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Richard W. Marklin Jr.
Marquette University, richard.marklin@marquette.edu

Jonathaon E. Slightam
Marquette University

Mark L. Nagurka
Marquette University, mark.nagurka@marquette.edu

Trent M. Wolff
Marquette University

Casey D. Garces
Marquette University

See next page for additional authors

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Authors
Richard W. Marklin Jr., Jonathaon E. Slightam, Mark L. Nagurka, Trent M. Wolff, Casey D. Garces, and Lovely Krishen

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Applied Force and sEMG Muscle Activity Required To Operate Pistol Grip Control in an Electric Utility Aerial Bucket

Richard W. Marklin, Jr.
Department of Mechanical Engineering, Marquette University, Milwaukee, WI

Jonathon E. Slightam
Department of Mechanical Engineering, Marquette University, Milwaukee, WI

Mark L. Nagurka
Department of Mechanical Engineering, Marquette University, Milwaukee, WI

Trent M. Wolff
Department of Mechanical Engineering, Marquette University, Milwaukee, WI

Casey D. Garces
Department of Mechanical Engineering, Marquette University, Milwaukee, WI

Lovely Krishen
Sr. Advisor R&D, Biosysco, Inc., Wilmington, DE

ABSTRACT

Electric utility line workers report high levels of fatigue in forearm muscles when operating a conventional pistol grip control in aerial buckets. This study measured the applied force and surface electromyographic (sEMG) signals from four upper extremity muscles required to operate the pistol grip control in two tasks. The first task was movement of the pistol grip in six directions (up/down, forward/rearward, clockwise/counter-clockwise), and the second task was movement of the bucket from its resting position on the truck bed to an overhead conductor on top of a 40 ft tall pole. The force applied to the pistol grip was measured in 14 aerial bucket trucks, and sEMG activity was measured on eight apprentice line workers.

The applied force required to move the pistol grip control in the six directions ranged from 12 to 15 lb. The sEMG activity in the extensor digitorum communis (EDC) forearm muscle was approximately twice as great or more than the other three muscles (flexor digitorum superficialis, triceps, and biceps). Line workers exerted 14 to 30% MVC_{EMG} to move the pistol grip in the six directions. Average $\%MVC_{EMG}$ of the EDC to move the bucket from the truck platform to an overhead line ranged from 26 to 30% across the four phases of the task. The sEMG findings from this study provide physiologic evidence to support the anecdotal reports of muscle fatigue from line workers after using the pistol grip control for repeated, long durations.

INTRODUCTION

For the past 30 years, aerial buckets have been used as the primary means by which electric utility line workers construct, maintain, and repair overhead electric lines. The truck boom, with one or two jointed segments that raise, lower, and rotate the aerial bucket, is powered by a hydraulic system with a power take-off (PTO) (**Figure 1**). In the aerial bucket a hand-operated control -- called a pistol grip control in the trade -- moves the aerial bucket up and down and rotationally (to the curb and street sides of the truck) (**Figure 2**). The shape and operation of the pistol grip control is very similar across brands of aerial buckets in the U.S. In addition, it appears that the current pistol grip control mechanism has not changed substantially in the last 30 years.

On most brands of buckets, the pistol grip includes a “dead-man” switch that must be depressed to activate the hydraulic system. Then, to raise/lower an aerial bucket attached to a boom with two jointed segments, a worker moves the pistol grip control up/down and forward/rearward (forward movement of the control is towards housing of pistol grip). To rotate the bucket clockwise (CW) and counter-clockwise (CCW), a worker rotates the pistol grip along the pistol grip’s longitudinally axis.

The worker exerts a power grip on the control while wearing a thick insulated rubber glove with a leather cover, and durations of continuous muscle exertion often exceed 60 s. Workers will typically make at least one complete movement up and down each hour (two 60 s exertions) during a shift. Based on anecdotal reports from interviews with line workers during the past 18 years, operating the pistol grip control results in a high level of fatigue in the forearm muscles. To date no studies in the published literature have evaluated the physical requirements to operate the pistol grip control.

The objective of this study was to measure the applied force to operate the control and the required muscle activity of major forearm muscles to determine if these forces provide biomechanical and physiological evidence for the reports of muscle fatigue from workers.

Figure 1. Typical electric utility aerial bucket truck with a 2-segmented boom.

Figure 2. Pistol grip control in aerial bucket that moves in six directions to maneuver the aerial bucket.

PISTOL GRIP APPLIED FORCE

The peak applied force to operate the pistol grip control was measured with a Chatillon™ force gage (capacity 50 lb) in 14 electric utility aerial trucks from five U.S. utilities. The utilities were medium to large electric utilities in five different regions of the U.S. (West, South, Southeast, North Central, and Northeast), and two to three trucks were tested at each utility. Six movement directions of the pistol grip were tested: up/down, for-ward/rear, and CW/CCW. Forward/rearward direction was defined as towards/away from the pistol grip's housing, and CW/CCW rotation was with reference to the longitudinal axis of the pistol grip from the worker's point of view.

A 3D printed nylon clamshell was attached to the pistol grip control, and a Chatillon™ force gage was temporarily bolted to the clamshell to measure the external force in the up/down, forward/rearward, and CW/CCW directions (**Figure 3**). Three peak force trials in each direction were taken and then averaged.

The average peak forces to move the pistol grip control were the following:

- 14.7 and 13.5 lb to move the control up/down
- 12.7 and 12.8 lb to move forward/rearward
- 13.8 and 15.5 lb at the surface of the control handle (mean torques of 1.16 and 1.30 ft-lb) to move the control CW and CCW.

The coefficient of variation (SD/mean) for the forces in the six directions ranged from 15 to 27%.

Applied force data from this study represent a baseline of forces from current pistol grip designs from four major manufacturers (Altec, Terex, Telect, and Lift All).

Figure 3. Chatillon™ force gage attached to the pistol grip control to measure forward/rearward force. A 3D printed clamshell (black) was secured to the pistol grip to provide a secure mount for the Chatillon™ gage.

sEMG MUSCLE ACTIVITY

Subjects

EMG activity of right arm muscles was monitored from eight male line worker apprentices from one U.S. Midwest utility while each operated the pistol grip in the six directions and also during a typical bucket movement from the truck platform to under a conductor at the top of a 40 ft high pole.

All subjects were in good health with no existing musculoskeletal pain or injuries and signed a Marquette University-approved Institutional Review Board (IRB) form before participation. The age of the eight workers ranged from 19 to 28 years old (mean = 23.8; SD= 2.5), and their average number of years performing electric utility field work at the host utility or a contractor was

2.6 (SD=2.7) with a range from 1 to 9 years. Their average height and weight were 71.8 in. (SD=1.97) and 195.4 lb (SD=46.2), respectively, and their right grip strength was 132.5 lb (SD=12.2).

Muscles and Equipment

The four muscles monitored with sEMG on the right arm were:

- Flexor digitorum superficialis (FDS)
- Extensor digitorum communis (EDC)
- Triceps
- Biceps

sEMG RMS signals of four right arm muscles were measured with Biometrics Ltd. (Gwent, UK) integral differential surface EMG sensors (model SX230). The EMG sensors were connected to a Biometrics Ltd. Data Logger, which was strapped to a subject's belt and transmitted EMG data wirelessly to a computer via Blue-tooth. Biometrics Ltd. data management software recorded and processed the signals and stored the data for subsequent analysis. Specifications of the EMG sensors and data acquisition system are the following:

- Inter-electrode distance was 20 mm on each surface bipolar unit.
- The electrode's gain was 1000 with a bandwidth from 20 to 450 Hz. Input impedance was greater than 10^{15} Ω, and the common mode rejection ratio at 60 Hz was greater than 96 dB.
- The reference electrode was attached at the ulnar styloid process of the right elbow.
- Raw EMG signals in volts were collected at a sampling rate of 1000 Hz and converted to RMS volts.

Experimental Procedure

Maximal and resting sEMG signals were recorded for each muscle and normalized to %MVC (maximum voluntary contraction). The subject then donned personal protective equipment (PPE) clothing (long sleeve shirt and sweater) and rubber sleeves. The subject and an investigator carrying the PC entered the 2-person aerial bucket. The subject positioned himself to operate the pistol grip control in a normal manner, and the investigator stood behind the subject. The investigator accompanied the subject in the bucket to minimize interference and signal loss from the Bluetooth Data Logger. The bucket was oriented so the worker was facing towards the area behind the truck, which is the typical bucket orientation.

The bucket was moved upward about 15 ft from its resting position on the truck bed. From this position, the worker made the six orthogonal movements of the pistol grip while sEMG data were collected. The investigator told the subject to start and stop each movement, which lasted approximately 10 s. The six orthogonal movements of the pistol grip and their subsequent boom motions were the following (in order of testing):

- UP: subject pulled the pistol grip straight upward until told to stop. This movement moved the upper boom upward.
- DOWN: subject pushed the pistol grip downward, which moved the upper boom downward.
- FORWARD: subject pushed the pistol grip forward (towards the housing of pistol grip), which moved the lower boom upward.
- REARWARD: subject pulled pistol grip rearward (away from pistol grip housing), which moved the lower boom downward.
- CLOCKWISE (CW): subject rotated the pistol grip to the right, which rotated the lower boom (and the bucket) to the right (driver's side of truck).
- COUNTER-CLOCKWISE (CCW): subject rotated the pistol grip to the left, which rotated the lower boom (and the bucket) to the left (passenger's side of truck).

Each orthogonal movement was repeated twice for a total of three trials for each movement. After the orthogonal movements of the pistol grip, the subject was instructed to move the bucket to its resting station above the truck bed. From this location, the subject moved the bucket to a position under a 40 ft tall conductor on top of the adjacent pole. This task is a typical bucket movement that a line worker makes on a daily basis. sEMG data were collected while the subject moved the bucket from its resting position upward to the conductor, which lasted approximately 60 s. Each upward movement was repeated twice, resulting in three trials.

The 50^{th} and 90^{th} percentiles (amplitude probability distribution function (APDF)) of normalized sEMG in %MVC during the trials were computed to represent summary statistics of the average and peak measures of EMG activity for each muscle during a trial.

RESULTS

Six Orthogonal Directions.

The sEMG activity between the two power grip muscles (FDS and EDC) varied substantially when the subjects moved the pistol grip in the six orthogonal directions, with the EDC exerting more muscle activity than the FDS (**Figure 4**). The 50^{th} percentile $\%MVC_{EMG}$ for the FDS ranged from 3.2 to 8.2% across the six directions. The averages of the 50^{th} percentile $\%MVC_{EMG}$ for EDC were approximately twice as great as those of the FDC, with the highest activity in the CCW movement (30%) and lowest in the CW direction (13.9% MVC).

The 50^{th} percentile biceps and triceps sEMG activity revealed a pattern of generally low levels of activity (<6%) across all directions except for specific movements. The 50^{th} percentile biceps activity was 8.1 and 10.2% for the up and forward motions, respectively, and triceps median activity was 8.8% MVC for the rearward movement.

These higher EMG levels can be explained by the actions of the muscles: the biceps contract to move the pistol grip upward while the triceps contract to pull the control rearward.

Truck to Overhead Line Movement.

For each subject, two of the three trials of the bucket moving from the truck platform to the overhead line were analyzed via video (the two trials were selected based on quality of video images). Video of one subject was not available, thus resulting in a sample size of seven subjects. Video of the bucket's movement in each trial was synchronized with EMG data from the four muscles, and bucket movement was categorized into four phases:

- Phase I: Vertical ascent from the bucket resting platform, typically to approximately 15 to 20 ft above the ground.
- Phase II: CW rotation without vertical ascent to orient the bucket to the overhead conductor. This phase occurred for only three of the seven subjects.
- Phase III: Simultaneous vertical ascent and CW rotation to position the bucket to within 6 ft under the overhead line.
- Phase IV: Final positioning of bucket to the conductor so the worker would be in the recommended position to work on the conductor (bucket under the conductor and conductor at worker's shoulder level).

The average duration of the bucket's movement was 61.3 sec. (SD 6.4), and the majority of the time (53.2%–33.1 sec.) was spent in Phase III --vertical ascent with rotation. The percentage of time in the other three phases was approximately uniform, ranging from 16.5 to 20.5%.

Summary statistics of 50th and 90th percentiles of $\%MVC_{EMG}$ were calculated for each trial's phase and then weighted across total time duration to produce the 50th and 90th percentiles of $\%MVC_{EMG}$ for each trial of bucket movement from the truck to the overhead line. Data from both trials for each subject were then averaged. As shown in **Figure 5,** the activity for the EDC muscle was much larger than the other three muscles and was approximately constant across all four phases. The average 50th percentile EDC $\%MVC_{EMG}$ during the entire task duration was 26% (SD=8.37), and the average ranged from 25.7 to 29.2% across all four phases. The biceps exerted the second highest sEMG activity, with an average 50th percentile of 14.7% (SD=5.6%). Biceps exertion during the first three phases was approximately the same (16.1 to 16.5%), and decreased during Phase IV to 11%. The average peak muscle activity of the EDC and biceps was 39% and 21.5% MVC_{EMG}, respectively, during the entire task.

DISCUSSION

The physiology literature regarding muscle fatigue appears to coalesce around a maximum relative muscle force of 8 to 10% that can be sustained for a long duration (Bystrom and Fransson-Hall, 1994; Bjorksten and Jonsson, 1977; Hagberg (1981). However, that does not mean that fatigue does not build up in the muscle at these force levels for a duration less than the maximum endurance time. Jorgensen et al. (1988) reported that a muscular contraction of 5% MVC could result in a reduction in muscular capacity of 12% after one hour of exertion.

The magnitudes of median EDC sEMG muscle activity levels in the present study, which ranged from 13 to 30% MVC during both tasks (orthogonal directions and truck to line movement) are substantially greater than the 8 to 10% of maximum muscle force that is recommended for long durations (which is defined as 60 min in the literature). While the duration of line workers' muscular exertions on the pistol grip is less than 60 min, the cumulative effect of approximately 60 s or longer grip exertions, performed repeatedly during a shift, may lead to buildup of muscle fatigue. Driven by data from handgrip muscles, Manenica (1986) developed an equation to predict maximum endurance time as a function of relative muscle force. At a 15% MVC, maximum endurance time is 8.5 min, and at 30% MVC the time is 4.3 min. At 40% MVC, which one subject experienced moving the bucket from the truck to conductor, the maximum endurance time is 2.7 min. El Ahrache et al. (2006) provided a review of other models to predict endurance time based on percentage of maximum muscle force.

The high median sEMG levels of the EDC muscle in this study provide some physiologic evidence that may explain the anecdotal reports by line workers of fatigue in the forearm after using the pistol grip control. However, the duration of pistol grip exertions (60 s) is shorter than maximum endurance time for 15% to 30% MVC sustained exertions so further research is needed to determine the causal pathways of workers' reports of muscle fatigue from operating the pistol grip control.

ACKNOWLEDGEMENTS

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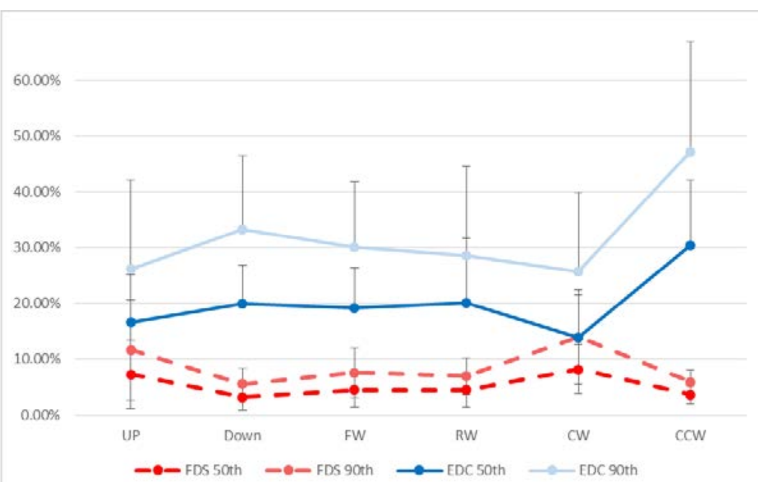

Figure 4. Mean and SD bars (N=8) of 50th and 90th percentiles of %MVCEMG of the FDS and EDC muscles during movement of the pistol grip control in the six orthogonal directions.

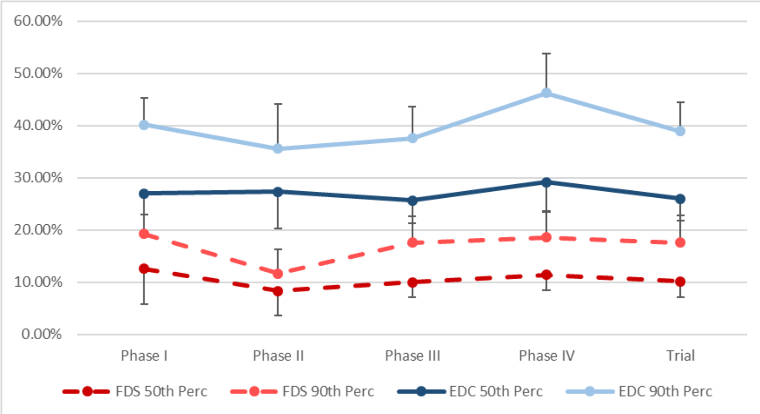

Figure 5. Mean and SD bars (N=7) of 50th and 90th percentiles of %MVCEMG of the FDS and EDC muscles during the four phases and entire trial of bucket movement from truck platform to overhead line.