The Effect of Phone Design on Upper Extremity Discomfort and Muscle Fatigue

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Objective: To compare a small cellular clamshell phone with a traditional office phone in the development of discomfort and muscle fatigue over time during phone use. **Background:** Phone use involves low-level static exertions that may be influenced by phone design. Phone design and its interactions with anthropometry may change shoulder and hand postures assumed during use, which in turn may modify the length-strength relationship and moment arms of the muscles. **Method:** Ten adults participated in a study that simulated phone use using a small clamshell and a traditional office phone. Discomfort information and electromyographic (EMG) muscle activity were monitored on four upper extremity muscles. Discomfort and fatigue data (EMG median frequency shifts) were analyzed to assess differences between phones as well as differing effects attributable to anthropometry. **Results:** Median frequency shifts supported discomfort claims and indicated muscle fatigue in the deltoid and thenar muscles. Biomechanical measures demonstrated that participants with short limb lengths developed more severe signs of thenar fatigue. Participants with longer arms developed greater discomfort in the neck, shoulder, and back. The deltoid confirmed this occurrence, showing signs of muscle fatigue. **Conclusion:** Phone design and anthropometry influenced the development of discomfort and fatigue during phone use. Phone design dictated grip style, resulting in differing discomfort and fatigue levels. Anthropometry influenced the severity of the discomfort and fatigue present in the shoulder and hand. **Application:** Use of small clamshell phones may contribute to a lack of rest and recovery from typical workday exposures. It should be explored from an ergonomic perspective.

INTRODUCTION

The recent technical explosion of cellular phones has changed the typical usage pattern of telephone devices worldwide. The Cellular Telecommunications and Internet Association reported that there were 158.7 million subscribers by December 2003. The numbers of users is increasing, as is the amount of time spent using cellular phones. Minutes of usage went up more than 30% from 2002 to 2003, with year-end totals yielding 800 billion minutes of call time used in 2003 alone (Cellular Telecommunications and Internet Association, 2004).

With the convenience of cellular phones increasing their frequency and duration of use, the design characteristics of these phones give rise to concerns regarding their impact upon body mechanics and the musculoskeletal system. The nature of cell phone use may facilitate the potential for the development of musculoskeletal symptoms. Continually ignored symptoms may lead to a musculoskeletal disorder over time. Upper extremity musculoskeletal disorders are associated with the following risk factors: repeated loading, awkward postures, mechanical pressure, force exertion, and duration of loading. Of these risk factors, awkward postures and the extended duration of loading are associated with cell phone use. The most reported upper extremity musculoskeletal symptom is muscle pain (Buckle & Devereux 2002).

Phone use is not traditionally thought of as physically taxing on the musculoskeletal system.

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However, the repeated light exertions performed over long periods of time may link phone use to risk of upper extremity musculoskeletal disorders via awkward postures and low-level static exertions. In phone use, the upper extremity is required to perform light work with little to no rest, often while stabilizing the head and neck for visual purposes (Punnett & Wegman, 2004; Nordin, Andersson, & Pope, 1997). Although low-level static exertions do not initially appear hazardous, if performed for extended durations they are associated with musculoskeletal complaints and signs of fatigue (Sjogaard & Jensen, 1999).

There are known preferred grip sizes and length-strength muscle relationships that maximize strength and minimize muscle activity. Moment arms, controlled by postural demands, alter muscle length. The length-strength relationship of muscles demonstrates that muscles have the greatest ability to generate active force when they are close to their resting length. Therefore, stretching or shortening the muscle length inhibits its ability to produce tension within the muscle (Marras, 1999).

Phone designs can be compared in order to expose inefficiencies in the muscle length-strength relationship (Chaffin, Andersson, & Martin, 1999; Marras, 1999). The current trend in cellular phone design continues to decrease the size of the devices, which may force the user into postures that suboptimize length-strength principles. Standard traditional office and cellular phones require the user to grip the device with a combination of the power and precision grips depending upon the size of the phone and the anthropometry of the user (Karwowski, 2001; Salvendy, 1997). If length-strength muscle properties are ignored in device design, musculoskeletal symptoms and fatigue will arise through product use.

The majority of research publications thus far have focused on either the implications of cellular phone use on driving or the exposure to radio frequency radiation during cellular phone use (McKnight & McKnight, 1993; Oftedal, Wilen, Sandstrom, & Mild, 2000; Redelmeier & Tibshirani, 1997; Salvucci & Macuga, 2002; Strayer & Johnston, 2001; Sundeen, 2003; Wilen, Sandstrom, & Mild, 2003). There is a void in the literature regarding upper extremity musculoskeletal symptoms, biomechanics, and cellular phone devices. Therefore, the objective of this research is to assess how two differing phone designs and participant anthropometry affect the development of discomfort and muscle fatigue over time during use.

This study involved the collection of body discomfort information and electromyographic (EMG) muscle activity of the trapezius, deltoid, flexor digitorum superficialis (FDS), and thenar muscles during a 1-hr simulated phone use session. In two separate sessions, two phone design models were tested: one small cellular clamshell phone and one traditional office phone. In this study, subjective discomfort surveys and muscle fatigue (median frequency analysis) were used as indicators of musculoskeletal stress. From these findings, design suggestions were made.

METHODS

Participants

The user population for telephones is generally representative of the general U.S. population, given their widespread use across the country. Ten healthy participants (5 men, 5 women) from the general population with no prior history of upper extremity musculoskeletal disorders volunteered to participate in the study. Calculations for an acceptable sample size were performed using data collected during a pilot study. The age range of the participants was 23 to 30 years, with an average age of 25 years (*SD* ± 2). Anthropometric data were collected for each of the participants for age, gender, height, weight, handedness, arm length, hand length, wrist circumference, palm width, elbow-to-fingertip length, thumb breadth, and thumb length (Kroemer & Grandjean, 2001). This information is shown in Table 1.

Experimental Design

A simple randomized paired comparison experimental design was used for this study. Upper extremity muscle activity and subjective discomfort measures during the static task were monitored under controlled laboratory conditions. The independent measure used in the experiment was phone design. Anthropometry measures of the upper extremity taken from each participant were also used as independent variables in statistical analyses. The dependent measures of this study were EMG median frequency slope for four upper extremity muscles and mean discomfort scores for each of five body regions for the duration of the task.

TABLE 1: Participants' Anthropometric Data

	Small		Large		Women (n = 5)		Men (n = 5)		U.S. Mean (*SD*)[a]	
Measure (cm)	Mean	Range	Mean	Range	Mean (*SD*)	Range	Mean (*SD*)	Range	Women	Men
Arm length	74.79	73.0–77.47	80.84	78.5–83.0	75.4 (3.1)	73.0–80.3	80.2 (2.3)	77.4–83.0	72.3 (3.8)	78.8 (3.9)
Hand length	16.54	15.4–17.6	18.66	17.7–19.7	16.6 (1.1)	15.4–17.9	18.6 (0.9)	17.4–19.7	18.0 (1.0)	19.3 (1.0)
Wrist circumference	14.96	14.5–15.2	18.15	17.4–19.3	14.9 (0.2)	14.5–15.1	17.6 (1.5)	15.2–19.3	17.4 (0.8)	15.1 (0.7)
Palm width	8.84	8.3–9.4	10.0	9.5–10.4	8.9 (0.5)	8.3–9.5	9.9 (0.6)	8.9–10.4	9.0 (0.4)	7.9 (0.4)
Elbow–fingertip length	41.98	40.9–43.3	46.92	45.0–48.8	42.7 (1.9)	40.9–45.5	46.9 (1.6)	45.0–48.8	48.3 (2.3)	44.2 (2.3)
Thumb breadth	1.37	1.3–1.4	1.65	1.5–1.8	1.4 (0.1)	1.3–1.5	1.6 (0.2)	1.5–1.8	2.3 (0.2)	1.9 (0.2)
Thumb length	5.28	4.8–5.6	6.23	6.0–6.6	5.8 (0.6)	5.1–6.6	5.5 (0.5)	4.8–6.1	5.1 (0.4)	4.7 (0.4)

Note. Handedness: 9 right, 1 left. Side monitored for study: 7 right, 3 left.

[a] Data from Pheasant (1999), pp. 84–85.

Apparatus

Phone models were selected after surveying the design parameters of both cellular and traditional office phone models currently in use. The designs varied in length, depth, breadth, and grip style because of the extensions at the heads of traditional office phones, which do not exist in cellular models. From information obtained in the market survey, cellular phones typically had a grip area of 600 to 1,300 mm^2 (Nokia, 2007a, 2007b). Traditional office phones' grip areas ranged from 550 to 1,860 mm^2. To minimize variability between these two categories, we selected two phones (one traditional office phone and one small cellular clamshell phone) that have similar small grip area openings (clamshell phone = 792 mm^2 ; traditional office phone = 558 mm^2), depth (clamshell and traditional office phones = 18 mm), and breadth parameters (clamshell phone = 44 mm; traditional office phone = 31 mm).

Panasonic Model KX-T3165, a traditional office-style desk phone, served as the control. The cell phone model used for the study, LG VX440, was a small clamshell or flip-style model (Figure 1). These models were chosen to minimize the change in the length-strength relationship of the muscles involved during their use.

The subjective measures consisted of a Borg survey for work-related discomfort that was administered every 10 min over the 1-hr period and at the beginning and end of the study period. The Borg scale ranged from 1 to 7, using the verbal landmarks of 1 = *no discomfort,* 4 = *some discomfort,* and 7 = *high discomfort* (Borg, 1982). Statistical analyses were performed using the mean of the seven readings taken over the 1-hr duration of the task.

Muscle activity was collected using surface electromyography. EMG activity was collected by bipolar silver-silver chloride surface electrodes spaced approximately 2 cm apart over four upper extremity muscles (the trapezius, the deltoid, the FDS, and the thenar muscle group).

A four-channel EMG amplification system was used to record the muscle activity information. Data signals were collected at 1024 Hz, then recorded and saved on a computer via an analog-to-digital conversion board (National Instruments PCI-6033E) and stored for later analysis.

Procedure

Upon their arrival, informed consent was obtained from the study participants. Participants were asked to select a preferred side (dominant or nondominant) with which they would typically hold a telephone. EMG was monitored on the preferred side only. Anthropometric measurements were taken, and electrodes were placed on the participants' trapezius, deltoid, FDS, and thenar muscles. Electrode locations were determined using palpation according to Cram & Kasman


Small Clamshell

Traditional Office

Figure 1. Phone designs used in experiment.

(1998) and Delagi, Perotto, Iazzetti, and Morrison (1980).

Specifically, the trapezius electrodes were placed 2 cm lateral to the midpoint of the line joining C7 to the acromion (Hermans & Spaepen, 1997). The deltoid electrodes were placed three fingerbreadths below the anterior margins of the acromion found by palpation during a test contraction of forward flexion of the arm. The flexor electrode locations were found by grasping the participant's volar surface of the wrist with the index finger pointed to the biceps tendon. The electrodes were placed just ulnarly to the tip of the index finger. The applicable test contraction was to flex only the fingers while supporting the arm with the wrist in the neutral position. The thenar electrodes were placed on either side of the midpoint line between the volar aspect of the first metacarpophalangeal joint and the carpometacarpal joint. The test contraction used was the palmar abduction of the thumb.

The resistance between the electrodes was kept below 300 kΩ. A ground electrode was placed on the lateral epicondyle.

Participants were asked to perform maximum voluntary contractions (MVCs). They were instructed to build up to their maximum exertion level over a period of 2 s and then to maintain the exertion for 4 s (Marras & Davis, 2001). The EMG of the monitored muscles was captured while the participant maintained a constant maximum exertion.

For the trapezius and deltoid MVC exertion, the participant was seated. With the shoulder in a neutral position (0° flexion, 0° abduction) and the elbow at a 90° angle, a cuff was wrapped around the bicep. This cuff was linked to a chain that provided constant resistance. To perform the MVC exertion, the participant exerted force in shoulder abduction, keeping the elbow at 90° (Schuldt & Harms-Ringdahl, 1988), and pulled against the restraint system. The maximum exertion of the flexor and thenar muscles was obtained by squeezing a grip dynamometer (TM Stoelting Co.). The grip opening was fixed for all participants at 7.49 cm. The shoulder and wrist were in neutral (shoulder: 0° flexion, 0° abduction; wrist: slight extension) and the elbow at 90°.

A standard protocol for capturing EMG maximum exertions using static muscle strength testing procedures were used (Caldwell et al., 1974; Redfern, 1992; Soderberg, 1992). The postures used for maximum exertions were close to the postures assumed during the low-level static exertion task to control for variability in muscle length and volume and to capture a maximum exertion in this posture.

Task

The static task performed by the participants required simulated use of the phone designs. Live airtime was not used because of the expense and potential interference with the electromyography equipment. Participants were placed in a supported-back sitting position and instructed to grip the phone with a grip using the index finger as a counterbalance (Figure 2). This posture was found to be prevalent through separate observation studies

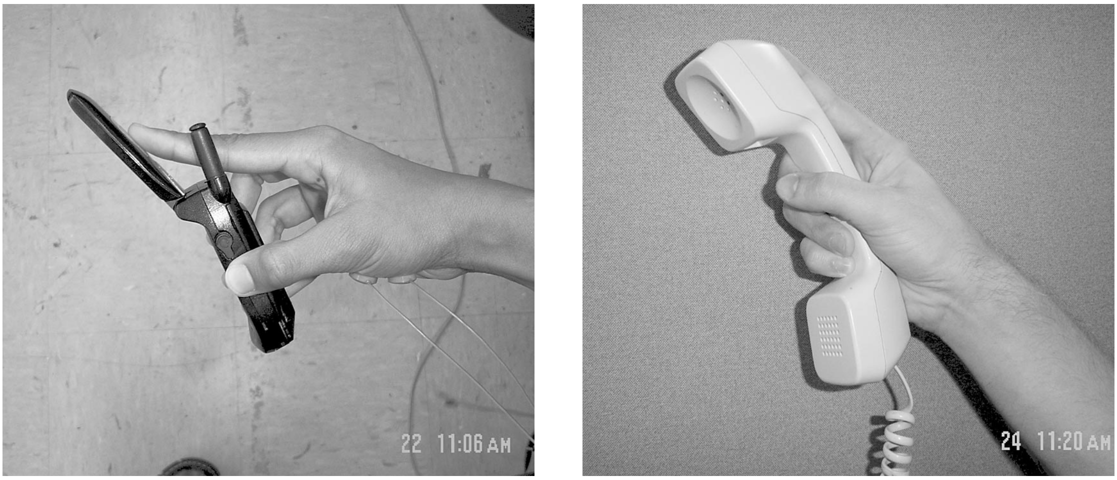

Figure 2. Grips used during small clamshell phone (left) and traditional office phone (right) conditions.

done by the experimenters. No arm supports were used. During the task, the participants were asked to hold the phone up to their ear as they would during actual use. The participant then engaged in conversation with the experimenter. Once the participant selected a posture and data recording began, he or she was not allowed to change posture.

Although participants were instructed to use a similar posture for both phone conditions, the design of the phones led them use a power grip with the traditional office model and a combination precision-power grip with the small clamshell phone. The index finger was used as a counterbalance; thus it was placed on the portion of the phone containing the ear receiver. The index finger was in slight flexion in this posture. The thumb and remaining three fingers were used in flexion to stabilize the phone in the user's hand. Thumb orientation was not controlled in the grip. The traditional office phone allowed for some support from the palm, and the thumb and fingers were able to wrap fully in flexion around the device. For the small clamshell phone, the thumb and fingers were utilized at their tips to create phone stability for use. Figure 2 displays common postures adopted by the participants during the experiment.

Participants were required to maintain their posture as still as possible for the duration of the experiment. Participants were monitored to ensure compliance with the experimental protocol. The recorded video allowed the experimenter to determine after the fact if participant movement made the data unacceptable. EMG data were taken continuously throughout the 1-hr experiment. Subjective discomfort scores were taken every 10 min throughout the experiment using a body discomfort map.

Data Analysis

EMG data were converted to the frequency domain using a fast Fourier transform for spectral analysis. From the spectral information, the median frequency was determined.

Data from the 1-hr experiment were saved into several individual data files 5 min in length. One summary median frequency was generated for each 5-min file. These summary median frequency data for each 5-min interval were plotted in time sequence to show the changing median frequency values of each muscle over the 1-hr duration of the experiment. Regression lines were generated from the series of median frequency data points over the 1 hr.

The slope of the regression line for muscle fatigue was then extracted for use in statistical comparisons in SAS (1999). If a monitored muscle generated a negative slope, as seen when looking at the regression line through the median frequency points of that muscle over the duration of the task, this was an indicator of fatigue. The literature has not quantified the amount of frequency drop (i.e., negative slope) needed to demonstrate fatigue (DeLuca, 1985). In contrast, if the regression line yields a positive slope, there is no fatigue and the muscle has been allowed rest and recovery (McLean, Tingley, Scott, & Rikards, 2000, 2001).

Statistical Analysis

A paired comparison test of the two test conditions (small clamshell vs. traditional office phones) was performed on all four monitored muscles. The difference between the test conditions was found and then compared with zero using the Proc Means procedure in SAS (1999). To better describe the factors associated with significant effects, we used a paired comparison using a two-sample Proc T-Test (SAS, 1999, Release 8.02) to isolate data into groups for comparison.

The means for the U.S. population norms for the studied anthropometry measures were compared with the means of the study population. The study population means adequately fit the norms for the U.S. male and U.S. female populations. Initial analyses found no significant effects of gender. However, separating the study population based upon anthropometric dimensions yielded a better fit than the traditional gender split. The mean of each anthropometry independent measure was found and determined to be the breakpoint for splitting the anthropometry measures into two categories. Participants with an anthropometry measure (i.e., hand length) below the collective study population mean were classified as *small.* Participants with anthropometry measures greater than the mean were classified as *large.*

This classification of anthropometry groups predominantly followed gender, with women predominantly constituting the small-anthropometry group. However, no participant belonged entirely to the small- or large-anthropometry group. Each anthropometry measure was classified independently. It is well documented in the literature that there is much variability in the anthropometry of an individual, and each body segment will belong to a different percentile of the population. Data for the study population are shown in Table 1 by both gender and anthropometry.

This allowed for four separate *t* test comparisons of the phone conditions and the anthropometry groupings. The first *t* test made comparisons between the two anthropometry groups within the small clamshell phone test condition; the second *t* test made comparisons between the anthropometry groups within the traditional office phone test condition; the third *t* test made comparisons between the two phone models within the small-anthropometry group; and the fourth *t* test made comparisons between the phone models within the large-anthropometry group. This controlled for any confounding that may have been present if the data had been tested collectively. This type of analysis was performed on the regression line slopes from the task duration and mean discomfort data.

The mean subjective discomfort for the seven readings of each body part was analyzed to find out where participants were experiencing discomfort throughout the experiment. Then, objective frequency analysis was performed to determine if there were physical manifestations of fatigue that supported the discomfort information. The literature on frequency analysis did not identify a fatigue effect threshold for median frequency drop necessary to indicate fatigue. Given the lack of literature on this issue, we examined the data for statistical significance between conditions via the slope of the median frequency.

RESULTS

Discomfort scores in five body regions were collected from participants at 10-min intervals. The mean discomfort score for each time interval for all participants in each of the phone conditions is shown in Table 2. Although the small clamshell phone test condition showed increased discomfort for the individual 10-min readings and the mean discomfort score for the entire test duration, the overall main effect of phone results are not statistically significant (see Table 3a).

Table 4 summarizes the mean body region discomfort findings for the effect of phone model by anthropometry group. Table 5 summarizes the mean body region discomfort for the effect of anthropometry by phone condition. Collecting this information was critical in exposing the test conditions in which greater discomfort developed. Participants with more abduction strength, larger palm widths, and larger thumb breadths had increased mean discomfort in the neck and shoulder in the small clamshell phone condition. When participants with large anthropometry were isolated to allow us to examine effects of the phone conditions, the hand/wrist and fingers demonstrated a clear significant effect. The majority of the surveyed anthropometry dimensions showed the small clamshell phone condition led to increased hand/wrist and finger discomfort for this group (shown in Table 4).

Analyzing the median frequency slope was an objective measure used to explain the development of discomfort. Table 3 shows that the main effect of phone design was significant for the thenar muscle ($p = .0028$), for which the mean slope of the small clamshell condition was –1.49 (SD = 2.38), whereas for the traditional office condition the mean slope was 1.15 (SD = 1.98).

To further demonstrate the main effect of phone, Table 6 summarizes the median frequency slope findings for the effect of phone model within an anthropometry group. Table 7 summarizes the median frequency slope for the effect of anthropometry within each phone condition. Participants with small anthropometry dimensions generally tended to show significant fatigue in the small clamshell phone condition, with median frequency slopes ranging from –2.05 to –3.30. The large-anthropometry group had lesser negative slopes (ranging from –1.00 to 0.24) in the small clamshell phone condition (significant for arm length and elbow-to-fingertip length). Both anthropometry groups showed positive slopes in the traditional office phone test condition.

A secondary finding of the frequency analysis showed that large-anthropometry participants developed significant deltoid fatigue for both phone conditions, with a slope near –2. Small-anthropometry participants developed fatigue slower, with slopes near –1 (significant for grip strength and elbow-to-fingertip length).

DISCUSSION

The primary finding of this study involved the presence of thenar muscle fatigue in the small clamshell phone condition and the lack thereof in the traditional office phone condition. Frequency

TABLE 2: Discomfort Summary by Reading for the 1-hr Experiment Duration by Phone Condition

	Mean Reading in Minutes (*SD*)							
Part of Body	0	10	20	30	40	50	60	Average of 60 min
				Small Clamshell Phone Condition				
Neck	1 (0)	1.4 (0.51)	1.4 (0.69)	1.8 (0.78)	2.1 (0.99)	2.2 (0.91)	2.5 (1.08)	1.8 (0.53)
Shoulder	1.1 (0.31)	2.1 (0.99)	2.4 (0.96)	2.7 (1.15)	3.4 (1.26)	3.6 (1.26)	4.1 (1.44)	2.8 (1.02)
Elbow/forearm	1 (0)	1.1 (0.31)	1.3 (0.48)	1.6 (0.51)	1.6 (0.51)	1.8 (0.78)	1.9 (0.73)	1.5 (0.35)
Hand/wrist	1 (0)	1.6 (0.69)	1.7 (0.48)	2.3 (0.94)	2.4 (0.69)	2.5 (0.97)	2.8 (1.31)	2.0 (0.62)
Fingers	1 (0)	1.8 (0.63)	2.0 (0.66)	2.4 (0.51)	2.9 (0.56)	3.5 (0.84)	3.8 (0.63)	2.5 (0.99)
				Traditional Office Phone Condition				
Neck	1 (0)	1.1 (0.31)	1.5 (0.52)	1.6 (0.69)	1.8 (0.78)	2.0 (0.94)	2.1 (0.56)	1.6 (0.42)
Shoulder	1 (0)	1.9 (0.73)	2.3 (0.67)	2.5 (0.70)	3.0 (1.05)	3.2 (1.22)	3.7 (1.25)	2.5 (0.89)
Elbow/forearm	1 (0)	1.1 (0.31)	1.1 (0.31)	1.4 (0.69)	1.4 (0.69)	1.6 (0.84)	1.7 (0.82)	1.3 (0.27)
Hand/wrist	1 (0)	1.2 (0.42)	1.6 (0.51)	1.8 (0.78)	2.0 (0.66)	2.3 (0.67)	2.3 (0.67)	1.7 (0.51)
Fingers	1 (0)	1.4 (0.51)	2.1 (0.73)	2.3 (0.82)	2.8 (1.13)	2.9 (1.10)	3.1 (0.99)	2.2 (0.79)

TABLE 3a: Main Effect of Phone for Discomfort

Body Part	Mean Discomfort (*SE*) Small Clamshell Phone	Mean Discomfort (*SE*) Traditional Office Phone	Difference Between the Mean Discomfort (*SE*)	*p* Value
Neck	1.78 (0.91)	1.61 (0.77)	0.17 (0.19)	.3608
Shoulder	2.80 (1.42)	2.49 (1.19)	0.31 (0.24)	.3133
Elbow/forearm	1.48 (0.61)	1.31 (0.63)	0.17 (0.09)	.1483
Hand/wrist	2.06 (0.98)	1.77 (0.75)	0.29 (0.20)	.1748
Fingers	2.51 (1.07)	2.22 (1.09)	0.29 (0.18)	.1879

*Statistical significance at $p < .05$.

TABLE 3b: Main Effect of Phone for Median Frequency Slope

Muscle	Mean Slope (*SE*) Small Clamshell Phone	Mean Slope (*SE*) Traditional Office Phone	Difference Between the Mean Slopes (*SE*)	*p* Value
Trapezius	–0.68 (1.01)	–0.05 (1.15)	–0.63 (0.62)	.3351
Deltoid	–1.46 (0.85)	–1.65 (1.03)	0.19 (0.21)	.3756
Flexor	–1.60 (1.18)	–2.24 (2.35)	0.64 (0.69)	.3834
Thenar	–1.49 (2.38)	1.15 (1.98)	–2.65 (0.65)	.0028*

*Statistical significance at $p < .05$.

analysis showed a negative slope in the small clamshell phone condition, indicating fatigue development over time. The traditional office phone condition's positive slope indicated recovery. Individual thenar data showed that the positive slope was generated because of on/off activity of the thenar muscle during the traditional office phone condition. It is suggested that this on/off activity allowed the muscle to rest and recover from any detrimental effects.

A fundamental difference in grip style between the two phone conditions (shown in Figure 2) may have resulted in the different thenar muscle activations required for the two phone models. Although participants were instructed to use a similar posture for both phone conditions, the design of the phone led the user into a power grip when using the traditional office phone model and a combination precision-power grip when using the small clamshell phone. The power grip was facilitated by the traditional office phone design because the body of the phone, where the hand gripped the device, was recessed from the circular ends for the ear and mouth. The traditional office phone power grip created an ideal length-strength position that required only an extremely low level of activation of the thenar muscle, if activation was required at all.

The combination precision-power grip was required for use in the small clamshell phone condition because the body of the phone rested against the face of the user. This prevented the use of the power grip in the small clamshell phone condition and altered the length-strength position of the muscles. Precision grips are known to reduce grip strength (Eastman-Kodak Co., 1986; Karwowski, 2001; Swanson, Matev, & de Groot, 1970) and thus may have influenced the development of fatigue with the small clamshell phone. This may explain the primary differences seen between the two phone conditions for the thenar muscle.

Additionally, there appeared to be basic differences in thenar fatigue between the small- and large-anthropometry groups when using the small clamshell phone. Although signs of thenar muscle fatigue were present in both groups, it was worse for those participants with smaller anthropometry dimensions.

There were interesting postural differences between the anthropometry groups. Participants with mostly small anthropometry dimensions tended to hold the small clamshell phone with the thumb pad flat against the phone, in parallel with the long edge of the phone (see Figure 3a). The bottom corner of the small clamshell phone along the

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TABLE 4: Discomfort Analysis Significant Effects of Phone (Clamshell vs. Traditional Office) Within the Anthropometry Group

		Anthropometry Dimension							
Part of Body	Phone	Hand Length	Arm Length	Grip Strength	Abduction Strength	Elbow-to-Fingertip Length	Palm Width	Thumb Breadth	Thumb Length
				Small Anthropometry					
Neck	Clamshell	1.85	1.97	1.95	1.73	1.85	1.47	1.69	1.97*
	Traditional	1.53	1.81	1.78	1.69	1.71	1.68	1.69	1.50*
Shoulder	Clamshell	2.64	2.74	2.63	2.43	2.53	2.61	2.54	2.37
	Traditional	2.25	2.41	2.39	2.45	2.28	2.71	2.57	2.28
Elbow/forearm	Clamshell	1.53	1.57	1.51*	1.53	1.57	1.55	1.38	1.53
	Traditional	1.32	1.36	1.19*	1.35	1.02	1.40	1.16	1.40
Hand/wrist	Clamshell	2.04	2.06	1.75	1.92	1.96	1.73	1.90	2.24*
	Traditional	1.89	1.89	1.65	1.88	1.85	1.88	1.80	1.76*
Fingers	Clamshell	2.46	2.37	2.51	2.41	2.39	2.38	2.35	2.63
	Traditional	2.46	2.36	2.31	2.38	2.46	2.31	2.38	2.47
				Large Anthropometry					
Neck	Clamshell	1.73	1.59	1.53	1.85	1.73	2.08*	1.92*	1.50
	Traditional	1.66	1.41	1.37	1.50	1.50	1.48*	1.42*	1.71
Shoulder	Clamshell	2.90	2.85	3.03	3.32*	2.95	2.94*	3.14*	2.85
	Traditional	2.64	2.55	2.62	2.52*	2.66	2.31*	2.42*	2.85
Elbow/forearm	Clamshell	1.43	1.38	1.51	1.39	2.58	1.40	1.62	1.39
	Traditional	1.30	1.26	1.42	1.25	2.07	1.25	1.57	1.21
Hand/wrist	Clamshell	2.07*	2.06*	2.50*	2.25*	2.09*	2.34*	2.25*	1.75
	Traditional	1.69*	1.64*	1.93*	1.60*	1.66*	1.60*	1.64*	1.71
Fingers	Clamshell	2.54*	2.65*	2.50	2.64*	2.58*	2.62*	2.74*	2.32
	Traditional	2.07*	2.09*	2.10	2.00*	2.07*	2.14*	2.00*	1.85

Note. Discomfort analysis represents the mean of the reported discomfort levels for the 1-hr duration of the experiment.

*Statistical significance at $p < .05$.

TABLE 5: Discomfort Analysis Significant Effects of Anthropometry Group Within the Phone Condition

		Anthropometry Dimension							
Part of Body	Anthro-pometry Group	Hand Length	Arm Length	Grip Strength	Abduction Strength	Elbow-to-Fingertip Length	Palm Width	Thumb Breadth	Thumb Length
		Small Clamshell Phone							
Neck	Small	1.85	1.97*	1.95*	1.73	1.85	1.47*	1.69	1.97*
	Large	1.73	1.58*	1.53*	1.85	1.73	2.08*	1.92	1.50*
Shoulder	Small	2.64	2.74	2.63	2.43*	2.53	2.61	2.54	2.37
	Large	2.90	2.85	3.03	3.32*	2.95	2.94	3.14	2.85
Elbow/forearm	Small	1.53	1.57	1.51	1.53	1.57*	1.55	1.38	1.53
	Large	1.43	1.38	1.42	1.39	2.58*	1.40	1.62	1.39
Hand/wrist	Small	2.04	2.06	1.75*	1.92	1.96	1.83*	1.90	2.24*
	Large	2.07	2.06	2.50*	2.25	2.09	2.62*	2.25	1.75*
Fingers	Small	2.46	2.37	2.51	2.41	2.39	2.38	2.35	2.63
	Large	2.54	2.65	2.50	2.64	2.58	2.62	2.74	2.32
		Traditional Office Phone							
Neck	Small	1.53	1.80*	1.78*	1.69	1.71	1.68	1.69	1.50
	Large	1.66	1.41*	1.37*	1.50	1.50	1.48	1.42	1.71
Shoulder	Small	2.25	2.41	2.39	2.45	2.28	2.71	2.57	2.28
	Large	2.64	2.55	2.62	2.53	2.66	2.31	2.42	2.85
Elbow/forearm	Small	1.32	1.36	1.19*	1.35	1.02*	1.40	1.16*	1.40
	Large	1.30	1.26	1.48*	1.25	2.07*	1.25	1.57*	1.21
Hand/wrist	Small	1.89	1.89	1.65	1.88	1.85	1.88*	1.80	1.76
	Large	1.69	1.64	1.93	1.60	1.66	2.14*	1.64	1.71
Fingers	Small	2.46	2.36	2.31	2.38	2.46	2.31	2.38	2.47*
	Large	2.07	2.09	2.10	2.00	2.07	1.60	2.00	1.85*

Note. Discomfort analysis represents the mean of the reported discomfort levels for the 1-hr duration of the experiment.

*Statistical significance at $p < .05$.

TABLE 6: Median Frequency Slope Analysis Significant Effects of Phone Within the Anthropometry Group

Part of Body	Phone	Anthropometry Dimension: Hand Length	Arm Length	Grip Strength	Abduction Strength	Elbow-to-Fingertip Length	Palm Width	Thumb Breadth	Thumb Length
				Small Anthropometry					
Trapezius	Clamshell	–0.35	–0.68	–0.44	–0.32	–0.48	–0.06	–0.75	–1.14
	Traditional	–0.63	–0.56	–0.33	–0.40	–0.63	–0.37	0.19	0.02
Deltoid	Clamshell	–1.21	–0.99	–0.84	–1.18	–0.76	–1.26	–1.20	–1.55
	Traditional	–0.95	–1.27	–1.10	–1.27	–0.96	–1.47	–1.55	–1.52
Flexor	Clamshell	–1.78	–1.50	–0.98	–1.54	–1.35	–1.32	–1.31	–1.88
	Traditional	–1.06	–1.14	0.98	–1.16	–0.81	–1.18	–2.16	–2.64
Thenar	Clamshell	–2.50*	–3.24*	–2.45*	–2.27*	–3.30*	–1.98	–2.05	–2.05*
	Traditional	2.00*	0.48*	0.20*	1.04*	0.45*	1.09	0.42	–1.15*
				Large Anthropometry					
Trapezius	Clamshell	–0.89	–0.67	–1.02	–1.21	–0.80	–1.29	–0.55	0.01
	Traditional	0.34	0.47	0.38	0.49	0.33	0.27	–0.40	–0.15
Deltoid	Clamshell	1.61	–1.91	–2.38	–1.85	–1.91	–1.65	–1.83	–1.30
	Traditional	–2.11	–2.02	–2.47	–2.21	–2.11	–1.83	–1.79	–1.84
Flexor	Clamshell	–1.48	–1.70	–2.53	–1.68	–1.76	–1.88	–2.03	–1.17
	Traditional	–3.02	–3.33	–4.12	–3.84	–3.18	–3.29	–2.35	–1.63
Thenar	Clamshell	–0.83	0.24	–0.07	–0.33	–0.02	–1.00	0.65	0.66
	Traditional	0.58	1.81	2.58	1.30	1.62	1.21	2.24	1.15

*Statistical significance at $p < .05$.

TABLE 7: Median Frequency Slope Analysis Significant Effects of Anthropometry Group Within the Phone Condition

		Anthropometry Dimension							
Part of Body	Anthro-pometry Group	Hand Length	Arm Length	Grip Strength	Abduction Strength	Elbow-to-Fingertip Length	Palm Width	Thumb Breadth	Thumb Length
				Small Clamshell Phone					
Trapezius	Small	–0.35	–0.68	–0.44	–0.32	–0.48	–0.06	–0.75	–1.14
	Large	–0.89	–0.67	–1.02	–1.21	–0.80	–1.29	–0.55	0.01
Deltoid	Small	–1.21	–0.99	–0.84*	–1.18	–0.76*	–1.26	–1.20	–1.55
	Large	–1.61	–1.91	–2.38*	–1.85	–1.91*	–1.65	–1.83	–1.30
Flexor	Small	–1.78	–1.50	–0.98*	–1.54	–1.35	–1.32	–1.31	–1.88
	Large	–1.48	–1.70	–2.53*	–1.68	–1.76	–1.88	–2.03	–1.17
Thenar	Small	–2.50	–3.24*	–2.45	–2.27	–3.30*	–1.98	–2.05	–2.05
	Large	–0.38	0.24*	–0.07	–0.33	–0.02*	–1.00	–0.65	–0.66
				Traditional Office Phone					
Trapezius	Small	–0.63	–0.56	–0.33	–0.40	–0.63	–0.37	0.19	0.02
	Large	0.34	0.47	0.38	0.49	0.33	0.27	–0.40	–0.15
Deltoid	Small	–0.95	–1.27	–1.10*	–1.27	–0.96	–1.47	–1.55	–1.52
	Large	–2.11	–2.02	–2.47*	–2.21	–2.11	–1.83	–1.79	–1.84
Flexor	Small	–1.06	–1.14	0.98	–1.16	–0.81	–1.18	–2.16	–2.64
	Large	–3.02	–3.33	–4.12	–3.84	–3.18	–3.29	–2.35	–1.63
Thenar	Small	2.00	0.48	0.20	1.04	0.45	1.09	0.42	1.15
	Large	0.58	1.81	2.58	1.30	1.62	1.21	2.24	1.15

*Statistical significance at $p < .05$.

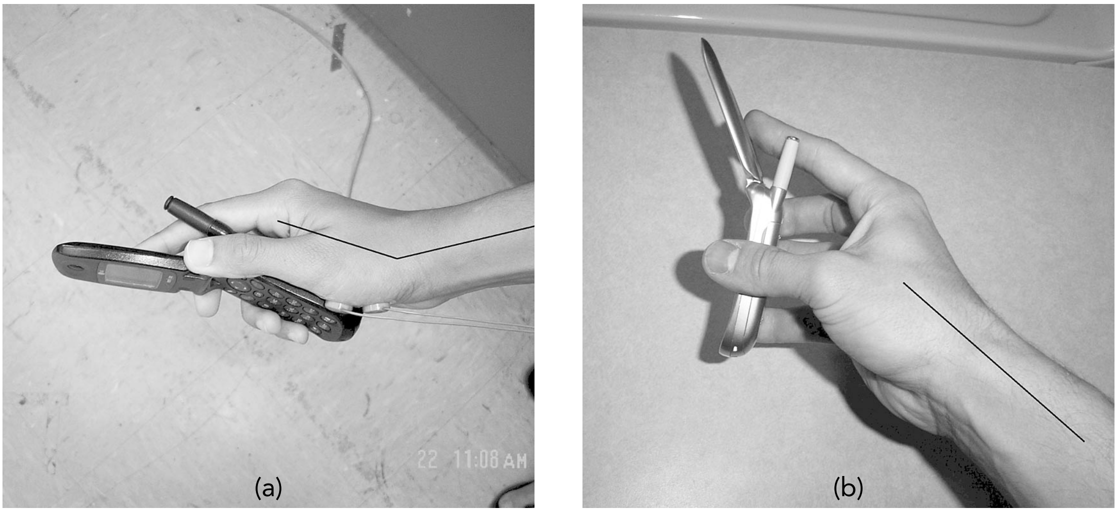

Figure 3. Postures observed during the study for small clamshell phone between anthropometry groups: (a) wrist in extension for the small-anthropometry group; (b) wrist in neutral position for the large-anthropometry group.

thenar side of the palm was cradled into the palm, supported by the thenar eminence. As a result of the posture used for balance of the phone, it was necessary for the wrist to be in extension. The large-anthropometry group held the small clamshell phone differently, with the thumb perpendicular to the long edge of the phone (see Figure 3b). The phone was thus more free standing than resting in the palm. This posture of the thumb and fingers allowed for a more neutral wrist posture. All participants were required to use the index finger as a counterbalance.

The signs of fatigue in the small-anthropometry group may be attributable to the extension of the wrist. This wrist posture changed the muscle lengths in the arm and hand. Any deviation of the wrist from neutral is known to produce losses in grip strength (Karwowski, 2001; Sporrong, Palmerud, & Herberts, 1996). Wrist posture may have affected the strength and endurance of the hand; also, the fundamental muscle length of the thumb was altered between the two anthropometry groups. The direction of applied force for the thumb remained the same in both cases, but the thumb changed orientation. The presence of more fatigue in the small-anthropometry group suggests that the thumb muscle length was not optimized in the parallel position. Fatigue developed quicker in participants performing static exertions using non-neutral postures and muscle lengths that were not optimal (Chaffin et al., 1999; Karwowski, 2001; Langton, 1998; Watkins, 1999).

Fatigue in the thenar muscle may prove to be significant when office occupational tasks are examined. The thenar muscle is being used more frequently with the advent of highly intensive hand and finger tasks associated with technology in the workplace. A lack of rest and recovery from typical workday office exposures may occur when similar tasks such as typing, using a mouse, and using a Blackberry are combined with using a small clamshell phone.

The secondary finding of this study was that large-anthropometry participants had increased fatigue in the deltoid in both phone conditions, which may be explained by the influence of anthropometry on biomechanics. In this task, the arm posture relative to the neck and shoulder for both phone conditions was not altered by phone design. Similar steep fatigue patterns in the deltoid developed for participants with long arm segments.

It is suggested that the presence of fatigue was attributable to the internal moment arm associated with holding the phone (Marras, 1999). The additional length of the arm segments changed the center of mass of the arm and created a longer moment arm. The resultant internal force increased to maintain shoulder stability during phone use for these participants. These accommodations for link length altered the length-strength relationship of the muscles when the anthropometry groups were compared (Chaffin et al., 1999). The longer arm segments may also have increased body mass associated with the additional length. Overcoming these additional forces to maintain stability may have caused muscle fatigue to develop at a faster rate.

In summary, the posture facilitated by the phone design was a significant contributor to the development of fatigue through an altering of the length-strength relationship. Anthropometry additionally modified the body's reaction to the phone designs. Specifically, the small clamshell phone presented an increase in discomfort for the hand, wrist, and fingers for all participants. Biomechanical measures demonstrated that participants with smaller limb lengths developed significant signs of fatigue in the thumb. This is proposed to be a result of using suboptimal length-strength positions of the hand. Also, participants with longer arms tended to develop greater discomfort in the neck and shoulder. Biomechanical data supported this theory, with signs of muscle fatigue attributed to increased moment and mass in participants with long limbs.

Statistical power for this study was based on a pilot investigation. Although this study had a limited sample size, statistically significant differences were observed in some of the muscles. A larger population of participants may have allowed us to identify even more statistically significant differences. These findings suggest that a study with more phone design styles may result in a greater understanding of proper design principles. Also, given the large number of tests that were done (128 *t* tests for frequency analysis, of which 12 were significant, and 160 *t* tests for discomfort analysis, of which 33 were significant), Type I error probability of any false significances is greater than the individual significance level of .05. Thus, the recommendations about phone design can be made only under the assumption that the multiple tests are simultaneously correct; they have not been proved by this single study alone.

Muscular fatigue as measured by the EMG median frequency shift may be confounded by muscle force and muscle length. Changes in muscle force and length also change the corresponding EMG signal and frequency spectrum. It is very difficult to isolate the true effects of fatigue. This experiment attempted to control for this effect by making the task a static activity and making the posture used by the hand and shoulder during the two test conditions constant. There was no feedback mechanism for isokinetic force during the task, but participants were asked to utilize the devices as they normally would use them.

In real-life phone use with live airtime, users will shift and adjust postures to better hear the conversation and optimize their body's use of the device. Users may adjust the forces with which they hold the phone, rather than remaining still as in our simulated task. For example, users may need to strain to hear the conversation through the device, possibly increasing the forces used to grip the phone when using live airtime. For the purposes of monitoring fatigue via EMG shifts for low-level exertions, we instructed participants to keep the task static during this study. The 1-hr duration was chosen based upon pilot data in an effort to capture enough data for fatigue to appear in a low-level static exertion. Despite the attempt to make the task purely static, during the experiment many participants subconsciously allowed their head and neck to nod as it would during conversation and actual phone use. The introduction of some movement allows for muscle recovery, and yet signs of fatigue were still present in the monitored muscles.

Although the long-duration, static use of the small clamshell phone in this study does not reflect typical phone use patterns, it is likely that intermittent small clamshell phone use contributes to a lack of rest and recovery from typical workday exposures when combined with other occupational upper extremity tasks, such as typing, using a mouse, and using a Blackberry.

Design Suggestions

The primary differences between phone conditions and anthropometry groups may highlight areas that need attention in order to optimize phone design for minimal fatigue and discomfort effects. The traditional office phone facilitated a power grip that required little use of the thenar muscle. Some participants also had a variation of the power grip when using a small clamshell phone, yielding less fatigue than those participants using a precision-pinch style. Thumb and finger grooves added to the side of the phone may facilitate a power-style grip, optimizing the length-strength relationship and correcting the nonneutral wrist posture.

Studies may be done to optimize the width of the phone. Anthropometry is known to influence grip capacity, which directly interacts with the parameters of phone design. Although this study cannot identify the ideal phone width, the importance of moment arms and length-strength properties of muscles was suggested by this study. The width of the phone may have a direct impact on these concepts. Additionally, studies comparing grip styles during identical tasks may highlight differences between anthropometry groups.

Although the static simulated phone use tested does not depict typical phone use patterns and this study was limited to testing one small clamshell phone design and one traditional office phone design, it is suggested that small clamshell phone use may contribute to a lack of rest and recovery from workday exposures. This study may serve as an initial investigation; further in-depth studies, including multiple phone models, are necessary to fully understand how phone use impacts fatigue in combination with the many upper extremity occupational tasks performed daily.

CONCLUSIONS

The small clamshell phone increased hand discomfort and thenar muscle fatigue during use, in comparison with the traditional office phone. Phone design and anthropometry interact to influence discomfort and the development of muscle fatigue. Grip style, as facilitated by phone design, contributed to the development of discomfort and muscle fatigue by changing muscle lengths. Anthropometry was found to additionally modify muscle length within the small clamshell phone test condition.

In general, the results of this study provided some insight into the effect of phone design on discomfort and muscle fatigue. The long-duration phone use tested in this study does not depict typical phone use patterns; however, it is possible that small clamshell phone use contributes to a lack of rest and recovery from typical workday exposures. This activity may contribute to the cumulative effect of exposures to risk factors in the upper extremity.

Although this study was limited to testing only two phone designs, one small clamshell phone and one traditional office phone, we hope it raises awareness of the biomechanical and ergonomic issues in this particular area of consumer product design. This study alone cannot yield definitive design recommendations, but it does provide a preliminary glance at the biomechanical consequences of the continuous miniaturization of cellular phones. Considering the increasing usage of these devices for both occupational and personal use, it is hoped that this study inspires further investigation into this topic.

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