Effect of visual display height on modelled upper and lower cervical gravitational moment, muscle capacity and relative strain

L. Straker a; R. Skoss a; A. Burnett b; R. Burgess-Limerick c

a School of Physiotherapy, Curtin University of Technology, Perth, Australia
b School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Perth, Australia
c School of Human Movement Studies, The University of Queensland, Brisbane, Australia

Online Publication Date: 01 February 2009
Effect of visual display height on modelled upper and lower cervical gravitational moment, muscle capacity and relative strain

L. Strakera*, R. Skossb, A. Burnettb and R. Burgess-Limerickc

aSchool of Physiotherapy, Curtin University of Technology, Perth, Australia; bSchool of Exercise, Biomedical and Health Sciences, Edith Cowan University, Perth, Australia; cSchool of Human Movement Studies, The University of Queensland, Brisbane, Australia

Head and neck posture is an important factor in neck pain related to computer use; however, the evidence for an optimal posture is unconvincing. This study measured the 3-D postures of 36 young adults during use of three different display heights. Cervical extensor muscle strain was estimated using modelled gravitational load moments and muscle capacities. The influence of more or less upper vs. lower cervical movement was also explored across a broad range of potential postures. Overall cervical extensor muscle capacity diminished away from a neutral posture whilst gravity moment increased with flexion. Overall cervical extensor muscle strain increased with head flexion but remained stable into head extension. Individual differences in the amount of upper and lower cervical movement had an important effect on strain, particularly for some muscles. Computer display height guidelines are an important component of ergonomics practice, yet the relative strain on neck extensor muscles as a function of display height has not been examined. The current findings provide more detailed biomechanical evidence that ergonomists can incorporate with usability and other evidence to determine appropriate display height recommendations.

Keywords: computer; biomechanics; musculoskeletal disorder; posture

1. Introduction

Neck pain is a common problem within the community with point prevalence rates of 10–20% (Walker-Bone et al. 2003) and annual prevalence rates of 31–48% (e.g. Hill et al. 2004). Sustained computer use is thought to be a risk factor for neck pain, with increased exposure associated with increased neck pain prevalence (Palmer et al. 2001, Gerr et al. 2002). Population exposure to computer use has increased both at work and at home. In the workplace, 55% of the USA workforce use computers in their job (United States Department of Labor 2005); whilst in the home, 67% of Australians have computer access (Australian Bureau of Statistics 2005), confirming the importance of this risk factor.

Computer use typically requires sustained low force demand on the neck and shoulder region and pain syndromes such as trapezius myalgia, tension neck syndrome and cervicalgia are a relatively common consequence (Juul-Kristensen et al. 2006). Recent research has found that by increasing muscle strength via a dynamic resistance training programme (and therefore increasing ‘muscle capacity’) neck/shoulder pain perception is markedly reduced in female office workers (Sjogaard et al. 2007). This may have been due to the so-called ‘work demand’ being similar and therefore the strain on neck/shoulder muscles consequently being decreased. This sustained decrease in muscular strain may relate to factors such as decreased muscle fatigue and improved muscle oxygenation and metabolic response (Sogaard 2007). It is this examination of the relationship between demand, muscle capacity and relative muscular strain that provides an attractive avenue of research with reference to computer use.

Furthermore, habitual head and neck postures, such as forward head posture, are thought to be important risk factors for neck pain (e.g. McAviney et al. 2005). Also, there has been evidence of increased neck pain being associated with both increased head extension (Aarás et al. 1998, Marcus et al. 2002) and increased head flexion (Hunting et al. 1981, Starr et al. 1985, Ariens et al. 2001) during computer use. Thus, it seems logical that head and neck posture would be an important factor to examine with regard to the computer use–neck pain relationship.

Guidelines for computer use have been developed to encourage appropriate head and neck postures in order to minimise musculoskeletal disorders (e.g. Standards Australia 1990, National Institute for Occupational Safety and Health 1999). Most guidelines recommend the top of the computer display...
be set around eye height when seated upright to promote a gaze angle (angle from eye to visual target) slightly below the horizontal (see Psihogios et al. 2001, Straker et al. 2008b for reviews). However, much lower (Ankrum and Nemeth 2000) and much higher (de Wall et al. 1992) display positions have also been recommended. Part of the reason for the diversity of recommendations is that evidence has come from both the visual system and musculoskeletal system perspectives. An increased prevalence of visual system symptoms (e.g. eye strain) has been consistently linked with higher displays (Izquierdo et al. 2004, Blehm et al. 2005) and a number of mechanisms have been proposed to explain this (Psihogios et al. 2001). However, the musculoskeletal evidence, which includes preferred head/neck postures, estimates of gravitational load moments and estimates of muscle activity, is less consistent. These factors are discussed below in turn. Following this, the concepts of musculoskeletal demand, capacity and strain are introduced and a section on how mechanical load may be distributed amongst the various structures of the cervical spine in different head/neck postures is presented.

1.1. Preferred head/neck postures

From previous laboratory studies, a gaze angle moderately below the horizontal has been usually preferred to gaze angles at eye level or substantially below eye level (Turville et al. 1998, Sommerich et al. 2001). In contrast, de Wall et al. (1992) found a preference for an expected gaze angle 15° above the horizontal when compared to 15° below. It should be noted, however, that these experiments constrained subjects to a choice of two or three possible positions. Allowing subjects to self-select the display height resulted in preferred gaze angles ranging between 6° above to 42° below horizontal (Burgess-Limerick et al. 1998). Evidence from field studies suggests a mean preferred gaze angle of ~7–9° below the horizontal (Grandjean et al. 1983, Jaschinski et al. 1998, Psihogios et al. 2001).

1.2. Estimated gravitational load moments

The underlying biomechanical concept behind this evidence is that load on the structures of the neck increases as the degree of neck flexion and lateral bending increases (Kilbom et al. 1986). Evidence to support recommendations for a more upright head posture has come from a number of studies. For example, de Wall et al. (1991) and Freudenthal et al. (1991) estimated that reduced neck moments (calculated about the seventh cervical vertebra, C7) were achieved via reduced head flexion as a result of using an inclined desk. However, moderate changes in computer display height have been shown to have little impact on neck flexion moments (Kietrys et al. 1998). A limitation with this evidence is that these gravitational moment calculations were only concerned with moments about the lower cervical spine in the sagittal plane.

The amount of available flexion of the cervical spine is not consistent across all levels with important regional differences existing between the upper and lower cervical spine (Bogduk and Mercer 2000). Therefore, more detailed gravitational models have examined the effects at both the upper and lower cervical spine regions. In manually assisted extreme head/neck postures, Harms-Ringdahl et al. (1986) found a marked effect in the resulting moment calculations on the moment calculated about C7, but not at the upper cervical spine (occiput-first cervical vertebra, OC1). Similarly, working in a highly flexed head/neck position in dentistry has been shown to result in increased moments about C7, but not OC1, when compared to a moderately flexed position (Finsen 1999).

When considering the magnitude of the moment arm in relation to the biomechanics of the cervical spine, it would be considered that the flexion moment is minimised when the centre of mass (COM) of the head/neck is located directly above the joint axes of rotation. Snijders et al. (1991) calculated the force requirements of neck extensors, via a 13 muscle, five joint model and found that the joint reaction force at C7 was minimised at a head position with a gaze angle of 15° above the horizontal. In this posture, the centre of gravity was considered to be vertically projected through C7. However, the position of the head where the COM passes through OC1 was reported to be at a gaze angle of 40° above the horizontal (Snijders et al. 1991).

A further consideration for gravity moment calculation is the individual differences in upper and lower cervical posture to view the same computer display set-up. For example, Burgess-Limerick et al. (1998) and Straker and Mekhora (2000) found different ratios of head, neck and trunk flexion responses to display height changes.

1.3. Estimated muscle activation

Further evidence to support computer display height guidelines has been provided by measures of activation of the cervical musculature. If the net gravitational moment is increased with head flexion, there should be an increased resistive extension moment generated by muscle, unless passive
structures such as the posterior disc and ligaments are being exposed to tensile loading. A number of laboratory studies have consistently shown an increase in cervical erector spinae muscle activity with increased head flexion across moderate ranges (e.g. Turville et al. 1998, Straker and Mekhora 2000, Sommerich et al. 2001, Straker et al. 2008a).

However, at end range flexed positions, muscle activity can be lower than in the mid-range positions (Harms-Ringdahl 1986, Schuldt 1988) suggesting loading of passive structures via a flexion–relaxation phenomena (Meyer et al. 1993).

The effect of head and neck posture on a number of other cervical muscles, including trapezius, levator scapulae, thoracic erector spinae/rhombooids and sterno-cleido-mastoid, is less clear (e.g. Harms-Ringdahl et al. 1986, Schuldt 1988, Straker et al. 2008a).

In a review of available studies, Straker et al. (2008a) found no overall relationship between upper trapezius muscle activity and head/neck flexion, which may suggest that different muscles may have different roles.

A significant limitation of the current evidence relating to cervical muscle activation is that most studies utilise surface electromyography (EMG) methods and few muscles are considered. Whilst surface EMG may have the potential to reflect activation of the deep musculature (Joines et al. 2006), fine wire EMG is required to accurately assess their activity (e.g. Mayoux-Benhamou et al. 1995). Fine-wire EMG evidence is available for some cervical extensor muscles, for example, semispinalis capitus and splenius capitus (Burnett et al. 2007), but its application to the study of computer postures is limited due to its invasiveness.

1.4. Musculoskeletal demand, capacity and strain

The mechanical demand placed on musculoskeletal structures of the cervical spine created by viewing a computer display may vary with display height. However, the amount of strain this actually places on the user’s cervical spine depends on the capacity of the system and it is the level of strain that has been associated with musculoskeletal disorder development in most theories (Karsh 2006).

Muscle activity is regularly reported relative to an individual’s maximum voluntary exertion (%MVE, alternatively called maximum voluntary isometric contraction) to allow comparison between studies, individuals, muscles and testing days. Whilst there are issues with MVE varying with position (Joines et al. 2006), reporting muscle activity as %MVE gives a clearer indication of the ratio between demand and capacity and thus strain.

In contrast, gravitational load moments are absolute figures that are usually reported as a demand only, without consideration for differences in the muscle capacity to cope with those demands between people and postures. From the calculation of gravitational moments, the evidence shows that the moment demand varies with head and neck position and this moment gets larger with increasing amounts of flexion. However, the capacity of muscles to cope with this demand is also known to vary. For example, females tend to have less neck extensor strength than males (Garces et al. 2002) and neck extensor strength decreases with age (Garces et al. 2002). The strength capacity of neck extensor muscles also varies with posture (Suryanarayana and Kumar 2005) and is at a maximum in a neutral position, whilst strength decreases with increasing flexion. However, there has been limited work relating moment demand to capacity (Finsen 1999).

1.5. Partitioning cervical extensor muscle loads across potential head postures

Maximal strength capacity is a result of the summed activation of a number of muscles with consideration of their individual torque-producing capability. However, partitioning of external load, such as that produced with head/neck flexion, to individual muscles is difficult. It is generally accepted that semispinalis capitis and splenius capitus contribute most to neck extension strength (Vasavada et al. 1998) but deep upper cervical muscles have been suggested to play an important role (Burgess-Limerick et al. 1998). While many muscles maintain about 80% of their peak force-generating capacity throughout their range of motion, the capacity of muscles such as splenius capitus with large moment arms and/or short fascicles can vary substantially with head posture (Vasavada et al. 1998).

The most advanced cervical spine musculoskeletal models (e.g. Snijders et al. 1991, Vasavada et al. 1998) allow for individual muscle morphology and architecture, e.g. muscle-specific cross-sectional areas, fibre lengths and orientation. Further, these models allow changes to the length–tension relationships of muscle with changes in postures. Specifically, software for interactive musculoskeletal modelling (SIMM) (Delp and Loan 1995) uses a graphical representation of bones and muscles of the cervical spine (Vasavada et al. 1998) in combination with specific anatomical data (Kamibayashi and Richmond 1998). This model utilises a Hill-type muscle model and allows calculation of neck muscle forces and moment-generating capacities.

Advances in muscle modelling such as that made with SIMM (Delp and Loan 1995) have provided an
opportunity to investigate the moment-generating capacity of cervical musculature at the level of muscle groups and individual muscles, as well as determine the extensor capacity of lateral flexors. However, the sensitivity of the model to changes in model constraints, in particular the number of joints modelled, is not known for the cervical spine.

In summary, despite some evidence being available pertaining to preferred postures, gravitational loads moments and activation of the cervical musculature, there is insufficient evidence to determine whether an optimal head and neck posture, about which some variation would be encouraged, for computer use exists. Guidelines for computer display height are currently based on limited preferred posture data, modelled net gravitational moment estimates, which have generally not been separated into upper and lower cervical estimates and have usually been limited to the sagittal plane only, and muscle activation data that has been collected from the superficial extensors only. In addition, there is little information regarding the relative contributions of deep cervical muscles across a range of potential head postures and how the gravitational load relates to muscle capacity. Hence, there is a clear need for further investigation into optimal head and neck posture in computer use using biomechanical modelling in order to address the limitations of the current evidence.

Therefore, the primary aim of this study was to elucidate the current conflict between biomechanical and epidemiological evidence regarding optimal display height by examining the capacity of superficial and deep cervical extensor muscles relative to gravity imposed moments. A secondary aim was to investigate the effect of flexing the neck using predominantly upper or lower cervical spine flexion strategies on cervical extensor muscle capacity. A subsidiary aim was to examine whether constraining the model to two cervical joints greatly affected the model output.

2. Method
The study was conducted in eight parts as represented in Figure 1 and described below.

(1) Collection of kinematic data from subjects working with different display heights (high, mid and book).

![Flow diagram of modelling inputs, models and outputs](image-url)

Figure 1. Flow diagram of modelling inputs, models and outputs (numbers relate to method part number). Model rectangles are shaded white for gravitational model, light grey for modified Vasavada et al. (1988) model and dark grey for original Vasavada et al. (1988) model. SIMM = software for interactive musculoskeletal modelling.
(2) Using the kinematic data collected in part 1 as input to calculate gravitational load moments about OC1 and C7 in the sagittal and frontal planes.

(3) Using the kinematic data collected in part 1 as input into a graphically based isometric musculoskeletal model of the cervical spine (Vasavada et al. 1998) to estimate the moment-generating capacities of selected cervical muscles.

(4) Deriving estimates of muscle strain based on the gravitational moments demand (part 2) and the cervical muscle extension moment-generating capacity (part 3) for each posture examined in part 1.

(5) Determining the gravitational moment and muscle moment-generating capacity across a theoretical range of possible head and neck postures in the sagittal plane.

(6) Modelling the effect of different postural strategies (either predominantly upper cervical spine movement or predominantly lower cervical movement) on overall muscle capacity.

(7) Modelling the effect that different postural strategies have on individual muscle moment generating capacity.

(8) Comparing outputs of a two-joint (6 degrees of freedom (df) modified from Vasavada et al. 1998) model with those of an eight-joint (24 df unmodified Vasavada et al. 1998) model.

2.1. Part 1 – Kinematic data collection

A total of 36 young adult participants (18 male (20.4 ± 2.1 years; 179.5 ± 6.9 cm; 74.8 ± 10.6 kg), 18 female (20.8 ± 2.4 years; 164.8 ± 5.6 cm; 61.7 ± 10.6 kg)) were recruited through notices in community newspapers and local universities. Subjects had no history of significant chronic musculoskeletal disorders in the neck or upper limbs, no current pain and normal vision. The study was approved by the Human Research Ethics Committee of Curtin University of Technology.

Subjects completed a task for 10 min in each of the three display conditions: 1) high – top of computer display set at participant’s eye height (mean gaze angle measured was −7.8°); 2) mid – bottom of computer display set at desk height (mean gaze angle = −30.8°); 3) book – paper on desk (mean gaze angle = −69.4°). The desk was a traditional straight desk set at 3 cm below the subject’s elbow height, with 0° shoulder flexion and forearms unsupported. A standard office chair set to subject popliteal height and upright backrest was used. The task was a general history knowledge task that required reading from an electronic (with navigation by mouse) or paper encyclopaedia and completing an activity sheet using keyboard and mouse for the computer conditions and pen and paper for the book condition.

3-D head and neck postures during each of these conditions were determined from bilateral markers placed on the outer canthi, external auditory meatus and acromion process, with an additional marker on C7. Skin markers were manually identified and automatically digitised at 50 Hz using PEAK Motus V8.2 data acquisition software (PEAK Performance Technologies Inc, Centennial, CO, USA). The direct linear transformation method was used to obtain 3-D coordinates of the markers and these data were smoothed using a low pass fourth order Butterworth digital filter set at 4 Hz.

The angles determined with regard to the vertical were head flexion/extension, head lateral bending, neck flexion/extension and neck lateral bending, while head rotation was determined with regard to the trunk. The average angles over the final 2 min of the task were used as input for parts 2–3 of the study. Two virtual markers were created to allow angle estimation: OC1 – mid-point external auditory meati, and Cyclops – mid-point canthi. The definitions of angles used were as follows:

- Head flexion/extension (HF): Sagittal plane angle between Cyclops, OC1 and vertical axis.
- Head lateral bending (HLB): Frontal plane angle between right external auditory meatus, OC1 and vertical axis (negative to the left).
- Head rotation (HR): Transverse plane angle between Cyclops, OC1 and anterior–posterior axis (negative to the left).
- Neck flexion (NF): Sagittal angle between OC1, C7 and vertical axis.
- Neck lateral bending (NLB): Frontal plane angle between OC1, C7 and vertical axis.

Further details of the kinematic data from the study have previously been reported in Straker et al. (2008a).

2.2. Part 2 – Estimation of the gravitational moment in the sagittal and frontal planes

The gravitational load moments of the head (about OC1) and head/neck (about C7) were calculated using the kinematic data obtained in part 1 and existing
segmental inertia parameters. The head and neck complex was considered as a lumped-mass rigid-link system with a 3 df joint (flexion/extension, lateral bending, rotation) at OC1 and a 2 df (flexion/extension, lateral bending) joint at C7. The locations of the COM of the head and head/neck were taken as 9 mm anterior and 23 mm superior to auditory meatus for the head (Camacho 1999) and 10 mm anterior to tragus, for the head/neck (Dempster 1955) with the head in a neutral posture. The relative mass of the head (WH) and head/neck (WHN) was considered to be 6.2 and 8.4% of body weight respectively (Pheasant 1986). Further details of the process to calculate gravitational load moments are presented in Appendix 1.

2.3. Part 3 – Modelling the maximum moment capacity of cervical musculature using a two joint model

The posture-specific maximum moment-generating capacities of those muscles included in the model were calculated using a graphically based isometric musculoskeletal model of the cervical spine (Vasavada et al. 1998). To estimate maximum capacity, no experimentally determined EMG data were used to drive this model as the muscle activation for all muscles in the model was considered to be 100%. The model included 21 muscle groups of the cervical spine and shoulder (Kamibayashi and Richmond 1998). For the purposes of the present study, these muscles were functionally grouped into flexors, lateral flexors and four subgroups of extensors (see Table 1).

The original Vasavada et al. (1998) model apportioned movement at each cervical level. To enable comparison with part 2 estimates of moment around OC1 and C7, the SIMM model was modified to constrain movement in the cervical spine to occur only at the OC1 and C7 joints. The mean HF and NF values for the subjects measured in part 1 (i.e. HF: OC1 = 27.3%; C7 = 72.7%) were used to apportion the relative contribution from the upper and lower cervical joint segments to the overall head posture.

SIMM defined head angle relative to a neutral position. The subject-specific head positions (HF, HLB, HR) obtained in each experimental condition in part 1 were therefore converted by transformation of the subject-specific neutral position (head upright and eyes straight ahead) to the neutral position defined by SIMM (HF = 65°). The extension moment-generating capacity of the upper superficial extensor, lower superficial extensor, upper deep extensor, lower deep extensor, lateral flexor and flexor groups were then determined. Likewise, the lateral flexion moment-generating capacity of extensors, lateral flexors and flexor groupings were also calculated.

2.4. Part 4 – Estimation of muscle strain

The ratio of task demand to muscle capacity (termed ‘strain’) was calculated from the gravitational load moments obtained from part 2 of the study and the modelled extensor muscle capacities from part 3. This was calculated for net muscle capacity, as well as for upper (upper superficial and upper deep compared with gravity moment about OC1) and lower (lower superficial and lower deep compared with gravity moment about C7) muscle groups listed in Table 1.

2.5. Part 5 – Calculation of gravitational moments and muscle capacities across a wide range of head flexion postures using a two-joint model

To examine head postures other than those investigated in the experimental study (part 1) and to determine the capacity of muscles to generate moments in the sagittal plane, gravitational flexion moments and extensor muscle capacities were simulated across a range of HF (5–115°, where 65° is neutral, looking straight ahead posture). This range of postures was the full range available using the SIMM model and this range was similar to the maximum range of movement measured in the experimental study. Head/neck lateral bending and head rotation were set at 0° (no deviation from neutral) for this part of the study. The

Table 1. Grouping of muscles in Vasavada et al. (1998) cervical model.

<table>
<thead>
<tr>
<th>Group Name</th>
<th>Muscles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexors</td>
<td>sternocleidomastoid, longus capitus, longus colli</td>
</tr>
<tr>
<td>Lateral flexors</td>
<td>levator scapulae, scalenus anterior, scalenus medius, scalenus posterior</td>
</tr>
<tr>
<td>Extensors</td>
<td>obliquus capitus inferior, obliquus capitus superior, rectus capitus posterior major, rectus capitus posterior minor</td>
</tr>
<tr>
<td>upper deep</td>
<td>longissimus capitus, semispinalis capitus, splenius capitus</td>
</tr>
<tr>
<td>upper superficial</td>
<td>iliocostalis capitus, longissimus cervicis, semispinalis cervicis</td>
</tr>
<tr>
<td>lower deep</td>
<td>semispinalis capitus, splenius capitus, splenius cervicis, trapezius (acromion and clavicular compartments)</td>
</tr>
</tbody>
</table>
gravitational flexion estimates were calculated using the same formula as part 2 using group mean data for moment arms and head/neck masses. The muscle capacity estimates were calculated using the same two-joint model used in part 3. The relationship between HF and NF across the range of HF postures was determined with a regression equation based on experimental data in part 1, where:

\[ NF = 0.65HF + 6.24 \quad R^2 = 0.76 \] (1)

2.6. Part 6 – Examining the effect of different posture strategies on extensor muscle capacity using a two-joint model

The relative contribution to head position from movement at different cervical vertebral joints is known to not be consistent over the range of movement (Bogduk and Mercer 2000) and individuals (Burgess-Limerick et al. 1998, Straker and Mekhara 2000). To allow for known differences in HF to NF movement ratios, the modelling approach utilised in part 5 was repeated using four more datasets. These datasets were based on the subject variation in head and neck flexion data from part 1 and included two datasets representing people with a tendency to respond to display height differences mostly at their upper cervical spine (mean ± 1 SD and mean ± 2 SD) and two datasets representing people with a tendency for more movement in their lower cervical spine (mean +1 SD and mean +2 SD). The majority of the population (~70%) is expected to lie within the plus and minus 1 SD, whilst the plus and minus 2 SD represent the 2nd and 98th percentiles respectively.

2.7. Part 7 – Examining the effect of different posture strategies on individual muscle capacities using a two-joint model

A modelling approach was also used to estimate the moment capacity, moment arm length and force generation capacity of particular cervical muscles (trapezius (cleido); semispinalis capitus; splenius capitus; splenius cervicus; rectus capitus posterior major; rectus capitus posterior minor). Thus, the individual contribution of the chosen muscles was assessed across the 5–115° given range of motion using the two-joint model using mean ± 1 SD and mean ± 2 SD.

2.8. Part 8 – Comparing the two-joint (6 df) model with the original eight-joint (24 df) model

An assessment of the sensitivity of the simplified two-joint model was also conducted by comparing the results of the two-joint (OC1 and C7 joints) model with the original SIMM eight joint (each cervical level) model when using the same dataset.

2.9. Statistical analysis

Results for parts 1–5 were analysed statistically using a repeated measures analysis of variance (RANOVA) to determine if there was any significant difference between display heights, \( p < 0.01 \). Where Mauchley’s sphericity could not be assumed, the Huynh-Feldt correction was used.

3. Results

3.1. Part 1 – Kinematic data

Significant differences were found in head/neck postures between the high, mid and book conditions (see Table 2). Head flexion increased 13.6° (1.5) in the mid condition compared to the high condition and increased a further 18.6° (1.4) in the book condition. A similar pattern was found for neck flexion with a 5.7° (2.1) increase in the mid condition compared to the high condition and a further 18.3° (1.9) increase in the book condition. In the book condition, subjects also displayed a greater degree of lateral bending.

Table 2. Mean (±SD) 3-D head/neck position (°) for three display heights.

<table>
<thead>
<tr>
<th>Posture</th>
<th>High</th>
<th>Mid</th>
<th>Book</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head flexion</td>
<td>75.8 (7.3)(^a)</td>
<td>89.4 (8.4)(^b)</td>
<td>108.0 (12.1)(^c)</td>
</tr>
<tr>
<td>Lateral bending</td>
<td>0.7 (4.6)(^a)</td>
<td>-1.6 (5.6)(^a)</td>
<td>2.4 (7.9)(^b)</td>
</tr>
<tr>
<td>Rotation</td>
<td>-3.1 (5.6)(^a)</td>
<td>-1.0 (5.7)(^a)</td>
<td>-4.3 (12.7)(^a)</td>
</tr>
<tr>
<td>Neck flexion</td>
<td>55.3 (5.6)(^a)</td>
<td>61.1 (12.6)(^b)</td>
<td>79.4 (9.7)(^c)</td>
</tr>
<tr>
<td>Lateral bending</td>
<td>0.5 (3.7)(^a)</td>
<td>0.6 (3.8)(^a)</td>
<td>-3.4 (5.9)(^a)</td>
</tr>
</tbody>
</table>

RANOVA = repeated measures analysis of variance.

\(^a,b,c\) Different superscript letters denote significant pairwise differences.
3.2. Part 2 – Estimated gravitational moment in the sagittal and frontal planes

In general, sagittal and frontal gravitational flexor moments about OC1 and C7 increased from high to mid to book conditions (Table 3). Gravitational moments about OC1 were small, with approximate values being 0.7 Nm in the sagittal plane and 0.08 Nm in the frontal plane, reflecting the small moment arm and minimal lateral bending and rotation of the head. Gravitational moments about C7 were around 7.7 Nm in the sagittal plane and 0.20 Nm in the frontal plane, reflecting the larger moment arm.

3.3. Part 3 – Modelled maximum moment capacity of cervical musculature using a two-joint model

In general, the capacity for production of extensor moment decreased from high to mid to book conditions (Table 3). Further, the total modelled muscle capacity was approximately 29 Nm. When considered fully activated, superficial muscles contributed the majority of total extensor capacity (upper ~27–30%, lower ~39–43%) with a smaller contribution from deep (upper ~5–6%, lower ~12–13%) and lateral flexor (~10–12%) muscles. Upper cervical deep muscle capacity marginally increased as a proportion of total capacity with increasing neck flexion, but remained fairly constant in magnitude across conditions.

3.4. Part 4 – Estimated relative muscle strain

In general, muscle strain increased from high to mid to book conditions (Table 3). Total extensor strain was estimated to be approximately 26%. Upper cervical strain was small (~3–11%) compared with lower cervical strain (~39–61%); however, strain of the deep muscles of the upper cervical spine was greater (33–57%).

3.5. Part 5 – Calculated gravitational moments and muscle capacities across a wide range of head flexion postures using a two-joint model

Figures 2 and 3 show the modelled muscle capacities across a full range of head flexion (5°–115° with 65° considered as neutral), for upper and lower, deep and superficial extensor groups as absolute and relative contributions. Figure 2 also shows the modelled gravitational moment around C7 and the three (part 1) experimental conditions are shown for comparison. In absolute terms, modelled extensor capacity was greatest near the neutral head position with some reduction in capacity into full flexion (115°) and marked reduction into full extension (5°). In relative

### Table 3. Mean (±SD) gravitational moments, muscle capacities (from two-joint modified Vasavada model) and strain (demand/capacity) for muscle groups across the high, mid and book display height conditions.

<table>
<thead>
<tr>
<th></th>
<th>High</th>
<th>Mid</th>
<th>Book</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gravitational Moments</strong> (Nm)</td>
<td></td>
<td></td>
<td></td>
<td>RANOVA</td>
<td></td>
</tr>
<tr>
<td>OC1 Sagittal*</td>
<td>0.5 (0.1)</td>
<td>0.7 (0.1)</td>
<td>0.8 (0.1)</td>
<td>a,b,c</td>
<td>120.8</td>
</tr>
<tr>
<td>Frontal*</td>
<td>0.01 (0.05)</td>
<td>-0.02 (0.1)</td>
<td>0.11 (0.17)</td>
<td>c</td>
<td>7.2</td>
</tr>
<tr>
<td>Frontal (Abs)*</td>
<td>0.04 (0.04)</td>
<td>0.07 (0.07)</td>
<td>0.15 (0.12)</td>
<td>c</td>
<td>18.8</td>
</tr>
<tr>
<td>C7 Sagittal</td>
<td>7.1 (1.9)</td>
<td>7.7 (2.0)</td>
<td>8.4 (2.1)</td>
<td>c</td>
<td>155.0</td>
</tr>
<tr>
<td>Frontal</td>
<td>0.9 (0.4)</td>
<td>0.04 (0.2)</td>
<td>-0.1 (0.2)</td>
<td>a</td>
<td>3.5</td>
</tr>
<tr>
<td>Frontal (Abs)</td>
<td>0.3 (0.3)</td>
<td>0.2 (0.1)</td>
<td>0.1 (0.1)</td>
<td>b</td>
<td>7.6</td>
</tr>
<tr>
<td><strong>Extensor Muscle Capacities</strong> (Nm)</td>
<td></td>
<td></td>
<td></td>
<td>RANOVA</td>
<td></td>
</tr>
<tr>
<td>Total extensor</td>
<td>32.1 (1.3)</td>
<td>29.2 (2.2)</td>
<td>25.3 (2.0)</td>
<td>c</td>
<td>188.2</td>
</tr>
<tr>
<td>Upper superficial</td>
<td>8.7 (0.1)</td>
<td>8.4 (0.3)</td>
<td>7.6 (0.4)</td>
<td>c</td>
<td>174.5</td>
</tr>
<tr>
<td>deep</td>
<td>1.54 (0.03)</td>
<td>1.56 (0.02)</td>
<td>1.49 (0.05)</td>
<td>c</td>
<td>41.5</td>
</tr>
<tr>
<td>Lower superficial</td>
<td>13.9 (1.0)</td>
<td>11.7 (1.5)</td>
<td>9.9 (1.1)</td>
<td>c</td>
<td>120.1</td>
</tr>
<tr>
<td>deep*</td>
<td>4.15 (0.02)</td>
<td>4.09 (0.08)</td>
<td>3.86 (0.14)</td>
<td>c</td>
<td>134.4</td>
</tr>
<tr>
<td>Lateral flexors</td>
<td>3.8 (0.1)</td>
<td>3.4 (0.4)</td>
<td>2.5 (0.5)</td>
<td>c</td>
<td>171.1</td>
</tr>
<tr>
<td><strong>Relative Strain</strong> (%gravitational moment/muscle capacity)</td>
<td></td>
<td></td>
<td></td>
<td>RANOVA</td>
<td></td>
</tr>
<tr>
<td>OC1/upper*</td>
<td>3.0 (0.7)</td>
<td>4.5 (1.1)</td>
<td>11.3 (1.9)</td>
<td>c</td>
<td>588.6</td>
</tr>
<tr>
<td>OC1/upper deep*</td>
<td>32.6 (6.4)</td>
<td>44.0 (6.3)</td>
<td>56.9 (8.4)</td>
<td>c</td>
<td>141.1</td>
</tr>
<tr>
<td>C7/lower</td>
<td>39.5 (11.9)</td>
<td>49.6 (15.0)</td>
<td>61.4 (17.3)</td>
<td>c</td>
<td>171.6</td>
</tr>
<tr>
<td>C7/total ext</td>
<td>22.2 (6.4)</td>
<td>26.7 (7.8)</td>
<td>33.3 (9.2)</td>
<td>c</td>
<td>208.2</td>
</tr>
</tbody>
</table>

**RANOVA** = repeated measures analysis of variance; OC1 = occiput-first cervical vertebra; Abs = lateral bending in either direction.

a,b,cDifferent superscript letters denote significant pairwise differences.

*Denotes Mauchley’s sphericity not assumed and Huynh-Feldt correction used.
terms, the contribution of each group of extensor muscles was quite consistent from maximum head flexion ($115^\circ$) to mid extension ($30^\circ$), where the relative contribution of low superficial muscles increases due to a decrease in the actual moment capacity in the other groups. Figure 4 shows the relative muscle strain from the moment calculated about C7 and highlights the gradual increase in strain with increased flexion past a neutral head position ($65^\circ$).
3.6. **Part 6 – The effect of different posture strategies on extensor muscle capacity using a two-joint model**

Figure 5 shows the total extension capacity around C7, using the two-joint model based on the variation in head flexion/neck flexion strategies measured in part 1. The different strategies clearly influence the extension capacity, with typical differences of ~15% in the range of usual computer display heights. Increasing the relative contribution of the lower cervical segment (i.e., +SD) reduces the capacity for developing extensor torque across neutral and flexion postures. Figure 6 shows that the different strategies have an important, yet varied, effect on each subgroup’s capacity.

3.7. **Part 7 – The effect of different posture strategies on individual muscle capacities using a two-joint model**

Figure 7a,b,c shows the extension moment, moment arm and force capacity of selected muscles. For

![Figure 4](image)

**Figure 4.** Estimated cervical relative strain (moment demand due to gravity around C7/lower extensor muscle capacity) across the postural range. Experimental head flexion positions (H = high; M = mid; B = book) are also shown.

![Figure 5](image)

**Figure 5.** Influence of head/neck variation in posture on modelled cervical extensor muscle capacity across the postural range. Mean head/neck relative movement and a larger (plus) and smaller (minus) contribution from lower cervical segment. Original eight-joint model mean estimates are also shown.
trapezius, it can be seen that different postures have little effect on force-generating capacity, but because of changes to moment arms there is a large effect on moment capacity, with greatest capacity in head extension. For semispinalis capitus there is a rapid loss of force capacity above some extension (40°), which, combined with a slight loss of moment arm, creates a substantial decrease in moment capacity. Splenius capitus and splenius cervicis also show reduced force capacity with extreme head extension and an increase in moment arm is insufficient to offset this, resulting in an overall decrease in moment. Semispinalis capitus and splenius capitus show increased loss of extensor capacity when movement is mainly at the upper cervical spine (the −2 SD condition). Rectus capitus posterior major and minor show marked reductions in extension for force, moment arm (major only) and moment into extension.

3.8. Part 8 – Comparison of the two-joint (6 df) model with the original eight-joint (24 df) model

As shown in Figure 5, the total extensor capacity across a wide range of head flexion as estimated from the original eight-joint model shows a very similar pattern to the revised two-joint model, with capacity greatest in the 40–70° range and reducing with more extreme extension and flexion. Compared with the original model, the two-joint model overestimated the extensor capacity when the head was in an extended posture, but underestimated capacity in neutral and flexed postures. Comparisons of the original model...
and the two-joint model estimates for cervical muscle subgroups (Figure 6) and individual muscles (Figure 7) show a similar pattern.

4. Discussion
The data in the present study provide the most comprehensive investigation of the effects of head and neck posture on modelled net gravity moments and cervical muscle capacities in an asymptomatic population. It therefore provides unique evidence to inform guidelines for posture during computer use.

4.1. Why is an ultra high display position not routinely recommended and used?
The net gravitational moments found in the present study confirm and expand prior reports (Harms-Ringdahl 1986, Finsen 1999), suggesting that net moment demand is reduced with head/neck extension and is increased with head/neck flexion. The muscle capacity data suggest that capacity is greatest across mid-range to extended postures and is reduced with head/neck flexion. Combining moment demand and muscle capacity, as undertaken in this study, has provided novel muscle strain data, which has shown an increase in strain with increasing head/neck flexion. Thus, the moment, capacity and strain data are consistent with previous surface cervical erector spinae EMG data (see review Straker et al. 2008a), which suggest that increasing head/neck flexion represents a greater stress to the musculoskeletal system and is therefore likely to represent a greater risk for neck pain disorders.

However, this is not consistent with evidence from field studies, nor is it consistent with observations of computer users. Marcus et al. (2002) found that increased head flexion was associated with a reduced risk of neck and shoulder symptoms and disorders. Further, if the modelling data truly captures risk, then why don’t people prefer display positions that minimise head flexion? Indeed the gravity moment and strain evidence suggests that more head extension is better, with the muscle capacity data suggesting head

![Figure 7](image-url)
extension above ‘80°’ and as much as ‘50°’ is optimal. However, this suggestion appears nonsensical as a direct translation of these results into workplaces would result in computer displays being placed almost overhead for each worker.

Guidelines to date have generally recommended computer displays below eye height. de Wall et al. (1992) determined that biomechanical modelling suggested a gaze angle at around 15° above the horizontal would be appropriate. However, following their logic consistently would require recommendations for even higher displays, as the net gravity moment, muscle capacity and muscle activity continues to decrease above 15°. Interestingly, the CAD workers in de Wall et al.’s study made postural adjustments such that their actual gaze angle was close to horizontal.

Given the very consistent prior biomechanical evidence, why don’t guidelines recommend ultra high display positions and why don’t computer users regularly place their display in an ultra high position to create head extension? The current authors suggest this inconsistency is because current evidence does not adequately capture postural risk and also that other factors may be important for neck pain development and usability.

4.2. The importance of deep sub-capital muscles

Prior suggestions for why ultra high displays are not widely used have included the notion that it may not be the overall moment, capacity and strain, but rather the specific strain on particular structures. Burgess-Limerick et al. (1998) suggested that deep sub-capital extensors may be particularly sensitive to head extension postures. The modelled muscle force and moment arm data presented in part 7 lend support to this hypothesis. The modelling of the deep sub-capital extensors revealed a reduced force-generating capacity of the muscles in more extended head positions, resulting in a reduced moment-generating capacity when the moment arm remains relatively constant (in the case of rectus capitus major) or when the moment arm is reduced (in the case of rectus capitus minor). The potential need for deep muscle activity to provide...
stabilisation in low-load tasks such as computer use to prevent local buckling of the neck, especially in extended postures (Winters and Peles 1990), suggests these muscles may be of importance.

4.3. Other possible reasons for conflict between biomechanical and other criteria

The muscle capacity estimates in this paper were only based on muscle extensor strength, with no examination of forces to passive connective tissue such as bone, disc and ligament. However, at extreme flexion, muscle activity has been shown to be less than in mid-range positions (Harms-Ringdahl 1986, Schuldt 1988) suggesting that the passive structures are being loaded.

Only estimating strain on muscles (as done in the present study) assumes they are the only structures that provide resistive torque and that they are the sole source of neck pain. Whilst neck muscles may be an important source of pain (e.g. Szeto et al. 2005), there are many other cervical tissues with nociception such as ligaments and joint capsules, which may be the source of neck pain related to computer use. Therefore, the current gravitational moment and muscle capacity evidence may not adequately capture postural risk.

The present data show that muscle capacity is reduced quickly as the head is placed into increasing degrees of extension – yet not more rapidly than the decline in net gravity moment. This resulted in a relatively constant level of strain in extension postures. However, the current model has many limitations (see below) and inaccuracies in the model may have underestimated the decline in capacity with extension. If this was the case, strain would have increased with head extension, rather than remaining relatively constant, as suggested by current modelling.

Other potential mechanisms for ultra high display positions contributing to neck pain include eye position/neck muscle activity coupling, vestibular discomfort/disorientation and visual system discomfort.

The development of neck pain related to computer use may not be from only mechanical loading, but may be due to cognitive and psycho-social factors (e.g. Larsson et al. 2007). The modelling evidence in this study also does not take account of usability issues. For example, a ceiling-mounted computer display may...
inhibit usability of pen and paper when interspersed with computer display interaction.

4.4. The importance of individual variation in upper vs. lower cervical strategies

The results obtained in part 7 of the study clearly demonstrate the sensitivity of cervical muscles to different strategies for head and neck flexion. This suggests that, for some computer users, a significant alteration of display height would not make a significant difference to upper or lower cervical strain. However, it also suggests that, for some computer users, fairly small changes in display height could lead to significant differences in cervical muscle strain. This may be a factor to help explain why within a group of workers performing similar tasks with similar workstation set-up, some develop neck/shoulders symptoms and some do not. Szeto et al. (2005) have also found differences in muscle activation between symptomatic and asymptomatic computer users and suggested that motor control differences may be an important aetiological factor.

4.5. Implications for guidelines

Ultra high display positions (display above eye height, gaze angles above horizontal) are likely to create excessive strain on deep upper cervical extensor muscles. Based on this evidence from part 7 of the current study, prior epidemiological evidence and usability considerations, ultra high display positions should therefore not be recommended. Ultra low display positions (gaze angles over 45° below horizontal) are likely to create increased strain on neck extensors. Based on this evidence from part 4 of the current study and on current and prior research examining estimated gravitational load moments and extensor muscle activity, ultra low display positions should not be recommended. Moderate display positions around eye height are likely to match maximum net extensor muscle capacity, as shown in part 3 of the current study. However, parts 6 and 7 of the current study provide clear evidence that the optimal posture between the ultra high and ultra low extremes is likely to vary between individuals.

Given the increasing exposure to computer use, minimising associated musculoskeletal risks is clearly important. Computer display height guidelines aim to encourage suitable head and neck postures and thereby reduce the risk of neck pain. The current study has provided clearer evidence to support guidelines suggesting computer displays should be positioned to suit the individual, within a moderate height range close to slightly below eye height.

4.6. Modelling limitations

Whilst the cervical biomechanical models used were the most advanced available, they were still vastly simplified when compared to real cervical spines. The primary limitation of the gravitational moment model was the assumption of where the COM of the head and head/neck lies relative to OC1 and C7 respectively. As with prior studies, this relied upon 2-D cadaver data from Dempster (1955). Although the SIMM model has shown great advances in neck modelling, the model was also limited in some respects. For example, the Vasavada et al. (1998) model obtained the isometric force-generating properties of individual muscles by scaling a generic model of muscle from Zajac (1989). Some of the architectural data for muscle were estimated from available data or were determined from the optimal fascicle length, pennation angle and cross-sectional area of neck muscles from cadavers. This may underestimate the moment-generating capacity of healthy young individuals (Kamibayashi and Richmond 1998). Another limitation of the muscle model is that the EMG is assumed to have a linear relationship with force generation, but this is not necessarily the case (Sommerich et al. 2000). This model only considered muscle loads with no loading of passive tissues, which is a major limitation considering the potential role for these tissues in pain development. Even the muscle capacities modelled should be considered relative, rather than absolute. The estimated extensor muscle capacity was approximately half of strength levels reported in some studies, although it was similar to those found by Choi (2003), who measured and modelled moments about C4/5. Whilst these muscle model limitations suggest areas for future refinement, they were unlikely to result in a different pattern of response when comparing the effects of display heights.

5. Conclusion

This study provides the first estimates of muscle strain at the upper and lower cervical regions with head and neck postures associated with computer displays by comparing estimates of gravitational load moments with modelled cervical extensor muscle capacity. The study also examined the effect of individual differences in the amount of movement at the upper or lower cervical spine on muscle strain. The evidence provides a clearer understanding of the potential role of deep upper cervical muscles and the importance of individual differences and that these factors may be responsible for the apparent conflict between prior biomechanical and epidemiological evidence. It
therefore considerably expands the evidence base for computer display height guidelines. It also provides a basis for future attempts at more detailed biomechanical modelling, which may include more accurate anatomy and the inclusion of passive connective tissues.

Acknowledgements
The authors acknowledge funding from the Australian National Health and Medical Research Council (project 229011) and data collection and manuscript preparation assistance from Jemma Coleman.

References


Appendix 1. Gravitational moment model

The relative location of the centre of mass (COM) from occiput-first cervical vertebra (OC1) in the measured posture was calculated via cardan angles (Craig 1989), with order of rotation XYZ, denoting head flexion/extension (HF), head lateral bending (HLB), head rotation (HR) (Hoef et al. 2001) from the COM location in neutral posture.

\[
\begin{bmatrix}
COM_x' \\
COM_y' \\
COM_z'
\end{bmatrix} = R_z(HR) \cdot R_y(HLB) \cdot R_x(HF) \cdot \begin{bmatrix}
COM_x \\
COM_y \\
COM_z
\end{bmatrix}
\]

The vertical component of neck length (between OC1 and C7) in the neutral position was determined using a regression equation based on the height of six subjects, \( R^2 = 0.8 \). (Data from only six subjects were used because the
acquisition of these data was time-consuming and the high R2 gave confidence that the error in group estimates was small. Both genders were equally represented.)

\[ NL_V = 0.0576 \cdot H + 0.0101 \]  
(A2)

Neck length was then calculated using the measured neutral neck flexion (NF):

\[ NL = NL_V \div \cos (NF) \]  
(A3)

Sagittal (s) plane distance between OC1 and C7 was determined by:

\[ NL_s = NL \cdot \cos (90 - NF) \]  
(A4)

Frontal (f) plane distance between OC1 and C7 was determined by:

\[ NL_f = NL \cdot \sin (NLB) \cdot \cos (NF) \]  
(A5)

Frontal and sagittal plane projections of neck length were checked using the cardan angle rotation order XYZ.

The gravitational moments about OC1 were calculated as follows:

\[ OC1GM_S = COM_y' \cdot W_H \]  
(A6)

\[ OC1GM_F = COM_x' \cdot W_H \]  
(A7)

The gravitational moments about C7 were calculated as follows:

\[ C7GM_S = \left( COM_y' + NL_S \right) \cdot W_{HN} \]  
(A8)

\[ C7GM_F = \left( COM_x' + NL_F \right) \cdot W_{HN} \]  
(A9)