

LOCALIZED MUSCLE FATIGUE: REVIEW OF THREE EXPERIMENTS

KUMAR S

Ergonomics Research Laboratory, Department of Physical Therapy, University of Alberta, Edmonton, Canada

Corresponding author: Shrawan Kumar, Ergonomics Research Laboratory, Department of Physical Therapy, University of Alberta, Edmonton, Canada T6G 2G4, e-mail: shrawan.kumar@ualberta.ca

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ABSTRACT

Background: Fatigue considerably affects rehabilitation and ergonomics. Many approaches to this complex phenomenon, ranging from physiological to psychological, have been used to obtain meaningful fatigue measurements. However, none of the methods in the literature measure fatigue directly. It is therefore of considerable interest to determine which indirect methods best represent the state. **Method:** Fatiguing contraction was measured at maximum voluntary contraction (MVC) and 40% MVC in the biceps brachii, quadriceps and erector spinae muscles (three separate experiments). The most-reported objective measurements (contraction force, median electromyographic frequency, heart rate, muscle bed oxygenation and muscle blood volume) and subjective measurements (visual analog score, body part discomfort rating and perceived exertion rate) were simultaneously recorded. The data from the three experiments underwent separate statistical analysis. Descriptive statistics, linear mixed effects (to examine force fatigue predictability) and trend analysis (with between and within-subject correlations) were calculated. **Results:** Univariate ANOVA on all objective variables showed that gender was a significant factor ($p < 0.001$). All subjective and objective variables were significant ($p < 0.05$ – 0.001) in predicting force fatigue. However, the percentage variability explained remained small. By combining variables, the variability explained increase to between 60.2% and 71.9%. Correlations between variables were small but significant ($p < 0.05$ – 0.001). Among single variables, median electromyographic frequency was a slightly better predictor of MVC fatigue ($p < 0.001$) and visual analog score for sub-MVC ($p < 0.001$). **Conclusion:** It is desirable not to measure or predict fatigue based on one variable alone. Combining variables improves measurement and prediction. Single-variable indexing of localized muscle fatigue is problematic.

Key words: fatigue, force, electromyography, visual analog score.

RESUMO

Fadiga Muscular Localizada: Revisão de Três Estudos

Contexto: A fadiga afeta consideravelmente a reabilitação e ergonomia. Muitas abordagens a este fenômeno complexo, incluindo fisiológicas e psicológicas, têm sido utilizadas para obter medidas significativas da fadiga. No entanto, nenhum dos métodos descritos na literatura mede diretamente a fadiga. É, portanto de interesse a determinação de quais dos métodos indiretos melhor representa a condição de fadiga. **Método:** A fadiga por contração foi medida na contração voluntária máxima (CVM) e 40% da CVM em músculos bíceps braquial, quadríceps e músculos eretores da coluna (três avaliações independentes). As medidas objetivas mais relatadas (força de contração, frequência mediana na eletromiografia, frequência cardíaca, oxigenação do leito muscular e volume sanguíneo muscular) e as medidas subjetivas (escala visual analógica, avaliação de desconforto em partes do corpo e avaliação percebida do esforço) foram anotadas simultaneamente. Dados dos três estudos foram submetidos a análises estatísticas separadamente. Dados estatísticos descritivos, efeitos lineares mistos (para avaliar a previsibilidade da força de fadiga) e análise de tendências (correlação comparativa intra e extra indivíduos) foram calculadas. **Resultados:** ANOVA univariada em todas as variáveis objetivas mostraram que o sexo foi um fator importante ($p < 0,001$). Todas as variáveis subjetivas e objetivas foram significantes ($p < 0,05$ – $0,001$) para prever a força de fadiga. No entanto, as variações explicáveis de porcentagem permaneceram pequenas. Através da combinação de variáveis, a variabilidade explicável aumentou entre 60,2% e 71,9%. As correlações entre as variáveis foram pequenas, porém significativas ($p < 0,05$ – $0,001$). Entre as variáveis simples, a medida da frequência da eletromiografia foi o fator preditivo um pouco melhor para fadiga CVM ($p < 0,001$), assim como a escala visual analógica para sub-CVM. **Conclusão:** É desejável que não se meça ou prediga a fadiga com base em apenas uma variável. A combinação de variáveis melhora as medidas e predição da fadiga. Indexar uma variável simples na fadiga muscular localizada é portanto problemático.

Palavras-chave: fadiga, força, eletromiografia, escala visual analógica.

INTRODUCTION

While the connotation of fatigue, in context, is easy to comprehend, its complexity in scientific domain is considerable. Fatigue, as it relates to human performance, is important from both physical and cognitive perspectives. Even in the physical domain, the nature of fatigue for the entire organism or a specific muscle is different. While the fatigue of organism may be described by the progressive reduction of reserve energy or the rate of its expenditures, a similar description for individual tissues is obscure. The organism fatigue can also be expressed by subjective measures, such as rate of perceived exertion¹. Individual tissues, such as connective tissues, can undergo mechanical fatigue as a result of prolonged or repetitive exertion. Muscles, on the other hand, generally undergo physiological and contractile fatigue. Whereas the experience of muscle fatigue has been wide spread, a universally valid method to determine it has not emerged.

A variety of methods have been used for measuring localized muscle fatigue. These fall under categories of objective and subjective methods. Objectively the most clear indication of fatigue is the duration for which a load can be held or decay in the force over time. The magnitude of force (strength) and duration it can be held (endurance) was initially demonstrated by Rohmert². However, the ability to sustain a load or increase the level of strength is subjectively modifiable. Also despite the discomfort, people can maintain their contraction for a period longer than the endurance time, if motivated to do so. Thus the strength and endurance curve is obscured making it difficult to measure even force fatigue quantitatively.

Electromyography has been considered a reliable tool for an indication of localized muscle fatigue^{3,4}. In recent years other authors have stated that the median frequency (MF) of the EMG power spectrum is sensitive to the physiological manifestation of fatigue^{5,6,7,8}. The rate of decline of the MF during a sustained contraction was used by them as an index of muscle fatigue. An accompanying increase in EMG amplitude has also been considered a quantitative measure of fatigue^{5,6,9,10}. Other spectral parameters of the EMG signal such as mean power frequency¹¹, the ratio of low frequency to high frequency¹² and the number of zero crossings¹³ have also been used in some studies as indices of muscle fatigue but were found to be more affected by noise than the measure of median frequency¹⁴. Though among EMG variables the slope of decline of the median frequency in sustained contractions has been considered as an index of fatigue, when it is compared against the standard of inability to hold or maintain a force the slope of MF decline does not mirror it^{5,6}. On the other hand, the EMG amplitude increases with the decrease in force and this inverse relationship is variable.

Therefore, the EMG variables though helpful indicators are far from being a gold standard measure of muscle fatigue.

Among other local factors which affect muscle fatigue is blood perfusion of the muscle and level of its oxygenation¹⁵. Until recently these measurements could not be made except invasively, hence largely ignored. With the advent of the Near-Infrared Spectroscopy such measurements can now be made noninvasively^{16,17}. This is a noninvasive technique which depends on detecting continuous stream of reflected light from the light source of the device through muscle tissue. The light source of the device emits 700-900 nm wavelength light into the muscle. The heme and the myoglobin are the primary absorbing compounds of these frequencies, and the absorption of light by the heme group is detected as change in optical density. This again is a semi quantitative measure and expressed in percent change in optical density allowing us to infer the oxygenation/deoxygenation of the blood in the muscle and its blood volume. Using this device several authors have presented their data. These variables have been studied in the fore arm muscles^{18,19,20,21}. De Blasi et al.¹⁷ studied oxygen consumption of the brachio-radialis muscle and its recovery time. They did not find any difference in the oxygen uptake of the muscle in isometric maximal voluntary contraction (MVC) with and without vascular occlusion. However, vascular occlusion resulted in complete desaturation of the haemoglobin and myoglobin in 15 to 20 seconds. A separate study reported that the oxygen desaturation rate occurring during incremental levels of isometric exercise without vascular occlusion was not proportional to the strength of the contraction¹⁹. It was reported that the tissue oxygenation at low levels of isometric contraction (5, 10, 15 and 50% MVC) of the extensor carpi radialis brevis muscle resulted in deoxygenation to 89%, 81%, 78% and 48% of the resting value, which was assigned 100%²¹. They stated that this oxygen depletion may be directly linked to the muscle fatigue. After a comparative study of submaximal isometric contractions (10% and 30% MVC) measured by NIRS and direct venous blood sampling suggested a caution in application of NIRS technology²⁰. However, a host of other studies have reported oxygenation and blood volume in mainly quadriceps and erector spinae. Nonetheless, a direct comparison between the force fatigue and deoxygenation and blood perfusion has not been reported.

It is generally understood that there is no direct reliable quantitative measure of localized muscle fatigue. Therefore, different authors have chosen one of a variety of indicators of fatigue, such as EMG median frequency, muscle deoxygenation, oxygen uptake, heart rate, rate of perceived exertion (RPE) and visual analog scale (VAS) scores. The objective of this study was to measure EMG amplitude, median frequency, heart rate, deoxygenation, blood volume, RPE, VAS and Body Part Discomfort Rating (BPDR) in one study for one muscle and examine their relationship with the

force fatigue and their inter-relationship in isometric MVC and 40% of MVC of the erector spinae in sustained contractions. The study was then repeated for quadriceps and biceps brachii in different subjects.

MATERIALS AND METHODS

Equipments and Tools

EMG Devices

The EMG electrodes were active surface electrodes (Model DE-2.3, Delsys Inc., Wellesley, MA). They were made of 2 silver – silver chloride bands (10 mm long and 1 mm wide) mounted in parallel 1 cm apart in a moulded block. The block also housed a miniature preamplifier with a gain of 10 (to amplify the signal on site) and a high pass filter at 20 Hz. These electrodes were connected to amplifiers worn around waist by means of a short cable which had multiple gain. The amplifiers had a time constant of 20 ms, a low nonlinearity, and 92 dB signal to noise ratio.

Polar Vantage XL Heart Rate Monitor

The device consisted of a transmitter incorporated in a chest band worn by subjects. The transmitter relayed the heart rate to a wristwatch receiver which could collect and hold data for up to 33 hours. This heart rate data was subsequently downloaded into a data logger.

Near Infrared Spectroscope

The model MRM-96 and the accompanying software NIRCOM from NIM, Inc., Philadelphia was used in this study. This was a noninvasive blood oxygen and blood volume trend monitor designed to measure data from the muscle bed. It was a continuous wave spectrometer that operated by transmitting light into the skin below the probe, collecting reflected light, and processing the signals by computing optical density from the measurements. The light that was not absorbed or scattered away from the detector, was collected by the photo-diode detectors in the probe and converted to digital data. The MRM-96 emitted lights of wave lengths 760 and 850 nm which were indicators of the relative quantities of oxy- and deoxy-haemoglobin. With the relative change in quantities of these compounds the light absorbed by them changed as well. The oxygenation level was indicated by the difference between two lights and the blood volume in the muscle bed was indicated by the sum of the two lights.

Load Cell and Force Monitor

A load cell (LCCB-IK) from Omega, Laval, PQ, was connected to the Force Monitor (Prototype Design, Ann Arbor, MI). The tension load cell fed to the Force Monitor which conditioned and amplified the signal and displayed the reading

through a LED display. The output of the Force Monitor was fed to the Data Translation A to D card (DT2801A) of the computer for continuous sampling of the signals.

Subjective Measures

Visual Analog Scale

The subjects were provided a 10 cm long horizontal line with anchors at the two ends reading “not fatigued at all” and “worst imaginable fatigue”. The subjects crossed the horizontal line according to their feeling at the time of measurement. For MVC the subjects were given this test before the start and after the end of the contraction. However, for 40% the subjects were given this test at the start and every minute thereafter till the end of the contraction.

Body Part Discomfort Rating (BPDR)

The subjects were provided with a blank line diagram of the entire body and asked to place a “x” on the part of the body where they felt discomfort due to fatigue. Subsequent to placing an “x” they were asked to rate their fatigue on a scale of 1 to 10, 1 being no fatigue and 10 being the maximal fatigue. Like the VAS scoring, this test was also given twice for MVC and one minute interval for 40% MVC.

Rate of Perceived Exertion

The rate of perceived exertion (RPE) was filled out by the subjects. The RPE was scored on a 20 point scale. Like other subjective measures, the subjects determined their RPE only twice. RPE was administered at the same times as the other subjective measures.

Common Procedures

The study was approved by the Health Research Ethics Board and all subjects provided an informed consent. The subjects were remunerated at the rate of \$10.00 per hour. Normal and healthy male and female subjects with no self-reported cardiovascular, musculoskeletal, neuromuscular or psychiatric disorders were recruited from the university student population through a campus wide advertisement. After the subjects had signed the informed consent form they were familiarized with the equipment and procedures. They were also given a practice session with the experiment. They were asked to come another day, when they were first weighed and measured. On the day of the experiment, the Polar chest band was applied after slightly wetting the contact of the device. The wrist band receiver was tied around the wrist and checked to ensure that the device was working properly. Such prepared subjects were allowed to rest for a period of five minutes to obtain the resting values of heart rate, blood oxygenation, blood volume and the EMG signals. Subsequently, the subjects were required to give their isometric

MVC for trunk extension without changing the postural preset angle. The subjects were instructed to build their strength to a maximum gradually within the first two seconds and maintain the maximal level of contraction for another three seconds at which time the contraction was terminated. Subsequent to this contraction the subjects were given a five-minute rest. This strength value was taken at the subjects 100% effort.

The subjects, after a five-minute rest, acquired the task position described above. In front of the subject a visual feedback mechanism was adjusted to show their 40% of isometric MVC. The subjects were instructed to build their strength to a maximum gradually within the first two seconds and maintain the maximal level of contraction for another three seconds at which time the contraction was terminated. Subsequent to this contraction the subjects were given a five-minute rest. This strength value was taken at the subjects 100% effort.

The subjects, after a five-minute rest, acquired the appropriate task position. In front of the subject a visual feedback mechanism was adjusted to show their 40% of isometric MVC. The subjects were instructed to exert in isometric mode such that their contraction indicator reached one displayed on the screen and they maintained it as long as they could without the force level dropping below 35% MVC. After this exertion the subjects were provided a rest of 30 minutes at which time they were asked to exert their MVC and hold it in maximal effort as long as they could.

Subjects

Erector Spinae

Six healthy male and six healthy female subjects volunteered with a mean (standard deviation) age, weight and height of 32.5 (4.7) years, 82.7 (9.0) kg and 170 (5.2) cm for males and 35.6 (15) years, 61.1 (8.8) kg, and 166.88 (7.4) cm for females.

Quadriceps

Ten healthy male and ten healthy female subjects with mean (standard deviation) age, weight and height of 28.5 (4.4) years, 76.3 (8.7) kg and 178.3 (5.5) cm; and 29.0 (8.7) years, 58.1 (6.8) kg, and 164 (8.0) cm for male and female samples respectively.

Biceps Brachii

Nine healthy male subjects with a mean (standard deviation) age, weight and height of the experimental sample was 25.7 (2.1) years, 78.9 (9.5) kg and 180.1 (4.3) cm respectively.

Task

Trunk Extension

The subjects stood in front of an iron chain anchored to the floor with an intervening load cell at one end and an industrial size handle at the other. The subjects flexed their trunks by 45° in stooping posture. The level of the handle was adjusted individually to the height of the subject's hands. In this position, the subjects provided their erector spinae contractions according to the protocol described above.

Knee extension

The subjects were required to give their isometric contractions of knee extension without changing the postural preset angle (knee and hip angles 90°) while seated on a Quadriceps Strengthening Table.

Elbow Flexion

The subjects stood upright in front of an iron chain anchored to the floor with an intervening load cell and a round handle at the upper end. The subjects flexed their right (dominant) arms by 90° at the elbow while the upper arms hung vertically down from the shoulders. The level of the handle was adjusted individually to the height of the subject's hand. In this position, the subjects were required to give their isometric contractions of elbow flexion without changing the preset angle at the wrist, elbow or shoulder according to the protocol described above.

Specific Procedures: Trunk extension

Their erector spinae were palpated and the pre-calibrated NIRS probe was applied on the right erector spinae muscle at L3 level. Adjacent to the NIRS probe, bipolar surface electrodes were applied to skin over the muscle after abrading it with alcohol-acetone soaked paper towel at T10 and L1 levels on the right side and T10 and L3 levels on left erector spinae. After application of the probe and the electrodes, the subjects were grounded and it was ensured that the two pre-calibrated measuring devices were working as desired.

Specific Procedure: Knee extension

Subjects' vastus lateralis and vastus medialis were palpated and the pre-calibrated NIRS probe was applied on the right vastus lateralis. Adjacent to the NIRS probe, bipolar surface electrodes were applied to the skin over the vastus lateralis and vastus medialis 2 cm and 4 cm proximal to the myotendinous junction after abrading it with alcohol-acetone soaked paper towel. After application of the probe and the electrodes, the subjects were grounded and it was ensured that the two pre-calibrated measuring devices were working as desired.

Specific Procedures: Elbow Flexion

The subject's biceps were palpated and the pre-calibrated NIRS probe was applied on the muscle. Adjacent to the NIRS

probe, a single bipolar surface electrode was applied to skin over bicep brachii after abrading it with alcohol-acetone soaked paper towel. After application of the probe and the electrode, the subjects were grounded and it was ensured that the two pre-calibrated measuring devices were working as desired.

Data Acquisition

The suitably conditioned and amplified data from the load cell, NIR Spectroscope and EMG amplifier were sampled at 1 kHz for the entire duration of isometric MVC, 40% MVC fatiguing contraction and maximal fatiguing contraction continuously. These data were fed to Data Translation (DT 2801A) A to D board for conversion into digital values. These were then stored in the computer memory. A Pentium computer was used as the controller and storage device. The data acquisition was carried out using a specially written software for data collection and controlling the experiment.

Data Analysis

The data of the three experiments were analyzed separately. The force trace was smoothed using 7-point smoothing routine repeated once. From this trace the peak value was read and the average value calculated. Task duration for each individual was divided into 10 equal parts and values corresponding to each decile of the task durations were extracted. The decile values of all subjects were pooled within each experiment separately and descriptive statistics calculated for further statistical analysis. A similar processing was done for heart rate, muscle blood oxygenation, muscle-bed blood volume, and EMG amplitude. The EMG signals were subjected to Fast Fourier Transform analysis to obtain the median frequency according to methods described in Kumar and Narayan⁵ and Kumar et al.⁶. These quantitative values were used to develop magnitude of the signal and the task decile plot.

The statistical analysis consists of four sub – analysis: Descriptive statistics of all characteristics (ii) Analysis based on linear mixed effects to examine the predictability of force through other characteristics such as blood volume, oxygen intake, RPE, VAS and EMG measurements; (iii) Trend analysis to examine progressive change with increasing task duration, and (iv) Between subject and within subject correlation analyses to study interrelationship among measurements.

Linear Mixed Effects Model

A linear mixed effects model with subjects as a random factor and task cycle as the repeated factor were fitted to predict Force under both MVC and 40% MVC contractions. In the model 'subjects' was used as a random component to incorporate repeated measure nature of the experiment in the analysis. Further, it should be noted that all measured characteristics, except gender, are not controlled by the design.

Hence, to study force through the remaining characteristics, like blood volume, oxygen intake, RPE, VAS, a conditional linear mixed model was adopted by considering force as the dependent variable. Pearson Product Moment Correlations among all variables based on both within-subjects covariance and between-subjects matrices were calculated between the magnitude of force and the magnitude of each of the measured variables to determine the marginal strength of correlation of each independent variable with force. A matrix of such correlations was developed for MVC and 40% MVC variables to glean the interrelationship between all independent variables. After eliminating non-significant predictors in the analysis the final model for predicting force was given for both MVC and 40% MVC contractions.

RESULTS

Force and Time

Trunk Extension

The mean maximal voluntary contraction forces were 899 N (238) N and 431 N (135) N for male and female samples respectively. The mean durations for which the maximal contraction effort could be sustained was 68.1 (39.9) s and 72.3 (37.0) s for males and females respectively though the force kept declining through the hold. Similarly the mean durations for 40% MVC were 150.6 N (85.7) s and 139.0 (104) s respectively for male and female samples.

Knee Extension

The mean maximal voluntary contraction forces (standard deviations) for the experimental sample of male and female experimental sample of subjects were 345.7 (125) N and 220.3 (47.4) N respectively. The maximal voluntary isometric contraction of the quadriceps was held for 85.0 (25.1) s and 87.0 (21.5) s by male and female samples respectively. The holding time for 40% MVC contraction for male and female samples were 66.4 (23.9) s and 56.7 (29.0) s, respectively.

Elbow Flexion

The mean maximal voluntary contraction force of the experimental sample for elbow flexion was 197.6 N (S.D. 25.9 N). The mean duration for which the maximal contraction effort could be sustained was 58.1 s (S.D. 17.6 s), though the force exerted kept on declining through the entire duration. Similarly the mean 40% force recorded was 79.0 N (S.D. 10.4 N) and the mean duration for sustaining this load was 275 s (S.D. 35.8 s).

Objective Variables at Maximal Voluntary Fatiguing Contraction

Trunk Extension

At the maximal voluntary contraction the continuous monitoring at 1 kHz of the force, EMG, blood oxygenation and blood volume provided continuous data of the lumbar and thoracic erector spinae are presented for males and females in Figures 1 and 2. The means and standard deviations were presented at every 10% task intervals. A spectral plot of the male lumbar and thoracic erector spinae in MVC fatiguing contraction is shown in Figure 3.

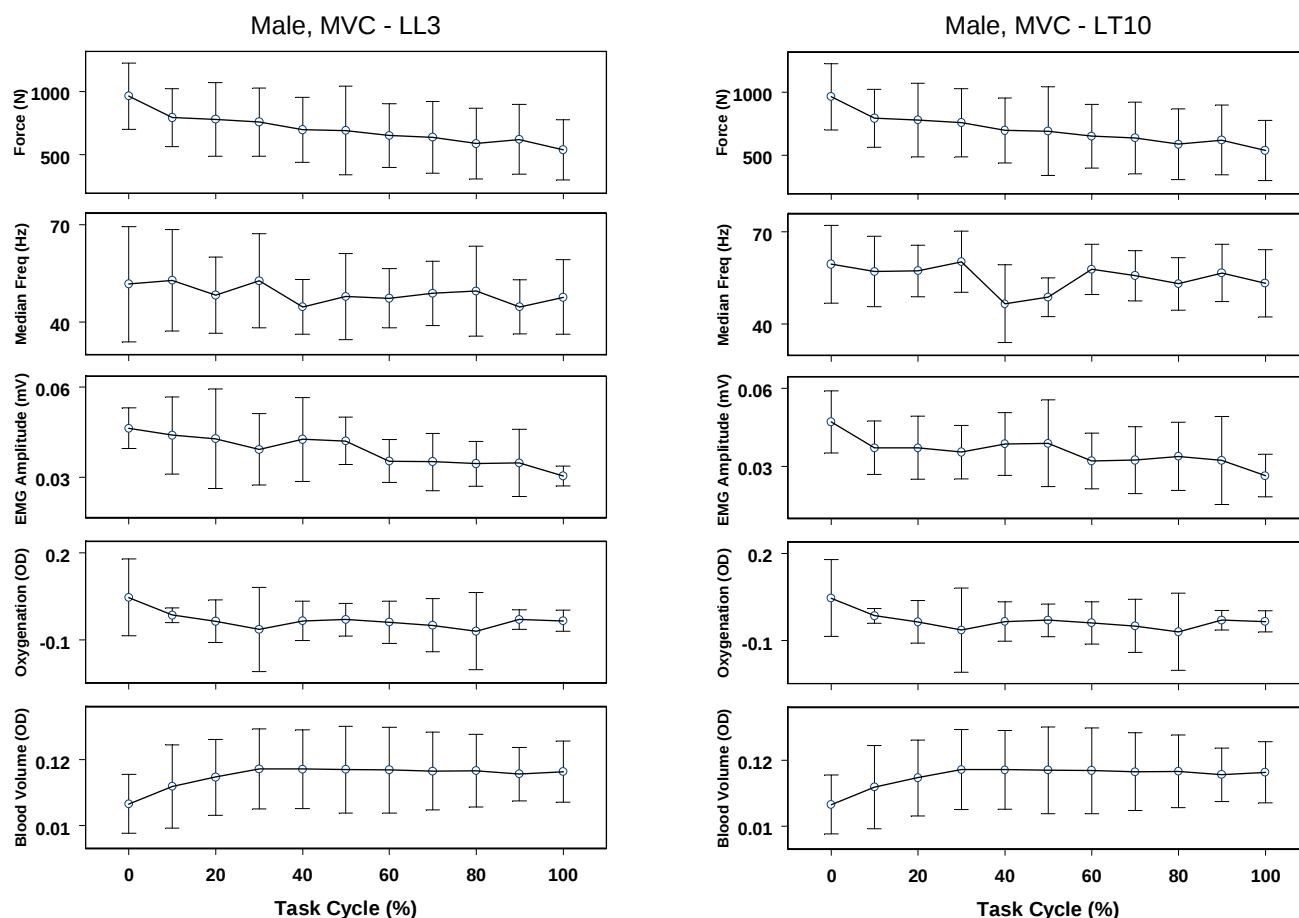


Figure 1. The objective measures at the lumbar and thoracic regions among males during fatiguing maximal voluntary contraction in trunk extension (LL3 – left lumbar erector spinae at 3rd lumbar vertebral level, LT10 – left lumbar ES at 10th thoracic vertebral level).

During the task, the median frequencies declined to 96%, 92%, 82% and 91% respectively. The blood oxygenation and blood volumes declined by 205% and 257%. The EMG amplitude for left lumbar, left thoracic, right lumbar and right thoracic among females declined to 75%, 81%, 76%, and 77% respectively. Their median frequencies declined to 87%, 91% and 98% respectively. Interestingly, the blood oxygenation declined only by 89% and the blood volume increased to 240%.

Knee Extension

The continuous data of the force, EMG amplitude, EMG

median frequency, blood oxygenation and blood volume sampled at 1 kHz are presented in Figures 4 and 5. The means and standard deviations are presented at intervals corresponding to 10% of each task. A steady decline in force was mirrored most closely by the EMG amplitude and less closely by the median frequency. Spectral plots of the vastus lateralis and vastus medialis muscle in MVC fatiguing contraction of males are presented in Figure 6. The spectral plots show a narrowing of the frequency band and decrease

in amplitude of the signals towards the end of the task. By the end of the contraction effort the force dropped to 40% in males and 44% in females. The EMG amplitude for VL2, VL4, VM2 and VM4, among men dropped to 50%, 51%, 44% and 43%, respectively. However, the median frequencies of these muscles in men were 100%, 87%, 93% and 88%, respectively, in the same order. In females the EMG amplitude dropped to 41%, 44%, 37% and 45.5% for VL2, VL4, VM2, and VM4, respectively. In the same order the drop in the median frequency was to 81%, 84%, 79% and 84.9%.

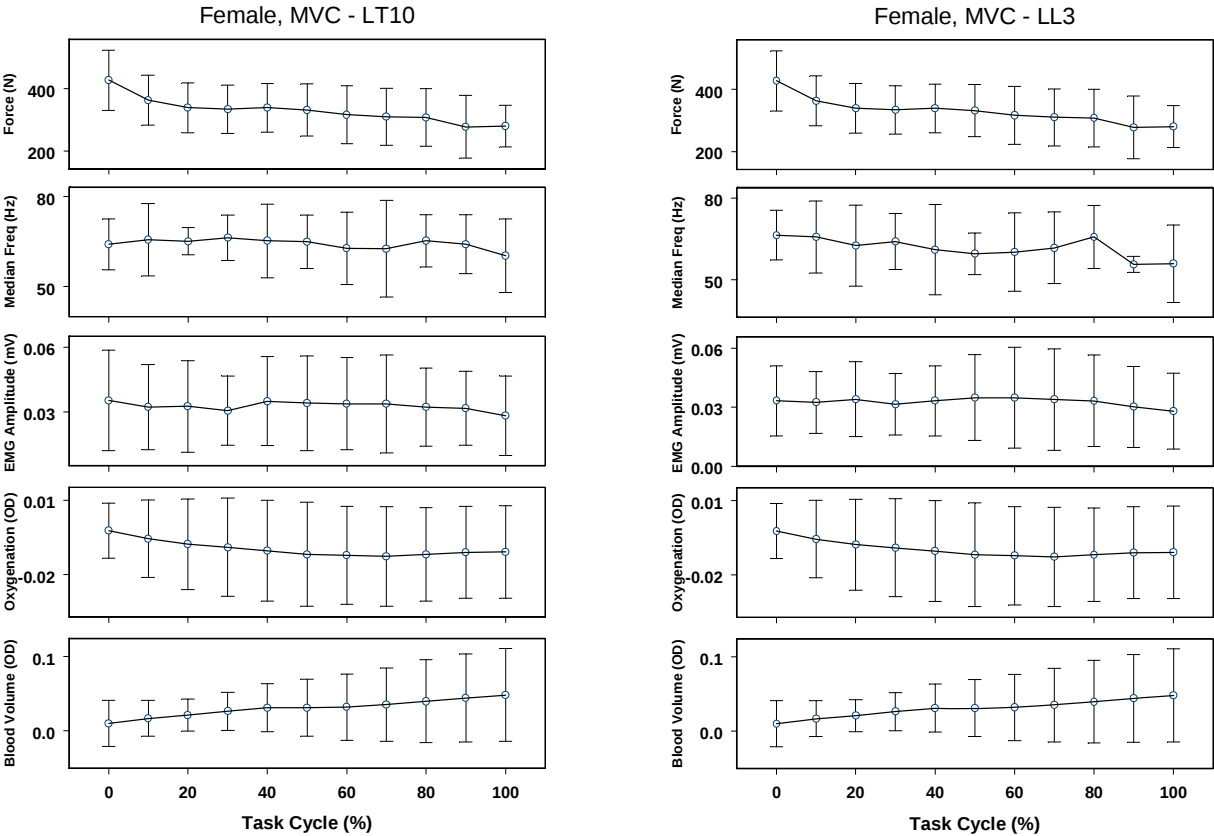


Figure 2. The objective measures at the lumbar and thoracic regions for females during fatiguing maximal voluntary contractions (LL3 – left lumbar ES at 3rd lumbar vertebral level, LT10 – left lumbar ES at 10th thoracic lumbar vertebral level).

Male, MVC

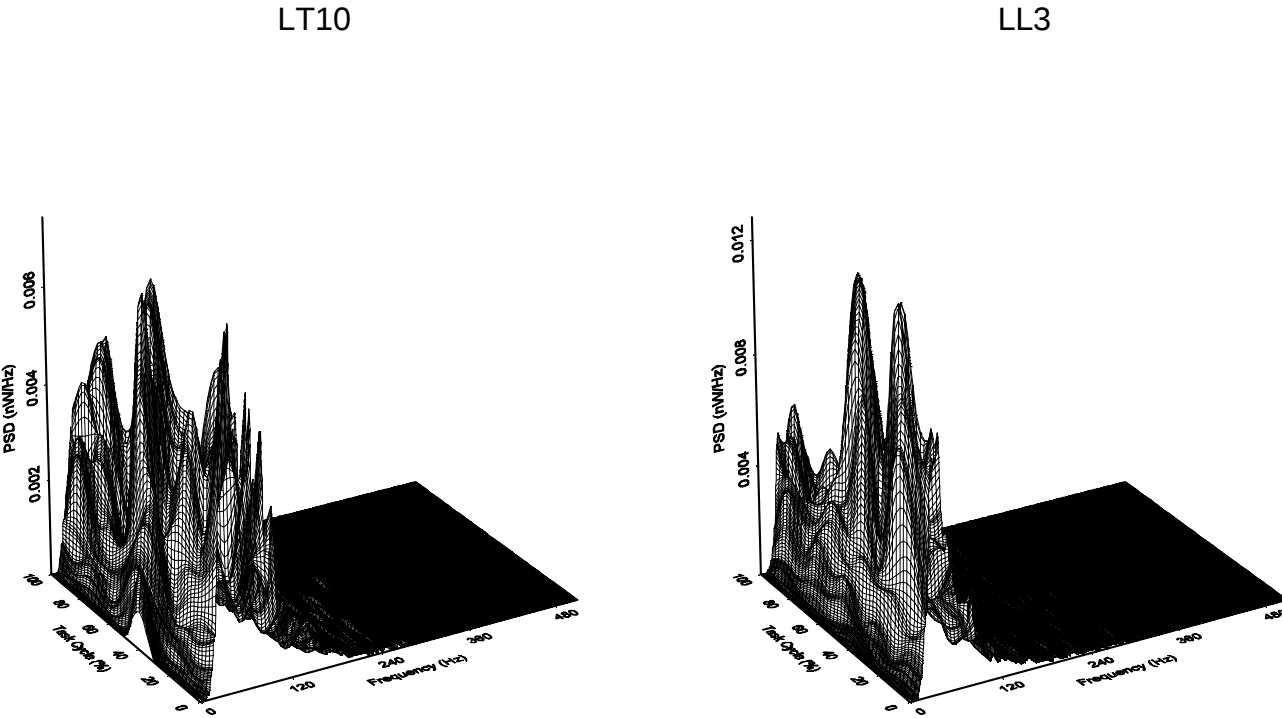


Figure 3. Spectral plots for male lumbar and thoracic regions during fatiguing maximal voluntary contractions.

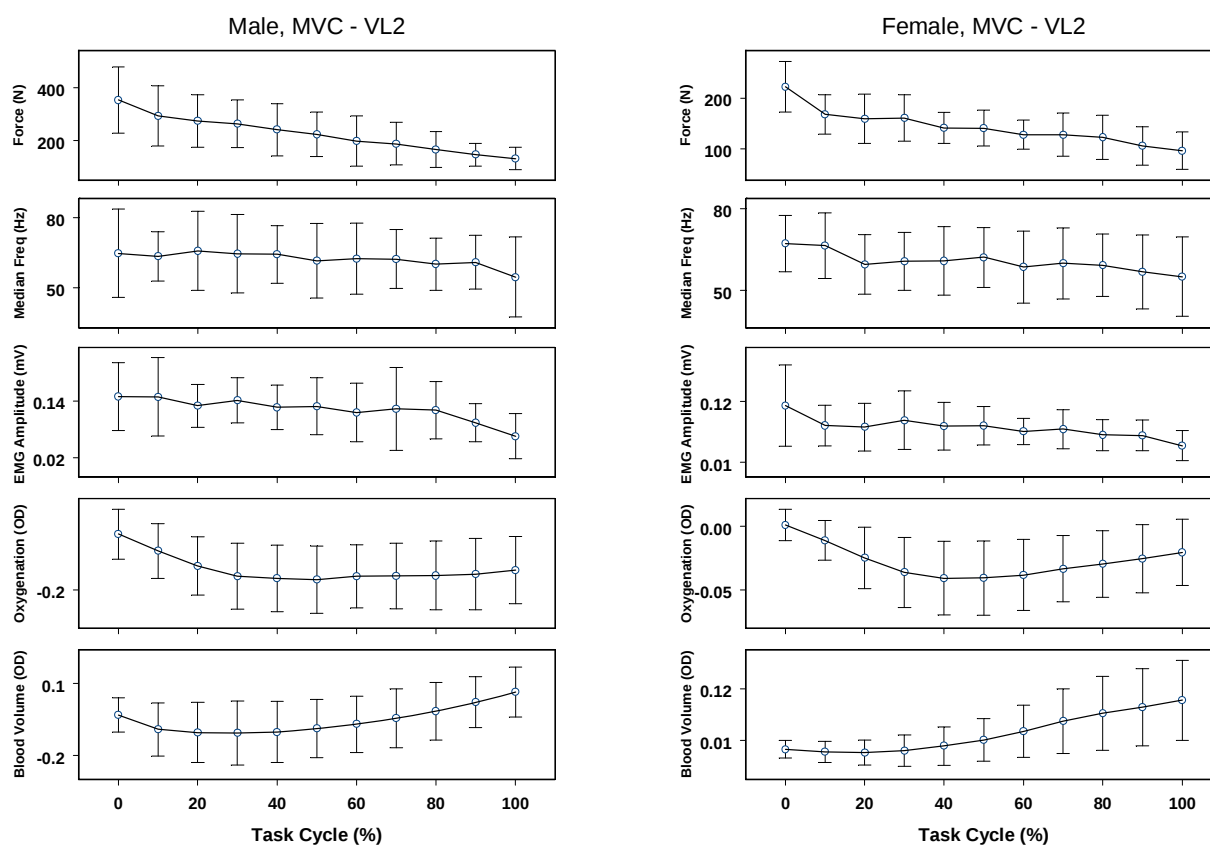


Figure 4. The objective variables measured at vastus lateralis (2 cm. from muscle-tendon junction) in males and females during maximal isometric knee extension fatigue.

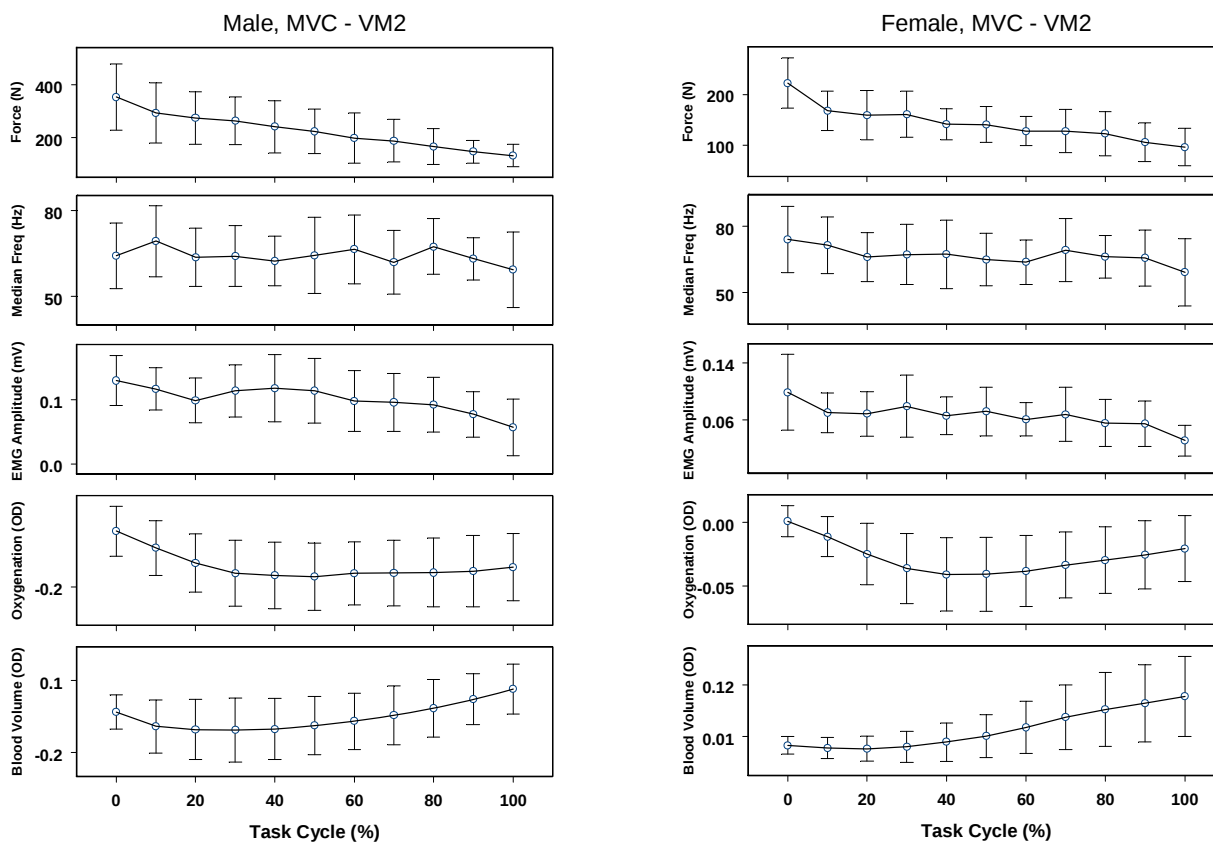


Figure 5. The objective variables measured from vastus lateralis (2 cm. from muscle-tendon junction) in males and females during maximal isometric knee extension fatigue.

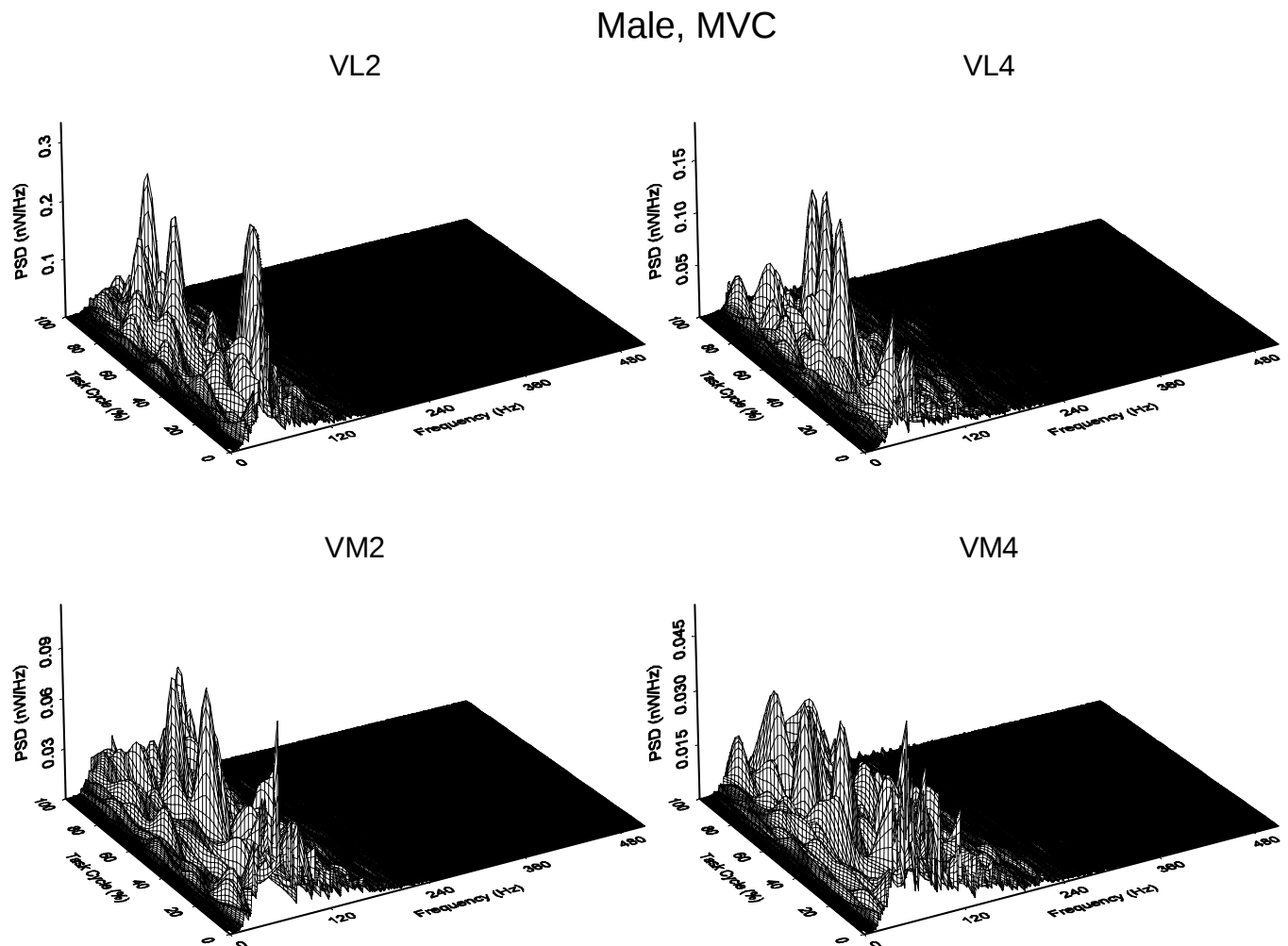


Figure 6. Spectral plots of vastus lateralis and vastus medialis (2 cm. from the muscle-tendon junction) in males.

Elbow Flexion

At maximal voluntary contraction the continuous monitoring at 1 kHz of the force, EMG, blood oxygenation and blood volume provided continuous data presented in Figure 7. The means and standard deviations are presented at every 10% task intervals. A steady decline in force was mirrored most closely by the median frequency of the recorded EMG. The EMG amplitude also declined steadily and progressively for up to 80% of the task cycle beyond which it dropped more rapidly.

Objective Variables at 40% MVC Fatiguing Contraction

Trunk Extension

In this contraction the patterns in variation of measures are presented in Figures 8 and 9. With a progressive and gradual

decline in force there was a gradual and progressive decline in the MF of the EMG and its amplitude (Figures 8 and 9). The spectral analysis of the EMG of the erector spinae in this contraction also demonstrated the same progressive shift of MF as in MVC contractions. The optical density of the blood oxygen and the blood volume continued to increase indicating progressive increase in blood volume (116%) as well as blood oxygen levels (145%) (Figures 8 and 9). The EMG amplitude for the left and right lumbar and thoracic regions were 35%, 45%, 40% and 45% declining from 55%, 53%, 70% and 52% respectively (order left lumbar, left thoracic, right lumbar and right thoracic). Among females the EMG amplitudes of the left lumbar and thoracic and right lumbar and thoracic erector spinae decreased from 70%, 68%, 61% and 64% to 66%, 57%, 56% and 60% respectively. Their median frequencies either remained the same or marginally declined.

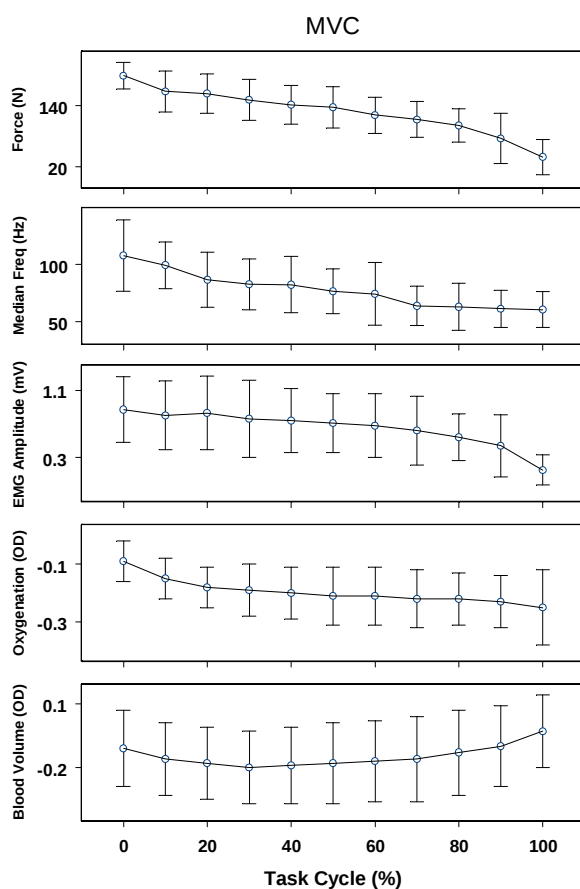


Figure 7. The pattern of the objective variable's response from the biceps brachii in maximal isometric effort of elbow flexion.

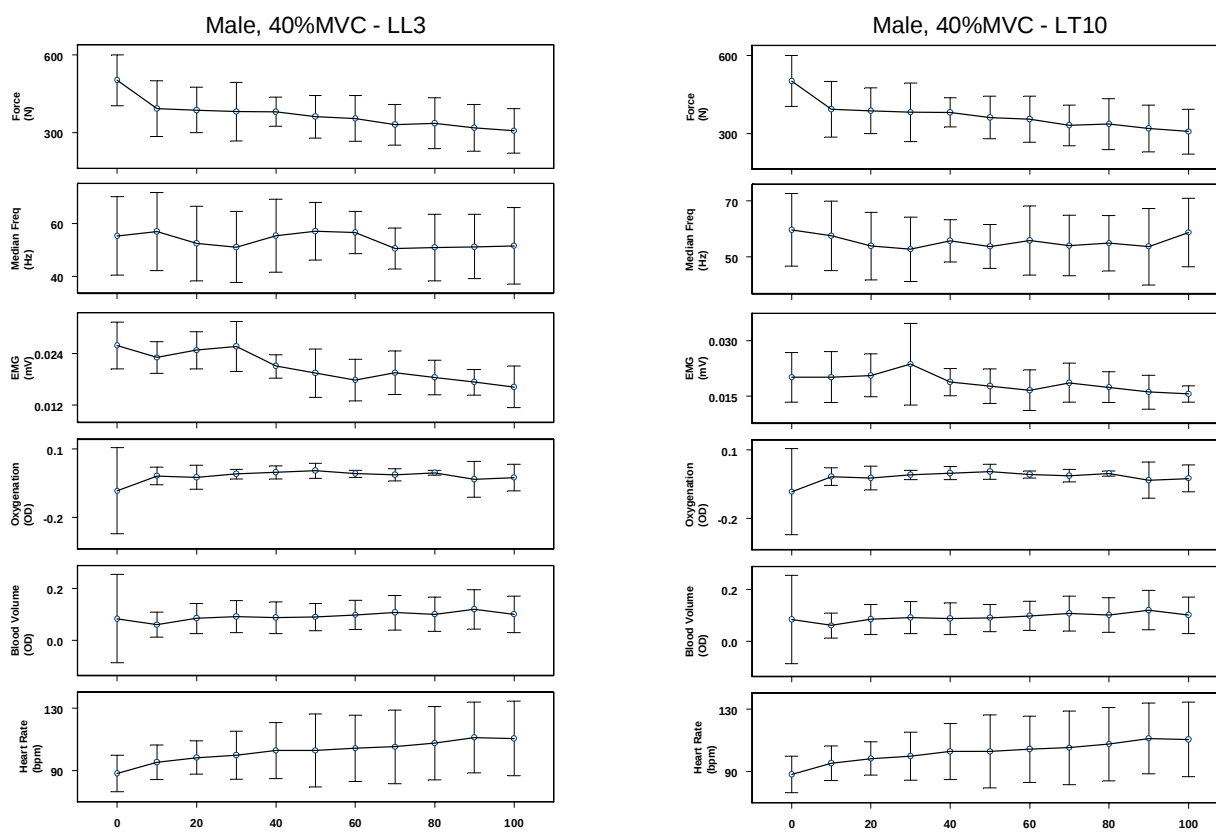


Figure 8. The pattern of the objective variable's response from the lumbar and thoracic erector spinae, in males during 40% MVC fatiguing effort for trunk extension.

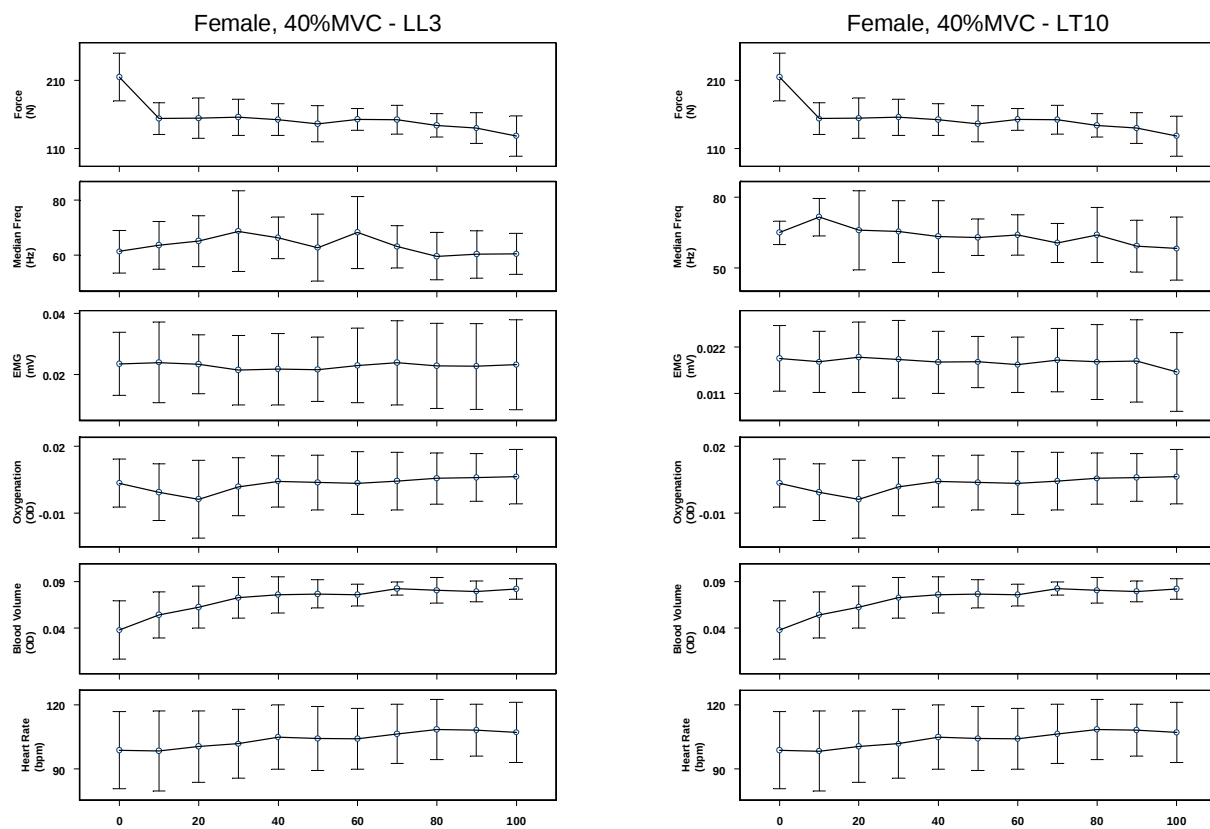


Figure 9. The pattern of the objective variables from the lumbar and thoracic erector spinae in females during 40% MVC fatiguing effort of trunk extension.

Knee Extension

The variable of force, EMG amplitude, median frequency, blood oxygenation, blood volume and heart rate recorded are presented in Figures 10 and 11. Also the subjective variables of visual analog score and the rate of perceived exertion measured at discrete intervals and interpolated in between are plotted in Figures 10 and 11 along with contraction period the force value declined to 23% in males and 24% in females. The EMG score of VL2, VL4, VM2, and VM4, in males dropped to 38%, 31%, 29.4% and 28% respectively. The corresponding median frequency values were 100%, 100%, 94.8% and 99%. In females, the EMG amplitude of VL2, VL4, VM2, and VM4 declined to 49%, 50%, 43.4% and 48%, while the corresponding median frequencies declined to 82%, 88%, 90.7% and 95%. The spectral plots of the vastus lateralis muscle did not show a clear and decisive drop in median frequency in both gender (Figure 12). The blood oxygenation initially dropped rapidly but remaining stable between 20% - 80% of the task cycles and subsequently demonstrated a small rise. The muscle bed blood volume, however, after an initial drop kept on increasing. The heart rate, VAS score and RPE score, after an initial stable

value, kept on rising through the entire duration of the contraction (Figures 10 and 11).

Elbow Flexion

The oxygen uptake, ventilation volume, heart rate, visual analog scale score and the RPE score were obtained at one-minute intervals. Between the intervals the data were interpolated and the values corresponding to appropriate task percentile value extracted from the interpolation. The pattern in variation of measures is presented in Figure 13. With a progressive and gradual decline in force there was a gradual and progressive decline in the MF of the EMG but its amplitude remained relatively stable (Figure 13). The spectral plot of the EMG of the biceps brachii in this contraction did not demonstrate the same progressive shift of MF as in MVC contractions. The optical density of the blood oxygen and the blood volume continued to increase indicating progressive increase in blood volume as well as blood oxygen levels (Figure 13). The oxygen uptake, ventilation volume, heart rate, VAS score and RPE score all progressively increased with a progressive decrease in force (Figure 13).

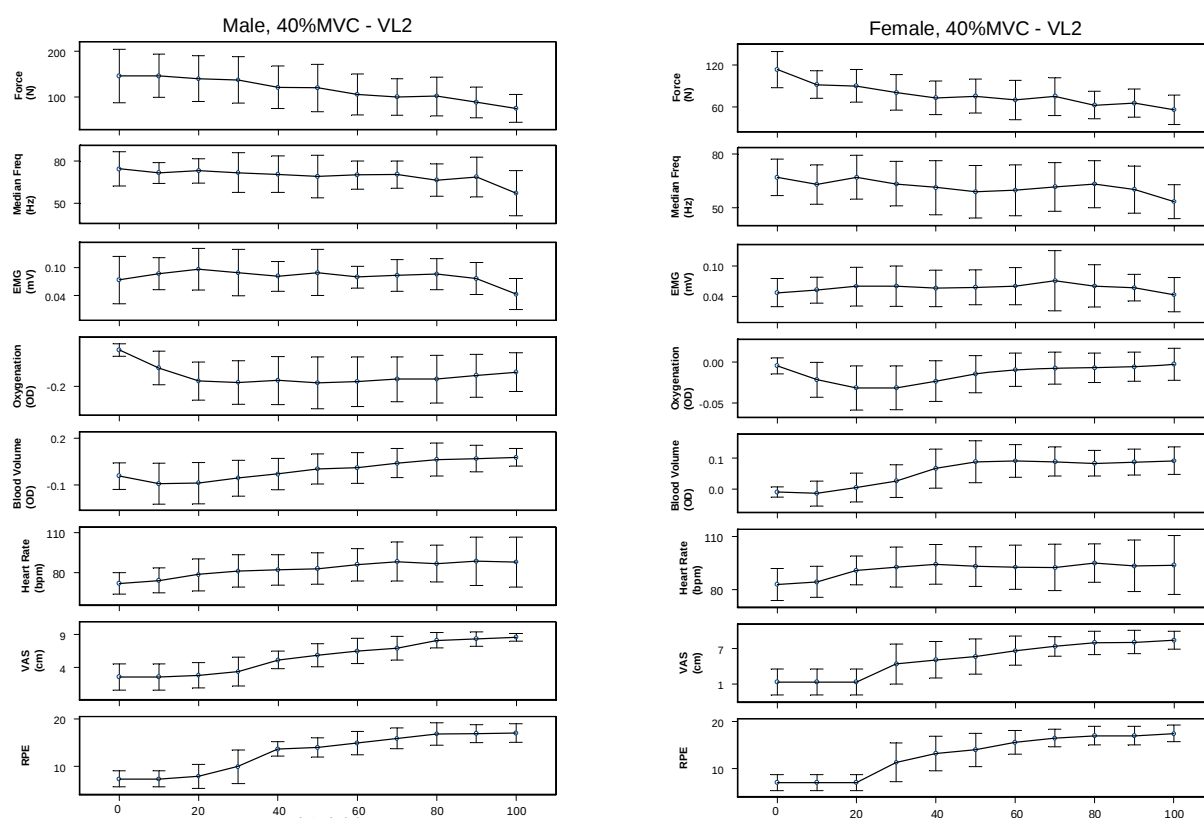


Figure 10. The pattern of objective variable from the VL2 muscle of males and females in 40% MVC fatiguing effort of knee extension (VL2 – vastus lateralis at 2 cm. above the musculotendinous junction).

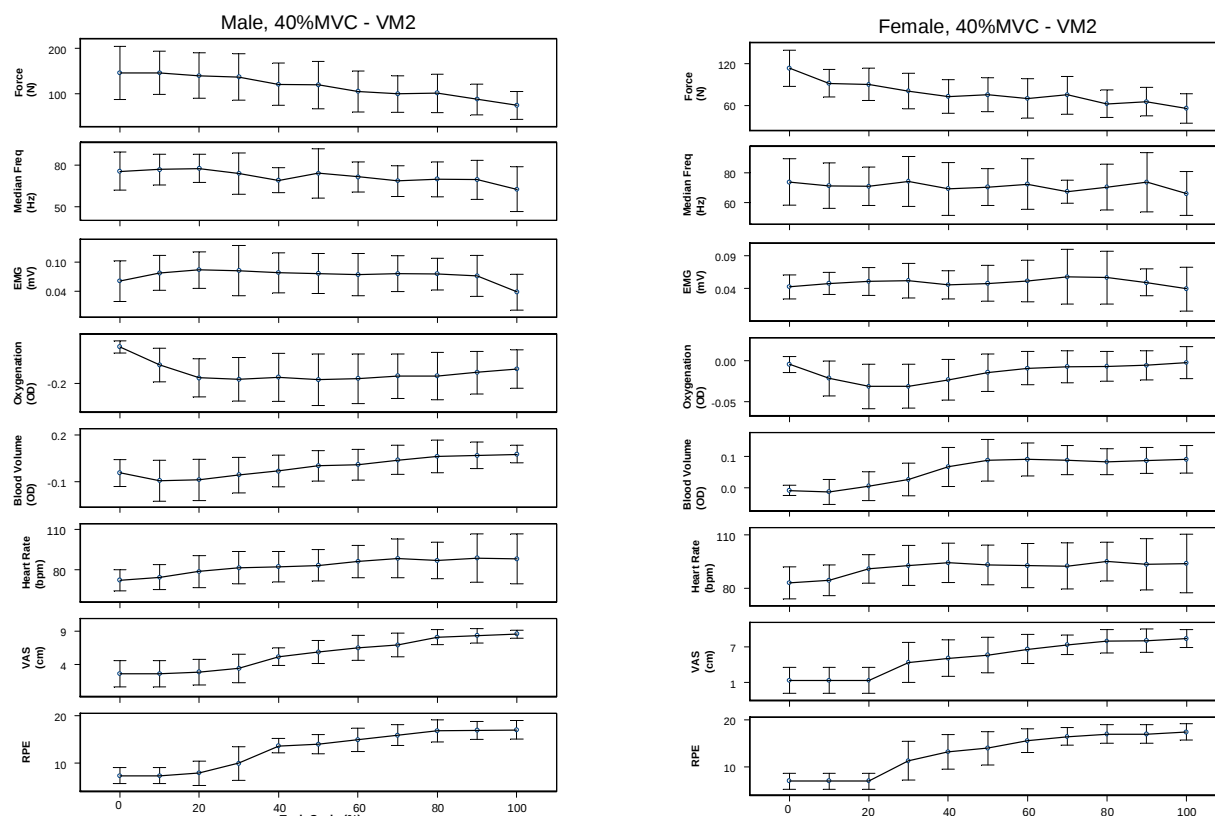


Figure 11. The pattern of the objective variables from VM2 muscle for male and female subjects in 40% MVC fatiguing effort of knee extension (VM2-vastus medialis at 2 cm. from the musculoskeletal junction).

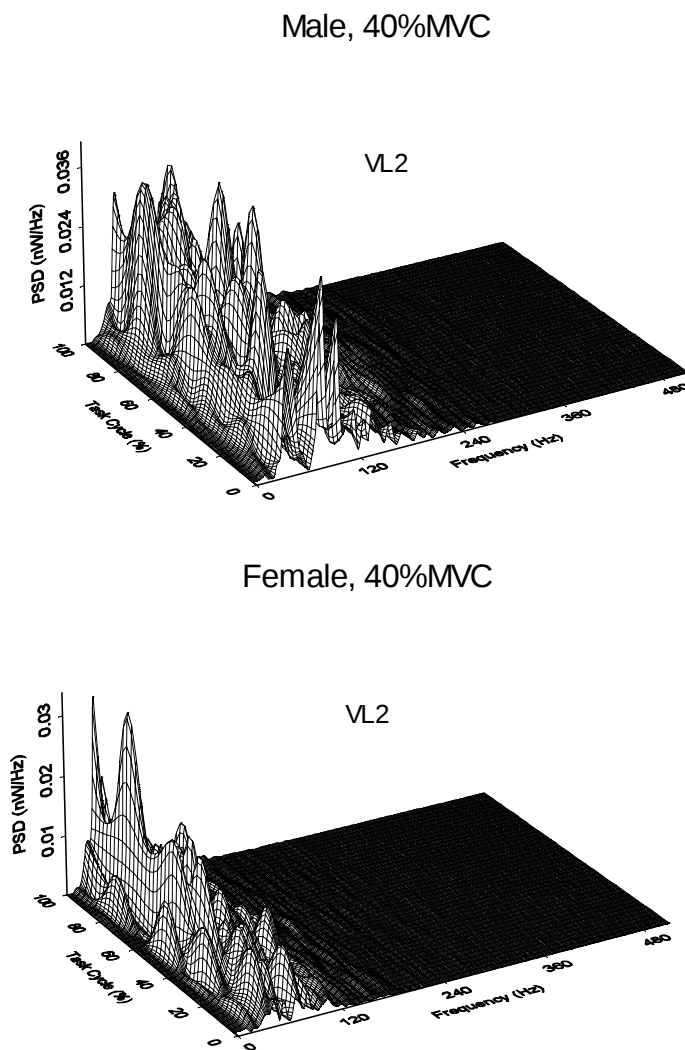


Figure 12. Spectral plots of VL2 muscle in 40% MVC fatiguing contraction of males and females (VL2-vastus lateralis at 2 cm. above the musculoskeletal junction).

Subjective Variables

The scores of visual analog scale and rate of perceived exertion is presented in Table 1. In both genders the scores for both visual analog scale and rate of perceived exertion were higher in 40% maximal voluntary contraction. The body part discomfort rating showed that the maximum discomfort was felt in low back with scores between 6.75 to 7.83 on a 10 point scale with the exception of females in MVC fatiguing contraction for females where the score was a mere 3.5. The behaviour of subjective variables for knee extension and elbow flexion is similar to those of the trunk extension.

Statistical Analyses

Trunk Extension

The summary tables of analyses of variance with repeated

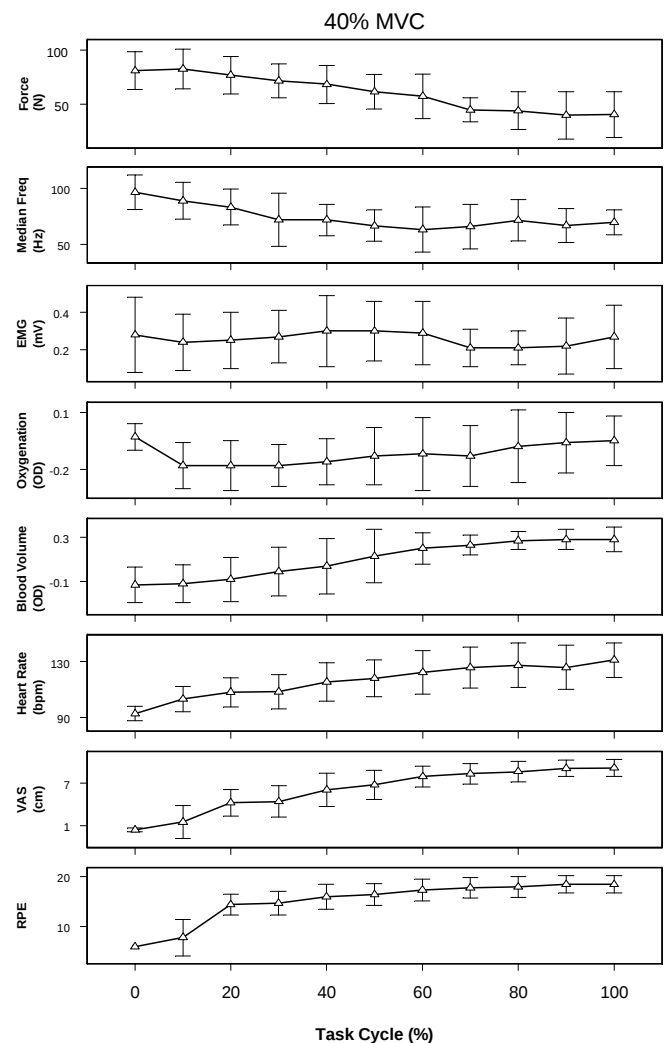


Figure 13. The pattern of the objective variables in 40% MVC fatiguing contraction of elbow flexion.

measures for the MVC fatiguing and 40% fatiguing contraction for all independent and the dependent variables are presented in Tables 2 and 3. The dependent variable of force and all independent variables (blood oxygenation, blood volume, EMG MF and EMG amplitude) were significant for gender and percentile levels between subjects ($p < 0.001$) in the MVC trial. The latter observation indicates though the two genders respond differently but there was a significant and progressive change with increasing task duration in both genders despite the effort of the subjects to maintain at a constant level. However, in 40% MVC the gender did not make a significant difference for the median frequency, but it did so for all other variables ($p < 0.01$). The task percentile level did not make a significant difference in blood volume and oxygenation but affected all other variables significantly ($p < 0.02$).

Table 1. Subjective variable scores due to the fatiguing isometric Spinal extensor efforts.

		VAS (cm)		RPE	
		Mean	Std Deviation	Mean	Std Deviation
Male	MVC	5.32	2.21	15.33	1.63
	40%				
Female	MVC	6.67	2.87	16.17	2.64
	MVC	4.2	2.36	14	2.45
	40%				
	MVC	6.95	1.33	14.67	1.63

Table 2. ANOVA Summary Table for main effects in MVC trunk extension contraction.

Variable	Source	dF	F-value	Significance
EMG-MF	Gender	1	6.829	0.009
	Task Percentile	10	3.045	0.001
EMG-mV	Gender	1	110.833	0.001
	Task Percentile	10	6.702	0.001
	Muscle	3	7.421	0.0001
Change in Force	Gender	1	183.127	0.001
	Task Percentile	10	15.634	0.001
Change in Blood Volume	Gender	1	60.646	0.001
	Task Percentile	10	5.909	0.001
Blood Oxygen	Gender	1	40.007	0.001
	Gender	1	26.553	0.001
Heart Rate	Gender	1	26.553	0.001
	Task Percentile	10	7.679	0.001

Table 3. ANOVA Summary Table for main effects in 40% MVC effort for trunk extension.

Variable	Source	dF	F-value	Significance
Median Frequency	Task Percentile	10	2.096	0.024
	Muscle	3	4.288	0.005
EMG-Amp	Gender	1	34.031	0.001
	Task Percentile	10	4.407	0.001
	Channel	3	4.194	0.006
Force	Gender	1	267.465	0.001
	Task Percentile	10	25.009	0.001
Blood Volume	Gender	1	6.601	0.010
Blood Oxygen	Gender	1	46.799	0.001
Heart Rate	Gender	1	88.053	0.001
	Percent	10	10.085	0.001

For MVC contractions, there was a significant interaction between EMG amplitudes and gender. Hence separate models were fitted for males and females. For males the significant predictors are (in the order of significance) EMG LL3, interaction between MFRL1 and MFRT10, BV and EMGRL1, while for females similar predictors are BV, EMG LL3, EMG RL1 and the interaction between EMG RL1 and EMG RT10.

For the fitted models the readers are directed to Kumar et al.²² which explain 98% and 97% of variance among males and females respectively for MVC. The regression models

for 40% MVC trunk extension explain 96% and 97% of variance for males and females respectively.

The summary tables of analysis of variance with repeated measures for the MVC fatiguing and 40% fatiguing contraction for all independent and dependent variables are presented in Tables 4 and 5. The dependent variable of force and all independent variables (blood oxygenation, blood volume, EMG MF and EMG amplitude) were significantly different at various task percentile levels within the subject ($p < 0.001$) and between subjects ($p < 0.001$) in the MVC trial. The latter observation

indicates significant and progressive change with increasing task duration despite the effort of the subjects to maintain at a constant level. Identical results were obtained in 40% MVC fatiguing trials where in addition to the dependent variable of force the independent variables blood oxygenation, blood volume, EMG amplitude, MF, heart rate, RPE score and VAS score showed significantly different magnitude of these variables at different task cycles within the subject ($p < 0.001$) and between the subjects ($p < 0.001$). Thus clearly in both contractions as the time progressed the fatigue progressed.

The set of independent variable for this case consists of blood volume, blood oxygenation, heart rate, EMG amplitude, EMG median frequency, visual analog scale, rate

of perceived exertion and body part discomfort rating. The final frequency model is given below.

Force = $140.92 + 53.17 \text{ EMG amplitude} - 41.9 \text{ blood volume} + 0.045 \text{ blood oxygenation} - 21.15 \text{ VO}_2 - 0.64 \text{ heart rate} + 0.68 \text{ rate of perceived exertion} + 1.39 \text{ discomfort rating of the upper arm}$.

The order of importance of significant predictors was determined based on absolute values of t-statistics. The goodness-of-fit of the final model was evaluated using reduction in mean squared error. An 80% reduction in mean squared error with significant predictors was observed compared to the model without any significant predictors.

Table 4. Univariate ANOVA (with repeated measures). Summary table for MVC fatiguing contraction.

S	F	Hypo dF	Sig	
Force	2133.0	6	.001	Within sub
O₂	759222.1	6	.001	Within sub
BV	1871.1	6	.001	Within sub
MF	5093.4	6	.001	Within sub
Ampl.	22266.2	6	.001	Within sub

Table 5. Univariate ANOVA (with repeated measures). Summary table for 40% MVC fatiguing contraction. Univariate for subjects

	F	Hypo-dF	Sig	
Force	36187.2	6	.001	Within
O₂	7467.7	6	.001	Within
Bl. Volume	8587	6	.001	Within
EMG Ampl.	13019.9	6	.001	Within
MF	4054.4	6	.001	Within
VO₂	1511.9	6	.001	Within
HR	31851.9	6	.001	Within
Vent.	22983.2	6	.001	Within
RPE	30255.0	6	.001	Within
VAS	611.9	6	.001	Within

Table 7. Correlation between different variables between subjects at 40%MVC of knee extension

[illegible]

Table 8. Correlation between force and measured variables for MVC fatiguing contractions in elbow flexion ($p < 0.001$).

		Force	Oxygenation	Blood	Med.	EMG
		(N)	(OD)	Volume	Freq.	Amp
				(OD)	(Hz)	(mV)
<i>Force (N)</i>	Correlation	1.00	.46	.30	.91	.39
Oxygenation (OD)	Correlation		1.00	-.35	.45	-.19
Blood Volume (OD)	Correlation			1.00	.18	.61
Med. Freq. (Hz)	Correlation				1.00	.36
EMG Amp (mV)	Correlation					1.00

Table 9. Correlation between force and measured variables for 40% MVC fatiguing contractions in elbow flexion ($p < 0.001$).

[illegible]

DISCUSSION

Localized muscle fatigue has been considered to be of considerable significance in possible injury mechanisms²³. Strenuous exercise, which includes fatiguing contractions causes disturbance of muscle homeostasis. Structural abnormalities in skeletal muscles of humans following stressful exertions have been reported^{24,25,26,27}. Progressive deterioration of muscle performance occurs with fatigue. Fatigue may be modulated through many different mechanisms and at many different sites. Possible sites and mechanisms include neurons, axon, terminal bouton, depletion of neurotransmitter, refractory response of the muscle cell membrane, depletion of Ca^{++} from the sarcoplasmic reticulum, depletion of ATP and its supply to the muscle cells.

With the onset and progression of fatigue, as indexed by the force magnitude and muscle discomfort, there is an initial reduction in EMG amplitude followed by an increment and eventual dissipation associated with cessation of activity. This suggests that the electrophysiological mechanism of muscle contraction remains intact till the end. It is due to a significant decline in force output that the synchronization of motor unit occurs^{12,28} to maximize the electrical impact on the contractile phenomenon. Univariate ANOVA for all objective variables revealed that the gender was a strong determinant. Thus females generated significantly less force on muscle contraction. Also, the EMG amplitude, MF, blood volume and blood oxygenation were significantly different between males and females ($p < 0.001$), for both MVC and 40% MVC contractions. In 40% MVC, men and women had significant differences in the heart rate as well. Clearly, men are heavier than women with significantly greater body mass. Force generation is dependent on the cross sectional area of the muscles which is greater in men, explaining this difference. Similarly, the larger cross sectional area of the muscle fibres will increase the conduction velocity of the action potential affecting the MF. Larger muscle mass will likely also, require larger amount of blood circulation and ATP for contraction. Where these are proportional to the cross sectional area is not clear, but it appears to be a likely cause of these differences. Interestingly, the subjective measures are not significantly different between genders. Thus information obtained through VAS, RPE, or BPDR do not discriminate between genders making them more universal tools for the assessment of fatigue.

In maximum voluntary contractions the EMG amplitudes at different sites within the experiment demonstrated the highest correlation coefficients with force. Though these were all significant but explained the variances in males only ranging from 20.4% to 62.4%. The variances explained in females ranged from 24% to 47.1%. The positive correlations clearly establish the relationship that, as the force is declining with progressive fatigue so is EMG amplitude, a finding also

supported by the works of Crone et al.²⁹, DiLazzaro et al.³⁰ and Kumar et al.³¹. Similarly, even in 40% MVC contractions, the EMG amplitudes demonstrate the highest correlation of all variables explaining from 26.1% to 43.0% variance in males and 16.8% to 32.4% variance in female sample. Surprisingly, the MF decline in maximal voluntary contraction and 40% maximal voluntary contraction was poorly correlated with force and explained variances between 2.4% to 19.8% and 5.5% to 10.8% in males and 1.7% to 16% and 1% to 16.4% in females. While correlations and variances explained were significant ($p < 0.01$), the weakness of association is less convincing than what is reported in the literature.

Muscle contraction is a resultant expression of nervous, metabolic, electrophysiological, mechanical and subjective factors. The primary energy source for muscle contraction is ATP. Since there is only a small amount of ATP present in skeletal muscles, it gets depleted quickly and needs to be replenished for sustained contraction through new blood supply. This physiological rationale suggests that the muscle blood volume and level of its oxygenation should faithfully mirror the degree of fatigue and decline in force. These variables, however, have shown only a modest negative correlation in MVC in males and females in quadriceps contraction, for example (blood oxygenation $r = -.159$ to $-.221$; $p < 0.01$; blood volume $r = .477$ to $-.637$; $p < 0.01$). The blood oxygen level during a MVC explained only 2.5% to 4.8% of variance, whereas the blood volume explained 22.7% to 40.5% of variance. In 40% MVC fatiguing contraction the blood oxygenation in males and females explained variances of 3.5% and 26.2%; whereas the blood volume explained 21.4% and 8.5% in males and females, respectively. Despite the assertions of McCully¹⁷ and Hamaoka, Murthy et al.²¹ and others that NIR spectroscopy provides valid data of muscle oxygenation and muscle blood volume, a low to moderate correlation coefficient and only low to modest variances explained in the current experiments, remain enigmatic. However, it is also fair to point out that MacDonald et al.³¹, reported unreliable results from NIRS of femoral blood gases with exercise. Extreme care taken in the experiments make it less likely that experimental error may have played a role.

The subjective variables of visual analog score, rate of perceived exertion and body part discomfort ratings, measured in 40% MVC fatiguing contractions, had a modest correlation with force among males ($r = -0.413$ to -0.493 ; $p < 0.001$) explaining 17% to 24.2% of variance. Among females, these values were further reduced ($r = -0.338$ to $-.0418$; $p < 0.01$) explaining variances between 11.4% to 17.4%.

The results obtained in these studies do not show any of the variables to be strongly correlated with force and reflecting it faithfully, though EMG amplitude was found to be the best among all variables, quantitatively. Whether these factors do not proportionally respond to fatigue quantitatively

or their response follows a pattern of small changes, is hard to say. It is possible that if the total response were to be assigned a value of 100%, even the smaller changes will then represent a proportionally higher percentage of force fatigue. In any case, it is also quite likely that none of the variables selected demonstrate total dependence on fatigue. When these variables are considered in batch, they together explain a variance of 64.4% and 60.2% in maximal voluntary contraction in males and females, respectively in the quadriceps experiment. Similarly, at 40% MVC contraction the variances of 71.9% and 68.6% were explained. The experiments with erector spinae and biceps brachii show very similar results in all aspects. From the results obtained, therefore, it is concluded that it will be desirable for us not to predict or measure fatigue based on any one variable. We rather need to consider a combination of variables for reliable information, regarding a given muscle with respect to fatigue.

In summary, with the series of experiments carried out it would appear that for high grade contractions the EMG amplitude and the median frequency follow the fatigue more closely explaining most variance out of all variables. In lower grade contractions however, the visual analog score is the better variable. However, neither of these variable account for most of the variance. Thus, a single variable indexing of localized muscle fatigue leaves a lot to be desired for.

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