6-19-2019

Shoulder Muscular Fatigue From Static Posture Concurrently Reduces Cognitive Attentional Resources

Mitchell L. Stephenson
Iowa State University, mistephe@iastate.edu

Alec G. Ostrander
Iowa State University, alecglen@iastate.edu

Hamid Norasi
Iowa State University, norasi@iastate.edu

Michael C. Dorneich
Iowa State University, dorneich@iastate.edu

Shoulder Muscular Fatigue From Static Posture Concurrently Reduces Cognitive Attentional Resources

Abstract

Objective: The goal of this work is to determine whether muscular fatigue concurrently reduces cognitive attentional resources in technical tasks for healthy adults.

Background: Muscular fatigue is common in the workplace but often dissociated with cognitive performance. A corpus of literature demonstrates a link between muscular fatigue and cognitive function, but few investigations demonstrate that the instigation of the former degrades the latter in a way that may affect technical task completion. For example, laparoscopic surgery increases muscular fatigue, which may risk attentional capacity reduction and undermine surgical outcomes.

Method: A total of 26 healthy participants completed a dual-task cognitive assessment of attentional resources while concurrently statically fatiguing their shoulder musculature until volitional failure, in a similar loading pattern observed in laparoscopic procedures. Continuous and discrete monitoring task performance was recorded to reflect attentional resources.

Results: Electromyography of the anterior deltoid and descending trapezius, as well as self-assessment surveys indicated fatigue occurrence; continuous tracking error, tracking velocity, and response time significantly increased with muscular fatigue.

Conclusion: Muscular fatigue concurrently degrades cognitive attentional resources.

Application: Complex tasks that rely on muscular and cognitive performance should consider interventions to reduce muscular fatigue to also preserve cognitive performance.

Keywords

peripheral fatigue, cognitive performance, electromyography, laparoscopy

Disciplines

Ergonomics | Human Factors Psychology | Industrial Engineering | Systems Engineering

Comments

This is a manuscript of an article published as Stephenson, Mitchell L., Alec G. Ostrander, Hamid Norasi, and Michael C. Dorneich. "Shoulder muscular fatigue from static posture concurrently reduces cognitive attentional resources." *Human Factors* (2019). DOI: 10.1177%2F0018720819852509. Posted with permission.

Stephenson, M.L., Ostrander, A.G., Norasi, H., & Dorneich, M.C. (2019). "Shoulder Muscular Fatigue Concurrently Reduces Cognitive Attentional Resources," Human Factors. http://dx.doi.org/10.1177/0018720819852509.

Shoulder muscular fatigue from static posture concurrently reduces cognitive attentional resources

Mitchell L. Stephenson[1], Alec G. Ostrander, Hamid Norasi, and Michael C. Dorneich

Iowa State University, Ames, Iowa, USA

Abstract

Objective: The goal of this work was to determine if muscular fatigue concurrently reduces cognitive attentional resources in technical tasks for healthy adults. **Background:** Muscular fatigue is common in the workplace, but often dissociated with cognitive performance. A corpus of literature demonstrates a link between muscular fatigue and cognitive function, but few investigations demonstrate if the instigation of the former degrades the latter in a way that may affect technical task completion. For example, laparoscopic surgery increases muscular fatigue, which may risk attentional capacity reduction and undermine surgical outcomes. **Methods:** Twenty-six healthy participants completed a dual task cognitive assessment of attentional resources while concurrently statically fatiguing their shoulder musculature until volitional failure, in a similar loading pattern observed in laparoscopic procedures. Continuous and discrete monitoring task performance was recorded to reflect attentional resources. **Results:** Electromyography of the anterior deltoid and descending trapezius, as well as self-assessment surveys indicated fatigue occurred; continuous tracking error, tracking velocity, and response time significantly increased with muscular fatigue. **Conclusion:** Muscular fatigue concurrently degrades cognitive attentional resources. **Application:** Complex tasks that rely on muscular and cognitive performance should consider interventions to reduce muscular fatigue to also preserve cognitive performance.

Keywords: peripheral fatigue, cognitive performance, electromyography, laparoscopy

[1] Address correspondence to Mitchell L. Stephenson, Department of Kinesiology, Iowa State University, 534 Wallace Road, Ames, Iowa, 50011, USA; email: mitch@biomch.net

Introduction

Physical task performance degradation and failure is often associated with muscular fatigue. Muscular fatigue is commonly experienced and has been the subject of academic investigation for more than a century (Giulio, Daniele, & Tipton, 2006). Muscular fatigue has been defined as the "inability of a muscle or group of muscles to sustain the required or expected force" (Bigland-Ritchie, Jones, Hosking, & Edwards, 1978). Despite this straightforward definition, the neurophysiological underpinnings to this effect are nuanced and complex (Enoka & Duchateau, 2008). While it is common to expect that fatigue is primarily due to physiological deficits and effects, strong evidence indicates a central, cognitive role in muscular fatigue as well (Bigland-Ritchie et al., 1978; Bigland-Ritchie & Woods, 1984; Davis, 1995; Enoka & Duchateau, 2008). For example, Bigland-Ritchie & Woods (1984) identified significant reductions of voluntary force in sustained isometric exertions that exceeded tetanic estimations, concluding the discrepancy was due to cognitive fatigue.

The precise separation of cognitive and muscular components of fatigue is difficult, as both play a significant role in observable performance decline in sustained fatiguing submaximal contractions (Davis, 1995; Gandevia, 2001). Physical performance degradation, such as hand tremor due to muscular fatigue, is a result of increased force output variability from shifts in recruitment of small to large motor units. Mitigating this variability requires larger cognitive control (Temprado, Vieluf, Bricot, Berton, & Sleimen-Malkoun, 2015). Concerningly, evidence indicates this is not a unilateral effect, and the influences of muscular and cognitive fatigue may be interactive (Lorist, Kernell, Meijman, & Zijdewind, 2002).

This generalized interaction between muscular fatigue and cognitive performance is also relatively nuanced. It does not appear that aerobic or anaerobic metabolic fatigue implemented on a treadmill affects visual perception performance (Bard & Fleury, 1978; Fleury, Bard, Jobin, & Carrière, 1981) unless dehydration occurs (Cian, Barraud, Melin, & Raphel, 2001). But high-intensity aerobic metabolic fatigue does appear to negatively affect reaction time (Féry, Ferry, Hofe, & Rieu, 1997). In contrast to these metabolic studies, targeted lower extremity muscular fatigue has created mixed effects on attentional resources (Bisson, McEwen, Lajoie, & Bilodeau, 2011; Porchet et al., 2002; Simoneau, Bégin, & Teasdale, 2006; Vuillerme, Forestier, & Nougier, 2002). This ambiguity may be because the instigated muscular fatigue in these studies targeted the musculature in the lower extremity while simultaneously using the same musculature to perform the cognitive assessments associated with posture and balance (Corbeil, Blouin, Bégin, Nougier, & Teasdale, 2003).

Past research has identified that acute, moderate physical exertion can actually cause *increases* in cognitive performance (Chang, Labban, Gapin, & Etnier, 2012) in some contexts, but these studies did not investigate the specific effects of muscular fatigue. The inverted-U principal accords that increases in arousal associated with moderate physical activity from rest increases cognitive performance, but further increases in arousal due to strenuous (and potentially fatiguing) exercise may subsequently decrease cognitive performance (Arent & Landers, 2003; Chmura, Nazar, & Kaciuba-Uścilko, 1994; Hebb, 1955; Simoneau et al., 2006). Accordingly, the beneficial effects of moderate physical activity are expected to be mitigated and eliminated once the exercise becomes fatiguing. More recent investigations indicate cognitive performance may decline lower than baseline in muscular fatigue conditions (Duncan, Smith, & Lyons, 2013; Smith et al., 2016).

Cognitive fatigue has been associated with declines in physical performance as well. Sustained cognitive demand, leading to mental fatigue, has been linked with declines in aerobic endurance and ratings of perceived exertion (Marcora, Staiano, & Manning, 2009), as well as gait parameter variability (Szturm et al., 2013). Increases in cognitive demand have been firmly associated with increased muscle activity in postural and task-related muscles (Leyman, Mirka, Kaber, & Sommerich, 2004; Roman-Liu, Grabarek, Bartuzi, & Choromański, 2013) including the shoulder musculature (Mehta & Agnew, 2012), and increased heart rate (Lundberg et al., 2002). Evidence also indicates that cognitive fatigue may induce increased muscle activity in musculature unrelated to the performed task (Wærsted & Westgaard, 1996). In combination, a cognitively- and physically-demanding task may promote accelerated cognitive and muscular fatigue via these interacting effects.

For example, the success of a medical surgical procedure is in part dependent on the physical performance of the surgical team. Degradation in that performance from complications such as the surgeon's fatigue during the operation should be avoided (Fargen, Turner, & Spiotta, 2016). The paradigmatic shift towards laparoscopic and endoscopic surgical techniques has been labeled an "impending epidemic" due to the significant increases in surgeon physical demand and fatigue (Park, Lee, Seagull, Meenaghan, & Dexter, 2010). While laparoscopic surgical techniques allow the surgeon to maintain a more upright position than in open surgeries, these techniques also limit the surgeon's capability to shift postural position (Berguer, Chen, & Smith, 2003; Kant, DeJong, Van Rijssen-Moll, & Borm, 1992; Nguyen et al., 2001; Szeto et al., 2012). These awkward static postures and associated with laparoscopic and endoscopic procedures place the surgeon at increased risk of physical demand and ergonomic discomfort that likely increases muscular fatigue, particularly in the neck and shoulder (Berguer et al., 2003; Choi, 2012; Park et al., 2010). Laparoscopic procedures increase surgeon shoulder muscle fatigue and hand tremor (Panahi & Cho, 2016; Quick et al., 2003; Slack & Ma, 2007; Uhrich, Underwood, Standeven, Soper, & Engsberg, 2002). Beyond potentially compromising the physical efficacy of the surgeon, this fatigue and associated tremor may indicate involvement of cognitive mechanisms as well.

Past literature considered the impacts of surgeon's muscular fatigue on their physical performance (Fargen et al., 2016) and sleep deprivation effects on surgeons' physical and cognitive performance (Landrigan et al., 2004; Lehmann et al., 2010; Lockley et al., 2004). However, little is known about the impacts of muscular fatigue on concurrent cognitive performance without the confound of concurrent cognitive fatigue. Acute cognitive performance degradation that affects attentional resources and temporal aspects of decision-making may have quite negative consequences on surgical performance and patient outcomes (Choi, 2012; Pugh, Santacaterina, DaRosa, & Clark, 2011). If the muscular fatigue associated with the surgical task negatively affects the cognitive performance inherent to the task's success (such as the physical demands of laparoscopic procedures degrading the performance of the surgeon), the efficacy of the task and safety of the patient may be at risk.

Based on support from these findings, the current study was implemented to test the hypothesis that muscular fatigue from static contractions (without parallel cognitive fatigue) causes a decline in cognitive performance. In application, the current study utilized a physical task that targeted musculature fatigued during laparoscopic procedures (Quick et al., 2003; Szeto et al., 2012) and a cognitive assessment that assessed surgically-relevant cognitive domains (Pugh et al., 2011). The methodological strategy used was designed to contrast dual-task cognitive performance in a non-fatigued and fatigued state. As reviewed above, some literature suggests that physical, muscular fatigue can lead to declines in cognitive performance. As such, we expected to observe a reduction in attentional capacity and choice response time in response to muscular fatigue.

Methods

Participants

Moderate effect sizes from previous research (Bisson et al., 2011; Quick et al., 2003; Simoneau et al., 2006; Vuillerme et al., 2002) indicated a conservative requisite minimum sample size of 25 participants was necessary to maintain a minimum statistical power of 80%. Twenty-six healthy adults (14 female; average ± standard error: 26 ± 1.3 years; 1.70 ± 0.02 m tall; 71 ± 2.6 kg) aged 18 to 52 years provided written informed consent to participate in the data collection procedure. To participate, volunteers were required to be healthy (without musculoskeletal injury, surgical intervention, postural/balance control issues, or fatigue) and physically active (participating in at least 150 minutes of moderate, or 75 minutes of vigorous physical activity per week). Health and injury questionnaires were used to assess these criteria. This investigation was approved by Iowa State University's Institutional Review Board and complies with the American Psychological Association Code of Ethics.

Tasks

A physical task (Figure 1) and cognitive assessment were utilized. The physical task consisted of the participants standing with an upright posture, feet roughly shoulder-width apart. In order to engage the anterior deltoid and descending trapezius musculature (Quick et al, 2003), participants maintained a static shoulder flexion angle of 70-90°, with wrists pronated and elbows extended. This posture was specifically chosen to reflect key components of the previously-identified challenges to laparoscopic surgeons, notably an upright trunk position (Berguer et al., 2003; Kant et al., 1992; Nguyen et al., 2001) with static shoulder musculature load (Choi, 2012; Quick et al., 2003; Szeto et al., 2012) that mitigates choice postural adjustments (Berguer et al., 2003; Kant et al., 1992; Szeto et al., 2012). To aggravate muscular fatigue in these muscles within a reasonable time and simulate potential laparoscopic tool load, 5 N weights were strapped to each wrist. Participants were asked to hold this static position for as long as possible (until volitional failure).

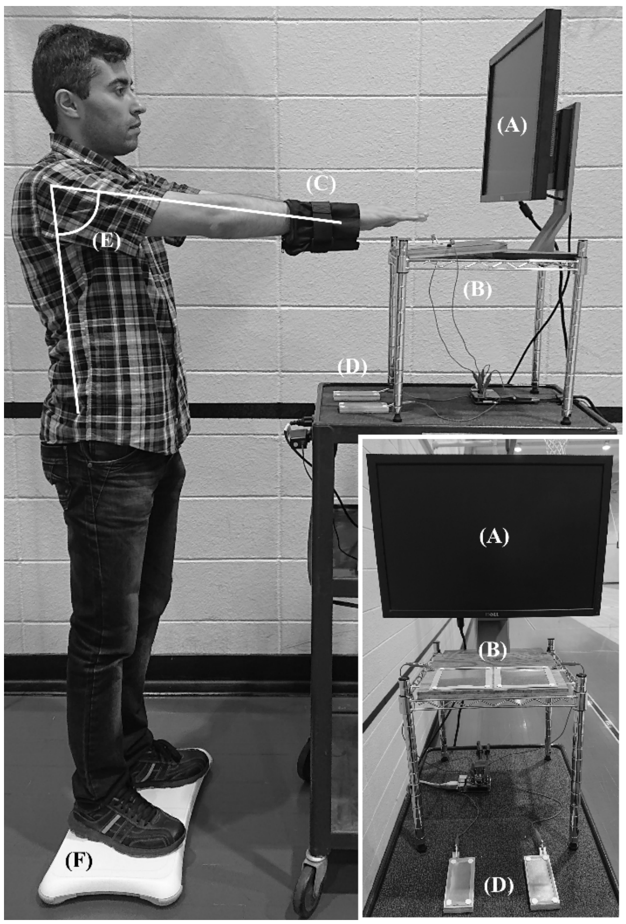

Figure 1: Experimental setup: A) Monitor screen, B) Primary touch pads C) 5N wrist weights, D) Secondary touch pads, E) Shoulder flexion angle, F) Instrumented balance board.

The cognitive assessment used a dual-task methodology, which assumes attentional capacity is a limited resource rationed between the two concurrent tasks (Huang & Mercer, 2001; Wickens, 2008). Often used to measure differences in attentional demand between tasks, substantial literature also employed dual-task paradigms to assess changes in attentional capacity while the tasks were held constant (Cicerone, 1996; Strayer & Johnston, 2001; Wright & Kemp, 1992). This strategy affords the flexibility to design assessments not physiologically connected to the physical task, thereby isolating performance changes to changes in attentional capacity.

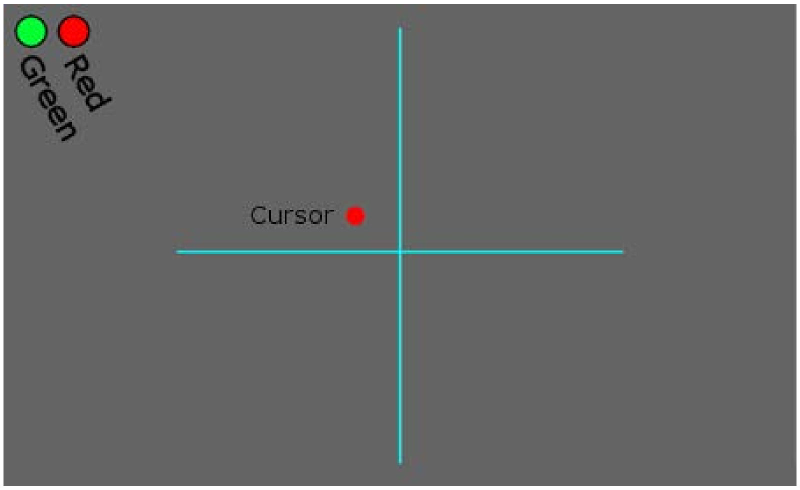

Figure 2: Computer display of cognitive assessment. Note the red and green indicators in top-left of display, as well as red indicator representing center of pressure in relation to blue target.

The two tasks chosen for assessment were adapted from the tracking and system monitoring task of the Revised Multi-Attribute Task Battery (MATB-II; Santiago-Espada, Myer, Latorella, & Comstock, 2011). A custom script implementing these two tasks operated on a Raspberry Pi and displayed on a computer monitor in front of the participant (Figure 2). Participants stood on a strain gauge-instrumented balance board that measured their center of pressure (COP). This was displayed on a computer monitor, superimposed on an anterior/posterior and medial/lateral reference with a target center location. Participants adjusted their stance such that the COP remained about the target center. A random digital drift was implemented on the COP display; the participant was prompted to keep the COP display at the target center by adjusting their COP through slight postural sway (Simoneau et al., 2006). The speed and amplitude of the drift was refined through pilot testing to be only moderately challenging but require sustained attention.

In parallel to the COP display, red and green indicators were displayed on the edge of the computer monitor. Participants were asked to keep the green indicator active; it uniformly randomly deactivated every 5-15 seconds and required a button press to reactivate. Similarly, the red indicator uniformly randomly activated; participants were asked to press a different button to deactivate. Capacitive touch pads that required only contact and no force to actuate were placed directly under each of the participant's hands such that only finger movements were required to activate; the position of these buttons was customized for each participant. The buttons were spatially mapped and the borders were color coded to match their function with the corresponding indicator.

Independent Variables

The independent variable for the current study was the relative muscular fatigue state of the participant at the start of the sustained trial (*non-fatigued*) and the end of the trial (*fatigued*). Dependent measures were compared between the non-fatigued and successively fatigued state.

Dependent Variables

Table 1 lists the dependent variables of the study. Muscular fatigue instigated via the physical task in the sustained trial was verified via mean amplitude and median frequency shift of electromyographic signals of the anterior deltoid and descending trapezius (Hagberg, 1981; Quick et al., 2003). Dependent measures of attentional resources, captured via a dual-task cognitive assessment, included error in a continuous tracking task and concurrent, intermittent choice response time. In addition to comparisons in non-fatigued and fatigued states, dependent measures were also compared in a baseline and post-performance trial occurring before and after the sustained task, respectively. These trials did not include the physical task and were used to confirm that cognitive fatigue did not occur and potentially compound identified effects.

Muscular fatigue was measured vis the amplitude and frequency of the anterior deltoid and descending trapezius muscles. All electromyographic data were captured at 2000Hz and filtered through a zero-lag 4th order Butterworth bandpass filter at 10-450 Hz. Filtered signals were rectified and smoothed via a root mean square with a 50ms mobile window. Five-second maximum voluntary isometric contraction (MVIC) data collected after the trial were further smoothed via a root mean square with a one second mobile window; the peak amplitudes per channel from these smoothed data were extracted; all dynamic electromyographic data were normalized to these values per participant. Median frequency of each muscle was calculated in each of these windows via Welch's power spectral density analysis.

Perceived fatigue was measured via a survey instrument (Borg, 1982) that asked participants to concurrently assess their own rating of perceived exertion (RPE) every 30 seconds during the trial. *Perceived workload* was assessed via the raw score of the overall NASA Task Load Index survey (NASA TLX; Hart & Staveland, 1988).

Table 1. Dependent variable metrics, units, and sampling/query frequency during data collection procedure.

Dependent Variable	Metric	Units	Frequency
Muscular fatigue	Anterior deltoid peak amplitude	% MVIC	During sustained trial (2000 Hz)
	Anterior deltoid median frequency	Hz	During sustained trial (2000 Hz)
	Descending trapezius peak amplitude	% MVIC	During sustained trial (2000 Hz)
	Descending trapezius median frequency	Hz	During sustained trial (2000 Hz)
Perceived Fatigue & Workload	Perceived exertion	Scale 1-10	Every 30s during sustained trial
	NASA TLX	0-100	Before and after sustained trial

Attentional resources	Tracking Error	% area	During baseline, sustained, and post-performance trials (60 Hz)
	Tracking Velocity	10^{-3} %·s^{-1}	During baseline, sustained, and post-performance trials (60 Hz)
	Response Time	ms	Every 5-15s in baseline, sustained, and post-performance trials

Cognitive Performance (attention) was measured through the performance of the two concurrent tasks: tracking and monitoring. Response times between the red and green indicator presentations and the associated button presses were calculated. For the tracking task, the distance of the displayed COP location from the target center, sampled at 60Hz, were normalized as orthogonal percentages of the displayed area, and then simplified as a resultant distance from the center. COP velocity was then calculated from this resultant distance as an analog to error correction. Erroneous choice button presses were also identified, but too infrequent to analyze.

We hypothesized that mean error and velocity in the tracking task, and response time in the system monitoring task, would increase from the non-fatigued condition to the fatigued. To confirm muscular fatigue during the sustained trial, mean electromyographic amplitude was expected to increase and median frequency to decrease with fatigue. Similarly, RPE and TLX scores were expected to increase with fatigue. To confirm a lack of cognitive fatigue, tracking task error and response time were not expected increase from the baseline to the post-performance trial.

Procedure

Participants followed a standardized protocol during the data collection (Figure 3). After providing informed consent and completing the health and injury questionnaire, they then completed a standardized warmup consisting of a five-minute light jog on the treadmill and a series of dynamic stretches. Anthropometry was recorded. Participants were then formally introduced to the cognitive assessment, practicing each component independently until they were comfortable, and then in combination; all participants were required to perform a minimum of two minutes of combined practice. Participants then performed a two-minute baseline trial. This trial consisted of the cognitive assessment without the physical task: Participants used a second set of buttons located at approximately waist-height and did not wear the 5 N wrist weights. After the baseline trial, participants completed the NASA TLX survey.

After the baseline trial and survey, wireless surface electromyography electrodes were placed on the dominant-side anterior deltoid and descending trapezius; electrodes were anatomically-placed by the same, trained researcher following objective guidance (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Participants donned the wrist weights, positioned

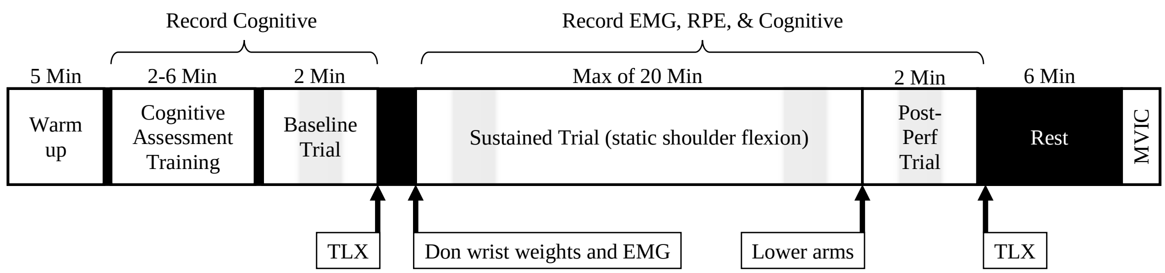

Figure 3: Data collection procedures timeline. Rest and transitions in black. Data for analysis shaded gray.

themselves on the instrumented board, and held the static position of the physical task. Participants attempted to perform this sustained trial for as long as possible (until volitional failure), or until 20 minutes had elapsed. At 30 second intervals an audio tone sounded, prompting the participant to verbalize their RPE on a scale from one to ten (Day, McGuigan, Brice, & Foster, 2004).

Once the participant could not maintain the static posture of the physical task, they lowered their hands to waist-level and continued to perform the cognitive assessment for two more minutes, using the second set of buttons from the baseline trial. RPE prompts continued through this post-performance trial every 30 seconds. After two minutes elapsed, participants stopped the cognitive assessment and completed a second NASA TLX survey, as well as a post-experiment questionnaire. A five-second MVIC was then recorded after at least 6 minutes of rest after the completion of the cognitive assessment.

Data Analysis

Pilot data indicated transient noise in the cognitive assessment data at initiation and termination of the tasks. As such, the average from the middle one-minute window from the baseline and post-performance trials, as well as the average from a one-minute window 30 seconds after the beginning and 30 seconds before the end of the sustained trial were calculated. Averages of the electromyographic amplitudes, the median frequency of each muscle, TLX scores, and RPE at the beginning and end of the sustained trial were statistically compared via pairwise t-tests after pairwise differences normality was confirmed with the Shapiro-Wilk's test.

Averages of the COP distance from target (tracking error), COP velocity, and indicator-button response time were compared between the beginning and end of the sustained trial, as well as between the baseline and post-performance trials. Shapiro-Wilks tests were again used to verify normality, and subsequent pairwise t-tests were used for statistical comparisons. Type I error was maintained at 5% or less. Pairwise standardized effect sizes (δ) were calculated for all comparisons (Dunlap, Cortina, Vaslow, & Burke, 1996). Standard interpretive targets of 0.2, 0.5 and 0.8 for small, medium, and large effect sizes, respectively, were employed (Cohen, 1977).

Results

Muscular Fatigue, Perceived Exertion, & Workload

The sustained trial consisted of a physical task designed to induce fatigue in the anterior deltoid and descending trapezius muscles. Participants were instructed to only stop performing the sustained trial once they reached volitional failure, under the assumption that trial failure was due to muscular fatigue in these muscles. Participants lasted an average (± standard deviation) of 6.9 ± 3.0 minutes; no participants reached the 20-minute cutoff. A functional validation of this fatigue can be performed by comparing mean electromyographic amplitude and median frequency. Fatigue should be demonstrated by increased mean amplitude and decreased median frequency.

Table 2: Mean and standard deviation (SD) of electromyographic data, rating of perceived exertion (RPE), and NASA task load index (TLX), at the start and end of the sustained trial. Mean differences and the associated 95% confidence intervals (CI) as well as paired t-test p-values and effect sizes.

	Trial Start		Trial End		Difference				
	Mean	SD	Mean	SD	Mean	95% CI Lower	95% CI Upper	*p*	Effect Size (δ)
Anterior Deltoid									
Amplitude (% MVIC)	22.1	13.2	25.6	15.3	3.4	0.02	6.66	0.037	0.23
Frequency (Hz)	80.0	16.8	71.7	18.6	-8.3	-4.4	-12.2	<0.001	0.46
Descending Trapezius									
Amplitude (% MVIC)	13.8	10.2	16.7	10.3	2.9	0.50	5.31	0.020	0.28
Frequency (Hz)	67.1	20.4	66.9	12.0	-0.2	-5.2	5.6	0.934	0.01
RPE (1-10)	2.5	1.4	8.4	1.4	6.0	5.3	6.6	<0.001	4.28
NASA TLX (0-100)	34	15	60	13	26	22	29	<0.001	1.81

As seen in Table 2 and Figure 4, the deltoid anterior and descending trapezius mean amplitude significantly increased from the beginning to the end of the trial. Muscular median frequency demonstrated mixed results (Figure 5). Anterior deltoid median frequency significantly decreased by an average of 8.3 Hz. In contrast, the descending trapezius did not significantly change across the trial. Rating of perceived exertion also significantly increased as the trial progressed. Both the RPE and TLX assessments significantly increased from the trial start to the end (Figure 6). Taken as a whole, these results provide evidence of physical fatigue occurring over the sustained trial.

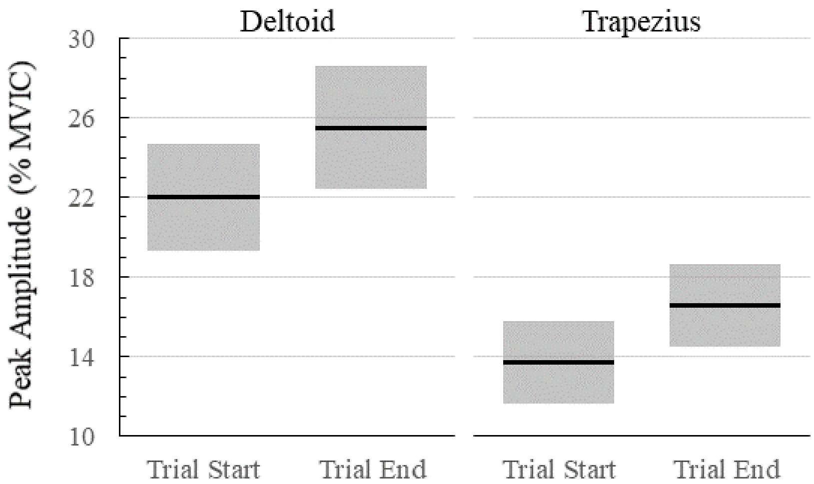

Figure 4: Peak amplitude of deltoid anterior and descending trapezius muscles at the start and end of the sustained trial. Means marked as black lines with 95% confidence intervals in gray.

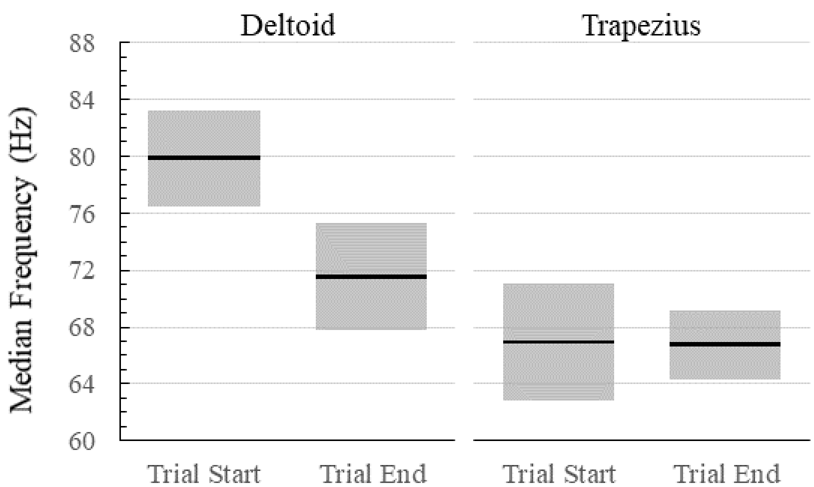

Figure 5: Median frequency of deltoid anterior and descending trapezius muscles at the start and end of the sustained trial. Means marked as black lines with 95% confidence intervals in gray.

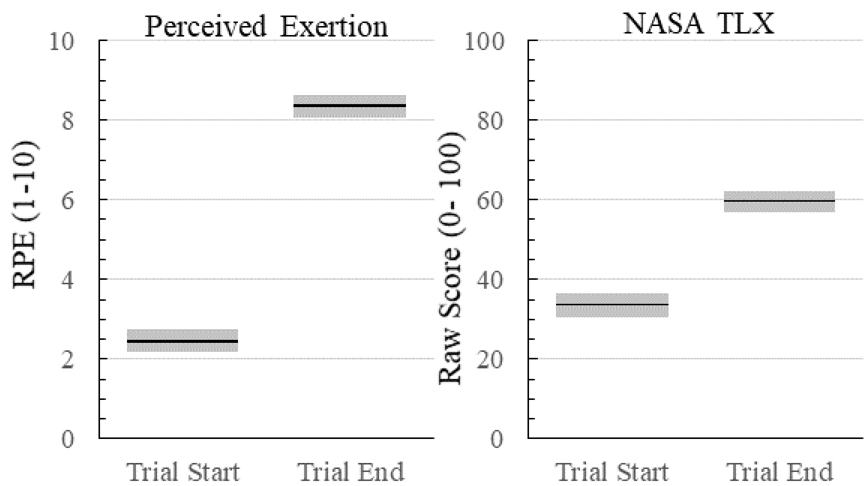

Figure 6: Rating of perceived exertion (RPE; 1-10 scale) and NASA TLX raw score at the start and end of the sustained trial. Means marked as black lines with 90% confidence intervals in gray.

Cognitive Performance

This study was implemented to determine if performance on the two, concurrent cognitive tasks worsened due to the physical fatigue experienced in the sustained task. This would be reflected in an increase in tracking error, tracking velocity, and response time. Tracking error significantly increased 1.7% of the possible range from the beginning of the trial to the end. Similarly, tracking velocity also significantly increased. Response time at the beginning of the sustained trials significantly increased 37 milliseconds from the start to the end of the trial as well. Detailed results are presented in Table 3 and Figure 7. These results indicate a reduction of cognitive performance.

Table 3: Mean and standard deviation (SD) of tracking variables, and response time at the start and end of the sustained trial. Mean differences and the associated 95% confidence intervals (CI) as well as paired t-test p-values and effect sizes presented.

	Trial Start		Trial End		Difference				
	Mean	SD	Mean	SD	Mean	95% CI Lower	95% CI Upper	*p*	Effect Size (δ)
Tracking									
Error (%)	13.8	2.6	15.4	3.1	1.7	0.8	2.5	<0.001	0.56
Velocity (10^{-3} %·s^{-1})	4.80	0.65	6.47	2.20	1.67	0.92	2.43	<0.001	0.79
Response Time (ms)	586	102	620	113	35	7	63	0.018	0.42

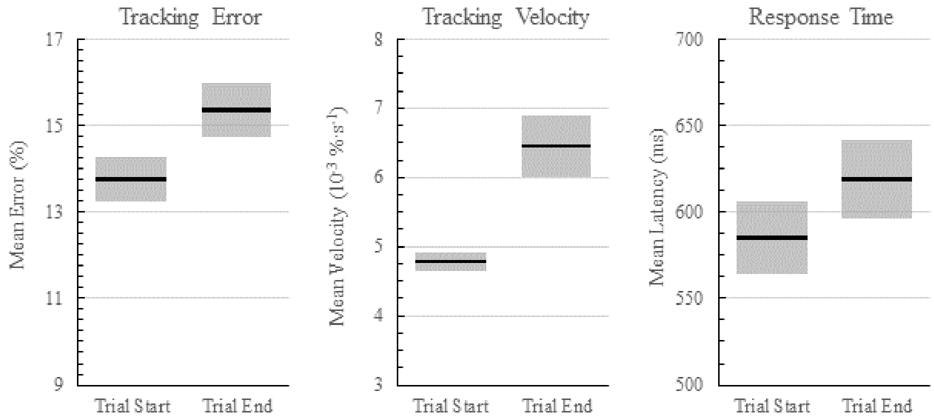

Figure 7: Mean error and velocity of the tracking task and mean response time of the monitoring task at the start and end of the sustained trial. Means marked as black lines with 95% confidence intervals in gray.

<u>Cognitive Fatigue</u>

There is a possibility that cognitive fatigue may also parallel the physical; separation of these two effects on cognitive performance may be difficult. If cognitive fatigue did occur, a decrement in cognitive performance is likely to exist after the sustained trail was completed. In order to determine if this was the case, comparisons of the baseline trial (without the physical task) to the post-performance trial (after the sustained trial, also without the physical task) were performed.

Table 4: Mean and standard deviation (SD) of tracking variables, and response time at the baseline and post-performance trials. Mean differences and the associated 95% confidence intervals (CI) as well as paired t-test p- values and effect sizes

	Baseline		Post-Perf		Difference				
	Mean	SD	Mean	SD	Mean	95% CI Lower	95% CI Upper	*p*	Effect Size (δ)
Tracking									
Error (%)	10.4	2.5	10.0	2.6	-0.3	-1.2	0.6	0.442	0.13
Velocity (10^{-3} %·s^{-1})	3.66	1.26	3.81	1.69	0.15	-0.53	0.83	0.651	0.10
Response Time (ms)	528	60	593	83	65	43	88	<0.001	0.85

Mean tracking error did not significantly differ between the baseline and post-performance trials; mean tracking velocity also did not significantly differ (Table 4 and Figure 8). In contrast, response time significantly increased an average of 65 milliseconds, indicative of a possible decrease in performance. Comprehensively, these results are indeterminant whether cognitive fatigue occurred.

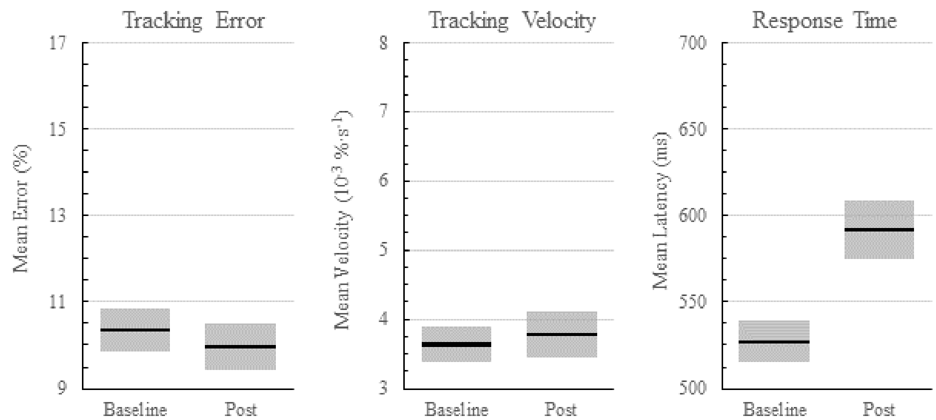

Figure 8: Mean error and velocity of the tracking task and mean response time of the monitoring task in the baseline and post-performance trials. Means marked as black lines with 95% confidence intervals in gray.

Discussion

We investigated the possible effect of muscular fatigue from static contractions on cognitive performance, specifically attentional resource capacity. The electromyographic amplitude and median frequency data demonstrated that anterior deltoid muscular fatigue was induced in all participants (Hagberg, 1981), and this was confirmed by the participants' perceptions report of rating of perceived exertion and workload. Comparing the results of the cognitive assessment in the baseline and post-performance trials is inconclusive as to whether cognitive fatigue occurred during the dual-task assessment; it is possible that participants inadequately recovered physically in 30 seconds before the post-performance trial data was selected for analysis. The assessment data indicated there were moderate decrements in performance between the beginning and end of the trial for all measures from the cognitive assessment. While individual measures could have varied as the participant chose to focus on one task or the other, the dual-task model does not account for the decline of both concurrently (Huang

& Mercer, 2001). Considering the measures jointly, these results indicate a general reduction in available attentional resources.

Based on the results of this experiment, there is evidence to suggest that muscular fatigue from static contractions, such that can occur in surgeons during laparoscopic procedures (Choi, 2012; Quick et al., 2003; Szeto et al., 2012), has a negative effect on attentional resource capacity. An explanation for this finding is that muscular fatigue may directly affect the amount of focus required to maintain the static posture. As the trial progressed and the shoulder became fatigued, participants had to reallocate attentional resources towards holding their arms in the required position, so fewer resources were available to attend to the cognitive task. Statements gathered from the post-experiment questionnaire provide further support for this explanation. The results are consistent with common models of attentional resources (Hirst & Kalmar, 1987; Wickens, 2008).

Previous research investigating this paradigm in the lower extremity has identified mixed results. Similar to our findings, one past investigation identified increases in center of pressure target tracking error and correction velocity, as well as 10^{th} percentile reaction time as the participants progressed to moderate fatigue from fast walking (Simoneau et al., 2006). Further research concluded that steady postural balance demanded increased attentional resources when the lower leg musculature was fatigued as well (Vuillerme et al., 2002). In contrast, another investigation did not identify significant changes in reaction time or COP velocity after a fatiguing bout (Bisson et al., 2011); the authors posit that their contrasting results may be due to a dynamic instead of isometric fatigue protocol that is found in the current and previous research (Vuillerme et al., 2002).

The combination of these previous works and the current research suggests that muscular fatigue from static postures negatively impacts attentional resources in both the lower extremity and the shoulder musculature. This bodes the question whether the attentional resource decline is independent of the muscular fatigue location. The physical demands previously identified for laparoscopic surgeons (Berguer et al., 2003; Panahi & Cho, 2016; Quick et al., 2003; Szeto et al., 2012) may have more far-reaching repercussions than previously heralded (Park et al., 2010); the current research demonstrates that the fatigue expected in the shoulder musculature may undermine the attentional resources and temporal decision-making necessary for procedural success (Goodell, Cao, & Schwaitzberg, 2006; Pugh et al., 2011). It is therefore doubly important that surgeons (and other workers that perform physically-fatiguing tasks that also demand attentional resources) attempt to mitigate this fatigue through job task manipulation (Raina & Dickerson, 2009), work breaks (Dorion & Darveau, 2013; Sundelin & Hegberg, 1989), or augmentation (Gillette & Stephenson, 2018) whenever possible (Bourne, Walcott, Sheth, & Coumans, 2013). Given that physical fatigue affects younger individuals more than older (Hunter, Critchlow, & Enoka, 2005), this may be of particular concern to younger laparoscopic surgeons.

Limitations

This investigation sought to explore the relationship between physical fatigue and cognitive attentional resources via a physical task generally contextualized to laparoscopic surgical procedures. As such, static shoulder muscular contractions were chosen, as this static load has been repeatedly identified as a physical challenge to laparoscopic surgeons (Berguer et al., 2003; Szeto et al., 2012). Some evidence also suggests that unusual or awkward movements may also be common in laparoscopic procedures (Nguyen et al., 2001). These movements may interrupt the static contractions this current investigation associated with declines in cognitive attentional resources, to unknown effect. Previous research demonstrated, however, that only self-selected rotations between static and dynamic work may reduce fatigue rate (Luger, Bosch, Hoozemans, Veeger, & Looze, 2016). It is advised to investigate the effects of static *and* dynamic muscular fatigue on cognitive resources; it may not be appropriate to generalize the results of the current investigation to more complex tasks, including dynamic surgical procedures.

This study made use of the dual-task paradigm to study the attentional resources of the participants. Generally, a dual-task experiment designates one task as the primary task and the other as secondary. The participant is instructed to maintain a certain level of performance on the primary task, so only the performance of the secondary task need be evaluated. Inherent to this methodology is the concern that participants might choose to attend more to the secondary task or switch between the tasks at different points in the trial. The attentional resources then cannot be evaluated accurately. Instead, the researchers chose not to designate a primary and secondary task; participants were free to allocate resources as they pleased. While this may have led to the effects of the muscular fatigue being split unevenly between the tracking and button response tasks for each participant, the significant results in all of the cognitive assessment measures alleviates concern during the sustained trial. However, this flexible prioritization effect may be demonstrated in the comparison of the cognitive performance in the post-performance trial.

Conclusion

This research establishes a link between muscular fatigue from static postures and the degradation in attentional resources. It is worth noting that other aspects of cognition may also be affected. It is suggested to investigate the effects of muscular fatigue on decision-making, working memory, long-term memory, and information processing. Research can be performed using methods similar to the current investigation, with assessments designed to measure the corresponding aspects of cognitive performance. As was done in this study, extra care should be taken to ensure the physical task and cognitive assessment are physiologically isolated from each other to avoid confounding effects.

The findings in this paper have important implications for occupations that involve complex physical work with little room for error that demand static postures, including surgeons as well as technicians, astronauts, and industrial workers, to name a few. Considering the negative consequences for not only physical performance, but cognitive performance as well, designers of equipment and processes in these occupations should take special care to avoid or mitigate muscular fatigue from static contractions.

Acknowledgments

The authors thank Dr. Gary Mirka and Dr. Richard Stone at Iowa State University and Dr. Susan Hallbeck at Mayo Clinic for advice and guidance throughout this investigation.

References

Arent, S. M., & Landers, D. M. (2003). Arousal, Anxiety, and Performance: A Reexamination of the Inverted-U Hypothesis. *Research Quarterly for Exercise and Sport*, *74*(4), 436–444. https://doi.org/10.1080/02701367.2003.10609113

Bard, C., & Fleury, M. (1978). Influence of Imposed Metabolic Fatigue on Visual Capacity Components. *Perceptual and Motor Skills*, *47*(3 Pt 2), 1283–1287. https://doi.org/10.2466/pms.1978.47.3f.1283

Berguer, R., Chen, J., & Smith, W. D. (2003). A Comparison of the Physical Effort Required for Laparoscopic and Open Surgical Techniques. *Archives of Surgery*, *138*(9), 967. https://doi.org/10.1001/archsurg.138.9.967

Bigland-Ritchie, B., Jones, D. A., Hosking, G. P., & Edwards, R. H. (1978). Central and peripheral fatigue in sustained maximum voluntary contractions of human quadriceps muscle. *Clinical Science and Molecular Medicine*, *54*(6), 609–14.

Bigland-Ritchie, B., & Woods, J. J. (1984). Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle & Nerve*, *7*(9), 691–699. https://doi.org/10.1002/mus.880070902

Bisson, E. J., McEwen, D., Lajoie, Y., & Bilodeau, M. (2011). Effects of ankle and hip muscle fatigue on postural sway and attentional demands during unipedal stance. *Gait & Posture*, *33*(1), 83–87. https://doi.org/10.1016/j.gaitpost.2010.10.001

Borg, G. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377–381.

Bourne, S. K., Walcott, B. P., Sheth, S. A., & Coumans, J.-V. C. E. (2013). Neurological surgery: The influence of physical and mental demands on humans performing complex operations. *Journal of Clinical Neuroscience*, *20*(3), 342–348. https://doi.org/10.1016/J.JOCN.2012.09.008

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. *Brain Research*, *1453*(250), 87–101. https://doi.org/10.1016/j.brainres.2012.02.068

Chmura, J., Nazar, K., & Kaciuba-Uścilko, H. (1994). Choice Reaction Time During Graded Exercise in Relation to Blood Lactate and Plasma Catecholamine Thresholds. *International Journal of Sports Medicine*, *15*(04), 172–176. https://doi.org/10.1055/s-2007-1021042

Choi, S. D. (2012). A review of the ergonomic issues in the laparoscopic operating room. *Journal of Healthcare Engineering*, *3*(4), 587–603.

Cian, C., Barraud, P. A., Melin, B., & Raphel, C. (2001). Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. *International Journal of Psychophysiology : Official Journal of the International Organization of Psychophysiology*, *42*(3), 243–51.

Cicerone, K. D. (1996). Attention deficits and dual task demands after mild traumatic brain injury. *Brain Injury*, *10*(2), 79–89.

Cohen, J. (1977). *Statistical Power Analysis for the Behavioral Sciences* (1st ed.). New York, NY: Routledge. https://doi.org/10.1016/C2013-0-10517-X

Corbeil, P., Blouin, J.-S., Bégin, F., Nougier, V., & Teasdale, N. (2003). Perturbation of the postural control system induced by muscular fatigue. *Gait & Posture*, *18*(2), 92–100. https://doi.org/10.1016/S0966-6362(02)00198-4

Davis, J. M. (1995). Central and peripheral factors in fatigue. *Journal of Sports Sciences*, *13*(sup1), S49–S53. https://doi.org/10.1080/02640419508732277

Day, M. L., McGuigan, M. R., Brice, G., & Foster, C. (2004). Monitoring Exercise Intensity During Resistance Training Using the Session RPE Scale. *The Journal of Strength and Conditioning Research*, *18*(2), 353. https://doi.org/10.1519/R-13113.1

Dorion, D., & Darveau, S. (2013). Do Micropauses Prevent Surgeon's Fatigue and Loss of Accuracy Associated With Prolonged Surgery? An Experimental Prospective Study. *Annals of Surgery*, *257*(2), 256–259. https://doi.org/10.1097/SLA.0b013e31825efe87

Duncan, M., Smith, M., & Lyons, M. (2013). The effect of exercise intensity on coincidence anticipation performance at different stimulus speeds. *European Journal of Sport Science*, *13*(5), 559–566. https://doi.org/10.1080/17461391.2012.752039

Dunlap, W. P., Cortina, J. M., Vaslow, J. B., & Burke, M. J. (1996). Meta-analysis of experiments with matched groups or repeated measures designs. *Psychological Methods*, *1*(2), 170–177. https://doi.org/10.1037/1082-989X.1.2.170

Enoka, R. M., & Duchateau, J. (2008). Muscle fatigue: what, why and how it influences muscle function. *The Journal of Physiology*, *586*(1), 11–23. https://doi.org/10.1113/jphysiol.2007.139477

Fargen, K. M., Turner, R. D., & Spiotta, A. M. (2016). Factors That Affect Physiologic Tremor and Dexterity During Surgery: A Primer for Neurosurgeons. *World Neurosurgery*, *86*, 384–389. https://doi.org/10.1016/j.wneu.2015.10.098

Féry, Y.-A., Ferry, A., Hofe, A. Vom, & Rieu, M. (1997). Effect of Physical Exhaustion on Cognitive Functioning. *Perceptual and Motor Skills*, *84*(1), 291–298. https://doi.org/10.2466/pms.1997.84.1.291

Fleury, M., Bard, C., Jobin, J., & Carrière, L. (1981). Influence of Different Types of Physical Fatigue on a Visual Detection Task. *Perceptual and Motor Skills*, *53*(3), 723–730. https://doi.org/10.2466/pms.1981.53.3.723

Gandevia, S. C. (2001). Spinal and Supraspinal Factors in Human Muscle Fatigue. *Physiological Reviews*, *81*(4), 1725–1789. https://doi.org/10.1152/physrev.2001.81.4.1725

Gillette, J. C., & Stephenson, M. L. (2018). EMG analysis of an upper body exoskeleton during automotive assembly. In *Proceedings of the 42nd Annual Meeting of the American Society of Biomechanics* (pp. 308–309). Rochester, MN.

Giulio, C. Di, Daniele, F., & Tipton, C. M. (2006). Angelo Mosso and muscular fatigue: 116 years after the first congress of physiologists: IUPS commemoration. *Advances in Physiology Education*, *30*(2), 51–57. https://doi.org/10.1152/advan.00041.2005

Goodell, K. H., Cao, C. G. L., & Schwaitzberg, S. D. (2006). Effects of Cognitive Distraction on

Performance of Laparoscopic Surgical Tasks. *Journal of Laparoendoscopic & Advanced Surgical Techniques*, *16*(2), 94–98. https://doi.org/10.1089/lap.2006.16.94

Hagberg, M. (1981). Electromyographic signs of shoulder muscular fatigue in two elevated arm positions. *American Journal of Physical Medicine*, *60*(3), 111–21.

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. *Advances in Psychology*, *52*, 139–183. https://doi.org/10.1016/S0166-4115(08)62386-9

Hebb, D. O. (1955). Drives and the C.N.S. (conceptual nervous system). *Psychological Review*, *62*(4), 243–54.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology*, *10*(5), 361–74.

Hirst, W., & Kalmar, D. (1987). Characterizing attentional resources. *Journal of Experimental Psychology: General*, *116*(1), 68–81. https://doi.org/10.1037/0096-3445.116.1.68

Huang, H. J., & Mercer, V. S. (2001). Dual-task methodology: applications in studies of cognitive and motor performance in adults and children. *Pediatric Physical Therapy*, *13*(3), 133–40.

Hunter, S. K., Critchlow, A., & Enoka, R. M. (2005). Muscle endurance is greater for old men compared with strength-matched young men. *Journal of Applied Physiology*, *99*(3), 890–897. https://doi.org/10.1152/japplphysiol.00243.2005

Kant, I. J., DeJong, L. C. G. M., Van Rijssen-Moll, M., & Borm, P. J. A. (1992). A survey of static and dynamic work postures of operating room staff. *International Archives of Occupational and Environmental Health*, *63*(6), 423–428.

Landrigan, C. P., Rothschild, J. M., Cronin, J. W., Kaushal, R., Burdick, E., Katz, J. T., … Czeisler,

C. A. (2004). Effect of Reducing Interns' Work Hours on Serious Medical Errors in Intensive Care Units. *New England Journal of Medicine*, *351*(18), 1838–1848. https://doi.org/10.1056/NEJMoa041406

Lehmann, K. S., Martus, P., Little-Elk, S., Maass, H., Holmer, C., Zurbuchen, U., … Ritz, J. P. (2010). Impact of sleep deprivation on medium-term psychomotor and cognitive performance of surgeons: Prospective cross-over study with a virtual surgery simulator and psychometric tests. *Surgery*, *147*(2), 246–254. https://doi.org/10.1016/J.SURG.2009.08.007

Leyman, E. L., Mirka, G. A., Kaber, D. B., & Sommerich, C. M. (2004). Cervicobrachial muscle response to cognitive load in a dual-task scenario. *Ergonomics*, *47*(6), 625–645. https://doi.org/10.1080/00140130310001629766

Lockley, S. W., Cronin, J. W., Evans, E. E., Cade, B. E., Lee, C. J., Landrigan, C. P., … Czeisler, C. A. (2004). Effect of Reducing Interns' Weekly Work Hours on Sleep and Attentional Failures. *New England Journal of Medicine*, *351*(18), 1829–1837. https://doi.org/10.1056/NEJMoa041404

Lorist, M. M., Kernell, D., Meijman, T. F., & Zijdewind, I. (2002). Motor fatigue and cognitive task performance in humans. *Journal of Physiology*, *545*(1), 313–319. https://doi.org/10.1113/jphysiol.2002.027938

Luger, T., Bosch, T., Hoozemans, M. J. M., Veeger, D. H. E. J., & Looze, M. P. De. (2016). Is rotating between static and dynamic work beneficial for our fatigue state ? *Journal of Electromyography and Kinesiology*, *28*, 104–113. https://doi.org/10.1016/j.jelekin.2016.04.001

Lundberg, U., Forsman, M., Zachau, G., Eklöf, M., Palmerud, G., Melin, B., & Kadefors, R. (2002). Effects of experimentally induced mental and physical stress on motor unit recruitment in the trapezius muscle. *Work & Stress*, *16*(2), 166–178. https://doi.org/10.1080/02678370210136699

Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans, 857–864. https://doi.org/10.1152/japplphysiol.91324.2008.

Mehta, R. K., & Agnew, M. J. (2012). Influence of mental workload on muscle endurance, fatigue, and recovery during intermittent static work. *European Journal of Applied Physiology*, *112*, 2891–2902. https://doi.org/10.1007/s00421-011-2264-x

Nguyen, N. T., Ho, H. S., Smith, W. D., Philipps, C., Lewis, C., De Vera, R. M., & Berguer, R. (2001). An ergonomic evaluation of surgeons ' axial skeletal and upper extremity movements during laparoscopic and open surgery. *The American Journal of Surgery*, *182*, 720–724.

Panahi, A. K., & Cho, S. (2016). Prediction of Muscle Fatigue during Minimally Invasive Surgery Using Recurrence Quantification Analysis. *Minimally Invasive Surgery*, *2016*, 5624630. https://doi.org/10.1155/2016/5624630

Park, A., Lee, G., Seagull, F. J., Meenaghan, N., & Dexter, D. (2010). Patients Benefit While Surgeons Suffer: An Impending Epidemic. *Journal of the American College of Surgeons*, *210*(3), 306–313. https://doi.org/10.1016/j.jamcollsurg.2009.10.017

Porchet, F., Wietlisbach, V., Burnand, B., Daeppen, K., Villemure, J.-G., & Vader, J.-P. (2002). Relationship between severity of lumbar disc disease and disability scores in sciatica patients. *Neurosurgery*, *50*(6), 1253-9; discussion 1259-60.

Pugh, C. M., Santacaterina, S., DaRosa, D. A., & Clark, R. E. (2011). Intra-operative decision making: More than meets the eye. *Journal of Biomedical Informatics*, *44*(3), 486–496. https://doi.org/10.1016/J.JBI.2010.01.001

Quick, N. E., Gillette, J. C., Shapiro, R., Adrales, G. L., Gerlach, D., & Park, A. E. (2003). The effect of using laparoscopic instruments on muscle activation patterns during minimally invasive surgical training procedures. *Surgical Endoscopy*, *17*(3), 462–465. https://doi.org/10.1007/s00464-002-8530-6

Raina, S. M., & Dickerson, C. R. (2009). The influence of job rotation and task order on muscle fatigue: A deltoid example. *Work*, *34*(2), 205–213. https://doi.org/10.3233/WOR-2009-0917

Roman-Liu, D., Grabarek, I., Bartuzi, P., & Choromański, W. (2013). The influence of mental load on muscle tension. *Ergonomics*, *56*(7), 1125–1133. https://doi.org/10.1080/00140139.2013.798429

Santiago-Espada, Y., Myer, R. R., Latorella, K. A., & Comstock, J. R. (2011). *The Multi-Attribute Task Battery II (MATB-II) software for human performance and workload research: A user's guide*. Hampton, Virginia: National Aeronautics and Space Administration.

Simoneau, M., Bégin, F., & Teasdale, N. (2006). The effects of moderate fatigue on dynamic balance control and attentional demands. *Journal of Neuroengineering and Rehabilitation, 3*, 22. https://doi.org/10.1186/1743-0003-3-22

Slack, P. S., & Ma, X. (2007). Time dependency assessment of muscular fatigue index and hand tremor under operating conditions. In *2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (pp. 4822–4825). IEEE. https://doi.org/10.1109/IEMBS.2007.4353419

Smith, M., Tallis, J., Miller, A., Clarke, N. D., Guimarães-Ferreira, L., & Duncan, M. J. (2016). The effect of exercise intensity on cognitive performance during short duration treadmill running. *Journal of Human Kinetics*, *51*, 27–35. https://doi.org/10.1515/hukin-2015-0167

Strayer, D. L., & Johnston, W. A. (2001). Driven to Distraction: Dual-Task Studies of Simulated Driving and Conversing on a Cellular Telephone. *Psychological Science*, *12*(6), 462–466.

https://doi.org/10.1111/1467-9280.00386

Sundelin, G., & Hegberg, M. (1989). The effects of different pause types on neck and shoulder EMG activity during VDU work. *Ergonomics*, *32*(5), 527–537. https://doi.org/10.1080/00140138908966123

Szeto, G. P. Y., Cheng, S. W. K., Poon, J. T. C., Ting, A. C. W., Tsang, R. C. C., & Ho, P. (2012). Surgeons' static posture and movement repetitions in open and laparoscopic surgery. *Journal of Surgical Research*, *172*(1), e19–e31. https://doi.org/10.1016/j.jss.2011.08.004

Szturm, T., Maharjan, P., Marotta, J. J., Shay, B., Shrestha, S., & Sakhalkar, V. (2013). The interacting effect of cognitive and motor task demands on performance of gait, balance and cognition in young adults. *Gait & Posture*, *38*(4), 596–602. https://doi.org/10.1016/j.gaitpost.2013.02.004

Temprado, J.-J., Vieluf, S., Bricot, N., Berton, E., & Sleimen-Malkoun, R. (2015). Performing Isometric Force Control in Combination with a Cognitive Task: A Multidimensional Assessment. *PLOS ONE*, *10*(11), e0142627. https://doi.org/10.1371/journal.pone.0142627

Uhrich, M. L., Underwood, R. A., Standeven, J. W., Soper, N. J., & Engsberg, J. R. (2002). Assessment of fatigue, monitor placement, and surgical experience during simulated laparoscopic surgery. *Surgical Endoscopy*, *16*(4), 635–639. https://doi.org/10.1007/s00464-001-8151-5

Vuillerme, N., Forestier, N., & Nougier, V. (2002). Attentional demands and postural sway: the effect of the calf muscles fatigue. *Medicine and Science in Sports and Exercise*, *34*(12), 1907–12. https://doi.org/10.1249/01.MSS.0000039062.36895.AB

Wærsted, M., & Westgaard, R. H. (1996). Attention-related muscle activity in different body regions during VDU work with minimal physical activity. *Ergonomics*, *39*(4), 661–676.

https://doi.org/10.1080/00140139608964488

Wickens, C. D. (2008). Multiple Resources and Mental Workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*(3), 449–455. https://doi.org/10.1518/001872008X288394

Wright, D. L., & Kemp, T. L. (1992). The dual-task methodology and assessing the attentional demands of ambulation with walking devices. *Physical Therapy*, *72*(4), 306-12; discussion 313–5.

Biographies

Mitchell L. Stephenson is a doctoral candidate in biomechanics and motor control at Iowa State University. He received his M.S. in Kinesiology from the University of Wyoming in 2015. His primary research investigates perception and action coupling in musculoskeletal injury events.

Alec Ostrander is a graduate research assistant at Iowa State University, where he is pursuing a master's degree in industrial engineering and human computer interaction. He earned a Bachelor's degree in Engineering Science and Computer Science at Wartburg College in 2017.

Hamid Norasi is a Ph.D. student in the department of Industrial and Manufacturing Systems Engineering at Iowa State University in the field of ergonomics and human factors. Hamid received his M.S. in the Department of Biomedical Engineering of the Amirkabir University of Technology in 2010.

Dr. Michael C. Dorneich is an associate professor at Iowa State University in the department of Industrial and Manufacturing Systems Engineering. Previously he was a Principal Research

Scientist in the Human Centered Systems department at Honeywell Laboratories. He earned his Ph.D. in the human factors program in the department of Industrial Engineering at the University of Illinois at Urbana-Champaign in 1999.