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Anita N. Vasavada[abc], Derek D. Nevins[ac], Steven M. Monda[a], Ellis Hughes[a] & David C. Lin[abc]

[a] Voiland School of Chemical Engineering and Bioengineering, Washington State University, Pullman, WA, USA

[b] Department of Integrative Physiology and Neuroscience, Washington State University, Pullman, WA, USA

[c] Department of Mechanical and Materials Engineering, Washington State University, Pullman, WA, USA

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Anita N. Vasavada[a,b,c]*, Derek D. Nevins[a,c], Steven M. Monda[a], Ellis Hughes[a] and David C. Lin[a,b,c]

[a]*Voiland School of Chemical Engineering and Bioengineering, Washington State University, Pullman, WA, USA;* [b]*Department of Integrative Physiology and Neuroscience, Washington State University, Pullman, WA, USA;* [c]*Department of Mechanical and Materials Engineering, Washington State University, Pullman, WA, USA*

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Tablet computer use requires substantial head and neck flexion, which is a risk factor for neck pain. The goal of this study was to evaluate the biomechanics of the head–neck system during seated tablet computer use under a variety of conditions. A physiologically relevant variable, gravitational demand (the ratio of gravitational moment due to the weight of the head to maximal muscle moment capacity), was estimated using a musculoskeletal model incorporating subject-specific size and intervertebral postures from radiographs. Gravitational demand in postures adopted during tablet computer use was 3–5 times that of the neutral posture, with the lowest demand when the tablet was in a high propped position. Moreover, the estimated gravitational demand could be correlated to head and neck postural measures ($0.48 < R^2 < 0.64$, $p < 0.001$). These findings provide quantitative data about mechanical requirements on the neck musculature during tablet computer use and are important for developing ergonomics guidelines.

Practitioner Summary: Flexed head and neck postures occur during tablet computer use and are implicated in neck pain. The mechanical demand on the neck muscles was estimated to increase 3–5 times during seated tablet computer use versus seated neutral posture, with the lowest demand in a high propped tablet position but few differences in other conditions.

Keywords: tablet computer; biomechanics; neck muscles; posture

1. Introduction

Tablet computer usage has increased dramatically in recent years, both in the number of users and type of applications. In 2014, it was estimated that 42% of the US population 18 years or older own a tablet computer, with the highest rate of ownership in the 35–49 age group (52%) (Zickuhr and Raine 2014). Despite the widespread use of tablet computers, the potential for use-related injury has not been evaluated, and ergonomics recommendations have not been developed. Specifically, there are no existing ergonomics guidelines for tablet computer use similar to those for desktop computer display height and keyboard placement (e.g. NIOSH publication 99–135). As with the guidelines for desktop computer usage, both epidemiological and mechanistic biomechanical studies of the postures adopted during tablet computer use are necessary for development of ergonomics recommendations.

The head–neck postures during tablet computer usage have been measured using external (skin) markers (Straker et al. 2008; Young et al. 2012) or electrogoniometers (Werth and Babski-Reeves 2014). In the different tablet configurations (with or without an accessory stand and/or a table or desk) and tasks (typing, colouring or watching a movie) investigated, head and neck flexion angles were greater than those typically occurring during desktop or notebook computer usage. These postures could be problematic biomechanically because flexed head and neck postures are associated with neck pain (Chaffin 1973; Harms-Ringdahl and Ekholm 1986; Ariens et al. 2001; Yip, Chiu, and Poon 2008; Silva et al. 2009; Lau et al. 2010). In support of this idea, in a study of over 3600 high school students, 44% of the students who owned a tablet computer reported neck/shoulder discomfort 'often' or 'always' (Shan et al. 2013). Further, correlational analysis showed an average odds ratio of 1.25 of having neck/shoulder discomfort for the factor of owning a tablet computer (Shan et al. 2013).

The mechanistic basis for the relationship between head flexion angle and neck pain arises from the increase in gravitational moment of the head mass during flexed postures (Harms-Ringdahl et al. 1986; Thuresson et al. 2005; Straker et al. 2009). This requires greater activation of neck extensor muscles compared to that in neutral posture (Schüldt et al. 1986; Caneiro et al. 2010). Thus, extensors of the neck are vulnerable to fatigue, which can ultimately cause short- and long-term pain (Harms-Ringdahl and Ekholm 1986). Retrospective studies have found that patients with neck pain have significantly more flexed neck posture compared to healthy subjects, and the amount of flexion was significantly correlated to subjective measures of neck pain in patients (Yip, Chiu, and Poon 2008; Silva et al. 2009; Lau et al. 2010). However,

*Corresponding author. Email: vasavada@wsu.edu

prospective studies in the workplace involving varying desktop computer display monitor heights have been inconclusive about the relationship between posture and pain. Some studies have shown a trend between flexed postures and neck pain (Ariens et al. 2001), but others have not able to establish correlations between head and neck angles and pain (Hünting, Laubli, and Grandjean 1981; Starr, Shute, and Thompson 1985; Marcus et al. 2002; Green 2008).

For flexed head–neck postures, a physiologically relevant variable for assessing the potential for muscle fatigue is the ratio of gravitational moment to maximal muscle moment capacity (i.e. the *gravitational demand*). The gravitational demand incurred by the use of different visual display heights was estimated previously using a musculoskeletal model of the cervical spine and skull (Straker et al. 2009). An important feature of the model is that the maximal moment capacity of the neck musculature varied in the different postures due to changes in musculoskeletal geometry (i.e. moment arm) and the muscle length-dependent forces (i.e. the force–length relationship) (Vasavada, Li, and Delp 1998). Analysis of the model indicated that there were substantial inter-individual differences in the gravitational demand around the recommended display heights, which could explain why self-selected optimal postures vary within the population.

In the earlier gravitational demand study, experimental data were limited to externally measured joint angles, and the model used did not include subject-specific intervertebral kinematics (IVK). Specifically, because of the mechanical redundancy of the cervical spine, the relative position of the vertebrae (i.e. the IVK) can be different for the same externally measured joint angles (Wu et al. 2010; Anderst et al. 2013). Incorporating experimentally observed inter-individual variation in IVK into a musculoskeletal model of the head–neck resulted in up to a 90% coefficient of variation in the estimate of gravitational demand (Nevins, Zheng, and Vasavada 2014). Thus, it is potentially important to incorporate subject-specific IVK into musculoskeletal models when evaluating gravitational moment in different postures.

In addition to tablet configuration (e.g. using an accessory stand or a table), other factors may affect the gravitational demand. Another study found differences in wrist posture and muscle activity among tasks such as web browsing, email and games (Young et al. 2013), but the effect of task on head and neck posture was not evaluated. In addition, sex differences exist in head mass and neck muscle strength, even in height-matched subjects (Vasavada, Danaraj, and Siegmund 2008), and there are known sex differences in neck musculoskeletal disorders (Côté et al. 2004), suggesting that gravitational demand may be different for male and female subjects. Therefore, both task and sex may be important factors in the gravitational demand imposed during tablet computer use.

The goal of this study was to evaluate the biomechanical ergonomics of the head–neck system while tablet computer users assumed a variety of usage conditions. These conditions included different tablet usage configurations (presence of a desk and/or accessory) and tasks (Reading and Typing), all in a seated position. We estimated the gravitational demand for the head–neck musculature from a musculoskeletal model which matched *subject-specific intervertebral postures* obtained by radiographs and included subject-specific size. Our primary hypothesis was:

Hypothesis 1: All tablet usage conditions would result in a gravitational demand significantly greater than that in neutral posture.

Related to this, we had three other hypotheses:

Hypothesis 2: For a given task (reading or typing), the tablet computer either in the lap or flat on a desk would result in a significantly greater gravitational demand than other positions.

Hypothesis 3: For a given usage position, gravitational demand would be different for reading versus typing tasks.

Hypothesis 4: Females would have higher gravitational demand than males.

A secondary study objective, related to implementation of practical ergonomics assessment, was to determine if gravitational demand could be correlated to external joint angle measurements. Our findings are important for developing ergonomics guidelines for tablet computer use under several tablet usage conditions, because they provide quantitative information about the requirements of the head–neck musculature, a likely source of pain-related problems.

2. Methods

2.1 Experimental design

A total of 33 subjects (17 males, 16 females, age 19–46) were recruited for the study from a university setting (staff, faculty and students). Approval for this study was obtained from the Institutional Review Board at Washington State University, and all subjects provided informed consent prior to participation in the study. No subjects reported any history of neck pain or neck injury. All subjects had been using a tablet computer for at least one month before the study and completed a survey about their tablet computer use (Table 1). Approximately half of the subjects reported that they used the tablet 'Often' (more than 50% of the time) in their lap, and one quarter indicated that they used the tablet 'Often' in their hands. Over half of the

Table 1. Tablet computer usage of subjects ($n = 32$).

Time spent using computers or hand-held devices	Often (>4 hours)	Sometimes (1–4 hours)	Rarely (<1 hour)	Never
Computer	65.6%	21.9%	12.5%	0%
Hand-held devices	12.5%	75%	12.5%	0%
How often the tablet computer is used in the following way	Often (>50%)	Sometimes (10–50%)	Rarely (<10%)	Never
On desk	12.5%	32.3%	46.9%	9.4%
In lap	43.8%	37.5%	12.5%	6.3%
In hands	25%	46.9%	21.9%	6.3%
Propped on a stand or other object	15.6%	31.3%	34.4%	18.8%

Note: Subjects were asked to respond Often, Sometimes, Rarely or Never for each question, as it relates to their average day. Results shown are the per cent of participants answering in each category.

subjects also reported that they 'Rarely' (less than 10% of the time) used the tablet on a desk, or propped on a stand or other object.

Prior to photographic and radiographic data collection, reflective markers (B & L Engineering, Santa Ana, CA, USA) and lead beads (Y-Spots, Beekley Corporation, Bristol, CT, USA) were placed on landmarks on the subjects' head, neck and trunk. Reflective markers were placed on the canthus, tragus, spinous process of C7, sternal notch and iliac crest (highest point). Lead beads were placed on the inferior border of the orbit, tragus, spinous process of C7 and sternal notch. Both the camera and X-ray imager were aligned with ground horizontal, and a level placed in the image confirmed the alignment. The camera was located 42–52 cm from the subject's midline; the X-ray tube was 55–64 cm from the subject's midline and 70.5 cm from the film.

We conducted all trials with subjects in a seated posture. While there has been no systematic study of tablet computer usage conditions in the general population, a survey of over 1000 high school students who owned tablet computers found that 'sitting' was the most common posture during tablet computer use (followed by 'semi-reclined,' 'lying,' and 'standing') (Shan et al. 2013). Sagittal photographs and radiographs were taken simultaneously with the subjects in a self-selected neutral posture (looking straight ahead at a marker placed at eye level) and in four tablet computer usage conditions (described later). Chair height and desk height were fixed at 48.3 cm and 73.7 cm, respectively, to replicate conditions common to the office environment; subjects could position the chair in the anterior–posterior direction relative to the desk, according to their preference. The same tablet (iPad 2, Apple, Cupertino, CA, USA) was used for all subjects, and reflective tape was used to document its position and angle during use. The tablet was always used in landscape orientation, and an accessory device (SmartCover, Apple, Cupertino, CA, USA) was used to prop the tablet into either a high (73° with respect to horizontal) or low (15° with respect to horizontal) angle.

Subjects were divided randomly into two groups, content consumption (Reading) and creation (Typing). Two different types of tasks were selected because they require different types of interaction with the tablet. Subjects were asked to perform the Reading or Typing tasks for approximately 2–5 minutes, after which photographs and radiographs were taken simultaneously. All subjects were photographed performing all Reading and Typing tasks (Figure 1; described later) but only radiographed in either four of the Reading or four of the Typing conditions, to limit radiation exposure. The order of the tablet usage conditions was randomised.

Reading tasks. Subjects were instructed to read content on a website with the tablet computer in the following conditions:

- *Desk High*: the tablet was placed on the desk with the SmartCover in the high position.
- *Desk Low*: the tablet was placed on the desk with the SmartCover in the low position.
- *Desk Flat*: the tablet was placed flat on the desk.
- *Lap Low*: the tablet was placed in the lap with the SmartCover in the low position. (This condition was only photographed, not radiographed, to limit radiation exposure in the Reading group.)
- *Self-Selected*: subjects were asked to adopt a posture they commonly used for reading content on the tablet (e.g. a posture similar to reading a book). For a few participants, this condition involved placing the iPad on the lap or propped on crossed legs, but they did not use the SmartCover.

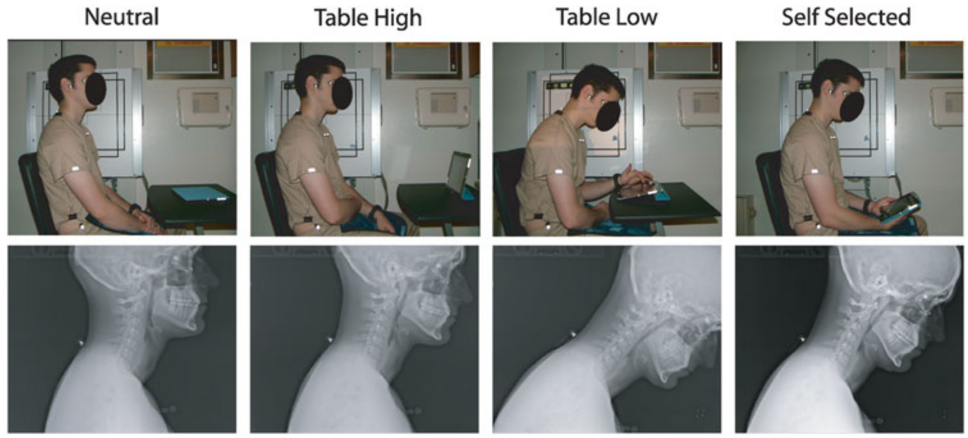

Figure 1. Photographs (top row) and radiographs (bottom row) of a single subject in representative tablet usage conditions.

Typing tasks. Subjects were instructed to type a short self-generated narrative using the onscreen keyboard, in response to a prompt ('Describe your dinner last night'). The tablet was used in the following conditions (described earlier): *Desk Low*, *Desk Flat*, *Lap Low* and *Self-Selected*.

One subject was eliminated from data analysis because she supported her chin in her hands during tablet computer use, which would influence the load supported by neck muscles. In addition, clothing obscured the reflective marker over the C7 spinous process in two male subjects in the Typing group. Their data were excluded from the results of photographic data (Section C.1), but their radiographic data were used to develop models and calculate relative gravitational demand (Sections C.2 and C.3). Finally, seven subjects in the Reading group were missing photographic data in the Self-Selected Typing condition, but they were radiographed in the Self-Selected Reading condition. Thus, the results of photographic data are from 15 male and 15 female subjects (16 Reading and 14 Typing, except for Self-Selected Typing), and results of the gravitational demand are from 17 male and 15 female subjects (16 subjects each in the Reading and Typing groups).

2.2 Data analysis

Head, neck and trunk angles were measured from reflective marker positions on the photographs (Figure 1). Head angle was defined by the line connecting the tragus and canthus; neck angle by the line connecting the C7 spinous process and tragus; and trunk angle by the line connecting the iliac crest to the C7 spinous process; all angles were defined relative to horizontal (Figure 2(A)). These 'absolute' angles are referred to as Head-Horizontal, Neck-Horizontal and Trunk-Horizontal. In addition, two relative angles between the head, neck and trunk were defined: Head–Neck (Head-Horizontal minus Neck-Horizontal) and Neck–Trunk (Neck-Horizontal minus Trunk-Horizontal). A linear measurement, the horizontal distance from the tragus to the C7 spinous process, was defined as r_{head} (Figure 2(A)).

Vertebral and skull positions and angles were measured on each radiograph by digitising the corners of each cervical vertebral body, sternal notch and anatomical landmarks on the skull (Figure 2(B)). Coordinate systems for C2–C7 were defined according to International Society of Biomechanics (ISB) recommendations (Wu et al. 2002). Vertebral positions were defined by the geometric centre of the digitised corner points of the vertebrae. C2–C7 angles were defined by the vector originating at the geometric centre and orthogonal to the line formed by the mid-points of the superior and inferior endplates (Figure 2(B)). The position of the C1 vertebra was defined by the mid-point between the posterior and anterior tubercle, and the C1 angle was defined by the vector connecting those two points. Skull position was defined by the tragus marker, and skull angle by the vector connecting the tragus and inferior border of the orbit (i.e. the Frankfort plane). X (positive anterior) and Y (positive superior) and angular position of each vertebra and the skull were defined with respect to the sternal notch in each posture.

2.3 Modelling

Radiographic and photographic data were used to modify a head and neck model of a 50th percentile male (Vasavada, Li, and Delp 1998) to create models which were specific to each subject's posture and size. Model head and neck posture was determined by setting the X, Y and angular positions for each subject's vertebrae and skull (relative to the sternal notch) to match radiographic data. Due to the limited field of view of the radiograph, location of the iliac crest and definition of trunk angle from radiographic data was not possible. Therefore, the trunk angle of the model in neutral position was used for each

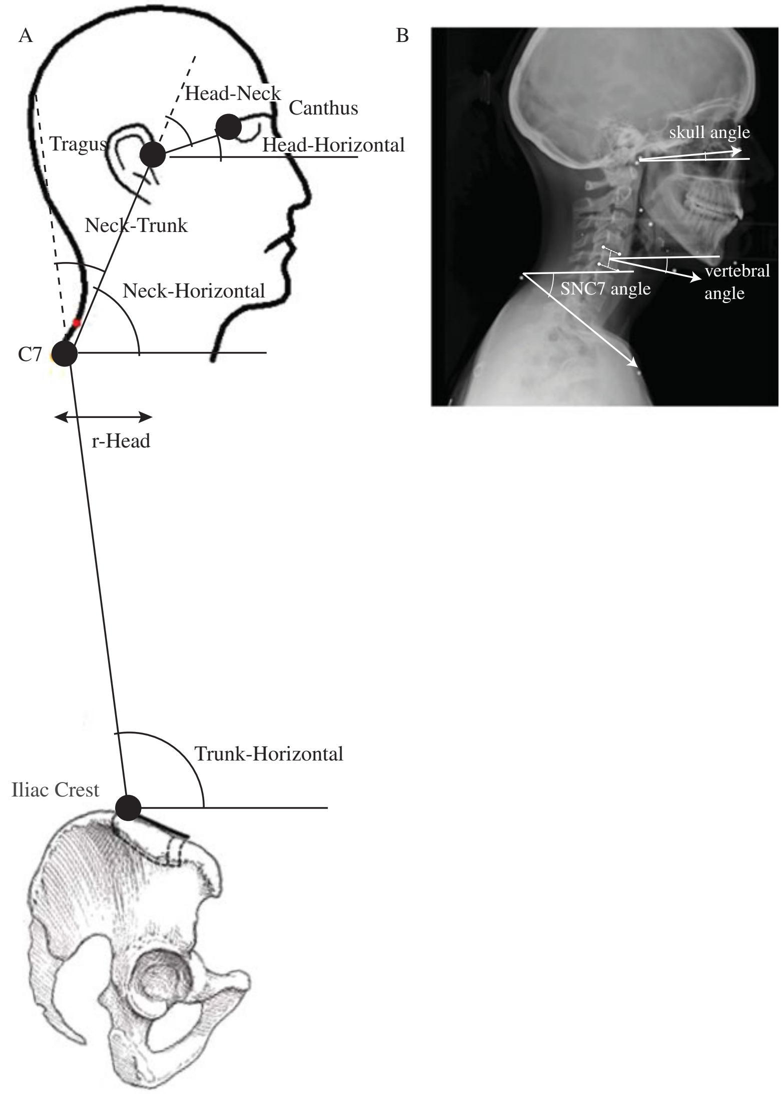

Figure 2. Definitions of postural angles. (A) Head, neck and trunk angles and r_{head} as measured from photographs. (B) Vertebral and skull locations and angles as measured from radiographs. SNC7 = Sternal Notch C7 line.

subject's neutral posture, and change in trunk angle from neutral (from photographic data) was applied to the trunk segment (thoracic spine, ribcage, clavicle and scapula) for all tablet usage postures.

Several adjustments were made in the model to scale neck muscle moment-generating capacity based on bone size (which influences moment arm) and muscle size (which influences force). Neck musculoskeletal geometry was scaled to vertebral and skull size obtained from each subject's radiographs. Muscle force-generating parameters that were modified were optimal fascicle length, tendon slack length and peak isometric force (Zajac 1989). Optimal fascicle length and tendon slack length were scaled based on the ratio of subject-specific musculotendon length to original model musculotendon length in the neutral posture. Peak force is proportional to the physiological cross-sectional area (PCSA); the proportionality constant is known as specific tension ($50\,\mathrm{N/cm^2}$ was used here). PCSA is the ratio of muscle volume to optimal fascicle length, and muscle volume was estimated from a previous study based on MRI data (Zheng et al. 2013). In that study, the total neck muscle volume could be predicted from neck circumference and sex:

$$\text{Muscle Volume}[\mathrm{cm}^3] = 13.7 \times (\mathrm{NC}[\mathrm{cm}]) - 233 \times \mathrm{Sex} + 269, \tag{1}$$

where NC = neck circumference and Sex = 0 for male and 1 for female. Volumes of individual muscle segments were then distributed as in the original model (Vasavada, Li, and Delp 1998).

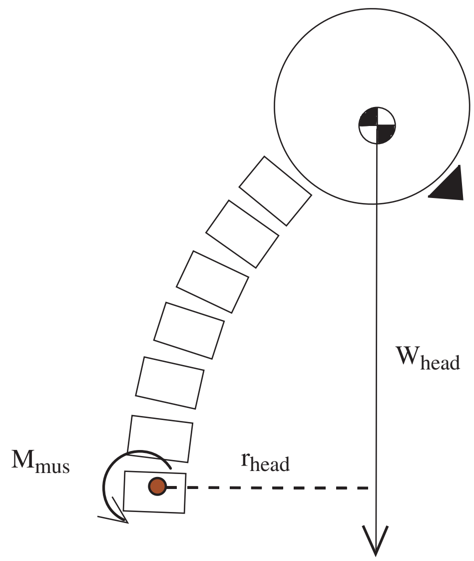

Figure 3. Definition of gravitational demand (ratio of gravitational moment to muscle moment). Gravitational demand $= (W_{head} \times r_{head})/M_{mus}$, where W_{head} = weight of head, r_{head} = distance from head CM to C6–C7 centre of rotation in the model, M_{mus} = maximum extension muscle moment.

For each subject-specific model in each usage condition, maximal neck muscle moment-generating capacity (M_{mus}) was obtained from the musculoskeletal modelling software SIMM (Software for Interactive Musculoskeletal Modeling, Musculographics, Inc., Santa Rosa, CA, USA). All muscles capable of generating a neck extension moment were included in the calculation of M_{mus}.

Gravitational demand was obtained by calculating the ratio of gravitational moment (M_g) to M_{mus}. M_g was defined as the product of head weight and the distance between the head centre of gravity (COG) and intervertebral joint centre of rotation (Figure 3). Subject head mass was estimated using a regression equation based on head circumference and body mass (Clauser, Mcconville, and Young 1979):

$$\text{Head Mass[kg]} = 01.04 \times (\text{HC[cm]}) + 0.015 \times (\text{BM[kg]}) - 2.189, \quad (2)$$

where HC = head circumference and BM = body mass. The COG location within the head was estimated according to the definition developed by NASA (1978) (17% of the distance between the tragus and the vertex of the skull). Results are presented for the gravitational demand at the C6–C7 centre of rotation (Amevo, Worth, and Bogduk 1991), the level where the gravitational moment would be greatest.

2.4 Statistical analysis

To test our hypotheses, the effects of the following factors were examined: tablet usage condition (hypothesis 1 about neutral vs. other conditions and hypothesis 2 about Desk Flat and Lap Low); task (hypothesis 3 about Reading vs. Typing); and sex (hypothesis 4). In addition to gravitational demand, we also tested head, neck and trunk angles and r_{head} from photographs and model-predicted gravitational moment and muscle moment for differences among usage conditions, because they are all intermediate variables that affect gravitational demand. Statistical analyses differed slightly for variables obtained from photographs versus models, because models were created from radiographs, which were only taken in neutral and four Reading or Typing configurations for each subject, whereas photographs were taken in all conditions.

Differences in model-predicted variables (gravitational demand, gravitational moment and muscle moment) were tested using a three-factor mixed-model repeated measures ANOVA with one within-subjects variable. The factors were (1) sex (between-subjects); (2) task (Reading or Typing; between-subjects); and (3) tablet condition (Neutral, Desk Low, Desk Flat or Self-Selected; within-subjects). If the ANOVA indicated no significant effect of task, the paired Reading and Typing group data were averaged. If the ANOVA indicated a significant effect of tablet condition, post hoc planned comparisons (paired t-tests) were performed to test hypotheses 1 and 2. Only those conditions directly pertaining to the hypotheses were tested in post hoc comparisons. The planned comparisons were: Neutral versus Desk Flat, Desk Low and Self-Selected (hypothesis 1); and Desk Flat versus Desk Low and Self-Selected (hypothesis 2). For these five planned comparisons, a

Bonferroni correction was applied for a significance level of $p = 0.01$. Desk High and Lap Low conditions could not be included in the three-way ANOVA because each condition was only X-rayed in either the Reading or Typing task, but not both. Desk High Reading and Lap Low Typing were compared to other conditions by one-factor repeated measures ANOVA within the Reading and Typing groups separately. The post hoc planned comparisons were: Desk High versus Neutral (hypothesis 1) and Desk Flat (hypothesis 2) in the Reading group, and Lap Low versus Neutral, Desk Low and Self-Selected in the Typing group. Adjusted p-values were 0.025 for the two planned comparisons in the Reading group and 0.0167 for the three planned comparisons in the Typing group.

Differences in photographic variables were tested using a three-factor mixed-model repeated measures ANOVA, with two within-subjects factors because all subjects had data in usage conditions while both Reading and Typing. The factors were (1) sex (between-subjects); (2) task (Reading or Typing; within-subjects) and (3) tablet condition (Desk Low, Desk Flat, Self-Selected or Lap Low; within-subjects). If the ANOVA indicated a significant effect of tablet condition, post hoc planned comparisons (paired t-tests) were performed to test hypothesis 2 that Desk Flat or Lap Low conditions were different from other usage conditions. As with the model data, only those conditions directly pertaining to the hypotheses were tested in post hoc comparisons. The planned comparisons (addressing hypothesis 2) were: Desk Flat versus Desk Low and Self-Selected; and Lap Low versus Desk Low and Self-Selected. For these four planned comparisons, a Bonferroni correction was applied for a significance level of $p = 0.0125$. The neutral condition was not included in the three-factor ANOVA because there was only one neutral photo for each subject, and the Desk High condition could not be included because it was only used in Reading (it was not considered practical for Typing). To compare Neutral and Desk High Reading to other conditions, we then performed a separate one-factor repeated measures ANOVA. If the ANOVA indicated significant differences, the planned post hoc paired t-tests were: Neutral versus all usage conditions (9 comparisons, to test hypothesis 1); and Desk High versus Desk Flat and Lap Low (2 comparisons to test hypothesis 2), using a corrected p-value of 0.0045 for 11 comparisons.

To examine the difference between radiographic and photographic measures, we compared variables that were measured on both photo and X-ray (head angle, neck angle and r_{head}) using the concordance correlation coefficient (Lin 1989), which measures the agreement between two variables. Finally, because gravitational demand was calculated using the horizontal distance between the head centre of mass (CM) and centre of rotation for C6–C7 in the model (Figure 3), we compared this value to r_{head} measured on photographs (defined as the horizontal distance of the tragus marker relative to C7 marker; Figure 2(A)) using a linear regression coefficient.

For the secondary study objective, linear regression was performed to assess the postural and ergonomics factors which potentially may be related to gravitational demand. Gravitational demand was regressed against the following variables obtained from photographs: Head, neck and trunk angles; r_{head} (horizontal distance of the tragus marker relative to the C7 marker); and tablet angle (with respect to horizontal), tablet height (vertical distance from the canthus marker to the centre of the tablet) and gaze angle (angle from canthus marker to centre of the tablet).

3. Results

3.1 Postural data from photographs

Neutral postures for all subjects were characterised by mean ($\pm$ standard deviation, SD) angles of 18.9° ($\pm$6.1°) for Head-Horizontal, 51.3° ($\pm$3.9°) for Neck-Horizontal and 103.9° ($\pm$7.0°) for Trunk-Horizontal (Table 2). Although the SDs of postural measurements were less than 10°, the range of each of the head and neck angles was approximately 25° over all subjects. Reading and Typing tasks were significantly different for Trunk-Horizontal and Neck–Trunk angles ($p < 0.03$), but not for other angles ($p > 0.20$). There were no significant sex differences in head, neck or trunk angles ($p > 0.27$), except for Neck–Trunk ($p = 0.03$).

Head and neck angles (Head-Horizontal, Neck-Horizontal, Head–Neck and Neck–Trunk) adopted by subjects while using the tablet for all conditions and tasks were significantly more flexed than neutral ($p < 0.001$). For the Trunk-Horizontal angle, all conditions were significantly more flexed than neutral ($p < 0.001$), except for Desk High and Self-Selected Reading ($p > 0.02$; not significant with Bonferroni adjustment). Moreover, the Desk Flat and Lap Low conditions usually had significantly more flexed head and neck angles than at least one of the other usage conditions (Desk High, Desk Low or Self-Selected; Table 2).

The horizontal position of the tragus relative to the C7 spinous process (r_{head}) was 9.9 ($\pm$1.4) cm in the neutral posture and increased significantly ($p < 0.001$) to 13.7 ($\pm$2.3) cm on average among tablet usage conditions (Table 2). Lap Low conditions had significantly greater r_{head} compared to Desk High and Desk Low conditions ($p < 0.001$), whereas Desk Flat had significantly greater r_{head} compared only to Desk High. The r_{head} measurement was influenced by Neck-Horizontal angle (correlation coefficient, $R^2 = 0.49$) and Head-Horizontal angle ($R^2 = 0.36$). There were no significant task or sex differences in r_{head}.

Table 2. Postural data from photographs: angles (degrees) and horizontal position of the tragus relative to C7 (r_{head} cm) for different conditions indicated by tablet positions (Desk or Lap) and the use of the support (SmartCover; Low or High).

Condition		Desk High	Desk Low		Self-Selected		Desk Flat		Lap Low	
Task	Neutral	Reading	Reading	Typing	Reading	Typing	Reading	Typing	Reading	Typing
Head-Horizontal	18.9	$-5.1^{N,DF,LL}$	$-11.1^{N,DF,LL}$	$-10.2^{N,DF,LL}$	$-14.8^{N,LL}$	$-14.8^{N,LL}$	-13.6^{N}	-12.1^{N}	-21.7^{N}	-17.3^{N}
	(6.1)	(8.2)	(8.4)	(8.9)	(10.5)	(10.7)	(8.2)	(11.0)	(9.4)	(10.0)
Neck-Horizontal	51.3	$39.2^{N,DF,LL}$	$33.2^{N,DF,LL}$	$35.0^{N,DF,LL}$	$32.2^{N,LL}$	$32.4^{N,LL}$	30.2^{N}	32.6^{N}	26.2^{N}	29.8^{N}
	(3.9)	(8.6)	(8.2)	(9.2)	(9.7)	(11.3)	(9.2)	(11.4)	(10.1)	(12.1)
Trunk-Horizontal^{T}	103.9	100.5^{DF}	98.1^{N}	94.7^{N}	100.9^{DF}	$97.2^{N,DF}$	95.7^{N}	92.2^{N}	97.3^{N}	96.6^{N}
	(7.0)	(7.8)	(7.0)	(9.6)	(6.3)	(8.1)	(8.0)	(10.0)	(7.4)	(8.7)
Head−neck	−32.4	$-44.2^{N,DF,LL}$	$-44.3^{N,LL}$	$-45.2^{N,LL}$	$-47.0^{N,DF}$	$-47.2^{N,DF}$	-43.8^{N}	-44.7^{N}	-47.9^{N}	-47.2^{N}
	(6.5)	(6.6)	(7.3)	(7.1)	(7.0)	(7.3)	(7.8)	(7.6)	(7.6)	(7.0)
Neck−trunk^{T}	−52.6	$-61.3^{N,DF,LL}$	$-65.0^{N,LL}$	$-59.7^{N,LL}$	$-68.7^{N,DF}$	$-64.8^{N,DF}$	-65.5^{N}	-59.6^{N}	-71.1^{N}	-66.7^{N}
	(6.9)	(8.2)	(8.3)	(8.2)	(9.3)	(9.5)	(6.1)	(8.6)	(7.8)	(9.3)
r_{head}	9.9	$12.5^{N,DF,LL}$	$13.5^{N,LL}$	$13.1^{N,LL}$	$13.9^{N,LL}$	$13.5^{N,LL}$	14.1^{N}	13.4^{N}	14.5^{N}	13.9^{N}
	(1.4)	(2.3)	(1.9)	(2.2)	(2.6)	(2.6)	(2.2)	(2.3)	(2.1)	(2.4)

Note: ^{T}Task difference. If there is no task difference, post hoc comparisons on conditions were made on pooled Reading and Typing data. Superscripts indicate significant differences from Neutral, Desk Flat or Lap Low. ^{N}Different from Neutral; ^{DF}Different from Desk Flat; ^{LL}Different from Lap Low.
Data presented are mean (SD).

3.2 Postural data from radiographs

Radiographic data were analysed to determine variations in postures among subjects. Similar to the photographic data, the neutral posture of the skull (with respect to horizontal) measured from the radiographic data had a SD of 7.5° and a range of 30° among subjects. The angles of each vertebral body and the angle of the line connecting the sternal notch to the C7 spinous process (SNC7) with respect to horizontal (see Figure 2(B) for definitions) also exhibited considerable variation, with SDs of 7–11° and ranges of 27–40° among subjects in the neutral posture.

For the tablet usage conditions, the skull flexed relative to the SNC7 line an average of 30° (± 12°) compared to neutral. The motion of the intervertebral levels (i.e. IVK) contributing to this change varied substantially among subjects. On average, however, the C1–C2 level had the greatest contribution to change in skull angle with respect to SNC7, followed by C2–C3 and C3–C4 (Figure 4). At each intervertebral level, at least one subject exhibited ‘paradoxical motion’, where the intervertebral joint actually *extended* while the head *flexed* relative to the SNC7 line (i.e. a negative contribution to change in head angle). In subjects exhibiting paradoxical motion, other intervertebral levels flexed more to compensate for that opposite motion, causing large variation in the per cent contribution values (Figure 4).

Postural variables that could be measured from both X-ray and photograph were compared using the concordance correlation coefficient. For head angle (based on tragus and canthus markers), the concordance correlation coefficient was 0.98. For neck angle and r_{head} (both calculated using tragus and C7 spinous process markers), however, the concordance correlation coefficients were lower (0.79 and 0.50 for neck angle and r_{head}, respectively), likely because of lack of direct correspondence between the C7 spinous process marker on the skin and the location of the C7 spinous process marked on the X-ray.

3.3 Gravitational moment, muscle moment and gravitational demand

Gravitational moment of the head acting at the C6–C7 intervertebral joint averaged 1.22 Nm (± 0.56 Nm) in the neutral posture and ranged from 0.48 to 3.15 Nm among all subjects. In tablet usage conditions, the gravitational moment increased to an average of 3.52 Nm (± 0.90 Nm), with a range of 1.68–5.85 Nm over all subjects in all usage conditions (Figure 5(A)). The gravitational moment was significantly greater in all tablet usage conditions compared to neutral ($p < 0.001$). Among the Reading conditions, Desk Flat Reading had a significantly greater gravitational moment compared to Desk High Reading ($p < 0.001$). Among the Typing conditions, Lap Low Typing had significantly larger gravitational moment than Desk Low Typing ($p < 0.001$). Males had 31% larger gravitational moment compared to females (average 3.4 Nm vs. 2.6 Nm, $p < 0.001$). There were no significant differences between Reading and Typing conditions ($p = 0.13$).

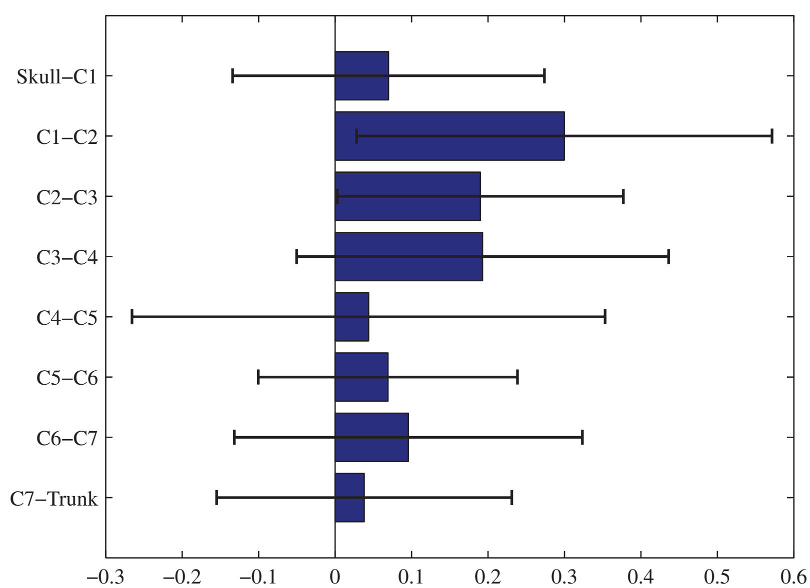

Figure 4. Per cent contribution of intervertebral levels to total Skull–Trunk motion from neutral. Mean and SD of all subjects over all usage conditions. The trunk was defined by the Sternal Notch–C7 (SNC7) line. The average Skull–SNC7 motion from neutral was − 30° (± 12°) over all subjects and tablet usage conditions.

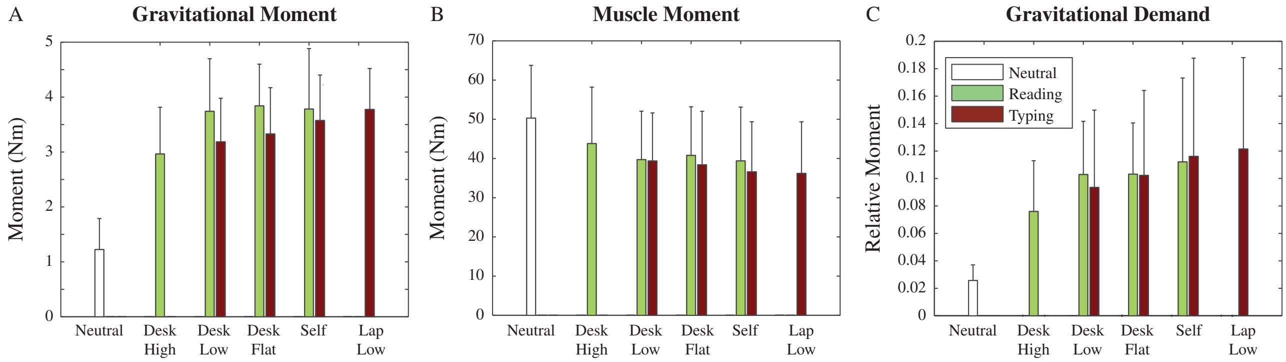

Figure 5. Model-predicted moments and gravitational demand. (A) Gravitational moment. (B) Muscle moment. (C) Gravitational demand (significant differences among conditions are defined in Table 3).

Estimated maximal muscle moment (M_{mus}) about the C6–C7 intervertebral joint averaged 50.3 Nm (± 13.5 Nm) for the neutral posture of all subjects and ranged from 30.0 to 83.9 Nm. In tablet usage conditions, M_{mus} decreased significantly ($p < 0.001$) to an average of 39.9 Nm (± 13.0 Nm) with a range of 15.4–71.7 Nm (Figure 5(B)). Among the Typing conditions, Lap Low Typing had significantly lower M_{mus} than Desk Low Typing ($p = 0.007$). Desk Flat Reading was not significantly different from other Reading conditions. Males had 39% larger M_{mus} compared to females (average 47.7 Nm vs. 34.4 Nm, $p < 0.001$). There were no significant differences between Reading and Typing conditions ($p = 0.39$).

The gravitational demand varied in a similar manner to the gravitational moment (Figure 5(C)). It was smallest in the neutral posture, with an average value of 0.026 (± 0.011) and a range of 0.006–0.053 among all subjects (Table 3). The gravitational demand increased significantly in all tablet usage conditions compared to the neutral posture ($p < 0.001$). When averaged over all tablet usage conditions, the relative gravitational demand was 0.103 (± 0.055), with a range of 0.032–0.325 over all subjects in all usage conditions (Figure 5(C)). Compared to the neutral posture, the relative gravitational demand in tablet usage conditions ranged from 3.4 times neutral position in the Desk High Reading condition to 5.4 times neutral position in the Lap Low Typing condition (Table 4).

For the Reading subjects, gravitational demand in the Desk Flat condition was significantly greater than Desk High ($p < 0.001$) but not different from other Reading conditions ($p > 0.4$). For the Typing subjects, gravitational demand was significantly higher for Lap Low compared to Desk Low ($p = 0.002$) and Desk Flat ($p = 0.01$) but not different from Self-Selected ($p = 0.64$). There were no significant differences between the Reading and Typing conditions ($p = 0.89$), nor any significant sex differences in the gravitational demand ($p = 0.71$).

Table 3. Gravitational demand (mean and SD) in neutral and tablet usage conditions.

Usage condition	Reading	Typing
Neutral	0.026 (0.012)	0.026 (0.011)
Desk High	0.076 (0.037)^{N,DF}	
Desk Low	0.103 (0.039)^{N}	0.093 (0.056)^{N,LL}
Desk Flat	0.103 (0.037)^{N}	0.102 (0.062)^{N,LL}
Self-Selected	0.112 (0.061)^{N}	0.116 (0.072)^{N}
Lap Low		0.121 (0.067)^{N}

Note: Superscripts indicate significant differences from Neutral, Desk Flat or Lap Low. ^{N}Different from Neutral; ^{DF}Different from Desk Flat; ^{LL}Different from Lap Low.

Table 4. Gravitational demand normalised to neutral posture (mean and SD).

Usage condition	Reading	Typing
Desk High	3.36 (1.79)	
Desk Low	4.70 (2.31)	4.13 (2.43)
Desk Flat	4.64 (2.12)	4.29 (2.05)
Self-Selected	4.95 (2.72)	5.01 (2.82)
Lap Low		5.37 (2.89)

Linear regression of gravitational demand on single postural variables showed that r_{head} was the best single predictor for gravitational demand ($R^2 = 0.55$), followed by Head-Horizontal angle ($R^2 = 0.53$) and Neck-Horizontal angle ($R^2 = 0.48$) (Figure 6). Other variables, such as Head–Neck angle, Neck–Trunk angle, Trunk-Horizontal angle, tablet height with respect to the canthus, tablet angle or gaze angle, had low and/or insignificant correlations with gravitational demand ($R^2 < 0.4$). Adding a second variable to regressions increased the correlation; the best combination was r_{head} and Head-Horizontal angle (Gravitational Demand $= -0.0395 + 0.0091 \times (r_{\text{head}}) - 0.0031 \times$ (Head-Horizontal Angle); $R^2 = 0.64$, $p < 0.001$. Adding a third variable did not improve the correlation.

4. Discussion

4.1 Study hypotheses

The goal of this study was addressed by testing the hypotheses that (1) all tablet usage conditions would result in a gravitational demand significantly greater than that in neutral posture; (2) for a given task (Reading or Typing), the tablet computer either in the lap or flat on a desk would result in a significantly greater gravitational demand than other positions; (3) for a given usage position, gravitational demand would be different for reading versus typing tasks and (4) females would have higher gravitational demand than males.

The results support the first hypothesis; the gravitational demand while using tablet computers in all conditions is approximately 3–5 times that found in the neutral posture. The gravitational demand is the ratio of gravitational moment to maximal muscle moment generating capacity in a given posture. Therefore, the increase in gravitational moment indicates that a greater proportion of the maximal moment-generating capacity is needed to hold the head in a static posture.

The second hypothesis concerned using the tablet flat on a desk or in the lap. We found that using the tablet in the Desk Flat condition resulted in significantly greater gravitational demand compared to the Desk High condition during Reading, but it was not significantly greater than any other conditions in Reading or Typing. Among the Typing tasks, we found that using the tablet in the lap had a significantly greater gravitational demand compared to the Desk Low and Desk Flat, but not Self-Selected conditions. Interestingly, the Self-Selected postures that subjects assumed did not result in significantly lower gravitational demand than other conditions ($p > 0.2$). Thus, the hypothesis with regard to the Desk Flat and Lap Low conditions was only partially supported by our results.

The results did not support our third hypothesis, that gravitational demand would be different for Reading versus Typing tasks. Note that we did not estimate gravitational demand in Lap Low Reading because we wanted to limit each participant's radiation exposure to only four tablet usage conditions plus neutral posture. For the Reading tasks, we wanted to compare three different Desk conditions (High, Low and Flat) to evaluate the effect of the accessory device and also examine the Self-Selected condition; therefore, we did not include Lap Low Reading. The fact that Reading and Typing tasks did not have significantly different gravitational demand for Desk Low, Desk Flat or Self-Selected conditions suggests that gravitational demand in Lap Low Reading would not be significantly different from Lap Low Typing.

Finally, the fourth hypothesis was also not supported because we did not find that females had higher gravitational demand than males. Males had 31% greater gravitational moment compared to females, but they also had 39% greater muscle moment to compensate. Overall, gravitational demand was 4% larger in males compared to females, but this difference was not significant.

4.2 Postures assumed during tablet computer use

The study experimental design used a combination of tasks (Reading and Typing) and conditions (Self-Selected, or with a Desk and/or accessory). For the joint angles measured from photographs, we found that Desk High was the least flexed condition and Lap Low was the most flexed condition. These results are in general agreement with a prior study of postures during tablet computer use, which also used external markers (Young et al. 2012). In that study, the high propped condition had the least flexion and the two lap conditions (low propped and hand-held) had the most flexion (Young et al. 2012). In terms of absolute joint angles for the conditions excluding Desk High, we found Head-Horizontal and Neck-Horizontal average angles ranging from $-10°$ to $-26°$ and 25° to 32°, respectively, which is comparable to those reported earlier ($-9°$ to $-12°$ and 36° to 41°, respectively) (Young et al. 2012). The slight differences in the magnitude could be a result of different trunk angles (not reported) and the lounge-type chair used in the study by Young et al. Another study evaluated postures during tablet use with electrogoniometers, so the angular measures are not directly comparable, but they also found that neck flexion was significantly greater while working on a sofa compared to a desk (Werth and Babski-Reeves 2014).

A limitation of the experimental measurements is the estimate of trunk angle, which relied on a marker placed on iliac crest. Ideally, trunk angle would be measured from radiographs, which was not possible given the field of view used. The importance of trunk angle uncertainty is that it limited our ability to incorporate absolute trunk angle into the musculoskeletal model (see the next section).

4.3 *Estimate of gravitational demand*

The average gravitational demand in the current study, ranging from 0.026 (in neutral) to 0.121 (Lap Low Typing), corresponds well with other studies that have estimated this value. Overall, the average increase in gravitational demand from neutral to any of the usage conditions ranged from 236% to 437%. This is at least 4 times greater than the average differences in gravitational demand among any of the usage conditions, which were 23–60%.

Harms-Ringdahl and Schüldt measured posture and neck strength in different head–neck postures, and estimated gravitational demand of 0.02 in the neutral posture, 0.10 with the lower cervical spine flexed 24° and 0.17 with the lower cervical spine flexed 41° (Harms-Ringdahl and Schuldt 1989). Thuresson et al. measured neck strength only in the neutral posture in pilots, and estimated the gravitational demand to be 0.037 in the neutral posture and 0.106 for neck angles flexed 20° from neutral (Thuresson et al. 2005). In our previous study which utilised subject-specific kinematics from radiographs and a biomechanical model, gravitational demand also ranged from 0.03 in the neutral posture and 0.11 for 16° neck flexion (Nevins, Zheng, and Vasavada 2014).

Straker et al. found larger gravitational demand than predicted here, ranging from 0.22 with a computer monitor in a high position to 0.33 while reading a book on a desk (Straker et al. 2009). Finsen and colleagues (Finsen 1999) also predicted larger gravitational demand in dentists, ranging from 0.32 in ‘medium flexed’ to 0.45 in ‘highly flexed’ postures; however, these angles are not directly comparable to our measures. The values for gravitational demand in these latter two studies are larger than our estimates because both their predicted gravitational moment at C7 was higher (4–8 Nm), and their predicted extensor moment-generating capacity was lower (approximately 15 Nm measured experimentally in neutral posture by Finsen et al. and 25–32 Nm predicted from a model by Straker et al.). On a relative basis between postures, however, the gravitational demand estimated by Straker et al. in the ‘book’ position was 1.5 times that of the ‘high’ position, which compares favourably to our ratio of Desk Flat to Desk High of 1.47 (±0.47). The musculoskeletal model used to estimate gravitational demand in that study (Straker et al. 2009) included motion only at two intervertebral levels, skull-C1 and C7–T1. In the current study, the model was enhanced to incorporate radiographic data, so that subject-specific posture was accounted for from all joints from skull to C7. These modelling differences can influence the location of the head CM, muscle moment and consequently the gravitational demand.

In our present study, the radiographs did not include the trunk, so it was not possible to include absolute trunk angle, or positions of thoracic vertebrae, scapula, clavicle or ribcage directly into the model. Therefore, we assumed that the model neutral trunk posture was similar for all subjects and input the *change in trunk angle* relative to neutral for tablet usage conditions. The trunk angle does not affect the gravitational moment because the model included the correct orientations of the skull and vertebrae C1–C7 from radiograph; therefore, the horizontal distance from the head CM to the C6–C7 joint centre was not affected by the trunk angle. The trunk orientation relative to the head may affect muscle moment for those muscles with attachments on the thoracic vertebrae, scapula, clavicle and ribcage. On average, changes in maximal muscle moment from neutral were approximately 25%, whereas changes in gravitational moment and demand were over 200%, so changes in muscle moment play a limited role in the predicted change in gravitational demand.

4.4 *Implications for ergonomics of tablet computer use*

In this study, we estimated the gravitational demand via musculoskeletal modelling which required both the external landmark and radiographic measurements. We investigated whether it was possible to predict gravitational demand through correlations with measurements from markers on photographs, which are more practical than using radiographs. The correlations between gravitational demand and r_{head}, head angle or neck angle from photographs were significant, but a large amount of variation existed ($0.47 < R^2 < 0.64$; Figure 6). In addition to inter-individual differences in size and neck strength, two methodological factors contribute to this variation: (1) in photographic data, neck angle is measured using a marker on the skin over the C7 spinous process, which leads to differences from radiographic data; (2) gravitational demand is calculated in the model using the horizontal distance (r_{head}-model) between the head CM and centre of rotation between C6–C7. The correlation coefficient between the r_{head}-model and r_{head}-photo was 0.53. Therefore, attempts to estimate the (model-predicted) gravitational demand must recognise the differences between photographic data and models based on radiographs.

We found that using a desk could decrease the gravitational demand on neck muscles (cf., Lap Low compared to Desk Low or Desk Flat conditions). Although we did not test a hypothesis about Self-Selected conditions, we found that the gravitational demand in this condition was similar to that in the Desk Flat or Lap Low conditions. Using the accessory

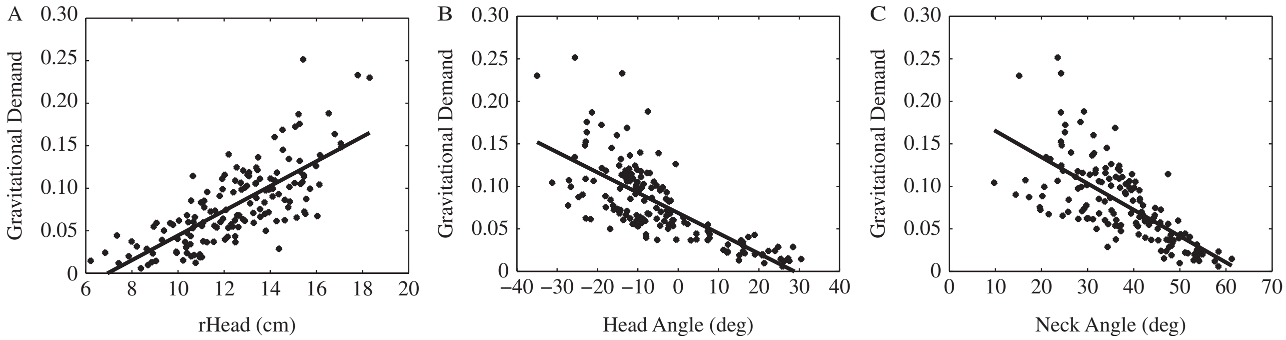

Figure 6. Single linear regression of relative gravitational demand on postural variables ($n = 30$ subjects and 5 postures each; two subjects were not included in the regression analysis because some photographic data were not available). (A) r_{head} (horizontal distance between the tragus and C7 spinous process markers), Gravitational demand $= -0.1008 + 0.0145 \times (r_{\text{head}})$; $R^2 = 0.55$, $p < 0.001$. (B) Head-Horizontal angle, Gravitational demand $= 0.0687 - 0.0024 \times$ (Head-Horizontal angle); $R^2 = 0.53$, $p < 0.001$. (C) Neck-Horizontal angle (Gravitational demand $= 0.1960 - 0.0031 \times$ (Neck-Horizontal angle); $R^2 = 0.48$, $p < 0.001$).

device only made a significant difference in gravitational demand if it were used in the High position. Although using the tablet with the cover in the High position resulted in significantly lower gravitational demand, there are many other considerations (especially ergonomics of the arms and wrists (Young et al. 2013)) which make this configuration impractical for most tasks. This is consistent with our survey results in which subjects ‘rarely’ used a tablet propped on a stand and ‘often’ used the tablet in the lap (see Table 1). Hence, the conditions in which tablets are commonly used while seated are potentially ergonomically compromising in that the gravitational demand is 3–5 times compared to that in neutral.

We separated the analysis of the Reading and Typing tasks because the hand position required in each of the tasks may influence head–neck posture (linked by shoulder positioning) (Young et al. 2013). However, we did not find significant differences between the tasks in either postural angles or gravitational demand. Therefore, our results indicate that head–neck posture, and related gravitational demand, is independent of the positioning of the hands.

Our findings are important for developing ergonomic guidelines for tablet computer use because they provide quantitative information about the mechanical requirements of the head–neck musculature, which are directly linked to mechanisms of pain-related problems, under several tablet computer usage conditions. We chose gravitational demand as the outcome variable because it can be linked to both muscle fatigue (larger moments requiring higher muscle activation) and compressive loads in other structures of the neck, which are linked to discomfort and pain (Adams and Dolan 2005). Specifically, the increase of gravitational demand from 0.026 in neutral up to 0.121 during tablet computer use is indicative of potential ergonomics problems.

Although we did not measure muscle activity during this study because electrodes may have interfered with vertebral images on radiographs, other studies have found neck extensor muscle activation levels while holding the head in 20° or greater flexed postures to be approximately 10–15% of maximum voluntary contraction (MVC) values (Schüldt and Harms-Ringdahl 1988; Finsen 1999), and in some cases even lower (Thuresson et al. 2005). In subjects using tablets, netbooks and laptops, muscle activity in trapezius was also found to be less than 6% of maximum and lowest while using tablets (Werth and Babski-Reeves 2014). The low levels of muscle activity in flexed postures are consistent with the increasing contribution of passive structures to counteract gravitational moment, estimated to be 2–3 Nm for head and neck flexion of 30° (McGill et al. 1994). Low muscle activity seems to implicate high compressive loads from passive structures rather than active muscles in neck pain. However, muscle fatigue may also play a role in the development of neck pain. Most studies that have induced fatigue in neck muscles have used higher load levels. For example, in studies using sustained low-level contractions of 25% MVC for neck extensor muscles in the neutral posture, muscle fatigue is present in the electromyographic signal at 10 minutes (Gosselin, Rassoulian, and Brown 2004). However, Chaffin found that flexing the head more than 30° increases neck extensor fatigue rates. In fact, in a study of five girls, Chaffin found that head flexion of 15° caused no subjective discomfort or electromyographic changes after 6 hours (50 minutes holding the posture and 10 minutes rest), whereas 30° flexion led to Class II fatigue, described as ‘cramping continuous with deep hot pain intermittent’ (Chaffin 1973).

Neck muscle fatigue has not been examined in detail at low MVC and in flexed postures. It has been recommended that for ergonomics considerations, no more than 5% of maximal moment capacity should be maintained for 1 hour (Jonsson 1982). Furthermore, in studies using sustained low-level contractions, muscle fatigue is present at 10 minutes for 10% MVC in wrist muscles (Blangsted et al. 2005). In addition, intermittent activations of 6 seconds of contraction followed by

4 seconds of relaxation at low level of activation (10% MVC) revealed muscle fatigue after 30 minutes for the biceps muscle (Søgaard et al. 2003). Although these studies do not exactly replicate the mechanical conditions in which neck extensors counteract gravitational moments, they do reflect that muscle fatigue occurs under conditions with low load, either in a sustained or intermittent pattern, similar to tablet computer use. Future ergonomics studies need to include other exposure variables, such as duration and frequency (repetitiveness), in addition to posture magnitude (Westgaard and Winkel 1996), as factors that may influence the development of neck discomfort and pain while using tablet computers.

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