The effect of operating time on surgeons' muscular fatigue

PS SLACK¹, CJ COULSON², X MA¹, K WEBSTER³, DW PROOPS³

¹Biomedical Engineering Research Group, Aston University, Birmingham, UK

²University Hospital of North Staffordshire, Stoke on Trent, UK

³Queen Elizabeth Hospital, Birmingham, UK

ABSTRACT

INTRODUCTION A study was completed to determine if operating has an effect on a surgeon's muscular fatigue.

SUBJECTS AND METHODS Six head and neck surgery consultants, two ENT registrars, 20 normal controls from two tertiary referral centres in the West Midlands participated in the study. Electromyography (EMG) measurements were taken throughout a day of operating and fatigue indices were compared to controls performing desk work.

RESULTS The percentage changes in mean frequency of muscular contractions were examined; there was no significant difference in fatigue levels between consultants and registrars. Operating led to an increase in fatigue in all subjects, compared to no increase in controls performing desk work. It was also found that the brachioradialis muscle is used more than the mid-deltoid muscle and, hence, fatigues at a faster rate.

CONCLUSIONS Surgeons should be aware that their muscular fatigue levels will increase as an operation progresses; therefore, if possible, more complex parts of the operation should be performed as early as possible, or, in the case of a very long operation, a change in surgeon may be necessary.

KEYWORDS

Muscular fatigue – Surgery – Electromyography

CORRESPONDENCE TO

Xianghong Ma, School of Engineering and Applied Science, Aston University, Birmingham B4 7ET, UK

T: (0)121 204 3592; F:(0)121 204 3583; E: x.ma@aston.ac.uk

Surgical decision making is the most important factor determining operative success. However, once a decision has been made, the performance of the surgeon comes into play. Similar to any job or task,¹ it is believed that mental and muscular fatigue is developed during a day of operating. It is likely that an increase in arm fatigue causes an increase in hand tremor. This leads to a reduction in the surgeon's fine motor control and, hence, a reduced precision of the surgeon's hand movement. Muscular fatigue manifests itself during and after prolonged voluntary muscular contractions, the level of which can lead to higher or lower endurance times.² It has been described in some respects as the point at which a specific muscle can no longer sustain a contraction. This can be misleading in practice, as this defines fatigue as a specific point, whereas fatigue is, in fact, a development stage.¹

Fatigue is a very subjective term and, therefore, difficult to quantify. The preferred way to quantify a fatigue trend is to examine the shift in frequencies from captured electromyographic (EMG) signals.³ Numerous studies have demonstrated that, as an individual fatigues during a sustained

isometric contraction, the mean frequency of these contractions decreases.^{4–6} This is due the muscle being unable to sustain the high levels of contractions (high frequencies) as it fatigues. We can, therefore, relate an increase in fatigue with a decrease in the mean frequency of the muscular contractions.

Our aim was to determine whether or not a surgeon's fatigue level does in fact increase, decrease, or remain the same throughout a day of surgery, compared to controls performing desk work. If the fatigue level increases during the day, then perhaps another surgeon should perform the more challenging parts of a single, lengthy operation, or that the more difficult operations should be performed at the beginning of the day.

Subjects and Methods

Subjects

Eight healthy surgeons (six male consultants, one male registrar, and one female registrar) volunteered to participate in the surgical arm of the study. Twenty non-surgical measurements

Table 1 Surgery description, length of operation, and the time between sets

Surgeon	Surgery description	Length (min)	Length between readings (min)
#1	Panendoscopy excision biopsy (right brachial cyst)	120	8
#2	Tracheostomy Left selective neck dissection Mandibulotomy Resection of tumour left tonsil Left palate reconstruction with radial forearm flap Abdominal skin graft	600	8
#3	Left modified radical neck dissection	180	2.5
#4	Excision left submandibular gland	60	0.5
#5	Left mastoid obliteration Bone anchor hearing aid	240	8
#6	Right combined approach tympanoplasty (stage 2)	210	3
#7	Tracheostomy Left selective neck dissection Mandibulotomy Resection of tumour left tonsil Left palate reconstruction with radial forearm flap Abdominal skin graft	480	10.5
#8	Cochlear implantation	180	5.5

were taken during the control arm. The surgeons' ages varied between 31 and 47 years (mean, 40.63 years). The non-surgeons' ages varied between 25 and 35 years (mean, 32.35 years). All the surgeons and all but one of the non-surgical controls were right handed. The surgical arm of the study consisted of acquiring fatigue measurements whilst performing an operation. The length of the operations varied from 1–10 h (Table 1). The control arm of the study consisted of acquiring 60-s fatigue measurements before and after several hours of routine desk work.

Measurement techniques

The electrodes were placed over the muscle belly of each subject's dominant arm. The deltoid lateral head and brachioradialis muscles (Fig. 1) were chosen for analysis to attempt to compare their fatigue levels, and how they are used throughout a day of operating. These two were chosen as they are used primarily for stabilising both the arm and forearm, and would be the most likely muscles to fatigue. The skin was cleaned with alcohol and all hair shaved, an interfacing film was attached to each of the electrodes, and these films were then attached to the skin. The EMG signals were collected using a Bagnoli-16 system (Appendix 1).

Procedures

The EMG measurements were taken from the beginning to the end of the operation. These consisted of 30-s sets, separated by 0.5–10.5 min between captures, depending on the operation length. Table 1 lists the time between sets based on the operation. The surgeons were asked to perform the operations as normal. Control fatigue measurements were taken at a variety of times throughout the day.

Figure 1 Electrode placement on the mid-deltoid and brachioradialis muscles.

Statistical analysis

Statistical comparisons were performed on the tremor data from all of the surgeons. All statistical and other analysis were performed using the Matlab R2006a (The Mathworks Inc., Natick, MA, USA) Statistical and Frequency Analysis Toolboxes. Any significant differences were defined at $P < 0.05$.

Results

The results from all surgical EMG measurements indicate a decrease in the mean frequency over the length of the operation for both the mid-deltoid and the brachioradialis muscles. The analysis on operation #3's mid-deltoid muscle has

been used as an example. All calculated mean frequencies are plotted in Figure 2A. A linear regression curve, with 95% confidence intervals, has been fitted to the data. Figure 2B demonstrates the mean percentage maximum voluntary contraction (bar graph) for each repetition superimposed with the change in mean frequency (line graph). This decrease in mean frequency suggests an increase in muscular fatigue level.

The mean frequency readings taken at the beginning of the day did not show any significant difference between the consultants (#1, #2, #3, #4, #7, and #8) and registrars (#5 and #6; ANOVA, $P = 0.7193$ [mid-deltoid], $P = 0.3458$ [brachioradialis]).

Figure 2 (A) The mean frequencies for the mid-deltoid muscle calculated throughout operation #3. The data have been fitted with a linear regression curve with 95% confidence intervals. (B) The mean percentage maximum voluntary contraction for each repetition during operation #3 (bar graph). The superimposed dashed line represents the change in the mean of the mean frequencies during each repetition.

Figure 3 Percentage decrease in mean frequency from baseline of the mid-deltoid muscle. This is based on the length of operation and normal working day conditions. Points indicate the percentage decrease of the surgical fatigue index (mean frequency); the solid line is the fitted linear regression to the data, and the dashed lines indicate the 95% confidence interval for the fitted data. Crosses indicate the percentage decrease of the non-operating fatigue index; the solid line is the fitted linear regression to the data, and the dashed lines indicate the 95% confidence interval for the fitted data.

Figure 4 Percentage decrease in mean frequency from baseline of the brachioradialis muscle. This is based on the length of operation and normal working day conditions. Points indicate the percentage decrease of the surgical fatigue index (mean frequency); the solid line is the fitted linear regression to the data, and the dashed lines indicate the 95% confidence interval for the fitted data. Crosses indicate the percentage decrease of the non-operating fatigue index; the solid line is the fitted linear regression to the data, and the dashed lines indicate the 95% confidence interval for the fitted data.

By analysing the percentage change of the mean frequency for each operation and correlating it with its length, we discover a linear relationship between the percentage change in fatigue index and the length of the operation for both muscles. A linear regression with confidence bounds of 95% has been fitted to the data and is shown in Figures 3 and 4. These figures demonstrate the constant increase in fatigue based on the length of the operation. They also demonstrated that it would be possible to predict the change in a surgeon's muscular fatigue index during an operation given a baseline measurement. It is also apparent that the brachioradialis muscle fatigues more than 1.5 times as fast as the mid-deltoid muscle. The results demonstrate that for every hour after the first hour of operating, the mid-deltoid mean frequency decreases by 0.84%, and the brachioradialis by 1.32%, and which is associated with a fatigue rate. There is also an offset of -10.781% and -11.969% for the mid-deltoid and brachioradialis, respectively, which occurs after the first hour of operating.

The mean percentage maximum voluntary contraction for both muscles has been averaged over all operations. Figure 5 shows that the mean percentage maximum voluntary contraction of the brachioradialis muscles is generally higher than that of the mid-deltoid muscles. This suggests that the muscular activity of the brachioradialis muscle is greater and indicates that the brachioradialis muscles are used more than the mid-deltoid during the operations.

In the control arm of the study, the volunteers' fatigue index increased throughout the day, although only fractionally (0.011%/min [mid-deltoid], 0.010%/min [brachioradialis]). A linear regression with confidence bounds of 95% has also been fitted to the data.

Figure 5 The percentage maximum voluntary contraction contribution of the mid-deltoid and brachioradialis muscles throughout all surgical operations.

Discussion

Comparison with other studies

Fatigue analysis has been performed in many fields of study, such as postural control on voluntary movements⁴ and during repetitive task dependent activities.⁵ The EMG measurements are primarily captured using surface EMG, although they can be captured using needle electrode. These unfortunately cause some risks of infection, damage to muscle fibres, and are painful to the subjects.⁷ These studies have determined that fatigue can be correlated with a shift in mean frequency towards lower frequencies,^{4,5} and is increased by higher levels of muscular contractions. The surgical studies that have been performed have examined aspects of fatigue during simulated laparoscopic surgery. These were conducted over short periods of time, and during sustained isometric muscular contraction levels.⁸ Others have examined the effects of laparoscopic training on muscular demand.⁹ These studies have examined the muscular contribution during specific surgical tasks. They have concluded that certain muscles are used more often than others and are, therefore, at a greater risk of fatiguing. However, they have not shown that the studied muscles had fatigued.

EMG fatigue analysis has been primarily applied to shorter muscular bursts at the similar strength levels (constant percentage maximum voluntary contraction).¹⁰⁻¹² The problem arises, however, when dealing with daily routine movements and muscular contractions, as the strength level of these contractions varies. Little is known as to what happens to the frequency of the muscular motor units over the long periods. Long-term studies have been performed whereby EMG has been captured throughout a 24-h period have examined parkinsonian and essential tremor,¹⁵ and wrist tremor.¹⁴ Christensen¹⁵ examined the mean frequency change throughout the day of the deltoid, trapezius, and infraspinatus muscles in subjects operating a pillar drill. However, to our knowledge, this is the first study to have examined the change in the fatiguing muscles during a day of operating.

Clinical applicability

This study focused on the development of fatigue by analysing the mean frequency shifts over the length of various operations, and correlating trends with the level of expertise of the surgeon.

We have demonstrated that there was no statistical difference between the pre-operative mean frequency between the consultants and registrars. The decrease in mean frequency throughout the day irrespective of the level of muscular contraction (percentage maximum voluntary contraction), suggests that surgeons fatigue throughout an

operation. It also suggests that baseline fatigue is not 'improved' with practice and it is likely that all people have different levels of muscular activation frequencies, over which they have little control.

We have shown that there is a very little decrease in fatigue index while performing desk work. This leads us to deduce that the decrease in fatigue index during an operation is solely due to the operating.

It should be noted that the mean frequency shift can only be considered as a fatigue index, and not actual fatigue. Fatigue is a very subjective term, and can vary from individual to individual. The change in mean frequency is, therefore, a representation of the muscle's shift towards a fatigued state.

As is shown from the percentage maximum voluntary contraction, each of the surgeons used their brachioradialis muscles at a higher level than they used their mid-deltoid muscles throughout the operations. Because of this, it stands to reason that both mid-deltoid and brachioradialis muscles should fatigue at different rates. The rate at which the brachioradialis muscle fatigued was approximately 1.57 times more than the mid-deltoid as shown in Figures 3 and 4. This suggests that this muscle is being used twice as much during the operations. This could be due to the fact that most of the actions performed during the operations use the forearms, and that they are continuously lifting the forearms and hands against gravity, and they are not being rested on supports for much of the operation. This correlates with all surgeons reporting that their forearms felt fatigued after a long operation. The linear relationship between percentage in mean frequency and time allows us to predict the fatigue index of both the mid-deltoid and brachioradialis muscles at the end of an operation based on an initial mean frequency measurement.

The surgical day often falls into two different categories, either many short operations (up to 90 min in length), or one long operation (up to 10 h in length). These can have differing levels of complexity requiring differing degrees of accuracy. It is likely that the decrease in fatigue index is associated with an increase in tremor. This will have an impact on long operations, as often the most technically difficult section, a vascularised free flap reconstruction, takes place at the end of the procedure. Surgeons should, therefore, be aware that their muscles will be fatigued by this stage and it may be worth a fresh surgeon performing this section of the operation. Short operations can also be very technically demanding, for example, a stapedectomy requires the creation of a 0.6-mm stapedotomy through which is 0.4-mm piston is inserted.¹⁶ Excessive hand tremor caused by muscular fatigue would, therefore, decrease the surgeon's accuracy and subsequently the outcome of this operation. Operations requiring high degrees of accuracy should therefore be performed early on in the day.

Limitations

It is very difficult to apply this practically, as there is no specific point at which an individual is fatigued. All that we can determine is that a person does fatigue during an operation. And that the longer the operation, the more fatigued they will be.

Conclusions

Muscular fatigue increases throughout a day of operating directly proportional to time. There is no significant difference in muscular fatigue between the consultants and registrars. The amount of muscular usage correlates with the level of muscular fatigue, with the brachioradialis muscle being used more than the mid-deltoid and it fatigues more rapidly. Surgeons should be aware that their fatigue levels will increase as an operation progresses; therefore, if possible, more complex parts should be performed as early as possible, or, in the case of very long operation, a change in surgeons may be necessary.

Acknowledgements

The authors would like to acknowledge support from the EPSRC for the funding of the project. They would also like to acknowledge the surgeons and theatre staff at the Queen Elizabeth Hospital Birmingham, UK, and the University Hospital of North Staffordshire, UK that participated in the collection of the data.

References

1. Enoka RM. Mechanisms of muscle fatigue: central factors and task dependency. *J Electromyogr Kinesiol* 1995; **5**: 141–9.
2. El Ahrache K, Imbeau D, Farbos B. Percentile values for determining maximum endurance times for static muscular work. *Int J Ind Ergonomics* 2006; **36**: 99–108.
3. Dimitrova NA, Dimitrov GV. Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. *J Electromyogr Kinesiol* 2003; **13**: 13–36.
4. Chabran E, Maton B, Fourment A. Effects of postural muscle fatigue on the relation between segmental posture and movement. *J Electromyogr Kinesiol* 2002; **12**: 67–79.
5. Roman-Liu D, Tokarski T, Wojcik K. Quantitative assessment of upper limb muscle fatigue depending on the conditions of repetitive task load. *J Electromyogr Kinesiol* 2004; **14**: 671–82.
6. Farina D, Merletti R. Comparison of algorithms for estimation of EMG variables during voluntary isometric contractions. *J Electromyogr Kinesiol* 2000; **10**: 337–49.
7. Rangayyan RM. *Biomedical Signal Analysis: A Case-Study Approach*. London: John Wiley, IEEE Press, 2002; 552.
8. Uhrich ML, Underwood RA, Standeven JW, Soper NJ, Engsborg JR. Assessment of fatigue, monitor placement, and surgical experience during simulated laparoscopic surgery. *Surg Endosc* 2002; **16**: 635–9.
9. Quick NE, Gillette JC, Shapiro R, Adrales GL, Gerlach D, Park AE. The effect of using laparoscopic instruments on muscle activation patterns during minimally invasive surgical training procedures. *Surg Endosc* 2003; **17**: 462–5.
10. Lin MI, Liang HW, Lin KH, Hwang YH. Electromyographical assessment on muscular fatigue – an elaboration upon repetitive typing activity. *J Electromyogr Kinesiol* 2004; **14**: 661–9.
11. Ebaugh DD, McClure PW, Karduna AR. Effects of shoulder muscle fatigue caused by repetitive overhead activities on scapulothoracic and glenohumeral kinematics. *J Electromyogr Kinesiol* 2006; **16**: 224–35.
12. Sogaard K, Blangsted AK, Jorgensen LV, Madeleine P, Sjogaard C. Evidence of long term muscle fatigue following prolonged intermittent contractions based on mechano- and electromyograms. *J Electromyogr Kinesiol* 2003; **13**: 441–50.
13. Bacher M, Scholz E, Diener HC. 24 hour continuous tremor quantification based on EMG recording. *Electroencephalogr Clin Neurophysiol* 1989; **72**: 176–83.
14. Boose A, Spieker S, Jentgens C, Dichgans J. Wrist tremor: investigation of agonist-antagonist interaction by means of long-term EMG recording and cross-spectral analysis. *Electroencephalogr Clin Neurophysiol* 1996; **101**: 355–63.
15. Christensen H. Muscle activity and fatigue in the shoulder muscles during repetitive work. *Eur J Appl Physiol* 1986; **54**: 596–601.
16. Hughes GB. The learning curve in stapes surgery. *Laryngoscope* 1991; **101**: 1280–4.
17. Knaflitz M, Bonato P. Time-frequency methods applied to muscle fatigue assessment during dynamic contractions. *J Electromyogr Kinesiol* 1999; **9**: 337–50.
18. Xie H, Wang Z. Mean frequency derived via Hilbert–Huang transform with application to fatigue EMG signal analysis. *Comput Methods Programs Biomed* 2006; **82**: 114–20.

APPENDIX 1

Collection and analysis of EMG signals

1. The EMG signals were collected using a Bagnoli-16 system, with a bandpass filter within the signal conditioning unit of 20–500 Hz, and pre-amplified with a system gain of 1000. The data were captured using the DE-2.1 electrodes, the Delsys EMGWorks Acquisition 3.1.0.5, and a National Instruments DAQ Card-6036E Data acquisition card sampled at a rate of 1000 Hz. The DE-2.1 electrodes are organised in a single differential configuration. It consists of two 10.0 × 1.0 mm Ag contacts separated by 10 mm. The contacts lie within a 41 × 20 × 5 mm casing. The data were acquired at a sampling rate of 1 kHz and 16-bit precision.
2. The raw EMG signals were analysed off-line without any pre-processing other than the bandpass of the signal conditioning unit (20–500 Hz). Because of the non-stationarity nature and the length of the captured signals,¹⁷ conventional power spectral density (PSD) methods for determining fatigue were not used. The mean frequency or fatigue index was calculated within each acceptable contraction using a derivative of the Hilbert–Huang transform technique.¹⁸ This method calculates the mean frequency within a time window using the sum of the mean instantaneous frequencies from each empirical mode, and has demonstrated low mean frequency variances between different window sizes. A 500 ms window size was chosen so that small bursts of muscle activity during the operation could be captured. As it is impossible to keep each muscle contraction at a specific percentage of their maximum voluntary contraction (MVC), each surgeon's 100% MVC was chosen as 607 mV for the mid-deltoid and 345 mV for the brachioradialis. These were chosen as MVC as it correlated to the average MVC voltage for the control part of the study. All portions of the EMG signals were scaled as a percentage of this maximum. This was performed by fitting a root mean squared (RMS) envelope to each recording's window, and the maximum RMS calculation was used as percentage maximum voluntary contraction. During the day, the collected EMG data were then normalised as a percentage of the MVC, so that it would be represented as the total effort in a percentage of the maximum required to complete the task. The choice of 100% maximum voluntary contraction seemed reasonable as most of the signal amplitudes analysed fell within the 5–30% maximum voluntary contraction. Using the Borg scale to calculate MVC, this is described as extremely weak-to-moderate muscular activity. Only contractions above 5% maximum voluntary contraction were used to determine the mean frequency.