (denoting posterior rotation of the hips in the seat pan) were increased in the Gesture chair ($p < 0.001$) and increased during tablet use ($p < 0.0001$). There was also a significant chair*device interaction for hip flexion/extension that showed that the change in hip extension between the computer and tablet devices was much more drastic in the Gesture chair than in the control chair ($p < 0.0001$). Mean torso flexion effects mirrored those effects observed in the hips; torso flexion was increased in the Gesture chair ($p < 0.0001$) and increased during tablet use ($p < 0.0001$). Finally, a secondary correlation analysis determined a relationship to exist between maximum hip extension and maximum posterior shear at the L3/L4 Inferior endplate and below. A separate correlation analysis was performed for each of the five spinal levels extending from L3/L4 Inferior to L5/S1 Inferior, and the correlation coefficients ranged between 0.88 and 0.95.

3.2. Discomfort

LF/HF calculated from HRV data showed statistically significant chair and device main effects ($p = 0.0001$) but no statistically significant chair*device interaction. As shown in Fig. 5, less physiological discomfort was reported in the Gesture chair than the control chair and during use of the tablet than the computer. Post-hoc analysis revealed that the Gesture chair/tablet computer was the incurred the least discomfort of the four seating conditions.

Subjective discomfort from VAS reports are shown in Fig. 6 for the body parts that were determined to be the most commonly afflicted during this study. Discomfort was rated the highest in the

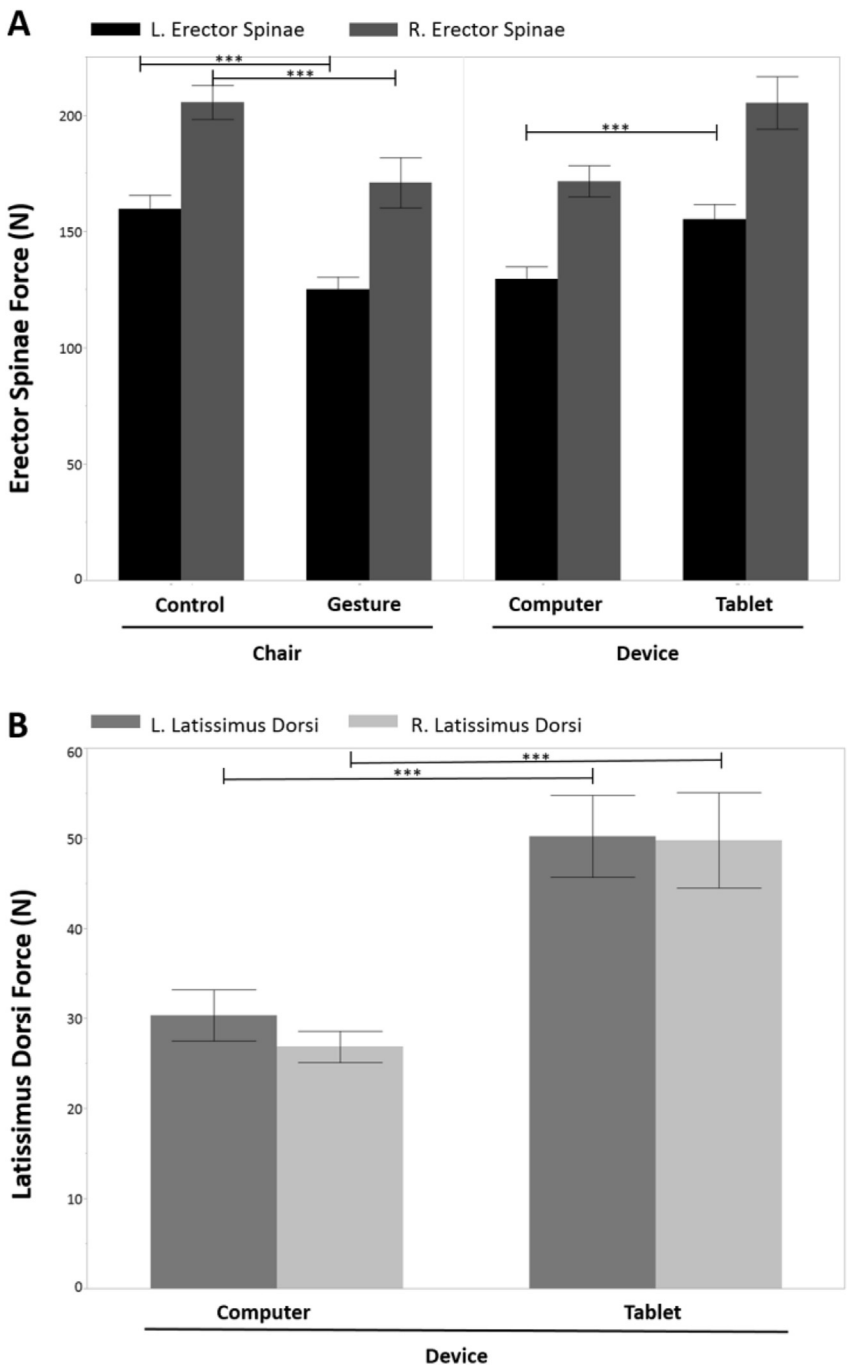

Fig. 2. Bilateral peak muscle forces for the **(A)** erector spinae and **(B)** latissiumus dorsi muscles for which statistically and biologically significant main effects were observed (***$p < 0.001$). Error bars denote standard error.

lower back, followed by the neck, upper back, and buttocks, and finally the distal upper extremity (hand/wrist). Subjective discomfort ratings were consistently higher for the control chair as compared to the Gesture chair ($p < 0.02$) for all body parts reported except for the hand/wrist. Though device was not found to be statistically significant for any body part, a general trend was observed for the neck in which discomfort was observed to be higher for the tablet device than for the computer in both chairs.

3.3. Cognitive performance

There was no statistically significant effect chair effect on typing speed or typing accuracy. Because different software was used to assess cognitive performance for each device, the potential effects of device or a chair*device interaction on cognitive performance measures of typing speed and accuracy were not evaluated.

Analyzing each device separately, a learning/order effect was observed during computer typing in which subjects typed faster ($p = 0.0218$) and more accurately ($p = 0.0345$) during whichever

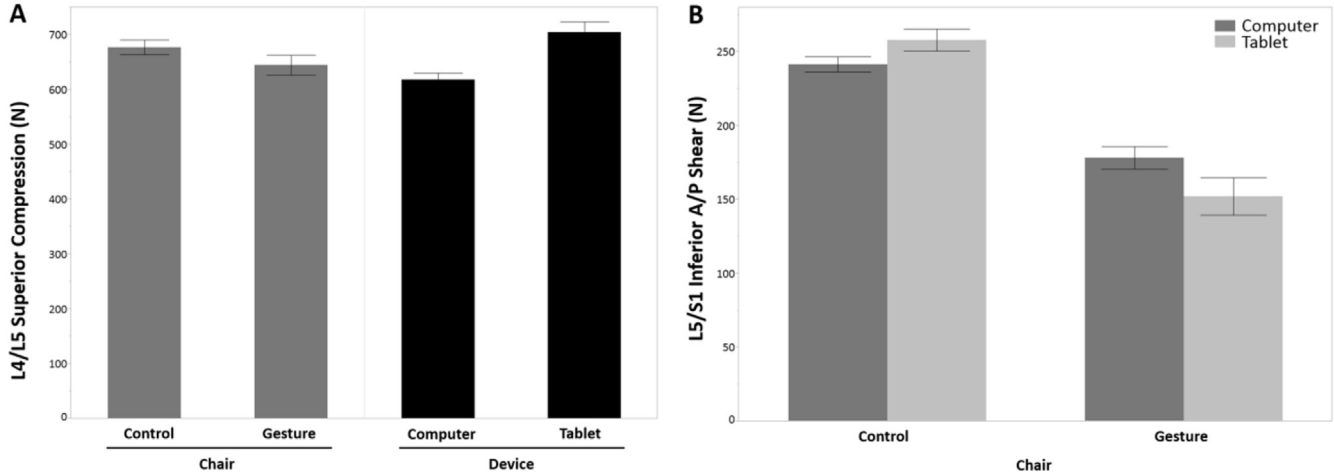

Fig. 3. Mean peak spinal loads in **(A)** compression and **(B)** anterior/posterior shear at the endplate levels with the highest spinal loads in each direction of loading. Compression was higher in the Control chair and higher during tablet typing with no significant chair*device interaction. Anterior/posterior shear was shifted towards posterior shear in the Gesture chair at lower spinal levels with a significant chair*device interaction. All effects shown were significant with a significance level of $\alpha = 0.05$; error bars denote standard error.

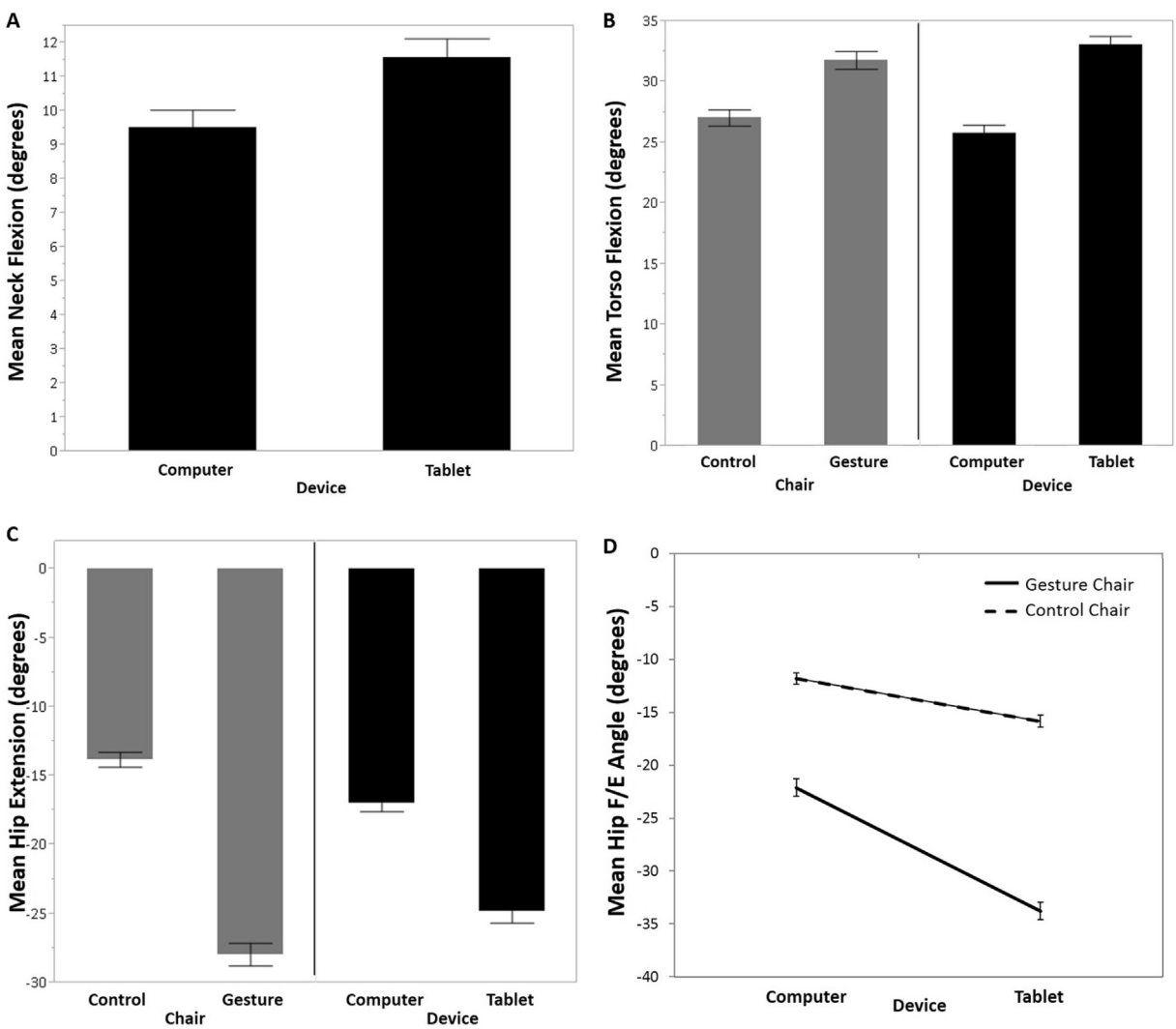

Fig. 4. Mean flexion (neck and torso) and extension (hip) angles assumed by chair, device, or chair*device. **(A)** Neck flexion was increased during tablet use. **(B)** Torso flexion angles were increased during tablet use and in the Gesture chair. **(C)** Main effects show that hip extension angles were increased (denoting posterior rotation of the hips) in the Gesture chair and during tablet typing. **(D)** The Gesture chair/tablet condition seems to be the experimental condition under which the most drastic changes in the hip angle are experienced. All effects shown were significant with a significance level of $\alpha = 0.05$; error bars denote standard error.

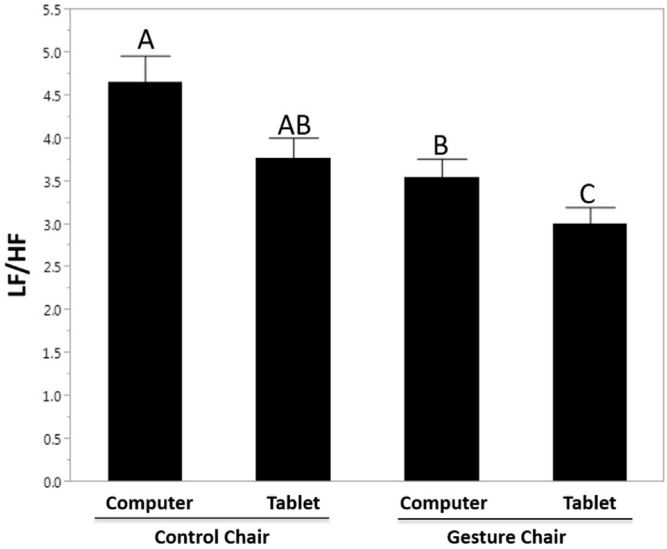

Fig. 5. Mean LF/HF discomfort for each of the four experimental conditions. Groups not connected by the same letter are significantly different from one another. Error bars denote standard error.

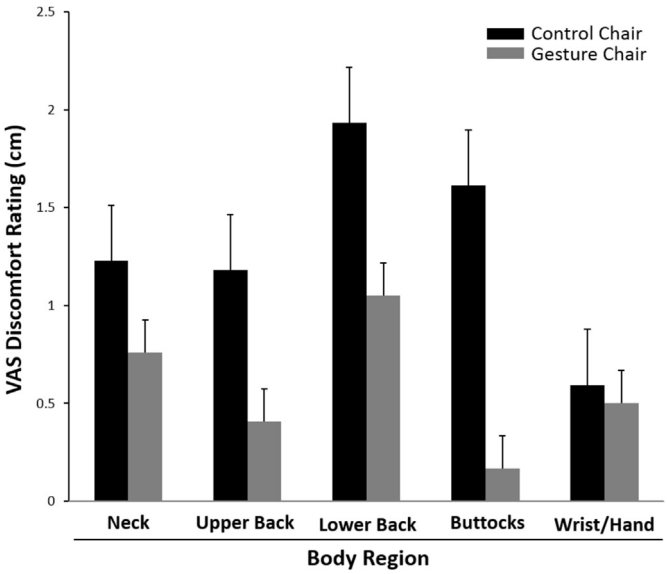

Fig. 6. Mean VAS subjective discomfort ratings by chair for the most afflicted body parts throughout the study. Discomfort was significantly increased ($p < 0.05$) in the Control chair for all body regions except for the wrist/hand. Error bars denote standard error.

hour was encountered second. A similar outcome occurred for the tablet typing conditions, during which subjects typed faster both as each hour progressed ($p = 0.0026$) and during whichever condition was encountered second ($p < 0.001$). However, accuracy, measured by the number of errors per sentence typed, remained consistent throughout each hour and across experimental conditions on the tablet.

4. Discussion

This study served as one of the first truly systematic, quantitative assessments of office seating from a biomechanical and physiological perspective. Measures were monitored continuously or in discreet intervals throughout conditions spanning an hour so as to not only determine how chair and device effects or interactions affect biomechanical measures but also investigate if or how these chair and device effects or interactions might change with prolonged seating. Time was not found to significantly influence biomechanical loading or physiological discomfort in this study. However, prolonged exposure to seated tasks as seen in office settings introduces the potential to induce a cumulative response over time.

Results indicated that chair, device, and chair*device interactions affect biomechanical and discomfort measures during seating. Overall, model outputs showed that spinal loads were consistently driven by compression forces and that spinal loads were consistently below damage thresholds (3400 N in compression and 700 N in shear) for spinal loading for all experimental conditions (Waters et al., 1994; Gallagher and Marras, 2012). However, relative differences in spinal loading between conditions may be insightful when placed into context with other measures such as recorded muscle forces, seating posture, and seating discomfort.

With the seat back and seat pan meeting nearly perpendicularly to one another in the control chair, subjects were forced to assume a nearly “right-angled” sitting posture as originally defined by Pynt et al. (2001). To maintain this “right-angled” (or what the authors of this study will refer to as “upright”) posture, required increased muscle forces were required in the left and right ES muscles. Upright postures have also been associated with faster muscle fatigue, slouched seating postures, decreased lumbar lordosis, and most notably, increased compression onto the spine (Andersson et al., 1974, 1975; Dolan et al., 1988; Floyd and Roberts, 1958). In contrast, the backrest of the Gesture chair had a more open angle between the seat back and seat pan with the ability to adjust this angle or perhaps even recline, allowing subjects to use the backrest to support much more of the weight of the torso than was supported in the control chair (Andersson et al., 1974; Grandjean and Hünting, 1977; Kayis and Hoang, 1999). As a result, peak muscle forces in the right and left ES muscles were reduced by 28% and 24% respectively, which by association reduced compression forces placed onto the spine. It is important to note, however, that a higher degree of recline could introduce a potential trade-off with other parts of the body such as the neck and shoulders; namely, torso flexion was increased in the Gesture chair, which could possibly require increased muscle activation in the shoulders.

The effect of device on muscle forces and spinal loading also seems to have been largely driven by posture. Typing on the tablet required subjects to either stabilize the iPad in one hand while typing with the other or rest the iPad on the desk (flat or sitting in the lap leaning against the desk edge) while typing with both hands. Muscle force in the latissimus dorsi increased by 66% bilaterally while typing on the tablet device as a result. In the control chair, subjects tended to maintain an upright posture in the control chair regardless of device, but the tablet device promoted either forward flexed or slouched postures that exacerbated the effects of an upright seating posture more so than the computer. When placing the tablet device flat on the desk surface, subjects often leaned over the desk to type, resulting in increased neck and torso flexion angles and increased left erector spinae forces relative to computer typing. When the tablet was not placed flat on the desk, subjects often set the tablet in their lap leaned against the desk edge and typed in a more slouched posture. A slouched seating posture has been implicated in other studies to be among the most dangerous seating postures that can be assumed. As slouching occurs, the lumbar spine becomes more flexed, which stretches and thins the posterior annulus of the IVD and adds tension to the posterior ligaments of the spine (Pynt et al., 2001). As a result, the facet joints are unloaded, and IVD and therefore spinal

compression forces are increased (Makhsous et al., 2003; Pynt et al., 2001; Reinecke and Hazard, 1994; Reinecke et al., 1994; Vergara and Page, 2000).

In contrast to the control chair, postures assumed in the Gesture chair were inherently different between computer and tablet conditions because of subjects' ability to recline in the Gesture chair during tablet typing. The chair*device interaction effect for hip extension angle showed in this study that the posture assumed during the Gesture chair/tablet experimental condition varied the most significantly from the other three conditions. As subjects reclined, they rotated their hips posteriorly, which increased their hip extension angle. As previously noted, this postural change was highly correlated ($r = 0.88$ or higher) with a posterior shift in the anterior/posterior shear forces on the lower portion of the spine during tablet typing. Posterior rotation of the hips has been associated with the reduction of lordosis on the lumbar spine (Pynt et al., 2001), which may explain the higher compression forces placed onto the spine during tablet typing relative to computer typing in the Gesture chair (Farfan et al., 1972; Grandjean and Hünting, 1977).

Previous work suggests that there may be a link between discomfort and both biomechanical and physiological measures (Helander and Zhang, 1997; Zhang et al., 1996). In the present investigation, HRV was used as an objective physiological measure of discomfort during prolonged seating. Le and Marras (2016) used the same analysis procedures in a recent study and found that HRV could detect differences in discomfort among standing, perching, and seated workstations. This study showed that HRV can also differentiate among two types of chairs and two devices in a seating environment, where differences are assumed to be subtle. Though individuals are not able to perceive spinal loads because of the lack of sensory organs in the disc (Adams et al., 1996), it is instead likely that discomfort may be mediated by the interaction of joint angles, magnitude and time-dependence of muscular loading, and changes in localized muscular oxygenation (Helander, 2010). The interaction of these biomechanical and physiological components may stimulate nociceptors, thus affecting the autonomic response of discomfort.

Similar to the explanations provided for biomechanical measures of muscle force and spinal load, it is postulated that the physiological discomfort differences observed can also largely be attributed to the postures assumed by subjects during each experimental condition. The postures assumed within the Gesture chair allowed for a wider hip to torso angle and reduced muscular loading in the erector spinae relative to the control chair. With this reduced muscular load, fewer nociceptors should be expected to be activated in the Gesture chair compared to the control chair, and a more even balance between parasympathetic and sympathetic divisions of the autonomic nervous system should be expected; the LF/HF HRV measure confirmed this expectation, as LF/HF was 19% lower for the Gesture chair as compared to the control chair.

Likewise, it is postulated that it was not the tablet device itself that caused the observed change in physiological discomfort, but the postures assumed while using the tablet device (particularly in the Gesture chair) that led to physiological discomfort differences. Post-hoc analysis of physiological discomfort derived from HRV noted no statistically significant difference based on device within the control chair (Fig. 5, Group A) where postures assumed for computer and tablet typing did not vary significantly. However, there was a statistically significant difference in physiological discomfort based on device within the Gesture chair (Groups B and C); this result directly aligns with the changes in hip extension due to the chair*device interaction effect previously described. Hip extension, or posterior pelvic rotation, is associated with passive loading of the posterior musculature and ligaments (Pynt et al., 2001). Passive loading of the posterior ligaments may result in excitability of the posterior musculature as a protective response (Solomonow, 2006; Granata et al., 2005). This in turn results in increased extensor activity and thereby increased compressive loading (erectors associated with compression) (McGill and Norman, 1986). Based on this, it is likely that the perception of pain/discomfort is extending from the loading of the ligamentous tissues (Solomonow et al., 1998).

Finally, subjective discomfort reports complemented objective HRV data and were beneficial in this study in determining which specific body regions were perceived to experience the most discomfort during the four experimental conditions tested. Consistent with seated subjective discomfort reports from Vergara and Page (2002), subjects reported discomfort most frequently in the neck, back, and buttocks. In our study, subjects also reported 35% higher discomfort in the neck for tablet typing relative to computer typing. Although not statistically significant, this trend appears to be viable in relation to the increased neck flexion during tablet use and is consistent with prior studies associating flexed head and neck postures with neck pain (Ariens et al., 2001; Harms-Ringdahl and Ekholm, 1986; McAviney et al., 2005).

4.1. Limitations

In this study, measures were predicted under laboratory conditions. Subjects were encouraged to move naturally within their seats but were restricted to their seat for the entirety of each hour. Employees in an actual office setting have the option to stand or walk around when uncomfortable, and it is recommended that breaks be taken for five to 10 min every hour (Toomingas et al., 2012). Thus, the experimental conditions tested may represent a 'worst-case' scenario for prolonged seated work.

While kinematic joint angles were measured for the neck, shoulders, and hips, the exact angle of recline assumed by subjects within the Gesture chair was not measured. The degree of recline assumed by subjects could have provided valuable information about the exact degree of recline at which a trade-off between off-loading of the spine via the seat back and decreased lumbar lordosis resulting from posterior hip rotation might be encountered. Likewise, the exact percentage of each subject's body weight that was supported by either the chair's backrest or desk surface and how these values change with varied postures were also unmeasured. Though neither of these limitations influenced the outputs derived from the EMG-assisted biomechanical spine model employed, recording the exact angle of recline or the percentage of the subject's body weight supported by external surfaces could have allowed for more direct comparisons with other prior seating studies (Grandjean and Hünting, 1977; Kayis and Hoang, 1999).

The subject population in this study was young (average 22.5 years) and physically fit (average BMI 23.3) and thus not perfectly representative of an expected office employee population. The Bureau of Labor Statistics reports the median age of the labor force to be 42.6 years, and it is estimated that a significant proportion of the population classifies as "Overweight" or "Obese," especially in sedentary jobs (BLS, 2015; National Institute of Diabetes and Digestive and Kidney Diseases, 2012). The population examined was instead representative of trends which specifically predict younger millennial workers to soon make up the largest proportion of the U.S. labor force (Fry, 2015; Lerman and Schmidt, 1999). Additionally, data were not recorded with respect to whether subjects were experienced tablet users, if subjects were accustomed to typing on an Apple device, if subjects were accustomed to typing on tablet devices in the landscape configuration, or if subjects were accustomed to typing on mobile devices such as tablets in seated postures.

A simplistic typing task was chosen to prevent cognitive factors from influencing discomfort measures and spinal load data. Activities requiring more cognition may distract the experience of pain and discomfort (Hashmi et al., 2013; Bushnell et al., 2013). Moreover, it should be noted that a typing task does not encompass all the cognitive demands of an entire office workday. Office employees use computers and electronic devices such as tablets for many other tasks aside from typing. Thus, it might be useful to investigate seating discomfort and biomechanical measures under varied tasks and cognitive demands.

Data was sampled in fixed intervals in this study to align different dependent measures (e.g. heart rate variability, muscle forces/spinal loads, cognitive performance) in 5 min sections over each hour during data analysis. Sampling in fixed intervals may not have captured important out-of-phase motions, so sampling at random intervals in future seating studies could be a more adequate approach in capturing motions that might otherwise have been missed by current data sampling methods. Nonetheless, the study as designed is the first to examine biomechanical and discomfort measures associated with tablet use over an extended period.

5. Conclusion

This study showed that low back and overall postural loading is associated with an interaction between individual, chair, and device. A lack of seat back mobility constrains individuals into an upright seating posture with increased extensor muscle forces and therefore increased compression placed onto the spine. These effects are exacerbated by increased forward flexion upon interaction with a tablet device or by slouching in the chair. It is recommended that reclined postures be assumed to allow for off-loading of the spine via the seat back. However, the extent of recline also plays a role in spinal loading while seated. In highly reclined postures, individuals tend to rotate their hips posteriorly while reclining, decreasing lumbar lordosis and increasing back extensor loading.

Furthermore, heart rate variability (HRV) can be used to measure physiological discomfort and differentiate among chair and device interactions within a seating environment. The physiological discomfort differences recorded for each experimental condition in this study were assumed to be even more subtle than the physiological discomfort differences recorded for standing, perching, and seated workstations in a prior investigation by Le and Marras (2016). The chairs evaluated were two extremes close to two opposite ends of a perceived comfort spectrum: a wooden, control chair that was expected to be uncomfortable and the Gesture chair which was specifically designed for mobile device (tablet) integration into the workplace. The degree of physiological discomfort experienced in each chair was assumed to be associated with seating posture and the associated interactions of joint angle and magnitude and time-dependence of muscular loading. Future research efforts could use a similar methodology to compare new chair design features to the two anchor points established in this study or examine chair/device/task interactions using varied chairs, cognitive tasks, or portable electronic devices.

As is consistent with the rapid popularity and adoption of tablets in the workplace, new technologies and adaptations made to existing technology (i.e., smaller touchscreens) are introduced and adopted in the workplace rather quickly. The tasks performed on these new devices and the postures endured while completing these tasks are inherently different than the tasks and postures associated with typical desktop computer work, rendering the need to investigate new potential risk factors surrounding the use of these new devices. Moreover, as technology advances, it will be important to think about designing seats that are adaptable to the human, the wide array of technologies, and the varied tasks that will be performed in office environments. Perhaps it is important to understand the technology that is upcoming to start thinking about the designs that may accommodate them.

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