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Neck kinematics and muscle activity during mobile device operations

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ABSTRACT

Neck pain is a significant health problem due to its high incident rates and economic costs. Increased use of touch screen mobile devices is becoming pervasive in the modern society and may further influence this already prevalent health problem. However, our current understanding of the cervical spine biomechanics during the operation of touch screen mobile devices is very limited. This study evaluated the neck extensor muscle activities and the kinematics of the cervical spine during the operation of a touch screen tablet and a smart phone. Three-variables, DEVICE, LOCATION and TASK were treated as the independent variables. NASA TLX revealed that "Gaming" was the least difficult task and "Typing" was the most difficult task. Participants of this study maintained significantly deeper neck flexion when operating a smart phone (44.7°), with the mobile devices set on a table (46.4°), and while performing a "Typing" task (45.6°). Lower levels of neck muscle activities were observed while performing a "Reading" task and holding mobile devices with hand. Lower levels of neck muscle activities were also observed when using a smart phone vs. a tablet, however such change was statistically insignificant.

Relevance to industry: The current study demonstrated that users maintain deep neck flexion when using touchscreen mobile devices. In the recent years, there is an increasing popularity of mobile smart devices in various occupational environments. The findings of this study may be useful in implementing human-centered task designs to reduce neck injury risks among mobile device users.

1. Introduction

In industrialized countries, neck pain is a significant musculoskeletal disorder (MSD) with high medical costs, social costs (Borghouts et al., 1999) and low rate of complete recovery (Cote et al., 2004). Previous studies have discovered high prevalence of neck pain among the general population (Makela et al., 1991; Bovim et al., 1994; Croft et al., 2001; Sim et al., 2006) and among computer users (Kamwendo et al., 1991; Chiu et al., 2002; Eltayeb et al., 2009). Neck pain reduces one's neck rotation range of motion and alters neck muscle activation patterns (Johnston et al., 2008). The impairment of neck muscle motor performance caused by neck pain could also decrease the stability of the cervical spine (Lindstrøm et al., 2011).

Previously, a number of risk factors that could contribute to the occurrence of neck pain have been identified. These risk factors can be generally categorized as individual factors, work-related factors and psychosocial factors. The major individual risk factors that are associated with neck pain are gender and previous history of neck complaints. Epidemiological studies discovered that females have significantly higher incidence rates of neck pain than males (Brandt et al., 2004; Andersen et al., 2008). History of neck pain is another predictive individual factor for neck pain. Studies have shown that neck pain is more likely to occur among individuals that have experienced it before (Jensen, 2003; Eltayeb et al., 2009). The association between work-related factors and neck pain has also been investigated (Ariëns et al., 2000). Previous studies concluded that prolonged neck flexion is highly associated with neck pain both among the general population (Sim et al., 2006) and among the office workers that use computers (Yu and Wong, 1996; Cagnie et al., 2007; Ming et al., 2004). *In-vitro* study suggested that human neck is more vulnerable in forward flexed postures than in upright neutral postures (Przybyla et al., 2007). Poor workstation design (e.g. the location of keyboard and mouse, height of

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computer screen) is another work-related factor that is significantly associated with the increase of neck pain (Sillanpaa et al., 2003; Korhonen et al., 2003). Previous studies have also discovered that psychosocial factors such as increase of task difficulty, psychological stress, and lack of social support could increase the risk of neck pain (Ariëns et al., 2001; Eltayeb et al., 2009; Hush et al., 2009; Nimbarte et al., 2012).

More recently, with the increasing use of portable handheld electronic devices such as touch screen tablets and smart phones, concerns are raised regarding the poor neck posture that users may employ and its potentials of causing neck and shoulder strain. One observational study showed that the majority of users maintained flexed neck postures during the use of mobile devices (Gold et al., 2012). A recent study identified neck pain as the most severe MSD problem among mobile handheld device users (Berolo et al., 2011). Two other recent studies have investigated the influence of different device setups on wrist, shoulder and neck postures during the use of tablet computers (Young et al., 2012, 2013). However there is still a lack of research that has quantitatively investigated the neck postures and neck muscle activities during the use of different mobile devices with various screen sizes. Therefore, the purpose of this study was to evaluate the neck muscle activation levels and kinematics of the cervical spine during the use of touch screen mobile devices. Among the three categories of previously identified risk factors, the current study focused on the evaluation of work-related factors. The hypotheses of the current study were: (1) users will maintain deeper neck flexion postures and higher neck muscle activation levels when using mobile devices with smaller screen sizes; (2) more difficult tasks will result in deeper neck flexion postures and higher neck muscle activities.

2. Method

2.1. Participants

A total of fourteen right-handed participants (10 males and 4 females) were recruited for data collection in this study. All the participants were free from any type of MSDs and had no history of neck injury or notable neck pain. Before data collection, the experimental procedures were explained to the participants, and their signatures were obtained on informed consent forms which were approved by the local Institutional Review Board.

2.2. Apparatus

2.2.1. Data collection apparatus

A wireless surface electromyography (EMG) system (Telemyo 2400T, Noraxon Inc., AZ, USA) was used to collect neck muscle activities. Disposable, self-adhesive Ag/AgCl snap electrodes were used for the signal collection. The bipolar electrodes were pregelled with 1 cm in diameter and an inter-electrode distance of 2 cm. The frequency of EMG data acquisition was set at 1024 Hz.

The cervical spine kinematics data were recorded using Functional Assessment of Biomechanics (FAB) (BIOSYN, Canada) system. This full body 3D kinematic system consists of 13 small, lightweight sensors ($4 \times 7 \times 2.4$ cm) that attach to the selected body areas of the user. Each sensor has a triad of accelerometer, gyrometer, and magnetometer that allows real-time detection of angular displacement within biomechanical bodies. This is a completely wireless system and the posture data were acquired at a frequency of 100 Hz.

2.2.2. Handheld mobile devices

An iPhone (4th generation, Apple, California, USA) was used in the current study to represent a touch screen smart phone. The screen size of the iPhone is 115.2 mm $H \times 58.6$ mm $W \times 9.3$ mm D, and the total weight is 140 g. An iPad (2nd generation, Apple, California, USA) was used to represent a touch screen tablet. The screen size of the iPad is 241 mm $H \times 186$ mm $W \times 8.6$ mm D and the total weight is 601 g. The font sizes of both devices were set to system default.

2.3. Experimental design

A three-variable full factorial experimental design was employed in the current study. The first independent variable is DEVICE, two different mobile devices were tested in the current study and they were: a touch screen smart phone (i.e. iPhone) and a touch screen tablet (i.e. iPad). The second independent variable was the LOCATION that these mobile devices were used, there were two conditions. In the first condition mobile devices were placed on a flat table surface adjusted to the elbow height of testing participants (referred to as the "table" condition). In the second condition, participants were required to hold the device using his/her left hand during the operation (referred to as the "handheld" condition). The third independent variable was the TASK that participants were required to perform. Three different tasks were selected and they were referred to as "Reading", "Typing", and "Gaming" tasks. During the "Reading" task, participants were required to read a short paragraph of verbal material using the iBook application in the iPhone/iPad. The "Typing" task involved the use of the touch screen keyboard to re-type a message that was demonstrated on the same screen of that mobile device. For the "Gaming" task, participants played the gaming application "Fruit Ninja". This is a generic gaming application, and it is primarily played using the right forefinger; it involves minimum tilting and twisting of the handheld device (Fig. 1(a)–(d)). Three dependent variables considered in the current study were the neck flexion angle, EMG activity at the left side of the cervical extensor muscle and EMG activity at the right side of the cervical extensor muscle.

2.4. Protocol

Before the experiment started, the details of data collection procedures and specific requirements of the experimental tasks were introduced to each participant. To record the surface EMG data, the skin over the anatomical landmarks was shaved (if needed), abraded, and cleaned with 70% alcohol, prior to the placement of the EMG electrodes. EMG data were recorded from the cervical extensor (CE) muscles by placing two pairs of electrodes bilaterally at the C4 level (Fig. 1(e)). The electrodes were placed slightly inclined (approximately 35°) about 3 cm away from the vertical line of cervical vertebras (Nimbarte et al., 2010). Postural data was recorded by using three FAB motion sensors. The pelvic sensor was mounted at the L5/S1 level. The trunk sensor was mounted at the T10/T11 level. The head sensor was mounted at about the occipital region. Once mounted with the EMG electrodes and FAB motion sensors, participants were secured in a custom made chair with their head flexed 40° forward and performed maximum isometric head extension motion against a constant resistance. During the maximal voluntary contraction (MVC) the neck extensor muscle EMG signals were recorded. Next, the FAB system was calibrated. The calibration process is explained elsewhere (Nimbarte et al., 2013).

Upon finishing the calibration, the participants were trained for approximately 10 min to allow them get familiar with the mobile devices and the tasks they were required to perform. Subsequently, the participants performed three repetitions for each of the 12 different conditions (2 DEVICE $\times$ 2 LOCATION $\times$ 3 TASK) in a completely randomized order. The duration of each task was

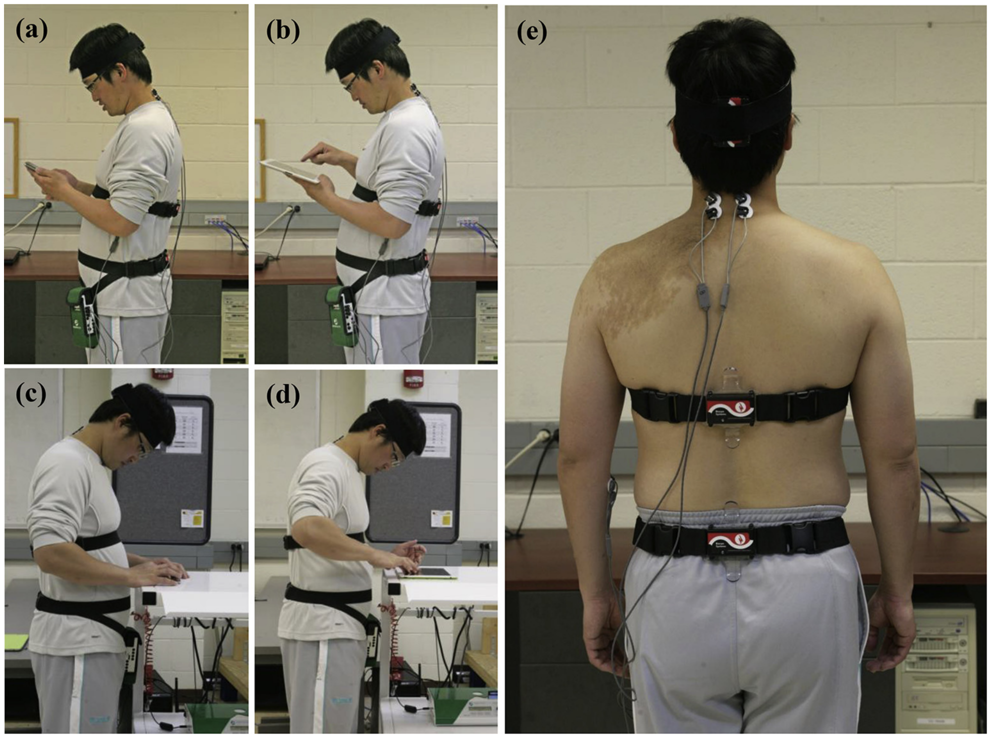

Fig. 1. Demonstration of the four experimental conditions: (a) handheld with smart phone; (b) handheld with tablet; (c) table with smart phone; (d) table with tablet. (e) Illustration of the locations of EMG and FAB sensors.

controlled at 90 s, during which participants were instructed to maintain a self-selected neck posture. A 2-min rest period was provided between the trials to avoid muscle fatigue. After the last repetition of each task, participants were required to complete a computer based NASA Task Load Index (TLX) survey to rate their perceived workload. The survey includes a total of six subscales: “Mental Demand”, “Physical Demand”, “Temporal Demand”, “Performance”, “Effort” and “Frustration”. Detailed descriptions of each subscale were presented in Hart and Staveland (1988).

2.5. Data processing and analysis

EMG data were first filtered using a 10 Hz high-pass filter and a low-pass filter of 500 Hz. A notch filter was used to eliminate ambient noise at 60 Hz and its aliases. The processed EMG data were then fully rectified and further smoothed using a 1/8 s (128 data points) moving data window. For each muscle EMG data collected during experimental trials were normalized to the corresponding maximum EMG values recorded during the MVC trials and presented as a percentage of the maximum. Since the neck postures were mostly stationary during individual tasks, the neck muscle activation was reported in terms of normalized EMG (NEMG) averaged over the duration of 90 s.

The tasks involved in the current study required mostly stationary sagittal neck flexion without much neck rotation or laterally bending. Therefore, the mean neck flexion angle was selected as the single kinematics variable to report. The neck flexion angle was defined as the sagittal angular deviation from the upright neutral posture.

Data from NASA TLX survey were processed to calculate the weighted ratings for each subscale. To obtain weighted ratings, the raw ratings for each subscale in the NASA TLX were multiplied by its weight, i.e., the contribution of each subscale to the workload.

2.6. Statistical analysis

As the first step of the statistical analysis, the independence of observations, normality of residuals and the homogeneity of variance of residuals (assumptions of the ANOVA procedures) were assessed on all dependent variables. Variables that did not satisfy one or more assumptions were transformed so that all assumptions were satisfied (Montgomery, 2005). After the assumptions verification, multivariate ANOVA (MANOVA) was performed to evaluate the effect of DEVICE, LOCATION, TASK and their interactions on all dependent variables collectively. Independent variables and interaction effects that were found to be significant were further tested using univariate ANOVA. The Tukey–Kramer post-hoc test was used to evaluate the significant effect for variables with more than two levels. Minitab 15 statistical analysis software (Minitab Inc., PA, USA) was used to perform all statistical analyses. A criteria p-value of 0.05 was used as the significance level.

3. Results

Results of the MANOVA demonstrated significant main effect of all three independent variables (i.e. DEVICE, LOCATION and TASK) on the set of three dependent variables. However, none of the interaction effects were significant. Detailed results of MANOVA and univariate ANOVA are shown in Table 1.

The kinematic analyses revealed that the participants maintained significantly deeper neck flexion while using smart phone (44.7°) as compared to tablet use (43.0°). The location of the device also significantly affected the neck flexion angle. Participants maintained on average 5.0° more flexed neck posture when using the mobile device on table (46.4°) than in a handheld posture (41.4°). This demonstrates a natural synergy between hand and neck in maintaining less stressful (more comfortable) head and

Table 1
The results of MANOVA and univariate ANOVA.

Independent variables	MANOVA	ANOVA		
		LCE NEMG	RCE NEMG	Neck flexion angle
Device	$P < 0.001$	$P = 0.26$	$P = 0.05$	$P < 0.001$
Location	$P < 0.001$	$P < 0.001$	$P = 0.05$	$P < 0.001$
Task	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Device*Location	$P = 0.17$	N/A	N/A	N/A
Location*Task	$P = 0.07$	N/A	N/A	N/A
Device*Task	$P = 0.19$	N/A	N/A	N/A
Device*Location*Task	$P = 0.72$	N/A	N/A	N/A

Note: MANOVA = multivariate ANOVA; LCE = left cervical extensor muscle; RCE = right cervical extensor muscle; NEMG = normalized EMG.

neck postures. The neck flexion angle also changed during the performance of different tasks. Results of the post-hoc analysis revealed that the "Typing" task introduced the deepest average neck flexion angle of 45.6°; while in "Gaming" and "Reading" tasks the neck flexion angles were on average 43.6° and 42.4° respectively (Fig. 2).

In general, lower muscle activity was observed for the cervical extensor muscles when using a smart phone but this difference was not statistically significant. Significantly higher muscle activity on the left side of the CE muscle (LCE) was observed when using the mobile device on the table than in handheld conditions (9.4% vs. 8.8%). A similar trend was observed on the right side of CE muscle (RCE); however the difference was not statistically significant (13.0% vs. 12.4%) (Fig. 3). Finally, the effect of the specific TASK was significant on both LCE and RCE muscles. Results of the post-hoc analysis showed that both left and right muscles had significantly lower activation levels when performing the "Reading" task. "Gaming" and "Typing" tasks introduced higher neck extensor muscle activities but the difference between these two tasks was not statistically significant (Fig. 4).

4. Discussion

Results of this study revealed that participants maintained 1.7° deeper neck flexion when using a smart phone in comparison to a tablet. This result is in line with our initial hypothesis that smaller screens will cause a deeper neck bending in order to reduce the distance between the eyes and the screen, as well as increase the clarity of vision. These results indicate that mobile devices with larger screen sizes are preferable from the MSD prevention

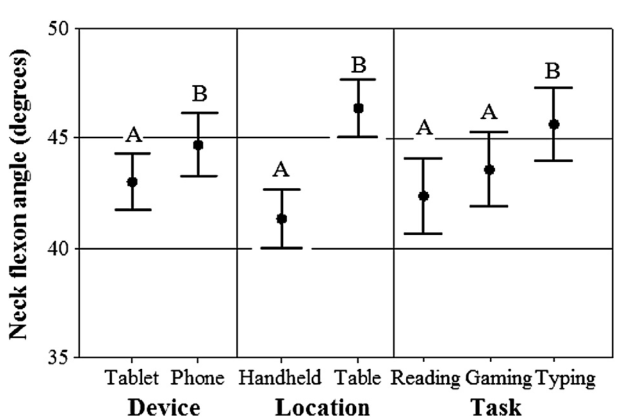

Fig. 2. The average neck flexion angles when using different devices, locations and tasks. Different letters denote angles that are statistically different from one another. Bars indicate the corresponding 95% confidence interval.

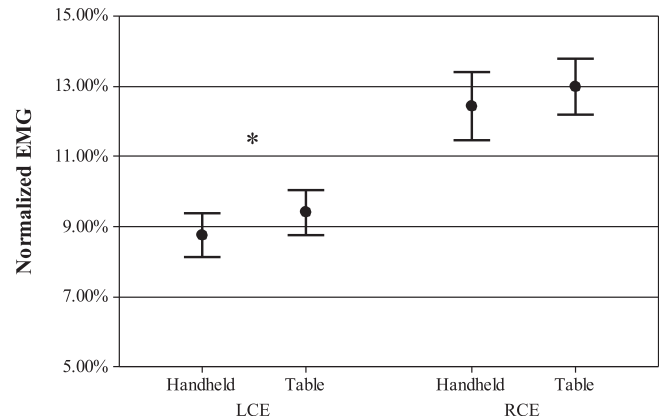

Fig. 3. The normalized EMG of left and right cervical extensor muscles when using mobile devices on a table vs. handheld condition. * Denotes EMG activities that are statistically different between the two conditions. Bars indicate the corresponding 95% confidence interval.

perspective. However, larger screen size may also increase the weight of the device, which could introduce fatigue to arm and shoulder muscles when holding these devices for long time periods. Larger neck flexion angles (5.0°) were also observed when using mobile devices on a table than in handheld conditions. From our observations, using mobile devices on a table produce a larger eye-screen distance as compared to the handheld conditions. This may suggest that participants adopted a larger neck flexion angle possibly as a compensatory strategy of reducing eye-screen distance and to increase the clarity of vision.

NASA TLX survey has been widely used in assessing the mental workload of various human machine interaction tasks (Smith et al., 2001; Vitense et al., 2003; Felton et al., 2012). In the current study, because of the distinctive task requirements and the relatively short task performance duration (i.e. only 90 s), the NASA TLX scores may mainly reflect participants' perceived task difficulty (mentally and physically combined) that linked to each task's unique visual requirements and physical interaction with the devices (i.e. pressing/touching vs. swiping). According to the NASA TLX scores, "Gaming" was the least difficult task (with average score of 34.4) followed by "Reading" (average score 39.6) and "Typing" (average score 47.4) (Fig. 5). However, contrary to our expectations, participants employed deeper neck flexion and

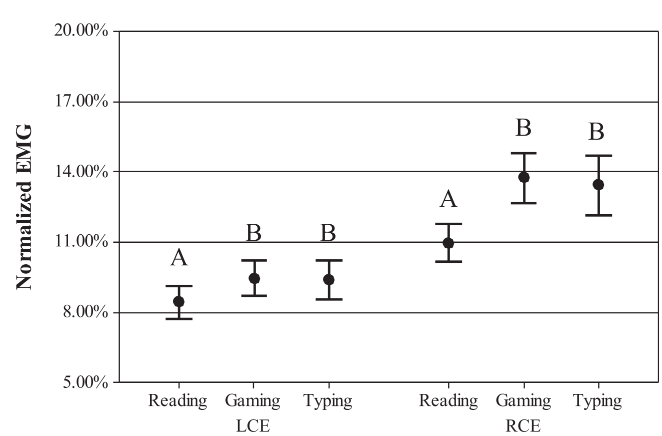

Fig. 4. The normalized EMG of left and right cervical extensor muscles when using mobile devices to perform different tasks. Different letters denote EMG activities that are statistically different from one another. Bars indicate the corresponding 95% confidence interval.

higher muscle activity during the "Gaming" task than the "Reading" task (Figs. 2 and 4) even though it was overall less difficult (Fig. 5). These results suggest that task difficulty is not the only determinant for the neck flexion posture. The different visual and physical interaction requirements could also affect the magnitude of neck flexion during the use of mobile devices.

A previous study concluded that holding a neck flexion angle of more than 20° for a prolonged period of time could increase the risk of neck injury (Andersen et al., 2003). In the current study, the neck flexion angles maintained in all conditions clearly exceeded this limit. Thus, prolonged use of a mobile device could pose significant risks for the development of neck injury.

In the current study participants demonstrated higher muscle activation level especially on the LCE muscle when using mobile devices on a table than in the handheld condition. There are two reasons that could explain the elevated neck muscle activation levels. First, deeper neck flexion posture may require larger muscle force to counterbalance the increased external moment. Second, more head movements may be required for the operation when the mobile devices are kept stationary whereas in the handheld condition, hand motions could compensate for the lack of neck flexion. It should also be noted that the LCE muscle activity increased by a relatively small (only 0.6%) amount. This may be due to the relatively simple tasks and short durations tested in the current study. Users may demonstrate larger change in the muscle activity when performing difficult tasks of longer durations. In addition, during the prolonged use of mobile devices, even small elevations of CE activities could result in cumulative effects such as muscle fatigue and other neuromuscular alternations at a much faster rate. Results also suggest that both left and right CE muscles had the lowest activation levels during the "Reading" task, which can be attributed to the smallest neck flexion angles maintained during this task. Both "Gaming" and "Typing" tasks showed higher neck muscle activation levels, but there was no difference between these two tasks. Although the neck flexion angle during "Gaming" was not as high as the "Typing" task, it was the authors' observation that participants were more engaged in the task performance during "Gaming" than the other two tasks. The requirement of instant responses during "Gaming" tasks may have increased the CE muscle activities.

In addition, it was consistently observed in our results that the right side of the neck extensor muscle had higher activation levels compared to the left side in all conditions. In the current study, all participants were right-handed and they were required to use their right hand to operate mobile devices. It is possible that larger activation levels from the right shoulder muscles (due to hand motions) could generate higher CE muscle activities on the same side. It is also possible that during the task performance participants maintained a slight leftward head bending posture, this posture could also generate higher muscle activities on the contralateral side of cervical extensors. This phenomenon has been observed among lumbar muscles before (Ning et al., 2011; Hu et al., 2013). The higher activation level observed on the right side of the CE muscle indicates that operation of mobile devices with the right hand could cause the right side of the cervical extensor muscles to reach fatigue sooner than the left side. This elevated muscle activation level may in turn increases the risk of neck dysfunction/injury.

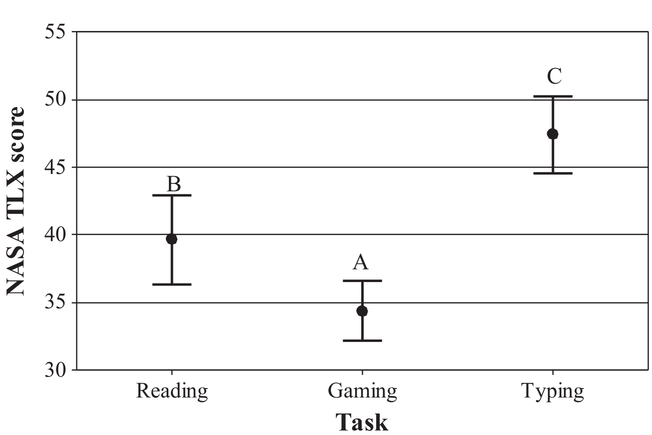

Fig. 5. The NASA TLX scores of the three tested tasks. Different letters denote scores that are statistically different from one another. Bars indicate the corresponding 95% confidence interval.

The short duration of the experimental task is the main limitation of the current study; future studies should investigate the impact of prolonged mobile device usage on shoulder and cervical tissues. The influence of mental workload during prolonged task performance should also be explored. Several other limitations should be noted as well. First, two specific mobile devices (i.e. the 2nd generation of iPad and the 4th generation of iPhone) with the same operation system were tested; future study may investigate other mobile devices with different weights, operation systems and screen sizes. Second, only three typical tasks were selected for assessment in the current study. Other tasks may demonstrate different neck postures and muscle activation patterns. In addition, the neck kinematics and muscle activities recorded during the "Gaming" task may only reflect the human responses for the specific or similar form of game (i.e. Fruit Ninja) tested in this study. Due to the large variation among different games the cervical spine kinematics and kinetics may change significantly. Finally, among the three tested tasks, no specific performance requirement was instructed. Future studies may test the effect of different performance requirements (e.g. reaching to certain reading/typing speeds or game scores). The same task with elevated requirements may increase the task demand and alter the physical responses of the participants.

5. Conclusion

In conclusion, the current study explored the kinematic performance of the cervical spine and cervical extensor muscles during the use of a touch screen tablet and a smart phone in different conditions. Results demonstrated that prolonged use of mobile devices exposes significant MSD risks to the cervical spine. Specifically, using a smart phone on a table and performing typing task showed the highest level of risk among all conditions tested in this study. Cervical extensor muscle activity is affected by the locations of the devices as well as the tasks being performed. The results indicate that more human-centered designs should be implemented in the design of touch screen mobile devices in order to reduce the risks of neck pain.

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