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Electromyographic response is altered during robotic surgical training with augmented feedback

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ABSTRACT

There is a growing prevalence of robotic systems for surgical laparoscopy. We previously developed quantitative measures to assess robotic surgical proficiency, and used augmented feedback to enhance training to reduce applied grip force and increase speed. However, there is also a need to understand the physiological demands of the surgeon during robotic surgery, and if training can reduce these demands. Therefore, the goal of this study was to use clinical biomechanical techniques via electromyography (EMG) to investigate the effects of real-time augmented visual feedback during short-term training on muscular activation and fatigue. Twenty novices were trained in three inanimate surgical tasks with the da Vinci Surgical System. Subjects were divided into five feedback groups (speed, relative phase, grip force, video, and control). Time- and frequency-domain EMG measures were obtained before and after training. Surgical training decreased muscle work as found from mean EMG and EMG envelopes. Grip force feedback further reduced average and total muscle work, while speed feedback increased average muscle work and decreased total muscle work. Training also increased the median frequency response as a result of increased speed and/or reduced fatigue during each task. More diverse motor units were recruited as revealed by increases in the frequency bandwidth post-training. We demonstrated that clinical biomechanics using EMG analysis can help to better understand the effects of training for robotic surgery. Real-time augmented feedback during training can further reduce physiological demands. Future studies will investigate other means of feedback such as biofeedback of EMG during robotic surgery training.

1. Introduction

We have previously used objective performance measures to investigate robotic surgical training (Judkins et al., 2006b, 2008a, b). Further, we showed that real-time augmented feedback can enhance training particularly by reducing grip force (Judkins et al., 2006b, 2008a). In these studies, augmented visual feedback was provided by overlaying speed, grip force, or coordination information in visual display of the surgeon's console of the da VinciTM Surgical System (dVSS). Speed and grip force feedback provided immediate benefits after training by increasing speed and reducing grip force, respectively. However, the physiological responses of surgeons, specifically with augmented feedback, remain unexplored.

Few studies have examined physiological measures of the surgeons during performance of robotic surgical techniques. In manual laparoscopy, physiological evaluations have been mainly limited to ergonomic measures (Berguer et al., 1997, 2001; Hemal et al., 2001; McClure et al., 1997). These studies have found increased stress and fatigue associated with manual laparoscopy due to the surgeons' postures. Additionally, researchers have investigated electromyography (EMG) during manual laparoscopy and found that both task and type of grasper contributed to muscle fatigue (Matern et al., 2004; Quick et al., 2003). We have also performed a frequency analysis of EMG during a four-week training period for robotic surgery and found that training leads to reduced muscular fatigue (Judkins et al., 2006a). However, these results are limited because it is difficult to place EMG electrodes in the same place across sessions. Therefore, short-term training (during one session) is necessary to corroborate our previous findings.
EMG can assist in the evaluation of physiological muscular fatigue (Basmajian and De Luca, 1985; Komi and Tesch, 1979). Specifically, frequency analysis of the electromyographic signals from the muscles involved has proven an effective method of measuring muscle fatigue and motor unit recruitment during static force exertion (Basmajian and De Luca, 1985). Specifically, increased muscle fatigue is associated with a decreased median frequency of the power spectrum (Basmajian and De Luca, 1985; Bonato et al., 2001). In addition, increases in the frequency bandwidth of the power spectrum imply additional recruitment of motor units with varying conduction velocities (Farina et al., 2002, 2004). More recently, it has been shown that frequency analysis can also be applied to cyclic dynamic tasks to evaluate muscular fatigue (Bonato et al., 2001). Hypothetically, training should decrease muscular fatigue (i.e., increased median frequency) during surgery and thus, improve the ability of a surgeon to operate. Even more, augmented feedback during training can possibly enhance such effects.

The purpose of this study was to investigate the effects of real-time augmented visual feedback during short-term training on physiological performance, while performing three different surgical tasks with the dVSS. A real-time augmented feedback interface was developed and investigated as a means to enhance short-term training during robotic surgical training tasks. We hypothesized that muscle activation and fatigue will decrease after short-term training as we observed previously with long- term training. Furthermore, we hypothesized that augmented feedback will further reduce muscle activation and fatigue.

Methods and materials

Subjects

Twenty novice users (1st and 2nd year medical students; 2575.1 years of age) of the dVSS were recruited to participate in this study. Novice users had no prior experience using the dVSS. All participants were right-handed. Informed consent was obtained from each subject prior to participation in accordance with the Institution Review Board of the University of Nebraska Medical Center.

Tasks

Subjects performed and/or practiced three tasks using the dVSS throughout this study (Fig. 1): bimanual carrying (BC), needle passing (NP), and suture tying (ST). The BC task required simultaneously picking up two 15 x 2 mm rubber pieces (one each with left and right graspers) from 30 mm (diameter) metal caps and placing them in two other metal caps 50 mm away. The NP task required passing a 26 mm surgical needle through six holes in a latex tube. The ST task required tying two knots with a 100 x 0.5 mm surgical suture using the intracorporeal knot. Videos of the tasks are available on Elsevier's website. The subjects performed the tasks by manipulating the dVSS from the surgeon's console (Fig. 1D). All three tasks were cyclic tasks designed to mimic actual surgical laparoscopic tasks that required significant bimanual coordination.

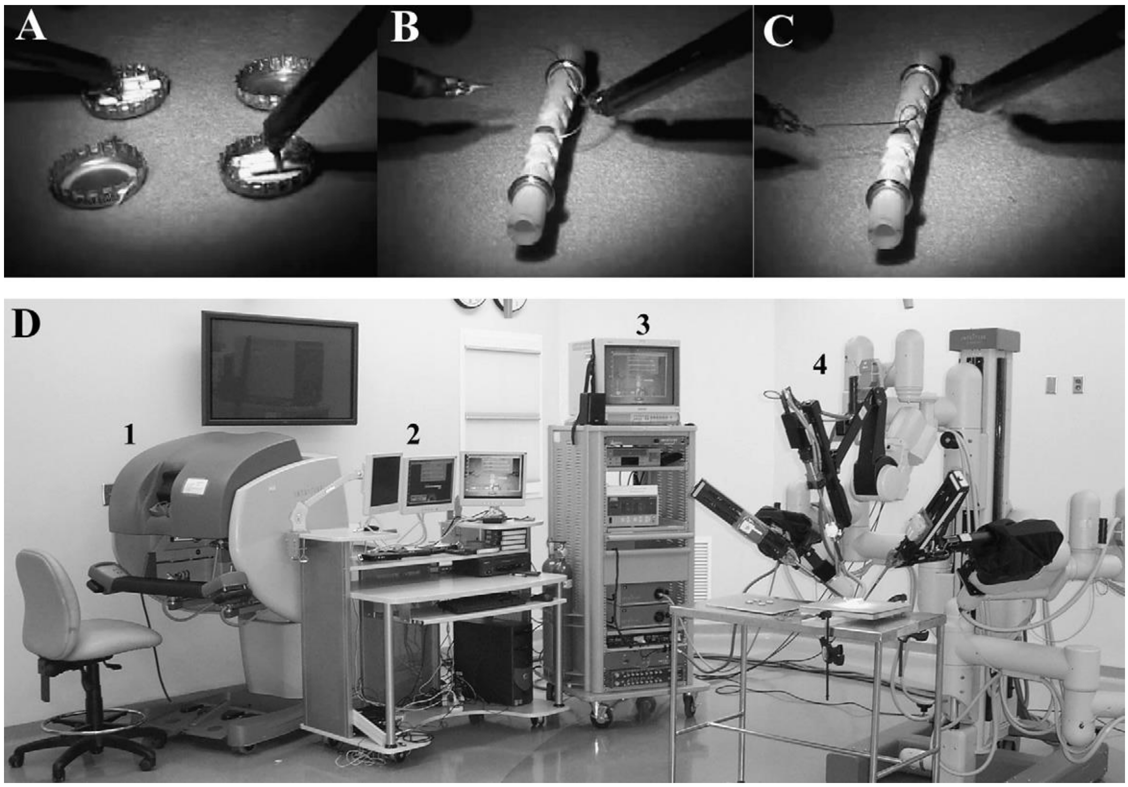

Fig. 1. Subjects performed and/or practiced three tasks using the dVSS throughout this study: (A) bimanual carrying—BC, (B) needle passing—NP, and (C) suture tying—ST. The BC task required simultaneously picking up two 15 x 2 mm rubber pieces (one each with left and right graspers) from 30 mm (diameter) metal caps and placing them in two other metal caps 50 mm away. The NP task required passing a 26 mm surgical needle through six holes in a latex tube. The ST task required tying two knots with a 100 x 0.5 mm surgical suture using the intracorporeal knot. The subjects performed the tasks by manipulating the dVSS (D4) from the surgeon's console (D1). Data were collected using custom LabVIEW software (D2), and movements were observed from the camera cart (D3).

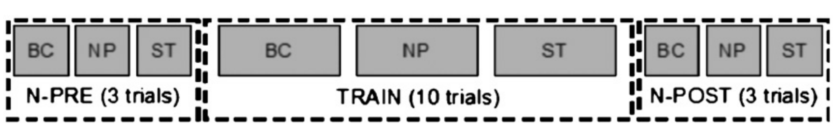

Fig. 2. Training paradigm. Each novice performed three tasks (BC—bimanual carrying, NP—needle passing, and ST—suture tying) in three training blocks: three pre-training trials (PRE), 10 training trials (TRAIN) and three post-training trials (POST). Task order was randomized between subjects, but was the same between training blocks.

Experimental protocol

Subjects performed 16 trials of each task divided into three training blocks (Fig. 2): three pre-training trials (PRE), 10 training trials with augmented visual feedback, and then three post-training trials (POST). Task order was randomized between subjects, but was the same between training blocks. We previously found that 10 training trials were sufficient to improve performance without causing fatigue as reported by the subject (Judkins et al., 2006b). Subjects were not allowed to practice with the dVSS before the experiment.

Subjects were randomly assigned to one of five feedback groups (Fig. 3): speed (SP; $n = 4$), grip force (GRIP; $n = 4$), relative phase between left and right grasper movement (RP; $n = 4$), video (VID; $n = 4$), and control (CTRL; $n = 4$). Real-time augmented feedback was overlaid on the video screen of the surgeon's console. SP feedback was presented as two green vertical bars (left and right arm). When the speed increased, the bar enlarged vertically. GRIP feedback was presented as two red vertical bars. When the grip force increased, the bar enlarged vertically. Coordination training via visual feedback has been used to improve the stability of the coordination patterns in other tasks (Wenderoth et al., 2002); however, it is unknown how coordination feedback affects muscle response in the context of robotic surgical training. RP feedback (a measure of coordination) was presented as a red circular dial with a moving needle. Relative phase is measured as the difference in phase angle between the left and right instrument movements, i.e., movements in the same direction with the same speed are in-phase and movements in opposing directions are out-of-phase. The needle pointed to the right for an in-phase relationship and to the left for an out-of-phase. The VID group (not shown) watched pre-recorded video of an expert with more than 5 years of experience using the dVSS performing each task. The CTRL group (not shown) received no additional feedback during the training trials. Videos of the augmented feedback are available on Elsevier's website.

Data analysis

Surface EMG was used to measure muscle activity of the flexor carpi radialis (FCR) and extensor digitorum (ED) of the left and right arms of each subject during training tasks. These muscles were selected because we have previously observed significant change in wrist flexor/extensor muscles with training compared to elbow flexors and extensors (Judkins et al., 2006a). Two Bagnoli-2 (Delsys, Inc., Boston, MA) surface EMG systems were used to collect data at 1000 Hz via custom LabView software. Time-domain and frequency-domain analyses were performed using MATLAB 6.5.

Mean EMG (EMG_{mean}) and EMG envelope (EMG_{env}) were calculated to provide a measures of the average muscle activity and work produced by a given muscle, respectively (Basmajian and De Luca, 1985). Before the experiment, maximum EMG was recorded for each muscle via isometric contraction for 3 s. Raw EMG was normalized from 0 to 1 by dividing by the maximum isometric EMG and then smoothed using a 150-ms root-mean-square (RMS) moving window. EMG_{mean} and EMG_{env} were then computed for each trial.

Median frequency (EMG_{fmed}) and frequency bandwidth (EMG_{fband}) were computed to provide a window into muscle fatigue and motor unit recruitment, respectively (Basmajian and De Luca, 1985). A complete description of the frequency analysis is given in our previous study (Judkins et al., 2006a).

Statistical analysis

Group means were compared using two-way mixed ANOVA at $\alpha = 0.05$, with condition (PRE, POST) as the within-subject factor and feedback group (SP, RP, GRIP, VID, CTRL) as the between-subject factor. Post-hoc pairwise comparisons with Bonferroni corrections were performed when factors were significant. The statistical analysis was performed for each task and dependent variable. Effects of feedback group are not reported because we were investigating learning effects. Condition effects provide overall learning effects. Interaction effects (feedback x condition) provide learning effects for individual feedback groups.

Results

Condition (PRE vs. POST—Fig. 4)

Right and left FCR_{mean} were slightly, although significantly, smaller during POST trials compared to PRE trials (R: $p = 0.002$; L: $p = 0.026$) for the BC task. All EMG_{mean} were significantly smaller during POST trials compared to PRE trials for the NP tasks (right FCR: $p = 0.001$; left FCR: $p = 0.023$; right ED: $p<0.0005$; left ED: $p = 0.001$). There were no significant differences in EMG_{mean} for the ST task. All EMG_{env} were significantly smaller during POST trials compared to PRE trials for the all tasks ($p<0.05$) (Fig. 4).

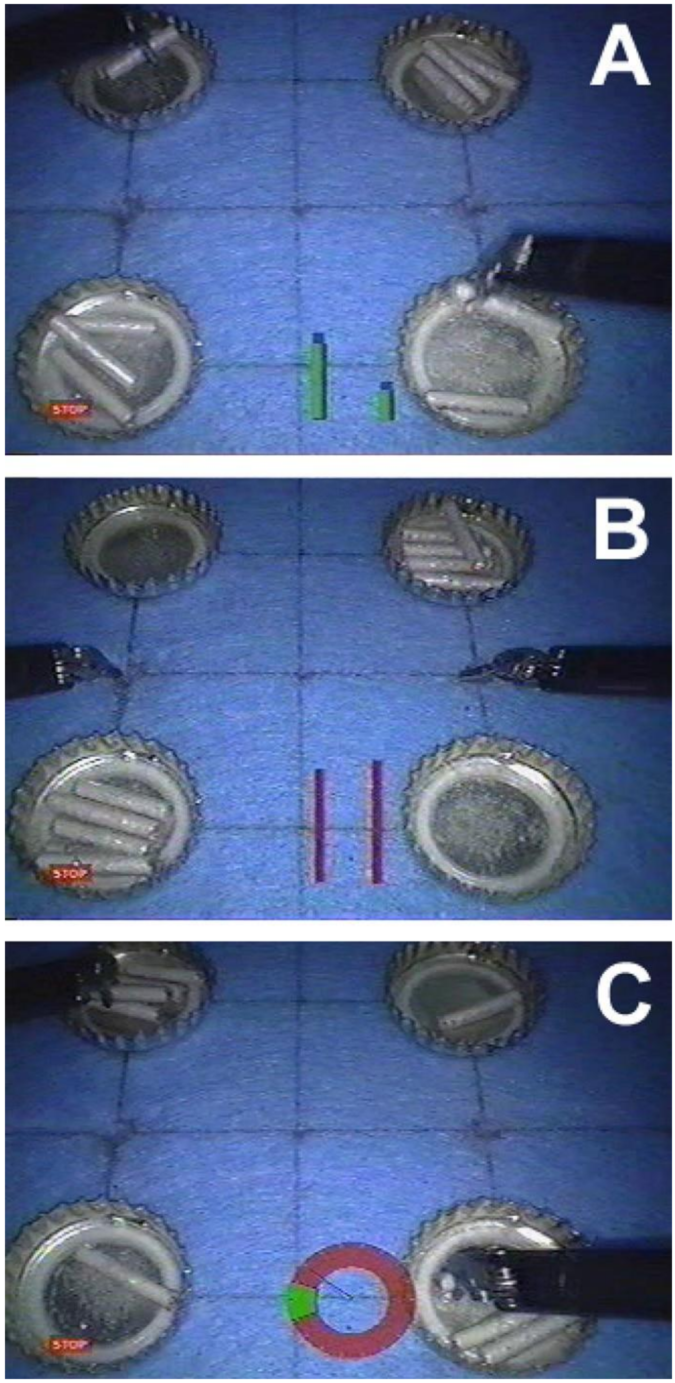

Fig. 3. Real-time augmented feedback. Subjects were randomly assigned to one of five feedback groups: speed (SP), grip force (GRIP), relative phase between left and right grasper movement (RP), video (VID), and control (CTRL). Real-time augmented feedback was overlaid on the video screen of the surgeon's console. SP feedback (A) was presented as two green vertical bars (left and right arm). When the speed increased, the bar enlarged vertically. GRIP feedback (B) was presented as two red vertical bars. When the grip force increased, the bar enlarged vertically. RP feedback (C) was presented as a red circular dial with a moving needle. The needle pointed to the right for an in-phase (0°) relationship and to the left for an out-of-phase (180°). In-phase is considered to be when the right and left grasper moved in the same direction and with the same speed. The opposite is an out-of-phase relationship. The VID group (not shown) watched pre-recorded video of an expert with more than 5 years of experience using the dVSS performing each task. The CTRL group (not shown) received no additional feedback during the training trials.

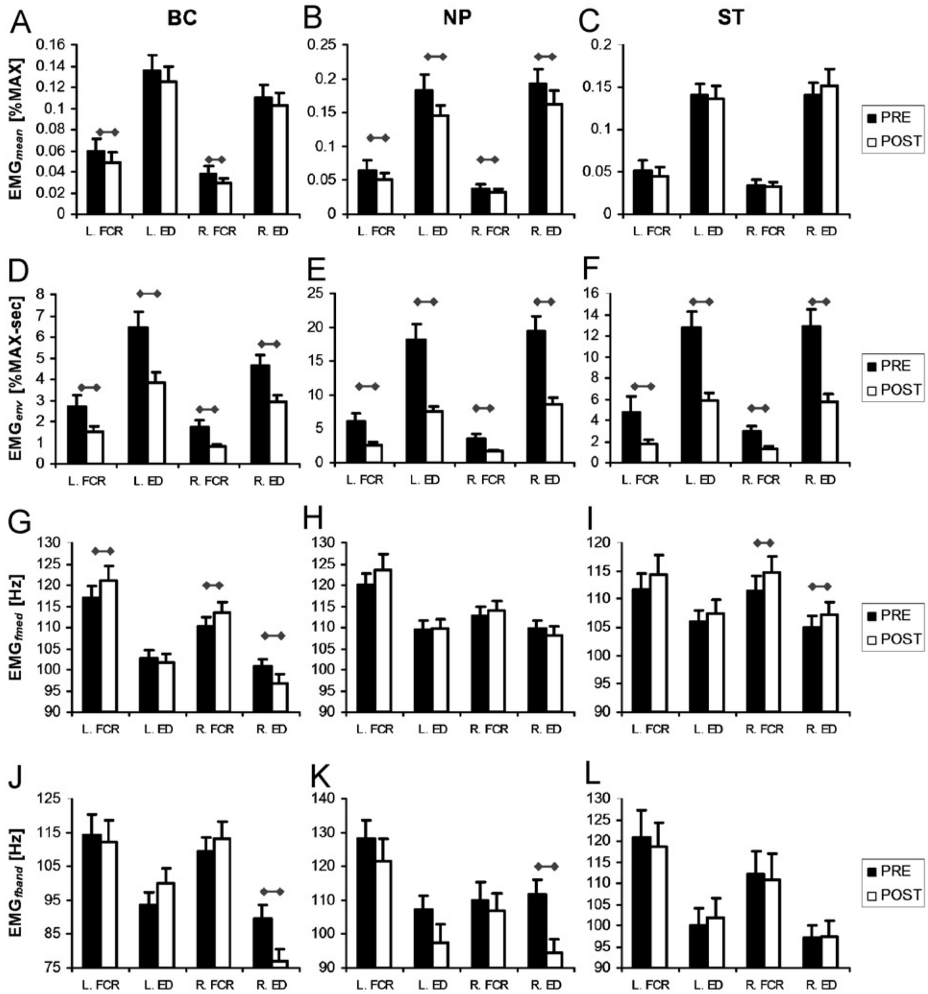

Fig. 4. Group means comparing PRE and POST training during bimanual carrying (BC), needle passing (NP), and suture tying (ST) movements for EMG_{mean} (mean EMG; A–C), EMGenv (EMG envelope; D–F), EMG_{fmed} (median EMG frequency; G–I), and EMG_{fband} (EMG frequency bandwidth; J–L) for left (L) and right (R) flexor carpi radialis (FCR) and extensor digitorum (ED). Lines above bars indicate a significant difference at $\alpha = 0.05$ level between PRE and POST for the variable indicated.

Right and left FCR_{fmed} were significantly larger during POST trials compared to PRE trials for the BC task (R: $p = 0.027$; L: $p = 0.025$). Right ED_{fmed} was significantly smaller during POST trials compared to PRE trials for the BC task ($p = 0.001$). No EMG_{fmed} were significantly different for the NP task. Right FCR_{fmed} and right ED_{fmed} were significantly larger during POST trials compared to PRE trials for the ST task (right FCR: $p = 0.02$; right ED: $p = 0.033$). Right ED_{fband} was significantly smaller during POST trials compared to PRE trials for the BC task ($p = 0.007$). Right ED_{fband} was significantly smaller during POST trials compared to PRE trials for the NP task ($p = 0.007$).

Interaction effects (Fig. 5)

All EMG_{mean} had significant interaction effects for the BC task ($p<0.05$). Right ED_{mean} and left FCR_{mean} had significant interaction effects for the NP task ($p<0.05$). Right ED_{mean} and left FCR_{mean} had significant interaction effects for the ST task ($p<0.05$). In general, mean EMG decreased for POST trials compared to PRE trials. The GRIP group decreased mean EMG more than other groups, i.e., smaller EMG during POST training compared to PRE training. The SP group increased mean EMG during POST trials compared to PRE trials (Fig. 5).

Left FCR_{env} and right and left ED_{env} had significant interaction effects for the BC task ($p<0.05$). Right ED_{env} and left FCR_{env} had significant interaction effects for the NP task ($p<0.05$). Left FCR_{env} and right and left ED_{env} had significant interaction effects for the ST task ($p<0.05$). All groups significantly decreased EMG envelopes during POST trials compared to PRE trial; however, the GRIP group decreased more than other groups.

Left FCR_{fmed} and left ED_{fmed} had significant interaction effects for the BC task ($p<0.05$). Left ED_{fmed} had significant interaction effects for the NP task ($p<0.05$). Left FCR_{fmed} and left ED_{fmed} had significant interaction effects for the ST task ($p<0.05$). Right ED_{fband} had significant interaction effects ($p<0.05$) for the BC task. Left FCR_{fband} had significant interaction effects for the ST task ($p<0.05$). The relatively few interaction effects in median frequency and frequency bandwidth did not show a clear directional effect for any group.

Discussion

This study has shown that training with the dVSS generally decreased mean EMG response, decreased EMG envelopes, and increased the median frequency and bandwidth of the EMG power spectrum when performing bimanual tasks. Significant reduction in mean EMG between pre-training and post-training was observed in the right and the left flexor carpi radialis for BC and NP tasks, and also in the right and the left extensor digitorum for the NP task. Since mean EMG is an indication of average muscle activation, subjects learned to perform the tasks with reduced muscular work. Furthermore, mean EMG decreased significantly for the GRIP group as compared to other groups indicating that grip force feedback is beneficial to further reduce muscle work. For the SP group, however, mean EMG increased post-training as compared to pre-training. Even though speed feedback was previously shown to improve kinematic performance measures (Judkins et al., 2008a), it may be detrimental to muscular performance.

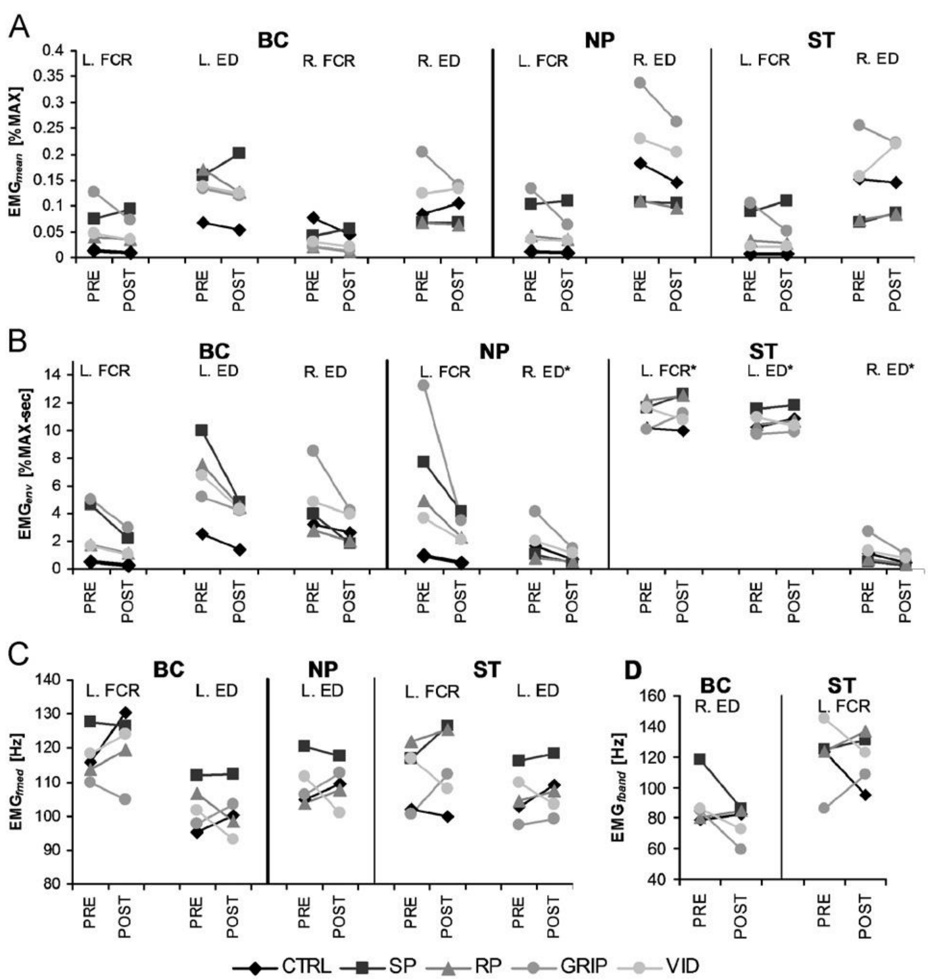

Fig. 5. Significant interaction effects between condition (PRE and POST training) and feedback group (SP—speed; GRIP—grip force; RP—relative phase between left and right grasper movement; VID—video; CTRL—control, no

feedback) during bimanual carrying (BC), needle passing (NP), and suture tying (ST) movements for EMG_{mean} (mean EMG; A), EMG_{env} (EMG envelope; B), EMG_{fmed} (median EMG frequency; C), and EMG_{fband} (EMG frequency bandwidth; D) for left (L) and right (R) flexor carpi radialis (FCR) and extensor digitorum (ED).

EMG envelopes for all muscles decreased from pre-training to post-training for all tasks. EMG envelopes are a measure of the total muscle activation for a given trial. EMG envelopes are dependent on muscle activation level as well as task completion time. Since previous kinematic results found a significant reduction on task completion time, it is likely that reduced EMG envelopes are a result of the reduced task completion time (Judkins et al., 2008a). EMG envelopes decreased between pre-training and post-training for most groups. Furthermore, EMG envelopes decreased significantly more for the SP and GRIP groups compared to the other groups. For the GRIP groups, the significant reduction in EMG envelopes is likely due to the significant reduction in mean EMG level. For the SP group, there was no mean EMG reduction; however, previous kinematic analysis found that the SP group had significantly smaller task completion time compared to other groups (Judkins et al., 2008a). This reduced task completion time would lead to reduced EMG envelopes. Both grip force feedback and speed feedback proved beneficial in reducing the total muscular work.

Median frequency significantly decreased between pre-training and post-training for the two muscles during the BC and ST tasks. Previous work using longer training periods (four weeks) also resulted in increased median frequency (Judkins et al., 2006a). There are two likely causes for this frequency shift. Based on the available literature and previous kinematic analysis (Hashizume et al., 2002; Hubens et al., 2003; Munz et al., 2004; Prasad et al., 2002; Sarle et al., 2004), training results in shorter task completion times. Therefore, each movement within a task occurred at a higher frequency in order to complete the task in a shorter time. These faster movements resulted in muscle bursts occurring at a higher frequency. In addition, a decrease in median frequency has been shown to be associated with muscle fatigue during sustained contraction (Basmajian and De Luca, 1985; Komi and Tesch, 1979). Training may increase efficiency when performing a task thereby, reducing muscle fatigue. Probably both of these factors resulted in the frequency shift.

The frequency content of electromyograms is also directly related to the conduction velocities of recruited motor units (Farina et al., 2004). It is well known that Type I and Type II muscle fibers have different conduction velocities (Farina et al., 2002). Therefore, it can be inferred that a larger frequency bandwidth is indicative of a larger range of recruited motor units with different conduction velocities, i.e., different muscle fibers. We found that the EMG bandwidth increased for the right extensor digitorum during the BC and NP tasks during post-training as compared to pre-training. While this only occurred for one muscle, previous research has found similar results over a longer training period (Judkins et al., 2006a). These results suggest that subjects recruited a larger range of motor units with varying conduction velocities with training.

While the GRIP and SP groups showed interaction effects, other feedback (RP and VID) did not benefit nor impaired performance. Subjects reported that the RP feedback was difficult to control and did not pay attention to it after time. While the VID feedback may have demonstrated better technique, this feedback did not have a specific goal (e.g. reduce grip force) associated with it. These two groups did not differ from the CTRL group in that they all decreased mean EMG response, decreased EMG envelopes, and increased the median frequency and bandwidth. Lastly, there appeared to be task effects for mean EMG and median frequency. Mean EMG decreased after training for the BC and NP task, but not for the ST task. This is likely due to task complexity. Similar effects were seen for the kinematic and kinetic performance measures in our previous study (Judkins et al., 2008a). Median frequency increased after training for the BC and ST tasks, but not for the NP task. This is likely due to the accuracy needed to pass the needle; therefore, subjects were inclined to grasp the needle harder to improve accuracy. The NP task showed similar effects for speed in our previous study (Judkins et al., 2008a).

There is a growing prevalence of robotic surgical systems worldwide and in laparoscopic surgical procedures. Thus, there is a need to understand the physiological demands of robotic surgery on the surgeon, and if training can reduce physiological demands. This study utilized clinical biomechanical measures via EMG to provide a window into the physiological response of the surgeon during robotic surgery and training. Surgical training decreased muscle work as shown by decreased mean EMG and EMG envelopes. Furthermore, grip force feedback further reduced average and total muscle work, while speed feedback increased average muscle work and decreased total muscle work. Training also increased the median frequency response as a result of increased speed and/or reduced fatigue during each task. More diverse motor units were recruited as revealed by increases in frequency bandwidth post-training. It is evident that an evaluation of the physiological demands of robotic laparoscopic surgery using clinical biomechanics can provide us with a meaningful quantitative way to examine performance and skill acquisition, and better understand the physiological demand on the surgeon.

Conflict of interest

None.

Acknowledgements

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