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Muscle Activity Patterns Change with Skill Acquisition for Minimally Invasive Surgery: A Pilot Study*

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***Abstract*— This paper presents a pilot study to investigate which arm muscles change their activity most through skill acquisition in Minimally Invasive Surgery (MIS), specifically through training for laparoscopy. Three novice subjects trained with a laparoscopy training box with the hoop transfer game, in five experiment sessions of 20 minutes each in two weeks. We monitored the activity of three upper and two lower arm muscles – upper arm: Lateral Deltoid (LD), Biceps, Triceps; lower arm: Extensor Digitorum (ED), and Flexor Carpi Radialis (FCR) – with Surface-Electromyography (EMG) during the first and fifth (last) experiment sessions, before and after training, respectively. A consistent change in the activity of any of these muscles across the initial and final measurements would indicate which muscles were of most importance and subject to a change in activity pattern during laparoscopy training. The results showed that, after training and consistently across all three subjects, the ED and FCR muscle activities reduced at pick-up, whereas ED increased and FCR decreased at drop-off of the hoops. We did not find any noticeably consistent change in the activation patterns of the upper arm muscles. The results of this pilot study show that the lower arm muscles ED and FCR are important for laparoscopy training and inform us that we should focus on these two lower arm muscles in our future and extended studies in order to associate quantified changes of muscle activity with laparoscopy skill acquisition. Such quantified knowledge can be used in assessment of skills and developing training systems with feedback of biological sensors.**

I. Introduction

Skill assessment in Minimally Invasive Surgery currently relies on either subjective evaluations in one-to-one training or measures of artificially constructed factors of performance in virtual training setups [1]. To our knowledge, there is yet no training and assessment system that uses direct biological data from the trainee, such as the EMG recordings. We believe that direct biological feedback from the trainee would be a more accurate and reliable indicator of skill level as it would be objective and relate directly to the actual activity of physical training and skill attainment [2, 3].

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Muscle activation patterns can potentially be used to identify skilled features as demonstrated in various domains, such as robotic minimally invasive surgery (RMIS) [4], an arm manipulation task [5], and tennis strokes [6]. MIS is a domain that an objective skill assessment is still under research [7], mostly because the current reliance on subjective and virtual environment based assessments are not precise and are time consuming [8].

A training system with a biological muscle activity feedback would require the quantified knowledge of the change in activity patterns of each of the most related muscles through skill acquisition. Deriving this knowledge precisely would require a quite long lasting experiments (a few months to a few years) with a large set of novice participants (15-20). However, there are a large number of muscles (at least 5 major muscles) in the upper and lower arms together, that measuring all the muscles with so many and so long duration experiments would not be practically easy and would generate a huge amount of data most of which might not be informative about skill acquisition. Such an extended study would benefit a lot if the number of muscles to be examined could be reduced to a few and the study could be focused on the quantification of the activity of these few muscles.

Figure 1. The laparoscopy training box and the timer.

TABLE 1. LIST OF TRAINING INSTRUCTIONS

Number	Instructions
1	Use the right hand tool only
2	Pick-up and place the hoops (do not drop)
3	Move from left to right, top to bottom
4	Once all moved, start again from right to left
5	Minimise disturbance to the training game platform
6	Repeat within 5 minutes duration
7	Minimise trunk (body) movement

This pilot study performs a series of limited duration experiments with a limited number of three novice subjects. In total 100 minutes long data were collected from each subject over a period of two weeks. The subjects participated in 5 sessions of experiments where each session had 4 trials of 5 minutes duration each. The purpose of this pilot study was to identify which muscles are most relevant for skill acquisition in laparoscopy and therefore which muscles should be focused on in a longer duration and more extensive study with a larger set of novice subjects.

A standard laparoscopy training box was used in the experiments and muscle activity levels were registered through EMG recoding from three upper and two lower arm muscles on the right arm. The results provide initial evidence that the activity of the lower arm muscles generally decrease with laparoscopy skill acquisition and the activity of some muscles increase at specific movements potentially to achieve high positional precision.

II. EXPERIMENTAL SETUP AND METHODS

A. *Experimental Setup*

In the experiments we used a standard laparoscopy training box purchased from a medical equipment provider and meant for surgeon training (Fig. 1). The training box has an embedded video capture function for post experiment visual analysis. We used a timer to set the training duration. The subjects performed the *hoop transfer game* (Fig. 2), which is one of the most common training games for laparoscopy and was recommended by professional laparoscopy surgeons for its suitability to the level of beginners[1]. The hoop transfer game setup was also purchased from a medical equipment provider. The training game platform was attached to the training box with a soft material (Velcro) in between, in order to have a non-rigid connection and to allow vibrations of the game platform in case of a hard contact with the laparoscopy instrument. We attached an accelerometer to the game platform in order to register the vibrations (disturbances) that result from such contact. The disturbances provided an indication of errors and undesired tool movements performed by the subjects.

The hoop transfer game consists of three key events: 1) Tool transfer from point-to-point, 2) pick-up of a hoop, and 3) drop-off of a hoop (Fig. 2). The goal is to move the hoops

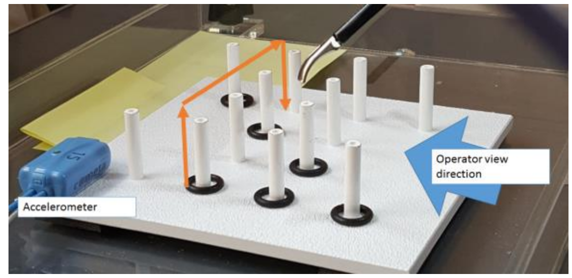

Figure 2. The hoop transfer training game platform and the three events in the game indicated by arrows.

from the left side columns onto the right side and then from right side to the left side once all the hoops have been transferred to the right. The pick and drop actions require the highest precision and the most skill compared to the other tool movements in the game, in order to avoid any disturbances through touching the platform. These two actions relate to two easily distinguishable instantaneous types of events throughout the game; therefore they provide clear same type of movement instances for cross subject comparisons. The participants were instructed as detailed in Table 1. Besides this procedural description they were also instructed to have a similar arm and body posture across all subjects. The pick-up and drop-off events are the most difficult as they require stabilization of the tool for precision in positioning. It is ideally required that the tool does not touch to the game platform during these events. Touching the platform is an indication of difficulty in stabilizing the tool movement, difficulty in picking-up the hoop, and finally dropping off the hoop and picking it up again from the surface of the platform. The more skilled subjects would touch less to the platform. We focused on the drop-off and pick-up events, either on-to and from the columns or the surface, and recorded the peaks in the accelerometer signal as an indicator of touches to the game platform.

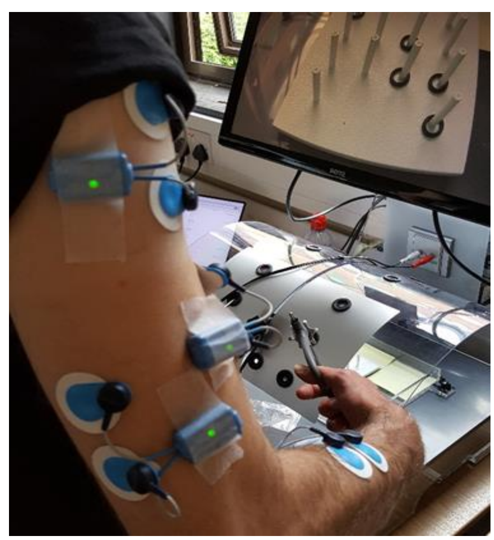

Figure 3. EMG instrumentation applied on Subject B.

[1] We thank Prof. Ghulam Nabi and Doc. Benjie Tang, professional laparoscopy surgeons from the Cuschieri Skills Centre in University of Dundee, for their guidance and suggestions in choosing the training game.

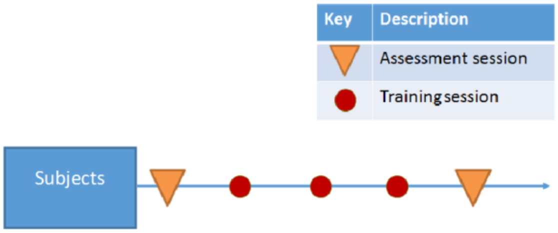

Figure 4. Experimental plan to train the subjects

TABLE 2. DATA OF RECRUITED SUBJECTS

Subjects	Gender	Age	BMI	Right handedness
A	Male	24	21.3	Right handed
B	Male	27	22.9	Right handed
C	Male	29	19.5	Right handed

The Cometa EMG recorder was used to measure the muscle activity of the Lateral Deltoid (LD), Biceps, Triceps, Extensor Digitorum (ED), and Flexor Carpi Radialis (FCR) muscles. The placement of electrodes followed the Innervation Atlas [9]. The application of the EMG instruments to five muscles with ten electrodes is shown on Fig. 3 and followed the European recommendations for surface electromyography [10].

B. *Subject Recruitment*

Three novice subjects took part in these experiments. The subjects were recruited on a voluntary basis among the students at Heriot-Watt University. They had no prior experience with laparoscopy and laparoscopy training. The age, gender, body mass index (BMI), and handedness of subjects were recorded as in Table 2. The experiments were approved by the Ethics Committee of Heriot-Watt University. All subjects gave Informed Consent prior to the experiments.

C. *Experimental Procedure*

The goal of the experiments was to increase the skill level of the subjects for laparoscopic hoop game through training and to measure their arm muscle activity at the beginning and end of the training.

Five experiment sessions were performed. Video of performance and accelerometer signals were recorded in all five experiment sessions. Among those, in the first and last sessions also the EMG data were recorded; hence we name these first and last sessions as Assessment Session 1 and Assessment Session 2 (Fig. 4). The remaining three sessions in between are named as Training Session 1, 2, and 3. Each session consisted of four 5-minutes long hoop transfer trials. We number the four trials in each of the experiment sessions with 1-4, 5-8, 9-12, 13-16, and 17-20 respectively.

D. *Method of Analysis and Performance Indicators*

The recorded videos of the performance and the accelerometer signals were used to measure the skill level of the subjects across the five experiment sessions. The time of each pick-up and drop-off event was identified based on the video recordings. The video data was aligned with the accelerometer data of all sessions, and also with the EMG data of the first and last sessions.

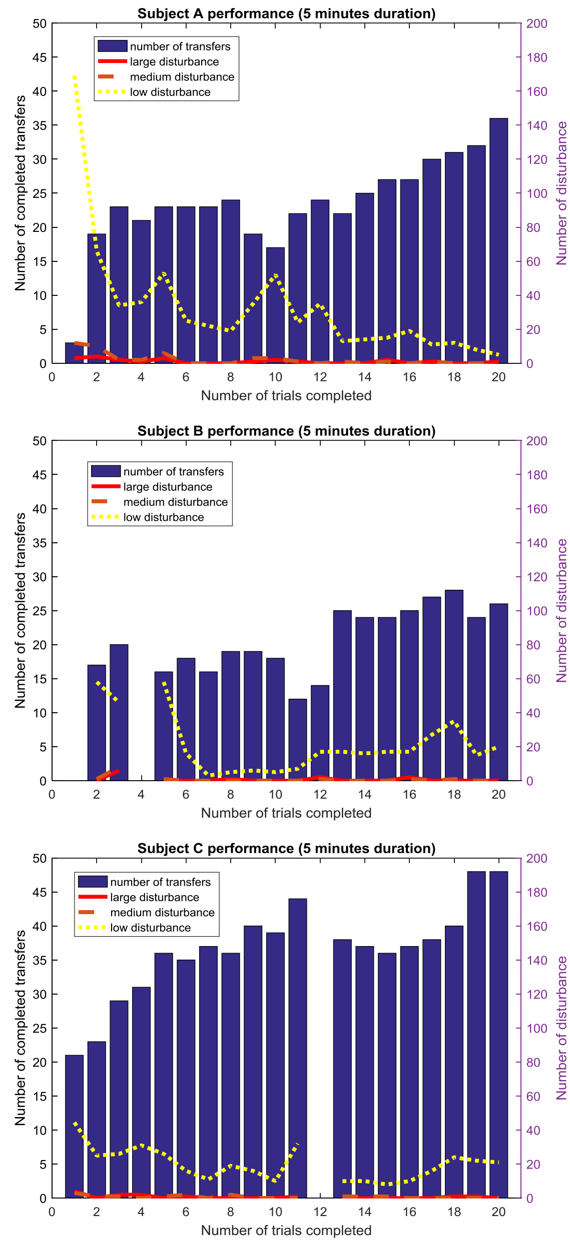

Figure 5. The performance measures for Subject A, B, and C across each trial throughout the twenty trials in five experiment sessions.

Four parameters in relation to the skill level were computed for each trial: *number of transfers*, *number of low-, medium-, and high-disturbances*. Among those, the number of transfers could be directly used as the first indicator of the skill level. The number of transfers was identified for each trial by visual analysis of the recorded videos.

The disturbances in each trial were extracted from the accelerometer data. These disturbances were classified as high, medium, and low level using ad-hoc determined thresholds. This classification was necessary because there

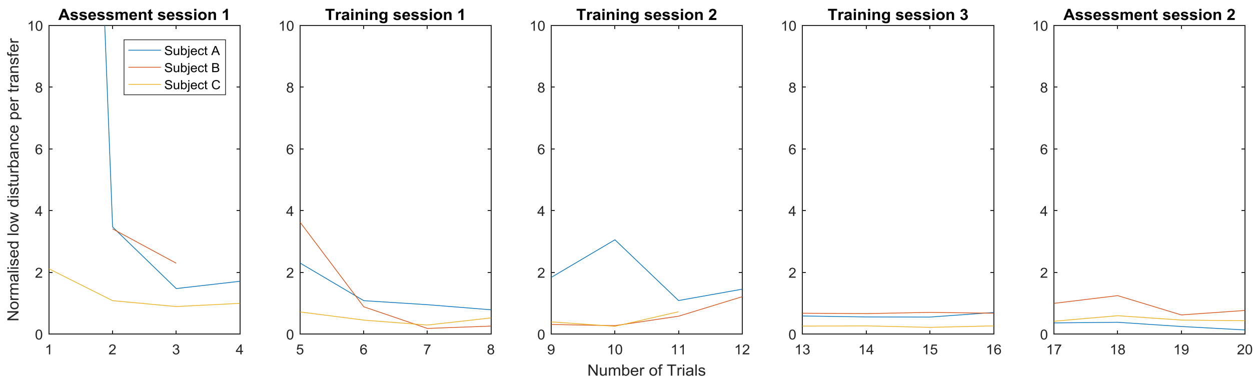

Figure 6. Performance improvement after 20 trials.

was a large difference in the magnitude of different group of disturbances. Among those most of the medium- and high-level disturbances were due to the collision of the instrument with the game platform during pick-up and drop-off of the hoops from and onto the hooks. The low-disturbance threshold was triggered mostly when the hoop was dropped on or picked from the platform.

The number of low-disturbances reduced throughout training. Therefore low-disturbances were both larger in number and better indicative of the change in performance. Fig. 5 plots the values of the four performance indicators for the three subjects across 20 trials in 5 experiment sessions. We observe that the number of transfers increased and the number of all three types of disturbances decreased, as a general trend, throughout training (most obvious with Subject A). We also observe that the number of low-level disturbances and the decrease in this number are much more and better indicative of skill acquisition compared to medium- and high-level disturbances.

There is a dependence between the number of disturbances and the number of transfers, because when more transfers are attempted, there will be more disturbances due to the increased activity. Therefore, in order the number of low-disturbances to be converted into a direct indicative of skill level, it should be normalized with respect to the number of completed transfers. We computed *normalized low-transfer per trial* for each subject and used that as the second indicator of the skill level.

The EMG sampling rate was 2 kHz. For each pick-up and drop-off event, a 256 point time history backwards from the time of the event was extracted from the recorded EMG data. The video frame rate was 25Hz. Each of the pick-up and drop-off events is likely to last around 2-3 frames which corresponds to 80-120 ms. The 0.128ms time frame with the EMG data was chosen because it was short enough to describe the discrete event and long enough to cover the potential error from the frame by frame video analysis. A Hann window was applied to the extracted data series. The frequency power spectrum was computed with Fast Fourier Transform (FFT) for each event occurrence. The peak magnitude of the FFT data of each event spectrum was

TABLE 3. AVERAGE NUMBER OF TRNASFERS IN A TRIAL BEFORE AND AFTER TRAINING

Subject	Average transfers before training (Assessment 1)	Average transfers after training (Assessment 2)
A	16.5	32.25
B	18.5	26.25
C	26	42.5

recorded and these were averaged across all the events in a trial. The average peak magnitude across a trial was used as an indicative of the level of muscle activity in that particular trial.

III. RESULTS

A. Measure of Skill Level

The first indicator of the skill level was the number of transfers in each trial. Table 3 gives the average number of transfers across the four trials in each of the first and second assessment sessions for the three subjects. We observe that the number of successful transfers increased with all three subjects. This shows that the subjects were faster in picking and placing the hoops in the hooks after training.

The second indicator of the skill level, the normalized low-disturbance per transfer, are plotted in Fig. 6. We observe that the normalized number of low-disturbance events per transfer decreased from around two at the start to lower than one at the end of the training, with some fluctuations in between. This shows that the subjects were more efficient and accurate in moving the hoops without dropping them onto the platform after training. These two indicators together and consistently provide evidence that the training indeed resulted in development of the manipulation skills of the subjects for the hoop transfer game for laparoscopy training.

The subjects commented that they needed to re-familiarize with the experimental setup each time they started a new experiment session and they felt tired in the fourth (last) trial of each session. Therefore they subjectively expected the second and third trials to be a better representative of their performance. This comment was

TABLE 4. MUSCLE ACTIVITY CHANGE AT PICK-UP

Description		Before Training	After Training	Change
Subject and muscle at Pick-up		*Averaged peak activity (μV)*	*Averaged peak activity (μV)*	*% decrease*
A	ED	5602	2671	52%
B	ED	3615	2545	30%
C	ED	7625	1865	76%
A	FCR	871	506	42%
B	FCR	1396	780	44%
C	FCR	1534	1285	16%

TABLE 5. MUSCLE ACTIVITY CHANGE AT DROP-OFF

Description		Before Training	After Training	Change
Subject and muscle at drop-off		*Averaged peak activity (μV)*	*Averaged peak activity (μV)*	*% decrease*
A	ED	3034	2092	31%
B	ED	5073	2536	50%
C	ED	3559	1762	50%
A	FCR	1229	1778	-45%
B	FCR	954	1068	-12%
C	FCR	1641	2307	-41%

supported by the quantitative results in Fig. 6: Subjects A and C in assessment session 1, Subjects B and C in training session 1 performed better in the second and third trials compared to the first and fourth, respectively. Based on this observation we decided to ignore the first and fourth trials and rather focus on the second and third trials of the assessment sessions while analyzing the EMG data.

B. Muscle Activity

In order to analyze the changes in muscle activity throughout training, we analyzed the EMG data in the vicinity of the pick-up and drop-off events in trials 2-4 of the first and last experiment sessions. The frequency power spectra at the pick-up and drop-off events were evaluated. The peak muscle activity from the frequency power spectra across the second and third trials of each assessment session were averaged.

The analysis showed little and inconsistent changes in the activity levels of upper arm muscles (lateral deltoid, biceps, and triceps) for the three subjects. Therefore, we do not report here the data for the upper arm muscles.

The analysis showed large and consistent changes of activity levels with the lower arm muscles (ED and FCR). The quantitative results of this analysis are shown in Table 4 and Table 5 for pick-up and drop-off events, respectively. There was a decrease in the activity level of ED and FCR muscles at pick-up and ED muscle at drop-off, consistently across all three subjects. This is a strong indication of reduction of the level of muscle activity in the lower arm through training. The reduction in activity quantitatively supported the subjective expression of the participants that the game became easier and less tiring throughout training.

However, the level of activity of the FCR muscle increased with training consistently across all three subjects at the drop-off events (Table 5). This increase in the level of activity is likely to be related to the necessity of a high precision in positioning for the drop-off event. During drop-off, the hoop contacts the platform as it is placed and this requires to be more precise in order to minimize the disturbance due to the contact of the hoop to the platform. Through training, the subjects are likely to have learned to increase their precision by being stiffer with the FCR muscle during those instances. This observation is in line with the results of our previous study that larger hand impedance (such as larger stiffness) is required for higher precision hand movements [11, 12]. It is likely that the stiffness was increased with an increased level of contraction of the FCR muscles. The ED muscle is likely to be less relevant to maintaining had-position precision during drop-off, therefore it is more relaxed and we observe a decrease with its activity throughout training.

IV. DISCUSSION

The performance data showed that the subjects improved after training and the EMG data showed that there were consistent changes in the level of muscle activity of the lower arm muscles across three subjects. Generally the activity level deceased with training, indicating an easier and less tiring hand/arm movement; but the activity of one muscle increased at the drop-off events with training, indicating a specific adaptation of muscle use to achieve precision when it is required. More specifically, the ED and FCR muscle activities were reduced with increased skills (with the exception of FCR at drop-off), in accordance with the fact that the subjects found the task easier and less effort requiring after training. The FCR muscle activity at drop-off increased after training, which potentially resulted in an improvement in accuracy with these moments.

This was a pilot study with limited number of participants and limited duration training. The purpose of the study was not to find out all the patterns of muscle activity changes throughout laparoscopy training, but rather to identify the muscles that are most affected by training. This would allow us to plan a more extended and longer term study with a larger number of participants in order to find out how, how much, and for what type of movements each of those identified muscle activities change with training and what quantified muscle activity levels relate to skill acquisition in laparoscopy. In that respect, the results of this pilot study showed that the lower arm muscles, specifically Extensor Digitorum and Flexor Carpi Radialis were most important for laparoscopic skill acquisition among the investigated five muscles. The results of the study provided evidence for further knowledge than it was aimed at in this study that the level of the activity of these muscles tend to decrease in most of the manipulation through skill acquisition in laparoscopy, but the same muscles might have also increased activity for specific movements and at specific instances when high precision is required in hand positioning. Specifically the activity of Flexor Carpi Radialis has been found to increase in drop-off events through skill acquisition. This indicates that we should be looking for not only a general trend of change of activity, but also specific changes of activity for pre-identified and specific type of movements. In other words, skill acquisition might relate not to a straight line of change in activity levels, but to a change in patterns of activity with respect to different movements and actions. Therefore, specific experimentation focused on individual and specific movement types as well as specific muscles might reveal the skilled muscle activity patterns for each type of movement and for each muscle.

These pilot results provide evidence that it might be possible to associate skill levels in laparoscopy operations with specific patterns and levels of activities of group of muscles in the lower arm. The muscle synergies [13, 14] related to the key movements during laparoscopy can be identified with such analysis. Such knowledge might be informative to develop advanced laparoscopy training systems, which get feedback from the biological dynamics of the trainees and provide biological feedback to the trainee. Such knowledge might also be useful to plan specific type of arm muscle training activities in order to speed up learning of skilled laparoscopy manipulation.

In our future study, we will be conducting an extended investigation of skilled muscle activity patterns with longer period training and data collection and with a larger number of subjects in order to find out more detailed and quantified patterns of muscle activity changes throughout laparoscopy training. With such study, we also aim to investigate the impact of laparoscopy procedures on muscle fatigue [15] and identify which muscles are more prone to fatigue during each of laparoscopy procedures.

V. Conclusion

We performed a pilot study for an initial investigation of whether MIS skill assessment can be related to EMG based muscle activity recording. We experimented with three novice subject who briefly trained with a laparoscopy training game. The performance, hence the skill level, of the subjects improved with training. The observation was that the activity of the forearm muscles showed characteristic changes through training consistently across all three subjects. Therefore, this study provides evidence that EMG based muscle activity monitoring can be used to assess the skill acquisition of subjects for MIS, which in turn can be used to enhance the current skill assessment and training practices of surgeons.

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