Neck Strength and Endurance and Associated Personal and Work-Related Factors

Suman K. Chowdhury, Texas A&M University, College Station, USA, and Texas Tech University, Lubbock, USA, **Yu Zhou**, **Bocheng Wan**, **Curran Reddy**, and **Xudong Zhang**, Texas A&M University, College Station, USA

Objective: The present study aimed to establish a normative database of neck strength and endurance while exploring personal and work-related factors that can significantly influence neck strength and endurance.

Background: A normative database combining both neck strength and endurance and delineating how they are affected by personal and work-related factors is currently lacking. It is needed for the development of tools and guidelines for designing work requiring head-neck exertions to contain the risk of occupational neck pain.

Methods: Forty healthy participants (20 males and 20 females) performed sustained-till-exhaustion head-neck exertions, while seated, at 50% and 100% of their maximal efforts in anterior, anterior-superior, and posterior-superior directions in neutral, 40° extended, and 40° flexed neck postures. Exertion force and endurance time data from 38 participants were recorded and analyzed using regression models.

Results: Overall, multiple regression analyses of the neck strength and endurance database revealed that head-neck posture is the most significant determinant of both neck strength and endurance. The time of day significantly influenced neck endurance. Among the personal factors, a significant sex effect on neck strength and significant age and body mass index (BMI) effects on neck endurance were identified.

Conclusion: The work-related factors play a more significant role in shaping both neck strength and endurance than personal factors and therefore are more important modifiable factors in meeting the physical demands of work.

Application: The study findings can aid in work design as well as in pre-employment screening to reduce the incidence of neck pain in the workplace.

Keywords: neck pain, strength, endurance, personal factors, work-related factors

Address correspondence to Xudong Zhang, Department of Industrial & Systems Engineering, Texas A&M University, College Station, TX 77843, USA; e-mail: xudongzhang@tamu.edu

HUMAN FACTORS
2022, Vol. 64(6) 1013–1026
DOI:10.1177/0018720820983635
Article reuse guidelines: sagepub.com/journals-permissions

INTRODUCTION

Neck pain has become a highly significant source of disability and a global health issue. According to the 2010 Global Burden of Disease (GBD) study, neck pain affected 4.82% (332 million) people globally and was ranked as the fourth leading cause of global disability (Hoy et al., 2014). In a following GBD study conducted in 2016, the global burden for neck pain, expressed in disability-adjusted life-years, was reported to increase by 21.9%—from 23.8 million in 2006 to 28.9 million in 2016 (Hay et al., 2017). Neck pain also appears to be an increasingly prevalent occupational health condition in workplaces. A study on the Bone and Joint Decade 2000–2010 Task Force data reported that neck pain affected 11%–14.1% workers per year globally (Côté et al., 2008). The 2017 National Health Interview Survey (NHIS), administered by the Centers for Disease Control and Prevention, showed that the prevalence of neck pain was about 15% (about 37.7 million) of U.S. working adults aged 18 and over (NHIS, 2017). As the sedentary trend of modern work persists, without effective prevention and control strategies in place, neck pain will continue to impair the quality of life of the working population and pose a tremendous socioeconomic burden on society.

One guiding principle for preventing or mitigating the onset of occupational neck pain is to design work according to the neck functional capacities of the workers. A good understanding along with a quantitative characterization of neck functional capacities has nevertheless not been readily available. Previous studies have substantiated that an individual's neck strength (i.e., force-generating capacity) and endurance (i.e., fatigue-resistant capacity) can be influenced by both personal and work-related factors. For neck-related occupational tasks, sustained exertions at a submaximal or moderate force level are more common than high-force exertions. Thus, endurance may be more pertinent to neck pain causation and prevention. The majority of the studies to date have been dedicated to identifying relationships between neck strength and measures of personal factors (Cagnie et al., 2007; Catenaccio et al., 2017; Garces et al., 2002; Peolsson et al., 2007; Salo et al., 2006). For instance, some of these studies have shown that men produce more force but endure less time than women in the neck muscles and that the force production capacity decreases with age (Catenaccio et al., 2017; Garces et al., 2002; Peolsson et al., 2007); some have demonstrated the influence of work characteristics such as posture and exertion direction on neck strength (Catenaccio et al., 2017; Chen et al., 2018; Peolsson et al., 2001; Petrofsky & Phillips, 1982; Vasavada et al., 2001), though little investigative attention has been paid to the influence on endurance. A search of literature indeed indicates existing neck physical capacity databases have documented either neck strength data alone (Garces et al., 2002; Hildenbrand & Vasavada, 2013) or results from a simple, clinical deep neck flexor endurance test alone (Domenech et al., 2011; Jarman et al., 2017). Furthermore, the effect of yet another work-related factor, diurnal variation, on neck strength or endurance has never been examined, although prior studies have observed circadian rhythm effects on physical capacity measures owing to environmental factors such as ambient temperature and solar cycle (Atkinson et al., 1993; Reinberg et al., 1980).

Therefore, the purpose of this study was to establish a normative database of neck strength and endurance capacities and examine associated personal and work-related factors. In establishing the database, we focused more on endurance, while recognizing its intrinsic, inverse relationship with varied levels of force exertion relative to strength. We envision such a database and related analytics can be incorporated into design tools and guidelines for recognition and prevention of work scenarios where prolonged neck exertions may challenge workers' capacities and instigate the pathogenesis of neck pain.

METHODS

Participants

A total of 40 participants (20 males and 20 females), aged 21–45 years and with body mass index (BMI) less than 30, were recruited in this study. The participants were in good health and free from any musculoskeletal abnormality, discomfort, neck-related disorder, or injury at the time of participation. The means ± standard deviations of age, weight, height, and BMI of the participants were 30.95 ± .63 years (male: 31.65 ± 6.83 years; females: 30.25 ± 6.53 years), 70.11 ± 2.30 kg (male: 75.62 ± 12.03 kg; female: 64.61 ± 10.10 kg), 172.41 ± .66 cm (male: 175.92 ± 7.95 cm; female: 169.90 ± 8.05 cm), and 23.63 ± .83 kg/m^2 (male: 23.05 ± 2.85 kg/m^2; female: 24.58 ± 2.53 kg/m^2), respectively. Twenty-two participants were tested in the morning (before 11:00 AM) and 18 participants in the afternoon (from 1:30 to 5:30 PM). Prior to undergoing any of the study procedures, the participants were explained the details of the study and its protocol, and then provided their written consent in a form approved by the local institutional review board.

Experimental Design

A custom-built workstation comprised an adjustable testing frame, a height-adjustable chair, two rails, and a triaxial load cell was used to allow subjects to perform the experimental tasks (Figures 1 and 2). We first produced a computer-aided virtual design of the workstation in the SolidWorks CAD environment to ensure that we could simulate all the experimental tasks while accommodating participants from a wide distribution of stature (5th–95th percentiles; Figure 1). The adjustable testing frame made of T-slotted aluminum bars of different widths and lengths was designed to provide five degrees of freedom: four translations (T1–T4) and one rotation (R1). The adjustability of this frame was designed to accommodate participants from a broad range of anthropometry and permit head-neck exertions in different directions by pressing against a tiltable load

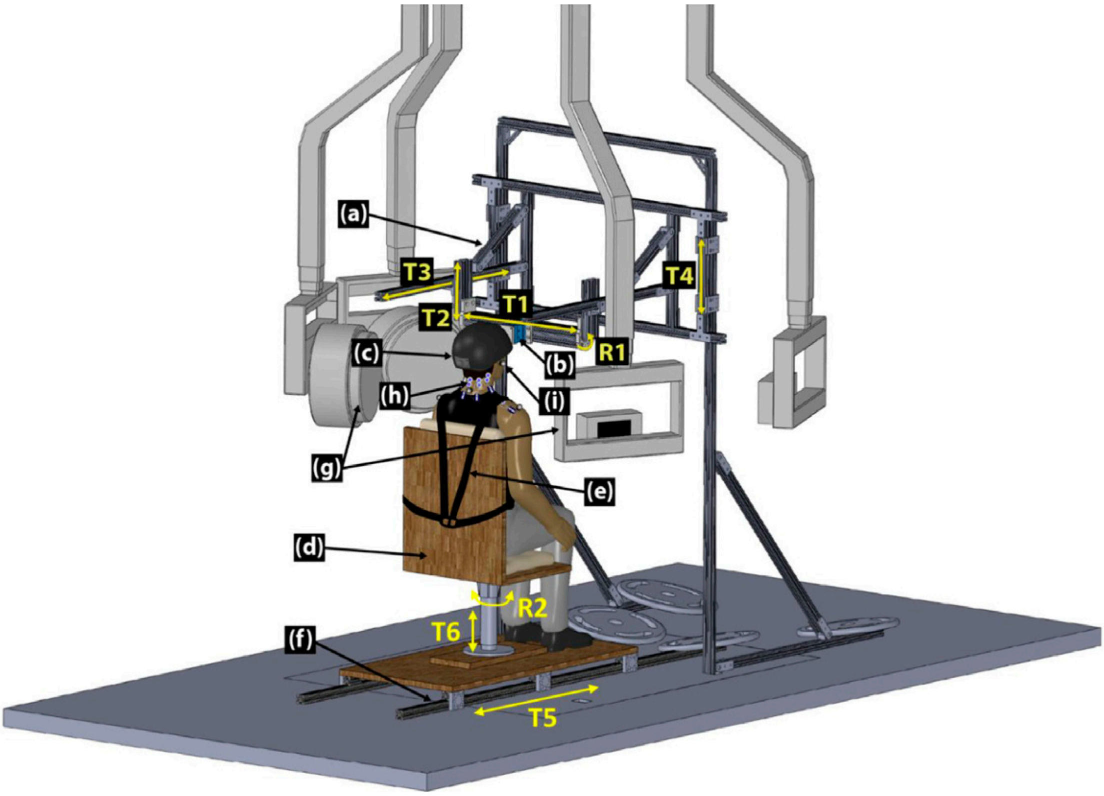
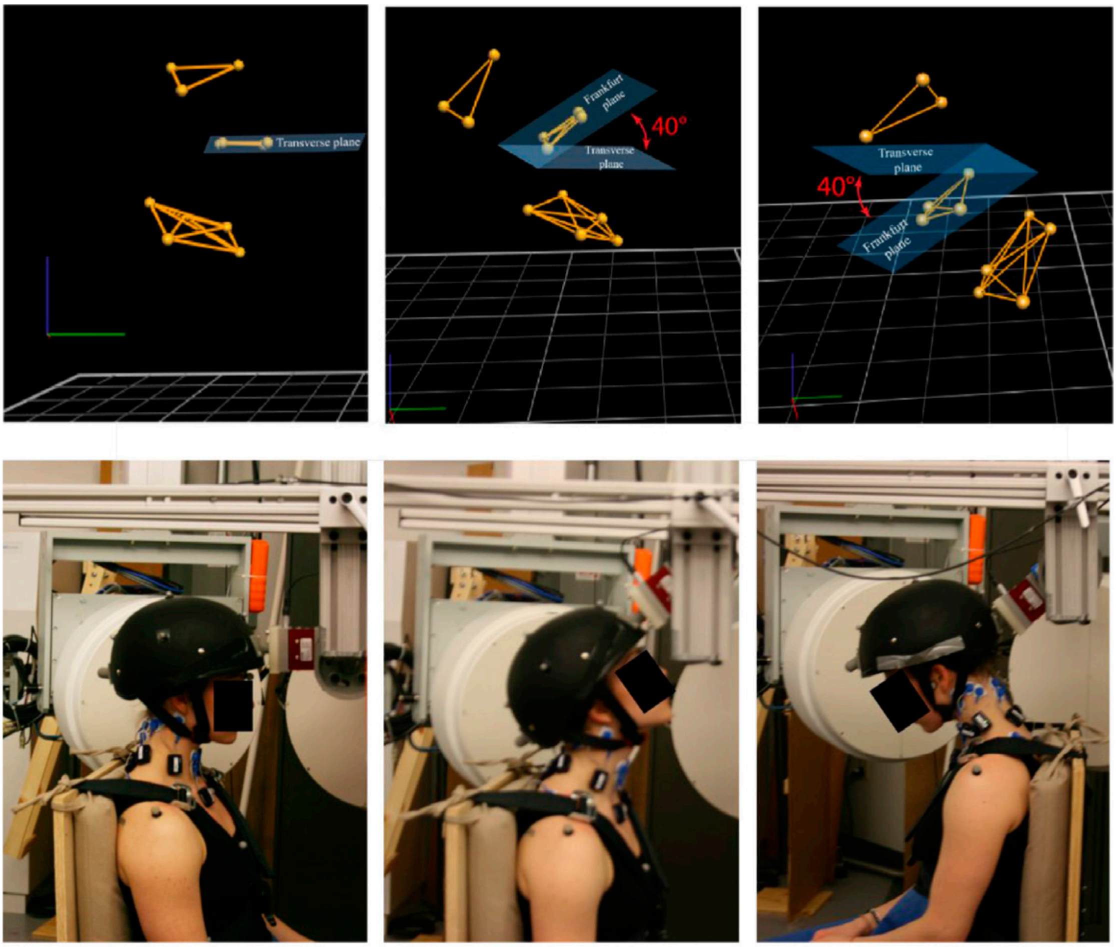


Figure 1. Computer-aided "virtual" design of the custom-built workstation in an integrated experimental setup, consisting of (a) adjustable frame, (b) load cell, (c) helmet, (d) adjustable chair, (e) strap, (f) rail, (g) dynamic radiographic imaging system (data were collected but not reported in the current study), (h) electromyography sensors, and (i) Vicon surface markers. The workstation permits eight degrees of freedom (i.e., adjustability): six translations are denoted as T1–T6 and two rotations are denoted as R1–R2.

cell. A height-adjustable, cushioned, and 360° swivel chair was constructed using wooden materials. The metallic swivel base of the chair was affixed to a rectangular wooden platform that was placed onto two T-slotted metallic rails, wherein the whole platform can be moved forward or backward to adjust the participants' sitting position. A four-strap harness secured at the back of the chair was designed to restrain the torso of the participants in performing the tasks. The structural design of the chair and the platform yielded three additional degrees-of-freedom: two translations (T5–T6) and one rotation (R2; Figure 1). The current study was part of a project that included simultaneous acquisition of a broad range of biomechanical data—head-neck strength, head-neck posture and motion, muscle fatigue, and cervical skeletal kinematics using force measurement, motion capture, electromyography (EMG), and dynamic stereo-radiography (DSX) systems, respectively (Figures 1 and 2). The details of the dynamic x-ray system, which have been presented elsewhere (Chowdhury et al., 2017), are not provided in this article, as the current study did not involve the vertebral kinematics data.

A triaxial MTA400 load cell was positioned in a custom-designed and 3D-printed case that was tiltable to allow for alignment of the load cell with the intended general direction of force application of participants' head-neck exertions (Figure 2). The sampling frequency of the load cell was 2160 Hz. Retro-reflective spherical markers were affixed to 10 anatomical



(a) Neutral **(b) 40° Extended** **(c) 40° Flexed**

Figure 2. Three experimental configurations wherein participants performed sustained neck exertions in anterior, anterior-superior, and posterior-superior directions, while seated at three corresponding head-neck postures: (a) neutral, (b) 40° extended, and (c) 40° flexed positions. The head-neck positions were measured as the angle between Frankfurt and transverse planes in the midsagittal plane. Surface markers placed on the tragion notches and infraorbitale landmarks defined the Frankfurt plane.

landmarks—tragion notches (left and right), infraorbitales (left and right), glabella, acromion processes (left and right), suprasternal notch, sternum, and the C7 spinous process—for a full capture of exertion postures of the participants using a 12-camera Vicon motion capture system (Vantage-Series, Vicon Motion Labs, Oxford, UK). The Cometa Wave wireless EMG system (sampling rate: 2160 Hz, inter-electrode distance: 20 mm, and band-pass filter: 10–500 Hz) was used to record surface EMG data from 10 neck muscles (Figures 1 and 2).

A Daytona half shell helmet (Ennis Kirk, Inc., Rush City, MN) with sufficient interior padding and chin straps was worn by the participants to facilitate head-neck exertions against the load cell. Mounted to the front and back of the helmet was a plastic spherical protrusion, which allowed the helmet to be accurately positioned and fitted with the spherical cavity of a plate attached to the outer surface of the load cell. The spherical mate was chosen to negate the likelihood of any slipping between the load cell and the helmet surfaces throughout the forceful head-neck exertions while permitting a quick disengagement (Figure 2). We used four different sizes of the helmets—M (head circumference: 53.7–55.9 cm), L (56.2–58.4 cm), XL (58.7–61 cm), and 2XL (61.3–63.5 cm)—to accommodate a broad range of head sizes.

Participants performed three types of neck exertions: (a) maximum voluntary isometric exertion (MVIE) to establish the strength baseline; (b) sustained-till-exhaustion exertion at 100% of their strength; and (c) sustained-till-exhaustion exertion at 50% of their strength with three different head-neck postures (neutral, extension, and flexion). These exertions required the participants to press their head with the augmented helmet, while seated, against the load cell. The exertion directions at neutral, extended, and flexed postures were respectively in (a) anterior, (b) anterior-superior, and (c) posterior-superior directions (Figure 2). The latter two directions were chosen to emulate real-world tasks requiring an extended or flexed neck while resisting a downward force (i.e., gravity). For example, over-the-shoulder welding tasks require a worker to be in a prolonged extended neck posture while wearing a helmet; a flexed head-neck posture is widely observed among surgeons or dentists who perform prolonged operations. The extension and flexion angles were set at 40°, as measured by the Frankfurt plane with respect to the neutral posture (Figure 2). At first, the participants performed two MVIE exertions for 5–10 s at each posture. A rest period of at least 2 min was provided between the MVIE exertions to avoid the effect of fatigue or discomfort. The maximum of these two exertions was used as the strength baseline to perform the latter two exertions. Each unique exertion was repeated once. Thus, a total of 18 exertion trials (three types, three postures, two repetitions) were completed by each participant. Inter-trial rest periods were administered to allow a full recovery: a period of 2 min or longer (if deemed necessary by the participant) was provided between the strength trials; at least twice the duration of the preceding trial was provided between the endurance trials. The order of different exertion types (and thus the experimental apparatus configurations) was randomized across the participants; at each configuration, the strength trials were performed first, and then the endurance trials were performed in a randomized order. Verbal feedback was provided during the sustained tasks to ensure that the participants achieved and maintained the target force level—100% ± 20% and 50% ± 10% of MVIE during the two respective levels of endurance trials.

Data Acquisition

The data acquisition process involved offline analysis of the load cell and Vicon surface marker data for the real-time feedback of exertion force level and direction, respectively. The exertion direction was measured by the head-neck flexion-extension (FE) angle defined as the angle between the global horizontal (or transverse) plane and the Frankfurt plane formed by four markers: left and right infraorbitales and left and right tragion notches (Figure 2). The unprocessed load cell data of the strength trials were smoothed using a moving 100-ms window. The maximum isometric force (F_{MVIE}) level of each trial was estimated by averaging the force data of a .5-s window ranging from $t_{max} - .25$ s to $t_{max} + .25$ s; where t_{max} was the time instance of the single maximum force value of that trial. A MATLAB program was developed to compute and display the exertion force level and exertion direction as real-time feedback to the participants.

We recorded surface EMG data from 10 neck muscles: the left and right infrahyoid (HYOID), left and right sternocleidomastoid (SCM), left and right cervical trapezius (TRAP) at C4–C5 level, left and right splenius capitis (SPL), and left and right upper trapezius (UTRAP). Before placing the EMG electrode pairs, we shaved and cleaned the skin underneath the anatomical locations with isopropyl alcohol. The EMG electrodes were placed in parallel to the muscle fibers of the individual muscles, as suggested by several previous studies (Joines et al., 2006; Nimbarte et al., 2014; Vasavada et al., 2002).

Data Analysis

The subsequent analysis used data of 38 participants (19 male and 19 female), as data of two participants were excluded due to missing trials

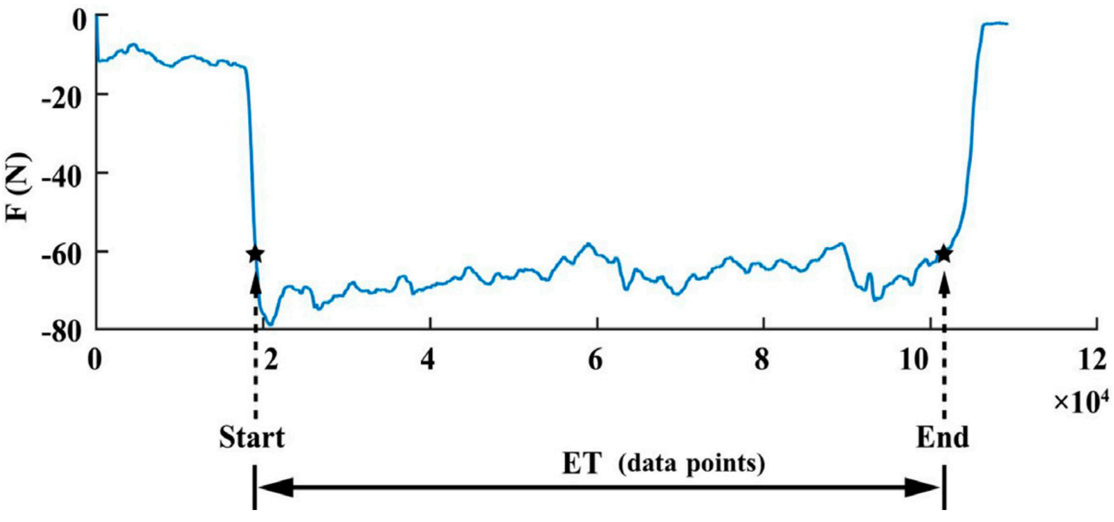


Figure 3. Filtered load cell data to indicate the start and end of the sustained exertions. ET (data points) and F (N) denote endurance time and exertion force, respectively. The ET(s) is expressed in terms of ET (data points): 1 s = 2.16 × 10^3 data points.

or poor data quality. The raw load cell data of all sustained exertion trials were full-wave rectified and then smoothed using a moving window of 100 ms (216 data points). We considered the start of the exertion (T_{beg}) as the time instance in which the buildup of force exceeded 80% of the target force level and the end of the exertion (T_{end}) as the time instance in which the receding force dropped below 80% of the target force level (Figure 3). The endurance time (ET) of each exertion was estimated as the duration between the start (T_{beg}) and end (T_{end}) of the sustained exertion task. Similarly, the sustained maximal ($F_{100\%}$) and submaximal ($F_{50\%}$) neck forces were calculated by averaging the force data between T_{beg} and T_{end} time instances of the sustained maximal and submaximal exertion trials, respectively. Then, both mean neck forces—$F_{100\%}$ and $F_{50\%}$—were normalized by the F_{MVIE} value of the corresponding posture to determine maximal and submaximal neck exertion levels (ELs). Data from two repetitions were averaged into a single dataset.

The surface EMG signals of eight neck muscles (left and right SCM, left and right HYOID, left and right TRAP, and left and right SPL) were used to evaluate neck muscle fatigue. A nonoverlapping sliding window of 500-ms (1080 data points) duration was employed between T_{beg} and T_{end} of the sustained exertion to estimate the median frequency (MF) by transforming the time-domain signal into the frequency domain using Fast Fourier Transform (FFT). As ET was varied across tasks and subjects, we scaled the task duration (ET) from 0% to 100%. We did not find any significant differences in muscle activation between the left and right sides of the same muscle group since the participants performed the exertions in the midsagittal plane. Therefore, the MF data, estimated at every 10% time interval of the scaled exertion duration, were pooled from both sides and averaged across all subjects. We employed linear regression analysis to estimate the MF slope for each of the four muscle groups. A negative value of the MF slope would confirm the occurrence of muscle fatigue (Chowdhury et al., 2013).

Multiple linear regression (MLR) models were employed to identify significant personal and work-related factors as predictors and characterize their relationships with neck strength (F) and ET as responses. The normality and homoscedasticity assumptions of the models were first examined using Kolmogorov–Smirnov and Levene tests, respectively. Since the data did not meet the normality assumption, a logarithmic transformation of the data were performed, which not only normalized their distributions but also fulfilled the homogeneity of variance assumptions. Moreover, the histograms of two continuous variables—age and BMI—showed skewness in the distribution, and the logarithmic data transformation to ln (Age) and ln (BMI) was able to bring together the spread-out data.

The multicollinearity assumption for the main effect and two-way interaction terms was also checked using the Pearson product-moment correlation (r) test and the value of the variation inflation factor (VIF). If the value of r was more than 0.30 and the value of VIF was more than 5, then we deemed a high degree of correlation between the pairs of predictor variables (Kutner et al., 2005). We observed a high degree of correlation ($r \geq .51$ and VIF $\geq$ 5.00) between main effect terms and two-way interaction terms: sex × time-of-day, head-neck posture × time-of-day, sex × head-neck posture, age × sex, ln (age) × time-of-day, ln (age) × head-neck posture, ln (age) × ln (BMI), ln (BMI) × sex, ln (BMI) × time-of-day, ln (BMI) × head-neck posture, EL × sex, EL × ln (BMI), EL × head-neck posture, and EL × time-of-day. Hence, in order to minimize the correlation, the continuous predictor variables were standardized (i.e., rescaled to have a mean of zero and a standard deviation of one), and the multicollinearity assumption was then re-checked. It was confirmed that only two interaction terms—head-neck posture × sex and head-neck posture × EL—showed a very low degree of correlation ($r \leq .26$ and VIF $\leq$ 3). Therefore, the subsequent regression analyses were carried out using ln (age), sex, ln (BMI), head-neck posture, time-of-day, EL, head-neck posture × sex, and head-neck posture × EL as the predictor variables and ln (F_{MVIE}) and ln(ET) as the response variables. The resulting regression models are as follows:

$$ln\left(F_{MVIE}\right) = \beta_0 + \beta_1 \times sex + \beta_2 \times head\text{-}neck\ posture + \beta_3 \times time\text{-}of\text{-}day + \beta_4 \times ln\left(age\right) + \beta_5 \times ln\left(BMI\right) + \beta_6 \times head\text{-}neck\ posture \times sex + \varepsilon \quad (1)$$

$$ln\left(ET\right) = \beta_0 + \beta_1 \times sex + \beta_2 \times head\text{-}neck\ posture + \beta_3 \times time\text{-}of\text{-}day + \beta_4 \times ln\left(age\right) + \beta_5 \times ln\left(BMI\right) + \beta_6 \times head\text{-}neck\ posture \times sex + \beta_7 \times EL + \beta_8 \times head\text{-}neck\ posture \times EL + \varepsilon \quad (2)$$

where, β_0 is the intercept and β_1, β_2, β_3, β_4, β_5, β_6, β_7, and β_8 are, respectively, the regression coefficients of sex (male: 1; female: 2), head-neck posture (40° extended posture: 1; neutral posture: 2; 40° flexed posture: 3), time-of-day (morning: 1; afternoon: 2), age (21–45 years), BMI (17.2–28.2 kg/m^2), head-neck posture × sex, EL (27%–120%), and head-neck posture × EL; ϵ is the random component (the rest of the model). Note that exertion level (EL) was only included in the ln(ET) regression model.

We considered the backward elimination procedure to determine if the individual predictor variables were significant. In the consecutive steps of the backward stepwise regression procedures, the significance level of .05 (p value $\leq$.05) was considered to remove the insignificant variables from the models. We used Cohen's (f^2) effect size ($f^2 = \frac{sr_i^2}{1-R_{full}^2}$ where sr_i^2 is the squared semi-partial correlation coefficient for the predictor of interest and R_{full}^2 is the squared multiple correlation coefficient for the full model) to measure the contribution of the significant variables in explaining the variance of a model (Cohen, 2013). All statistical analyses were performed in SPSS for Windows, version 20.0 (SPSS Inc., Chicago, IL), except for calculations of descriptive statistics such as mean, standard deviation (SD), standard error (SE), and confidence intervals, which were made in Microsoft Excel 2017 (Microsoft Corporation, Redmond, WA).

RESULTS

The actual force levels of the targeted 50% strength ($F_{50\%}$) and 100% strength ($F_{100\%}$) sustained-till-exhaustion exertions were 45.23% ± 7.63% and 80.77% ± 19.73% of baseline strength (F_{MVIE}), respectively (Table 1). The negative EMG MF trends (Figure 4) confirmed that all measured neck muscles experienced fatigue in all exertions; in particular,

TABLE 1: Descriptive Statistics (Mean ± *SD*) of Baseline Strength (F_{MVIE}), 100% Strength ($F_{100\%}$), and 50% Strength ($F_{50\%}$) and Multiple Regression Analysis Results of Neck Strength (F_{MVIE}) Data

Predictors	F_{MVIE} (*N*)	$F_{50\%}$ (*N*)	$F_{100\%}$ (*N*)	T-Stat	*p*-value	f^2
Sex						
Male	107.69 ± 25.44	48.11 ± 17.14	85.05 ± 33.66	−5.04	.000	0.42
Female	70.52 ± 19.08	32.25 ± 13.38	57.54 ± 24.29			
Head-neck posture						
40° extended	51.17 ± 22.25	21.80 ± 10.73	39.94 ± 20.90	5.50	.000	0.43
Neutral	88.28 ± 31.62	41.11 ± 14.61	69.54 ± 28.11			
40° flexed	127.84 ± 37.54	57.63 ± 16.64	104.41 ± 32.29			
Time-of-day						
Morning	83.83 ± 19.92	38.17 ± 14.36	66.39 ± 26.26	0.57	.573	-
Afternoon	98.26 ± 32.88	43.63 ± 20.16	79.69 ± 38.96			
Age						
-		-	-	−1.05	.297	-
BMI						
-		-	-	1.16	.248	-
Head-neck posture × sex						
Male						
40° extended	64.16 ± 20.59	26.82 ± 14.92	48.86 ± 30.76	0.28	.779	-
Neutral	108.03 ± 27.23	50.42 ± 17.63	83.03 ± 40.07			
40° flexed	151.06 ± 34.30	67.09 ± 20.01	123.27 ± 46.54			
Female						
40° extended	38.25 ± 15.50	16.78 ± 12.02	31.01 ± 22.62			
Neutral	68.52 ± 22.11	31.81 ± 14.18	56.04 ± 29.59			
40° flexed	104.62 ± 24.10	48.17 ± 16.70	85.56 ± 31.31			

Note. A *p* value ≤.05 denotes statistical significance. F^2 represents the measure of effect size. Approximate effect sizes of ≥.15 and ≥.35 signify moderate and large effect sizes, respectively (Cohen, 2013).

exertions in the anterior-superior (40° extended posture) direction showed about 40.56%, 31.81%, 55.19%, and 65.27% greater and exertions in the anterior (neutral posture) direction displayed about 33.23%, 39.60%, 68.56%, and 63.99% larger negative values than in the posterior-superior (40° flexed posture) direction for SCM, HYOID, TRAP, and SPL muscles, respectively.

The regression analysis results (Tables 1 and 2) demonstrated a significant effect of sex on neck strength ($p < .000$) but an insignificant effect ($p = .917$) on neck endurance time, with male participants showing about 34% higher neck strength and 8% less endurance in sustaining the submaximal exertion ($ET_{50\%}$) than female participants. The results revealed a decreasing trend for age effect and an increasing trend for BMI effect on strength (Table 1, statistically not significant) and endurance time (Table 2, statistically significant). Among work-related factors, the results showed a significant effect of head-neck posture on both neck strength ($p < .000$) and endurance ($p < .000$; Tables 1 and 2) and time-of-day ($p < .000$) and head-neck posture ($p < .000$) on endurance (Table 2). The effect of head-neck posture indicated that neck extensors in a posterior-superior exertion (at a 40° flexed posture) are about 34% and 64%, respectively, stronger than the neck flexors in anterior (at neutral posture) and anterior-superior (at a 40° extended posture) exertion tasks. Similar to neck strength results, the neck endurance data also

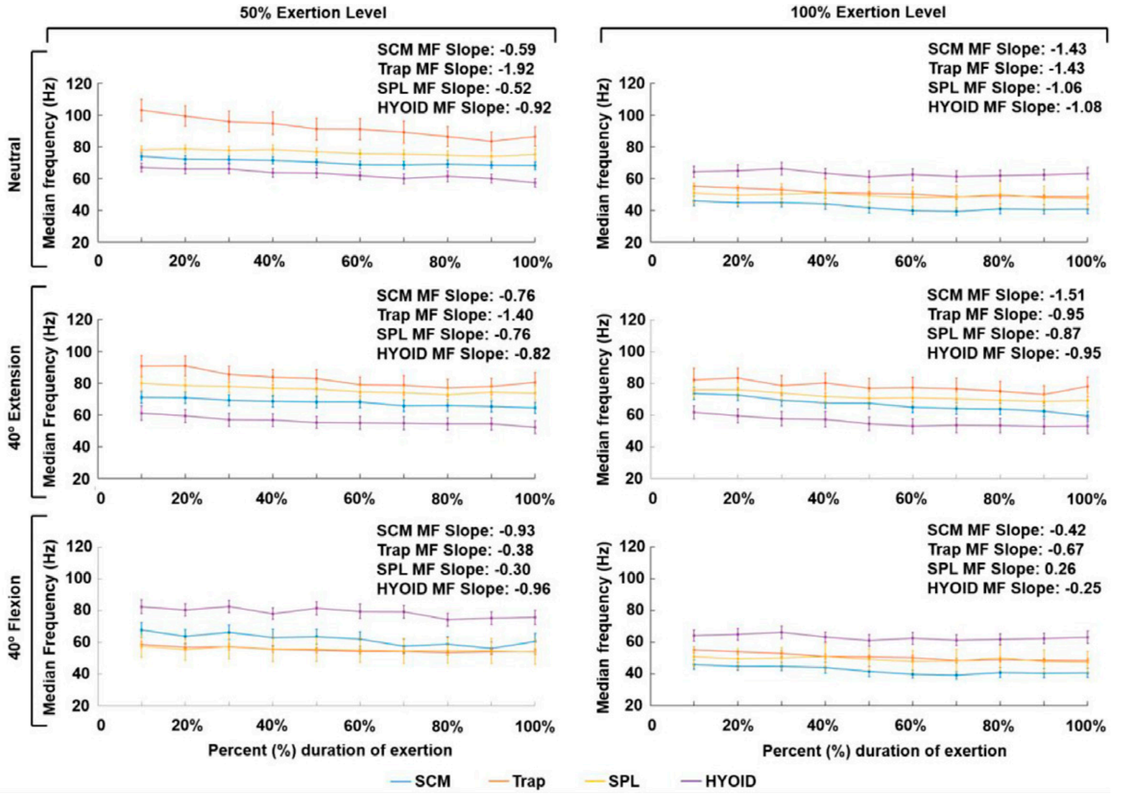


Figure 4. The median frequency (MF) plots at every 10% of the sustained duration, juxtaposing the frequency trends of four neck muscle groups—sternocleidomastoid (SCM), cervical trapezius (TRAP), splenius capitis (SPL), and infrahyoid (HYOID) at two exertion levels (ELs)—50% and 100%, and at three different postures—40° extension, neutral, and 40° flexion.

showed higher endurance of neck extensors than neck flexors (more than 10% and 26% at anterior and anterior-superior exertion tasks, respectively). Further, the strength and endurance of the flexor muscles during anterior exertion tasks at the neutral posture were, respectively, about 43% and 18% greater than during anterior-superior exertion tasks at 40° extended posture.

The effect of time-of-day on neck endurance time revealed that the participants tested in the morning showed about 15% and 29% longer endurance time than the participants tested in the afternoon during sustained submaximal and maximal neck exertion trials, respectively (Table 2). The interaction between head-neck posture and EL was found to be a significant predictor of neck endurance time, indicating a posture-dependent effect of EL on neck endurance time: significantly higher endurance time for $F_{50\%}$ exertion trials—about 51.5% more at the 40° extended posture, 59.3% more at the neutral posture, and 64.4% more at the 40° flexed postures—than corresponding $F_{100\%}$ exertion trials.

The effect size (f^2) data revealed that work-related factors (head-neck posture, eEL, and time-of-day) accounted for most of the variance in both regression models as compared to individual factors (sex, age, and BMI; Tables 1 and 2). In particular, the effects of head-neck posture largely contributed to predicting neck strength (head-neck posture: f^2 = .43; 30.5% of the variance;) and both head-neck posture and EL in predicting endurance (head-neck posture: f^2 = .62, 38.39% of the variance; head-neck posture × EL:

TABLE 2: Descriptive Statistics (Mean ± *SD*) and Multiple Regression Analysis Results of Neck Endurance Time (ET) Data

Predictors	$ET_{50\%}$ (S)	$ET_{100\%}$ (S)	T-Stat	*p*-Value	f^2
Sex					
Male	84.57 ± 44.63	32.62 ± 13.81	−.11	0.917	-
Female	83.92 ± 42.35	35.33 ± 17.69			
Head-neck posture					
40° Extended	58.90 ± 31.31	28.60 ± 13.75	11.78	<.000	0.62
Neutral	85.50 ± 48.14	34.76 ± 13.93			
40° Flexed	108.34 ± 63.61	38.57 ± 22.56			
Time-of-day					
Morning	89.17 ± 39.45	38.04 ± 14.79	−3.76	<.000	0.06
Afternoon	75.81 ± 47.89	27.00 ± 14.79			
Age					
-	-	-	−4.99	<.000	0.11
BMI					
-	-	-	2.28	0.023	0.02
Exertion level					
-	84.24 ± 30.64	33.97 ± 11.22	−1.13	0.261	-
Head-neck posture × Exertion level					
40° Extended	58.90 ± 31.31	28.60 ± 13.75	−11.46	<.000	0.59
Neutral	85.50 ± 48.14	34.76 ± 13.93			
40° Flexed	108.34 ± 63.61	38.57 ± 22.56			
Head-neck posture * Sex					
Male					
40° Extended	64.04 ± 56.09	30.74 ± 22.07	0.14	0.886	-
Neutral	78.80 ± 59.98	32.44 ± 26.75			
40° Flexed	110.84 ± 97.14	34.67 ± 23.79			
Female					
40° Extended	53.74 ± 27.74	26.46 ± 16.46			
Neutral	92.19 ± 75.82	37.07 ± 30.39			
40° Flexed	105.83 ± 84.63	42.26 ± 38.22			

Note. A *p* value ≤.05 denotes statistical significance. Sustained maximal and submaximal exertion times are denoted as $ET_{100\%}$ and $ET_{50\%}$, respectively. F^2 represents the measure of effect size. Approximate effect sizes of ≥.15 and ≥.35 signify moderate and large effect sizes, respectively (Cohen, 2013).

f^2 = .59, 37.24% of the variance). Among the personal factors, sex (f^2 = .42; 29% of the variation in strength model) and age (f^2 > .11, 10.04% of the variation in endurance model) exhibited relatively greater effects on neck strength and endurance time, respectively. A relatively small effect size was observed for BMI (f^2 = .06, 5.66% of the variance) and time-of-day (f^2 = .06, 5.98% of the variance) on neck endurance.

The MLR models, after stepwise elimination of insignificant variables, rearranged, unstandardized, and taking antilog in both sides, take the following forms:

$$F_{MVIE} = \exp\ (4.471 + 0.286\ \textit{head-neck posture}\ - 0.461\ \textit{sex}) \quad (3)$$

$$ET = \exp\ (4.340 + 0.842\ \textit{head-neck posture} - 0.859\ \ln(Age) + 0.742\ \ln(BMI) - 0.286\ \textit{time-of-day} - 0.888\ EL \times \textit{head-neck posture}) \quad (4)$$

where F_{MVIE} is the neck strength (N) and ET is the endurance time (s); sex is coded as 1 for male and 2 for female; head-neck posture is coded as 1 for 40° extended posture, 2 for neutral posture, and 3 for 40° flexed posture; time-of-day is coded as 1 for the morning and 2 for the afternoon; age is in years (21–45 years); BMI is in kg/m^2 (<30 kg/m^2); and EL is in decimal (e.g., 0.50 for 50% MVIE EL). The adjusted R^2 was 0.35 and 0.51 for strength Equation (3) and endurance time Equation (4), respectively.

DISCUSSION

The current study investigated the effects of work-related and personal factors on neck strength and endurance as it established a normative database of these two important, interrelated neck functional capacity measures. The study identified significant effects of sex and head-neck posture on neck strength, and of age, BMI, head-neck posture, time-of-day, and posture-EL interaction on neck endurance and produced regression models delineating the relationships.

In general, both muscle strength and endurance depend on the proportion of fast (type II) and slow (type I) twitch muscle fibers (Billeter & Hoppeler, 2003; Hickson et al., 1994; Miller et al., 1993; Wilson et al., 2012). Type II fibers have relatively higher strength but are more fatigable, whereas type I fibers have relatively lower strength but are more fatigue-resistant (Wilson et al., 2012). The proportion of these two fiber types across various muscles and different sex groups largely determines the variation of muscle strength and endurance time. For example, females have a higher proportion of type I fibers, whereas males have a larger proportion of type II fibers (Miller et al., 1993; Simoneau & Bouchard, 1989). That explains why males were found to have significantly greater neck force-generating capacity than females. The female-to-male ratio of neck strength was found to vary from 0.6 to 0.8, which is consistent with what has been reported in the literature (Cagnie et al., 2007; Catenaccio et al., 2017; Garces et al., 2002, Peolsson et al., 2007; Vasavada et al., 2001). While we did not see a sex difference in endurance at the maximum EL, we did observe higher neck endurance in females at the submaximum EL, as was previously reported (Peolsson et al., 2007).

The head-neck posture and EL had the most pronounced effects: head-neck posture accounted for about 31% of the variance in the neck strength model, whereas the combined effect of head-neck posture and EL accounted for about 74% of the variance in the endurance model (Tables 1 and 2). A change in muscle length as a result of postural change affects the binding between actin and myosin filaments, which, in turn, modulates the force-generating and enduring capacities of the muscle (Billeter & Hoppeler, 2003; Rassier et al., 1999; Wilson et al., 2012). For this reason, we observed the anterior neck muscles (flexors) produce more force in the neutral posture than in the 40° extended posture as the optimal muscle length where maximum tension can be produced is likely at or near the neutral neck posture (Vasavada et al., 1998). For the same reason, we also observed higher neck endurance for the neck flexors at the neutral posture than the 40° extended posture. This could also be due to the increased torque by the gravitational force at an extended neck posture (e.g., 40° extended posture) that must be counterbalanced by the neck flexors. Furthermore, we observed higher neck capacities (both strength and endurance) for the extensors at exertion tasks in the posterior-superior direction at the 40° flexed posture as compared to the flexors in the anterior-superior direction at 40° extended posture and the anterior direction at the neutral posture. The muscle fatigue data also displayed the same trend—extensor muscles (SPL and TRAP) are less fatigable than the flexor muscles (HYOID and SCM). This may be attributable to a greater muscle size (e.g., volume, cross-sectional area, length; Billeter & Hoppeler, 2003; Miller et al., 1993) and a relatively higher proportion of type I fibers in neck extensors compared to neck flexors (Uhlig et al., 1995).

One interesting finding was that the participants tested in the afternoon on average had lower neck endurance than those tested in the morning, indicating a possible diurnal effect. It is well established that circadian rhythms govern many daily habits and activities (e.g., body temperature cycle, patterns of hormone secretion; Andrews et al., 2010). A lack of synchronization between one's circadian rhythm and diurnal rhythm—the day/night cycle—can affect mental and physical performance (Bennie et al., 2014; James et al., 2017). We nevertheless must acknowledge this was a serendipitous finding, as our experiment was not designed to test the diurnal variation effect. A more dedicated systematic investigation of this time-of-day (i.e., diurnal variation) effect on neck functional capacities may be warranted.

Our results demonstrated that the neck endurance significantly decreases with age. An extensive literature search found only one relevant study, which identified no age effect on neck endurance (Peolsson et al., 2007). No significant relationship between age and neck strength was found in the current study, as in previous studies (Cagnie et al., 2007; Chiu et al., 2002). We, however, did observe a trend of decreasing neck strength with age (Garces et al., 2002; Jordan et al., 1999; Peolsson et al., 2001). Interestingly, BMI was found to be a significant predictor of neck endurance time: participants with a higher BMI showed significantly greater endurance time than participants with a lower BMI. Prior studies have identified a positive relationship between BMI and neck strength (Catenaccio et al., 2017; Salo et al., 2006), but no study could be found that explored the relationship between BMI and neck endurance.

The neck strength and endurance regression models derived from this study may be used to predict neck functional capacities for a particular neck exertion task (e.g., computer use, medical operations particularly with head-worn protective equipment, and over-the-head drilling and metal work). Nevertheless, the R^2 values indicated that about 63% and 49% of the model variance were left unexplained by the derived neck strength and endurance regression models, respectively. One of the reasons is that we considered only two interaction terms and excluded all others due to multicollinearity.

There are caveats associated with using the derived regression models. For example, the results represent a healthy and relatively young cohort: their mean age of 30.95 years and mean BMI of 23.63 kg/m^2 were lower than the means for the industrial population—38.21 years and 25.97 kg/m^2, respectively (Marras & Kim, 1993). It is also important to note that exertions of lower force levels (e.g., 30% of MVIE) could not be administered in our experiment for practical considerations. Thus, extrapolation of the endurance model to much lower force exertions would not be prudent without validation based on data from complementary studies.

Finally, the regression models and related analytics showed a dominant effect of the work-related factor that combined head-neck posture and exertion direction and a relatively moderate effect of personal factors—sex and age. This can potentially provide a rationale for setting priorities between work design and worker selection in prevention and control measures to curtail the incidence of neck pain.

ACKNOWLEDGMENTS

The work was funded by a research grant (R01OH010587) from the Centers for Disease Control and Prevention/National Institute for Occupational Safety and Health (CDC/NIOSH).

KEY POINTS

- The work-related factors, such as neck posture, exertion direction, and exertion level play comparatively a greater role in shaping neck functional capacities than personal factors, such as sex, age, and BMI.
- Neck extensor muscles have greater force-generating (strength) and fatigue-resistant (endurance) capacities than neck flexor muscles.
- Participants tested in the morning session showed significantly higher neck endurance than participants tested in the afternoon.
- Females showed a lower level of neck strength but a higher level of neck endurance than males.
- The neck strength and endurance of a healthy cohort (aged between 21 and 45 years and BMI between 17 and 28 kg/m^2) appeared to decrease with age but increase with BMI.

ORCID iD

Xudong Zhang https://orcid.org/0000-0002-7976-2045

REFERENCES

Andrews, J. L., Zhang, X., McCarthy, J. J., McDearmon, E. L., Hornberger, T. A., Russell, B., Campbell, K. S., Arbogast, S., Reid, M. B., Walker, J. R., Hogenesch, J. B., Takahashi, J. S., & Esser, K. A. (2010). Clock and BMAL1 regulate MyoD and are necessary for maintenance of skeletal muscle phenotype and function. *Proceedings of the National Academy of Sciences*, *107*, 19090–19095. https://doi.org/10.1073/pnas.1014523107

Atkinson, G., Coldwells, A., Reilly, T., & Waterhouse, J. (1993). A comparison of circadian rhythms in work performance between physically active and inactive subjects. *Ergonomics*, *36*, 273–281. https://doi.org/10.1080/00140139308967882

Bennie, J., Davies, T. W., Duffy, J. P., Inger, R., & Gaston, K. J. (2014). Contrasting trends in light pollution across Europe based on satellite observed night time lights. *Scientific Reports*, *4*, 3789. https://doi.org/10.1038/srep03789

Billeter, R., & Hoppeler, H. (2003). Muscular basis of strength. In P. V. Komi (Ed.), *Strength and power in sport*. Blackwell Science.

Cagnie, B., Cools, A., De Loose, V., Cambier, D., & Danneels, L. (2007). Differences in isometric neck muscle strength between healthy controls and women with chronic neck pain: The use of a reliable measurement. *Archives of Physical Medicine and Rehabilitation*, *88*, 1441–1445. https://doi.org/10.1016/j.apmr.2007.06.776

Catenaccio, E., Mu, W., Kaplan, A., Fleysher, R., Kim, N., Bachrach, T., & Kim, M. (2017). Characterization of neck strength in healthy young adults. *PM&R*, *9*, 884–891.

Chen, X., O'Leary, S., & Johnston, V. (2018). Modifiable individual and work-related factors associated with neck pain in 740 office workers: A cross-sectional study. *Brazilian Journal of Physical Therapy*, *22*, 318–327. https://doi.org/10.1016/j.bjpt.2018.03.003

Chiu, T. T. W., Lam, T.-H., & Hedley, A. J. (2002). Maximal isometric muscle strength of the cervical spine in healthy volunteers. *Clinical Rehabilitation*, *16*, 772–779. https://doi.org/10.1191/0269215502cr552oa

Chowdhury, S. K., Byrne, R. M., Zhou, Y., Gale, T., Zheng, L., Anderst, W., & Zhang, X. (2017). *Integrating multi-modality imaging and biodynamic measurements for studying neck biomechanics during sustained-till-exhaustion neck exertions* [Paper presentation]. Proceedings of the Human Factors and Ergonomics Society Annual Meeting.

Chowdhury, S. K., Nimbarte, A. D., Jaridi, M., & Creese, R. C. (2013). Discrete wavelet transform analysis of surface electromyography for the fatigue assessment of neck and shoulder muscles. *Journal of Electromyography and Kinesiology*, *23*, 995–1003. https://doi.org/10.1016/j.jelekin.2013.05.001

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. Academic press.

Côté, P., van der Velde, G., David Cassidy, J., Carroll, L. J., Hogg-Johnson, S., Holm, L. W., Carragee, E. J., Haldeman, S., Nordin, M., Hurwitz, E. L., Guzman, J., & Peloso, P. M. (2008). The burden and determinants of neck pain in workers. *European Spine Journal*, *17*, 60–74. https://doi.org/10.1007/s00586-008-0626-9

Domenech, M. A., Sizer, P. S., Dedrick, G. S., McGalliard, M. K., & Brismee, J.-M. (2011). The deep neck flexor endurance test: Normative data scores in healthy adults. *PM&R*, *3*, 105–110.

Garces, G. L., Medina, D., Milutinovic, L., Garavote, P., & Guerado, E. (2002). Normative database of isometric cervical strength in a healthy population. *Medicine & Science in Sports & Exercise*, *34*, 464–470.

Hay, S. I., Abajobir, A. A., Abate, K. H., Abbafati, C., Abbas, K. M., Abd-Allah, F., Abdulkader, R. S., Abdulle, A. M., Abebo, T. A., Abera, S. F., Aboyans, V., Abu-Raddad, L. J., Ackerman, I. N., Adedeji, I. A., Adetokunboh, O., Afshin, A., Aggarwal, R., Agrawal, S., Agrawal, A., . . .Murray, C. J. L. (2017). Global, regional, and national disability-adjusted life-years (DALYs) for 333 diseases and injuries and healthy life expectancy (HALE) for 195 countries and territories, 1990–2016: A systematic analysis for the global burden of disease study 2016. *The Lancet*, *390*, 1260–1344. https://doi.org/10.1016/S0140-6736(17)32130-X

Hickson, R. C., Hidaka, K., & Foster, C. (1994). Skeletal muscle fiber type, resistance training, and strength-related performance. *Medicine & Science in sports & Exercise*, *26*, 593–598. https://doi.org/10.1249/00005768-199405000-00011

Hildenbrand, K. J., & Vasavada, A. N. (2013). Collegiate and high school athlete neck strength in neutral and rotated postures. *Journal of Strength and Conditioning Research*, *27*, 3173–3182. https://doi.org/10.1519/JSC.0b013e31828a1fe2

Hoy, D., March, L., Woolf, A., Blyth, F., Brooks, P., Smith, E., Vos, T., Barendregt, J., Blore, J., Murray, C., Burstein, R., & Buchbinder, R. (2014). The global burden of neck pain: Estimates from the global burden of disease 2010 study. *Annals of the Rheumatic Diseases*, *73*, 1309–1315. https://doi.org/10.1136/annrheumdis-2013-204431

James, S. M., Honn, K. A., Gaddameedhi, S., & Van Dongen, H. P. A. (2017). Shift work: Disrupted circadian rhythms and sleep—implications for health and well-being. *Current Sleep Medicine Reports*, *3*, 104–112. https://doi.org/10.1007/s40675-017-0071-6

Jarman, N. F., Brooks, T., James, C. R., Hooper, T., Wilhelm, M., Brismée, J.-M., & Sizer, P. S. (2017). Deep neck flexor endurance in the adolescent and young adult: Normative data and associated attributes. *PM&R*, *9*, 969–975.

Joines, S. M. B., Sommerich, C. M., Mirka, G. A., Wilson, J. R., & Moon, S. D. (2006). Low-level exertions of the neck musculature: A study of research methods. *Journal of Electromyography and Kinesiology*, *16*, 485–497. https://doi.org/10.1016/j.jelekin.2005.09.007

Jordan, A., Mehlsen, J., Bülow, P. M., Østergaard, K., & Danneskiold-Samsøe, B. (1999). Maximal isometric strength of the cervical musculature in 100 healthy volunteers. *Spine*, *24*, 1343. https://doi.org/10.1097/00007632-199907010-00012

Kutner, M. H., Nachtsheim, C. J., Neter, J., & Li, W. (2005). *Applied linear statistical models* (Vol. 5). McGraw-Hill Irwin.

Marras, W. S., & Kim, J. Y. (1993). Anthropometry of industrial populations. *Ergonomics*, *36*, 371–378. https://doi.org/10.1080/00140139308967894

Miller, A. E., MacDougall, J. D., Tarnopolsky, M. A., & Sale, D. G. (1993). Gender differences in strength and muscle fiber characteristics. *European Journal of Applied Physiology and Occupational Physiology*, *66*, 254–262. https://doi.org/10.1007/BF00235103

NHIS, C. (2017). Summary health statistics: National health interview Survery, 2017. https://ftp.cdc.gov/pub/Health_Statistics/NCHS/NHIS/SHS/2017_SHS_Table_A-5.pdf

Nimbarte, A. D., Zreiqat, M. M., & Chowdhury, S. K. (2014). Cervical flexion-relaxation response to neck muscle fatigue in males and females. *Journal of Electromyography and Kinesiology*, *24*, 965–971. https://doi.org/10.1016/j.jelekin.2014.09.002

Peolsson, A., Almkvist, C., Dahlberg, C., Lindqvist, S., & Pettersson, S. (2007). Age- and sex-specific reference values of a test of neck muscle endurance. *Journal of Manipulative and Physiological Therapeutics*, *30*, 171–177. https://doi.org/10.1016/j.jmpt.2007.01.008

Peolsson, A., ÖBerg, B., & Hedlund, R. (2001). Intra- and inter-tester reliability and reference values for isometric neck strength. *Physiotherapy Research International*, *6*, 15–26. https://doi.org/10.1002/pri.210

Petrofsky, J. S., & Phillips, C. A. (1982). The strength-endurance relationship in skeletal muscle: Its application to helmet design. *Aviation, Space, and Environmental Medicine*, *53*, 365–369.

Rassier, D. E., MacIntosh, B. R., & Herzog, W. (1999). Length dependence of active force production in skeletal muscle. *Journal of Applied Physiology*, *86*, 1445–1457. https://doi.org/10.1152/jappl.1999.86.5.1445

Reinberg, A., Andlauer, P., Guillet, P., Nicolai, A., Vieux, N., & Laporte, A. (1980). Oral temperature, circadian rhythm amplitude, ageing and tolerance to shift-work. *Ergonomics*, *23*, 55–64. https://doi.org/10.1080/00140138008924718

Salo, P. K., Ylinen, J. J., Mälkiä, E. A., Kautiainen, H., & Häkkinen, A. H. (2006). Isometric strength of the cervical flexor, extensor, and rotator muscles in 220 healthy females aged 20 to 59 years. *Journal of Orthopaedic & Sports Physical Therapy*, *36*, 495–502. https://doi.org/10.2519/jospt.2006.2122

Simoneau, J. A., & Bouchard, C. (1989). Human variation in skeletal muscle fiber-type proportion and enzyme activities. *American Journal of Physiology-Endocrinology and Metabolism*, *257*, E567–E572. https://doi.org/10.1152/ajpendo.1989.257.4.E567

Uhlig, Y., Weber, B. R., Grob, D., & Müntener, M. (1995). Fiber composition and fiber transformations in neck muscles of patients with dysfunction of the cervical spine. *Journal of Orthopaedic Research*, *13*, 240–249. https://doi.org/10.1002/jor.1100130212

Vasavada, A. N., Li, S., & Delp, S. L. (1998). Influence of muscle morphometry and moment arms on the moment-generating capacity of human neck muscles. *Spine*, *23*, 412–422. https://doi.org/10.1097/00007632-199802150-00002

Vasavada, A. N., Li, S., & Delp, S. L. (2001). Three-dimensional isometric strength of neck muscles in humans. *Spine*, *26*, 1904–1909. https://doi.org/10.1097/00007632-200109010-00018

Vasavada, A. N., Peterson, B. W., & Delp, S. L. (2002). Three-Dimensional spatial tuning of neck muscle activation in humans. *Experimental Brain Research*, *147*, 437–448. https://doi.org/10.1007/s00221-002-1275-6

Wilson, J. M., Loenneke, J. P., Jo, E., Wilson, G. J., Zourdos, M. C., & Kim, J.-S. (2012). The effects of endurance, strength, and power training on muscle fiber type shifting. *Journal of Strength and Conditioning Research*, *26*, 1724–1729. https://doi.org/10.1519/JSC.0b013e318234eb6f

Suman K. Chowdhury is an assistant professor in the Department of Industrial, Manufacturing and Systems Engineering at Texas Tech University, USA. He obtained his PhD in industrial engineering from West Virginia University in 2016.

Yu Zhou is a PhD student in the Department of Industrial & Systems Engineering at Texas A&M University, USA. He received his MS in mechanical engineering from University of Pittsburgh in 2017.

Bocheng Wan is an MS student in the Department of Industrial & Systems Engineering at Texas A&M University, USA. He received his BS in mechanical engineering from Beijing Institute of Technology in 2017 and was an exchange student at University of California at Berkeley from 2016 to 2017.

Curran Reddy is an MD/PhD student at Texas A&M University, USA. He received his BA from Cornell University in 2013.

Xudong Zhang is a professor in the Department of Industrial & Systems Engineering at Texas A&M University, USA. He received his PhD in industrial and operations engineering from University of Michigan in 1997.

Date received: December 31, 2019
Date accepted: December 1, 2020