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Original Article

Analysis of fatigue in the three heads of the triceps brachii during isometric contractions at various effort levels

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Abstract

Objective: The objective of this study was to investigate fatigue in the three heads of the triceps brachii (TB) muscle using surface electromyography (sEMG) obtained at 30%, 45% and 60% of maximal voluntary contraction (MVC). **Methods:** Twenty-five subjects performed isometric elbow extension until failure, and the rate of fatigue (ROF), time to fatigue (TTF) and normalized TTF (NTTF) were statistically analysed. Subsequently, the behaviour of root-mean-square (RMS), mean-power frequency (MPF) and median-power frequency (MDF) under pre-, onset- and post-fatigue conditions were compared. **Results:** The findings indicated that, among the heads, ROF was statistically significant at 30% and 45% MVC ($P<0.05$) but TTF and NTTF at all intensities was statistically insignificant ($P>0.05$). For every head, only TTF was statistically significant ($P<0.05$) at different intensities. MPF and MDF under pre-, onset- and post-fatigue conditions were statistically significant ($P<0.05$) among the heads at all intensities, whereas RMS showed no such behaviour. **Conclusion:** The investigated parameters reveal that the three heads of TB act independently before fatigue onset and appear to work in union after fatigue. Synergist head pairs exhibit similar spectral and temporal behaviour in contrast to the non-synergist TB head pair. We find spectral parameters to be more specific predictors of fatigue.

Keywords: Muscle Fatigue, Triceps Brachii, Isometric Contractions, Surface Electromyography

Introduction

As the largest arm muscle, the triceps brachii (TB) plays an important role in the movement and stabilization of the limb[1-3]. Because this skeletal muscle is mainly composed of type II muscle fibres, it is expected that this muscle will experience fatigue earlier and have a longer recovery time compared with a muscle dominated by type I muscle fibres[4]. The TB consists of three heads, namely, the lateral, long and medial heads. As TB is a large muscle, it is expected that each of its head has an individual role in the activities performed by the TB. The individual activity of the TB heads has been recently studied by some researchers[5-7], but these previous studies did not include elbow extension and arm abduction, which are the main tasks performed by the TB. An in-depth analysis of the response of the three heads of the TB to fatiguing contractions at different intensities based on temporal and spectral parameters has not been performed, and these observations could be used for the targeted training of muscles and thus for rehabilitation.

The phenomenon of skeletal muscle fatigue has been known for many decades and has been investigated in detail by many researchers. Fatigue can be defined as a decrease in the force-generating capacity of a muscle or group of muscles during or after a particular task[8]. The TB is the main muscle responsible for elbow and shoulder extension and arm abduction and acts as an antagonist during elbow flexion[1]. Within the TB, the lateral-and-long and the lateral-and-medial head pairs act as synergists[7,9]. The role of an individual head in the development of fatigue and the behaviour of these synergists remain to be explored, and these observations could be useful for prosthetic control and rehabilitation.

The authors have no conflict of interest.

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During isometric contractions, the length of the muscle and the joint angle do not change during the generation of force. Thus, these contractions have been widely used for the observation of fatigue in a muscle because they provide the best response in the observed muscle[10]. The motor unit recruitment threshold is higher and firing rate is lower during isometric contractions compared with dynamic contractions[11]. Surface electromyography (sEMG) has been widely used to assess muscle behaviour for decades[12], and many researchers have used temporal [root mean square (RMS), average rectified value (ARV), mean amplitude value (MAV)][13,14] and spectral [mean power frequency (MPF) and median power frequency (MDF)] parameters[15] obtained from sEMG to assess muscle fatigue during isometric contractions. The assessment of fatigue based on physiological signals has primarily focused on evaluations of the RMS, MPF and MDF, but muscle fatigue could also be assessed through measurements of the blood lactate concentration, torque, and force level[16], among other parameters. The temporal parameters, particularly RMS, typically reflect the physiological activity of motor units in a muscle and are thus affected by the exercise intensity[16,17]. In contrast, a change in the exercise intensity has a negligible impact on spectral parameters, but fatigue has a high impact on these parameters[18]. These findings indicate that in order to assess the effects of changes in exercise intensity and of tasks performed until failure using only physiological signals, both temporal and spectral parameters should be analysed.

Many recent studies have observed the TB during fatiguing contractions, but some related questions remain to be addressed. The three heads of the TB were recently studied during elbow extension, but no load was applied against the extension[7]. Similarly, in another investigation, the three heads were observed during a forceful handgrip task, but no load was used against the extension[5]. Repetitive isometric contractions were used to study the effects of fatigue on the three heads of the TB[19]. Another study[20] investigated the three heads of the TB during low-intensity isometric contractions at two different shoulder angles until task failure was achieved and concluded that the long head behaves differently at different positions. However, the exercise intensity was not varied in any of the above-mentioned studies. To date, the three heads of the TB have not been evaluated during isometric contractions at different intensity levels until task failure. All previous researchers have noted that the three heads show different behaviour during fatiguing contractions and that sEMG activity from one head is not representative of that of elbow extensor muscles.

The aim of the current work was to analyse the impact of fatigue in the three heads of the TB during isometric contractions at different intensities. Rate of fatigue (ROF), time to fatigue (TTF) and normalized time to fatigue (NTTF) were investigated among the three heads of the TB at different effort levels. The same parameters were also investigated among different exercise intensities for a particular head. In addition, the temporal (RMS) and spectral (MPF and MDF) features of sEMG signals from the three heads of TB were analysed to examine the changes in the attributes of the various heads during pre-, onset- and post-fatigue conditions.

Figure 1. Subject performing an isometric contraction. **A.** Bipolar sEMG electrodes placed on the lateral head of the TB. **B.** Shimmer device, which wirelessly transmits sEMG signals to a computer. **C.** Reference electrode. **D.** Dominant hand holding the load.

Methods

Participants

Twenty-five young, healthy, non-athlete male university students were recruited for this experiment. Some of the recruited subjects either performed routine gym exercises or regularly participated in recreational but not professional sport activities. The recruited subjects had no history or on-going diagnosis of neuromuscular disorder in the upper arms. The age of the subjects was 23.8(3.6) years, and their height and weight were 169.1(5.5) cm and 71.2(11.2) kg, respectively. The experimental protocol was approved by the Medical Research and Ethics Committee of Malaysia and was performed according to the Declaration of Helsinki due to the involvement of human subjects. Subjects were given instructions prior to data collection and written informed consent was taken. The experiment was conducted at the university gymnasium, and a medical officer was available to aid the researchers and handle any emergency.

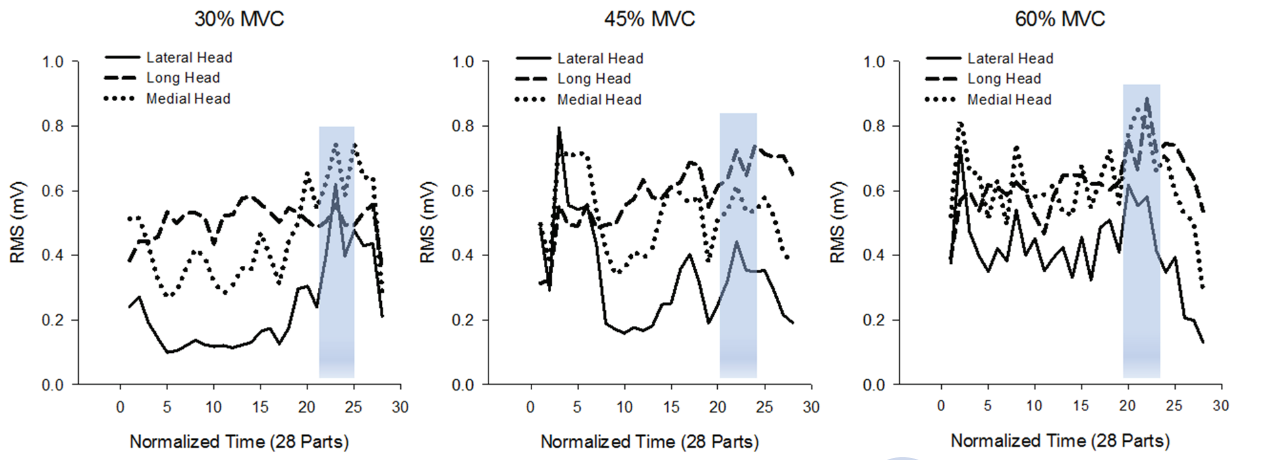

Figure 2. RMS curve obtained from one subject at different intensities. The horizontal axis shows the normalized time, i.e. the entire exercise duration is divided into 28 equal sections. The shaded area indicates the fatiguing zone.

Experiment set-up

The three heads of the TB were observed via disposable pre-gelled bipolar sEMG electrodes (Kendall™ 100 MediTrace®, Tyco Healthcare Group, USA). The heads were identified as mentioned by Perotto[21], and based on SENIAM's recommendations, the electrodes were placed on the belly of each head in line with the muscle fibres. The inter-electrode distance was 20 mm, and the skin was shaved (if needed), abraded and cleaned prior to electrode placement.

Shimmer 2.0r Model SH-SHIM-KIT-004 (Realtime Technologies Ltd., Ireland) was used to record the sEMG signals. This wireless system consists of three strap-on three-channel shimmer boards, each of which has dimensions of 53 mm × 32 mm × 15 mm and weighted approximately 25g. For each board, two channels were used for observing the signals from the muscles, and the third was used as the reference electrode. The reference electrode was placed over an electrically neutral area in the vicinity of the muscle, i.e., lateral epicondyle and olecranon of the shoulder and elbow.

Muscle identification and electrode placement were validated by the medical officer present on the site. The system was interfaced with a computer via class 2 Bluetooth®. Raw sEMG signals were recorded at a sampling rate of 1 kHz. The computer was placed at a distance of 2 to 3 metres from the subject, and a line of sight was maintained between them. The Shimmer Sensing LabVIEW programme, accompanying the device, was used to store the obtained data on the computer.

Experimental procedure

The electrodes were placed on the dominant arm of the subject prior to the familiarization session. Subjects were then asked to perform a warm-up that consisted of upper body stretching and exercises with 5 to 8 reps using light weights. Subsequently, a resting period of approximately 2 minutes was given.

Subjects then stood straight in front of the triceps push-down exercise machine with their dominant arm slightly abducted (25-35°) and fully extended, as shown in Figure 1. While maintaining this posture, subjects were then asked to hold the weight and it was ensured that the subjects did not use their body weight to hold the load. The maximum load that the subject could sustain for 2-3 seconds was recorded. This routine was performed three times, with a rest time between trials of at least 5 minutes, and the maximum load obtained in these three trials was considered as the maximum voluntary contraction (MVC). Subjects were allowed a 10 minutes rest after MVC was determined.

Subjects were then asked to perform the aforementioned exercise at 30%, 45% and 60% MVC until task failure, with an inter-exercise rest at least 5 minutes. The order of the exercise was random and subjects were not informed of the order prior to the commencement of the exercise. If a subject was frequently unable to maintain the correct posture, a new subject was recruited as a replacement. The participants performed the exercise until reaching exhaustion, and the exercise was terminated if the subject was unable to maintain the correct posture for more than 3 seconds. During the experiment, subjects were continuously given verbal encouragement. sEMG data were recorded during the tasks performed at the MVC and throughout the duration of submaximal exercises.

Data analysis

The collected data were stored on a computer system for further analysis. Custom-written programmes in MATLAB 17 (MathWorks Inc., USA) were used to filter, normalize and evaluate the RMS, MPF and MDF. A fourth-order 5-450 Hz band-pass Butterworth filter was used to obtain the sEMG

Table 1. Results of statistical analysis for TTF, ROF and NTTF (p-value) and post hoc tests (a – lateral & long , b – long & medial , c – lateral & medial, d – 30% & 45%, e – 45% & 60%, f – 30% & 60%).

	Comparison of the three heads			Comparison of the three intensities		
	30%	45%	60%	Lateral	Long	Medial
TTF	0.834	0.967	0.931	**0.002**^{d,f}	**0.0003**^{d,f}	**0.001**^{e,f}
ROF	**0.041**^{a,b}	**0.019**^{b}	0.06	0.928	0.946	0.332
NTTF	0.710	0.847	0.739	0.440	0.893	0.559

**Bold font indicates statistically significant.*

signal. For each subject, amplitude normalization was performed using the highest RMS computed from a non-overlapping 100 ms time window from their respective MVC. A 512-point Fast Fourier Transform (FFT) computed with a Hamming window with 50% overlap was used to estimate MPF and MDF. For each subject, the entire exercise duration (from start until task failure) was divided into 28 equal slots (time normalization)[22], and the MPF, MDF and average normalized RMS for each normalized time slot were computed. This subdivision of the time allowed comparisons among the subjects with different time to task failure, also known as endurance time (ET).

Furthermore, the entire duration was divided into three main sections: prior to fatigue (increasing RMS), onset of fatigue (maximal RMS value) and after fatigue (decreasing or stable RMS). The RMS curves obtained for the three heads of each subject at three different intensities are shown in Figure 2. NTTF was designated as the slot number in which the maximal RMS was observed. The time from the start of the exercise to the onset of fatigue was considered as TTF, and this measure was calculated using equation 1.

$$TTF = \frac{NTTF}{28} \times ET \qquad (1)$$

Some researchers have used MVCs obtained prior to, during and/or after exercise to determine the ROF, but in general, this technique is used for longer experiments that involve both exercise and rest periods. In the particular experiment performed in this study, the slope of the RMS under pre-fatiguing conditions was evaluated through a regression analysis to obtain the ROF, as described previously[5,23].

Statistical analysis

For each subject at the three heads, the ROF, TTF and NTTF were obtained at different intensities, and the RMS, MPF and MDF values were obtained under pre-, onset- and post-fatigue conditions. In the statistical analysis, the data were first analysed for normality, which showed that the data were not normally distributed. Hence, the Kruskal-Wallis test was used to investigate the behaviour of the parameters among the three heads at the same intensity and in the same head at three different intensities. For the post hoc analysis, the Mann-Whitney test with Bonferroni adjustment was applied to observe the behaviour of parameters among pairs of TB heads. A selected dataset was considered significant if $P<0.05$, which means that a confidence level of 95% was considered. IBM SPSS 20.0 (SPSS Inc., USA) was used for the statistical analyses.

Results

Table 1 summarizes the results for ROF, TTF and NTTF. Among the three heads, for all investigated intensities, TTF was not statistically significant ($P>0.05$) suggesting that fatigue develops in the three heads at a similar rate. ROF only showed significant difference at 30% and 45% MVC. A post hoc analysis of the ROF indicated that the lateral and long heads revealed statistical significance at 30% MVC, whereas the long and medial heads were statistically significant at all intensity levels. The lateral and medial heads showed no significant difference in the ROF at any of the tested intensities ($P>0.05$). For each head, TTF exhibited significant difference among the three intensities. In contrast, ROF was statistically insignificant among the different intensities. NTTF was found statistically insignificant among the three heads at same intensity and in the same head at different intensities ($P>0.05$). Figure 4 shows the observed parameters at the different intensities.

The statistical results of RMS, MPF and MDF measured during pre-, onset- and post-fatigue conditions is given in Table 2. Figure 3 shows the average RMS values of a single head at different intensities and the values of the three heads of the TB at the same intensity. For all intensities, RMS observed statistical insignificance among the three heads. In contrast, MPF and MDF were statistically significant ($P<0.05$) at all intensities and at all exercise stages (pre-, onset- and post-fatigue conditions). However, interestingly, the post hoc tests reveal the long and medial head pair to be statistically insignificant for all comparisons. For each head, at different intensities, all tests were statistically insignificant with the exception of RMS in long head (pre- and on-set of fatigue conditions) and in medial head (pre-fatigue condition). These results signify that spectral parameters are independent of the exercise intensity, and this finding is in agreement with the literature[18]. Figure 5 summarizes the observed parameters obtained during the three exercise stages at different intensities.

Table 3 presents the change in RMS, MPF and MDF (Δ%)

Table 2. Results of statistical analyses under pre-, onset- and post-fatigue conditions for RMS, MPF and MDF (p-value) and post hoc tests (a – lateral & long, b – long & medial, c – lateral & medial, d – 30% & 45%, e – 45% & 60%, f – 30% & 60%).

	RMS			MPF			MDF		
	Pre	Onset	Post	Pre	Onset	Post	Pre	Onset	Post
30%	0.226	0.321	0.096	**0.000001**[a,c]	**0.000005**[a,c]	**0.000001**[a,c]	**0.00002**[a,c]	**0.00005**[a,c]	**0.00003**[a,c]
45%	0.101	0.542	0.292	**0.00004**[a,c]	**0.000007**[a,c]	**0.0000004**[a,c]	**0.0001**[a,c]	**0.0002**[a,c]	**0.00002**[a,c]
60%	**0.046**[b]	0.355	0.133	**0.00003**[a,c]	**0.000002**[a,c]	**0.0000002**[a,c]	**0.001**[a,c]	**0.00003**[a,c]	**0.00001**[a,c]
Lateral	0.085	0.069	0.176	0.648	0.936	0.971	0.795	0.924	0.995
Long	**0.037**[f]	**0.029**[f]	0.069	0.840	0.923	0.825	0.852	0.926	0.744
Medial	**0.018**[f]	0.074	0.174	0.809	0.962	0.954	0.805	0.970	0.829

**Bold font indicates statistically significant.*

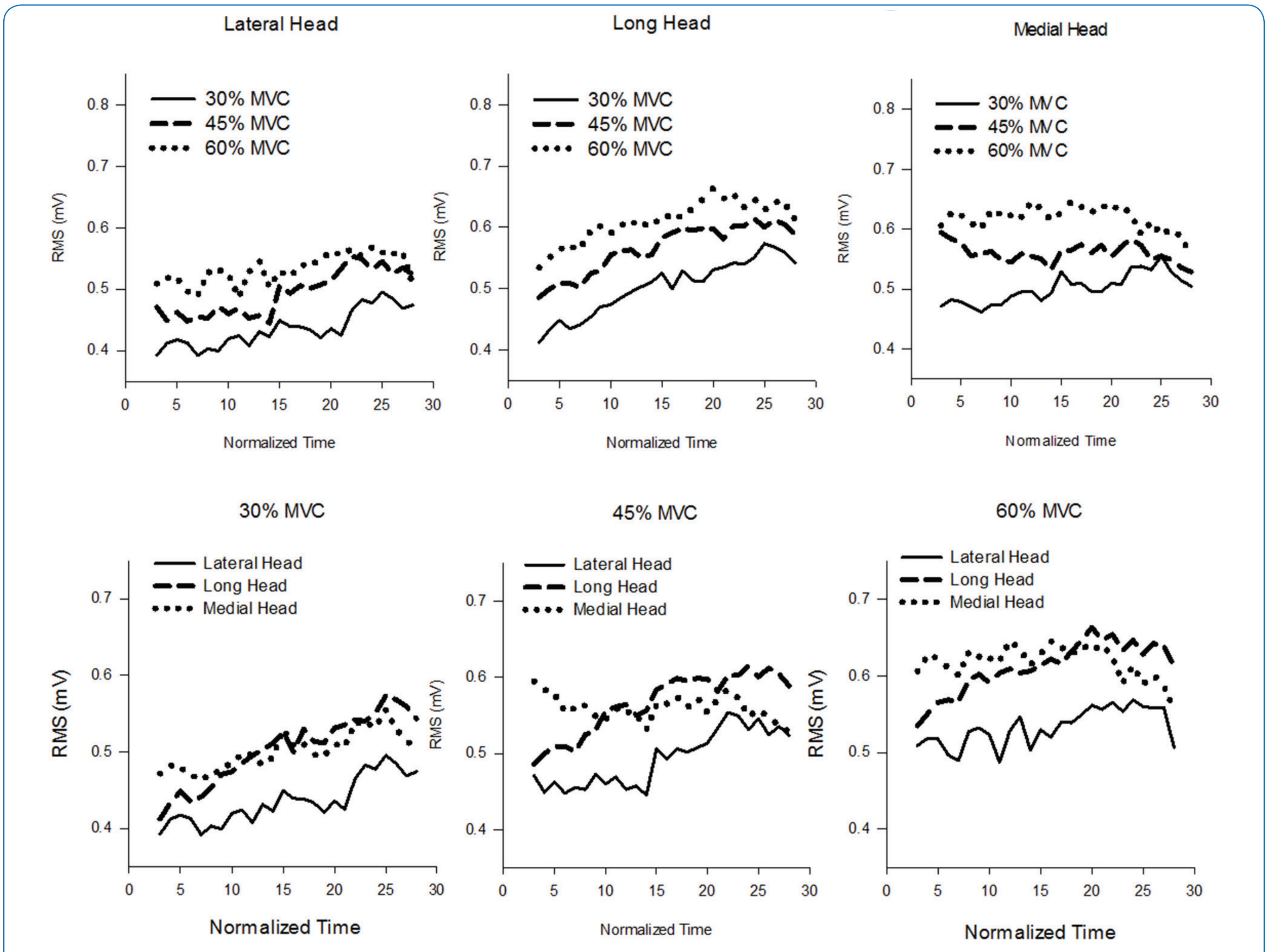

Figure 3. Mean RMS of all subjects for a particular head at 30%, 45% and 60% MVC (Top). Mean RMS of the three heads at a particular intensity (Bottom).

to determine the variability before, during, and after fatigue onset in each of the three heads of the TB muscle. From the pre- to onset-fatigue stage, the highest and lowest changes in MPF and MDF were observed in the long head and the lateral head respectively. On the other hand, we did not observe significant variations in these parameters during the onset to post-fatigue condition among the three heads. The change in the RMS from pre- to onset of fatigue was almost similar in all the three heads but appeared lowest in long head during onset to post-fatigue condition.

Table 3. ΔRMS (%), ΔMPF (%) and ΔMDF (%) during progression from pre- to onset-fatigue and onset- to post-fatigue conditions, mean (SD).

		Lateral head		Long head		Medial head	
		Pre-fatigue to fatigue onset	Fatigue onset to post-fatigue	Pre-fatigue to fatigue onset	Fatigue onset to post-fatigue	Pre-fatigue to fatigue onset	Fatigue onset to post-fatigue
ΔRMS (%)	**30%**	25.56 (10.95)	-15.5 (10.72)	25.67 (8.54)	-12.63 (6.96)	21.53 (10.37)	-16.44 (9.54)
	45%	26.18 (9.64)	-17.42 (7.32)	23.82 (8.42)	-11.77 (7.58)	18.90 (9.21)	-17.04 (6.79)
	60%	23.30 (9.81)	-18.49 (8.95)	21.13 (6.38)	-12.72 (5.88)	17.60 (6.12)	-17.84 (6.31)
ΔMPF (%)	**30%**	-9.05 (8.29)	-5.19 (5.69)	-17.12 (6.63)	-6.58 (2.75)	-13.28 (7.81)	-5.19 (2.82)
	45%	-8.14 (6.99)	-3.91 (4.42)	-17.22 (6.30)	-7.18 (4.16)	-12.23 (5.61)	-6.53 (3.04)
	60%	-5.49 (4.36)	-4.97 (4.09)	-13.44 (5.55)	-6.15 (4.63)	-11.50 (5.56)	-5.96 (2.62)
ΔMDF (%)	**30%**	-8.82 (9.87)	-3.36 (6.77)	-17.74 (7.21)	-5.28 (3.95)	-15.08 (9.33)	-4.29 (4.80)
	45%	-8.31 (9.15)	-4.91 (6.09)	-17.80 (8.48)	-6.97 (5.57)	-11.73 (8.01)	-8.01 (4.18)
	60%	-4.80 (4.99)	-6.24 (5.33)	-12.71 (8.73)	-6.02 (6.32)	-9.91 (5.82)	-7.29 (5.50)

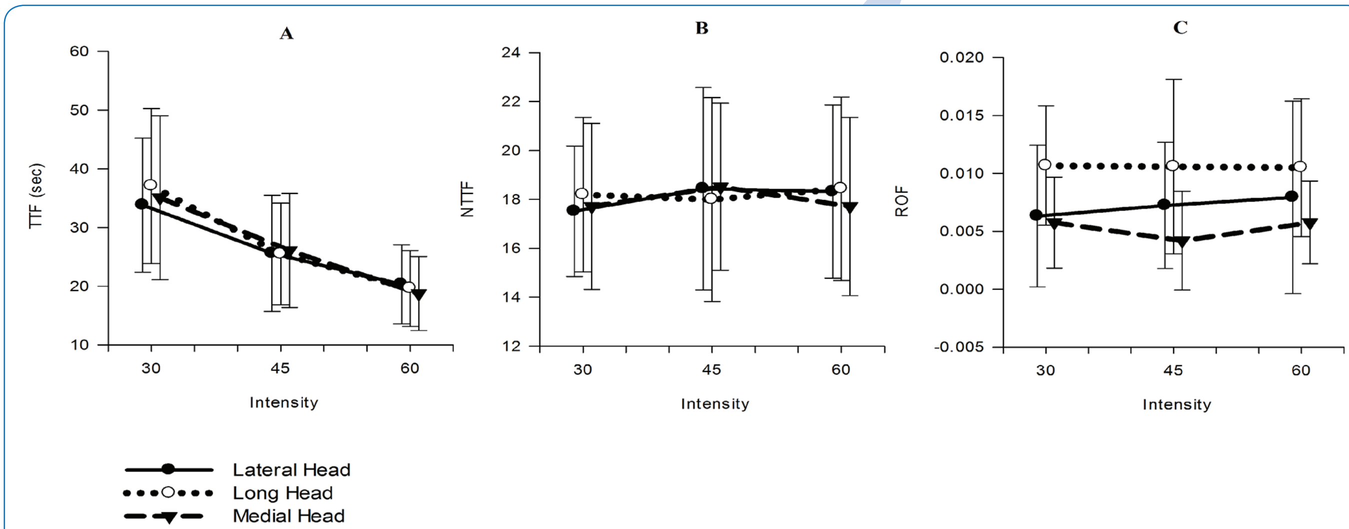

Figure 4. **A.** Exercise intensity (30%, 45% and 60% MVC) as a function of time to fatigue in seconds during isometric contractions. **B.** Exercise intensity as a function of normalized time to fatigue. **C.** Rate of fatigue in the three heads of the TB as a function of exercise intensity. All the graphs are plotted to allow comparisons among the three heads of the TB

Discussion

This research was undertaken to assess the effect of fatigue in the three heads of the TB during isometric contractions at different intensities. Several functional variations, including variations in the ROF, TTF and NTTF, were observed. The RMS, MPF and MDF were calculated during pre-, onset- and post-fatigue conditions, and the values were compared among the three heads and the different intensities. The aim was to investigate whether the three heads of the TB exhibit different behaviour during fatiguing contractions. We further investigated whether exercise intensity has a significant impact on fatigue in the TB heads. Individual assessment of the three heads can provide additional biomechanical insights as the literature reveals that the three heads of TB do not work in union.

The ROF was statistically significant among the three heads of the TB at a particular intensity, with the exception of 60% MVC suggesting that at higher intensities, the three heads appear to work in union. Based on the post hoc test, we observe that although biomechanically the lateral and long heads act as extension synergists[9], their individual characteristics becomes diminished at higher intensities. This finding also shows that the motor unit recruitment pattern differs among these two synergist heads at lower intensities. In contrast, post hoc test on the lateral and medial heads showed no significant difference in ROF at any of the tested intensities. As synergists[7], this behaviour was

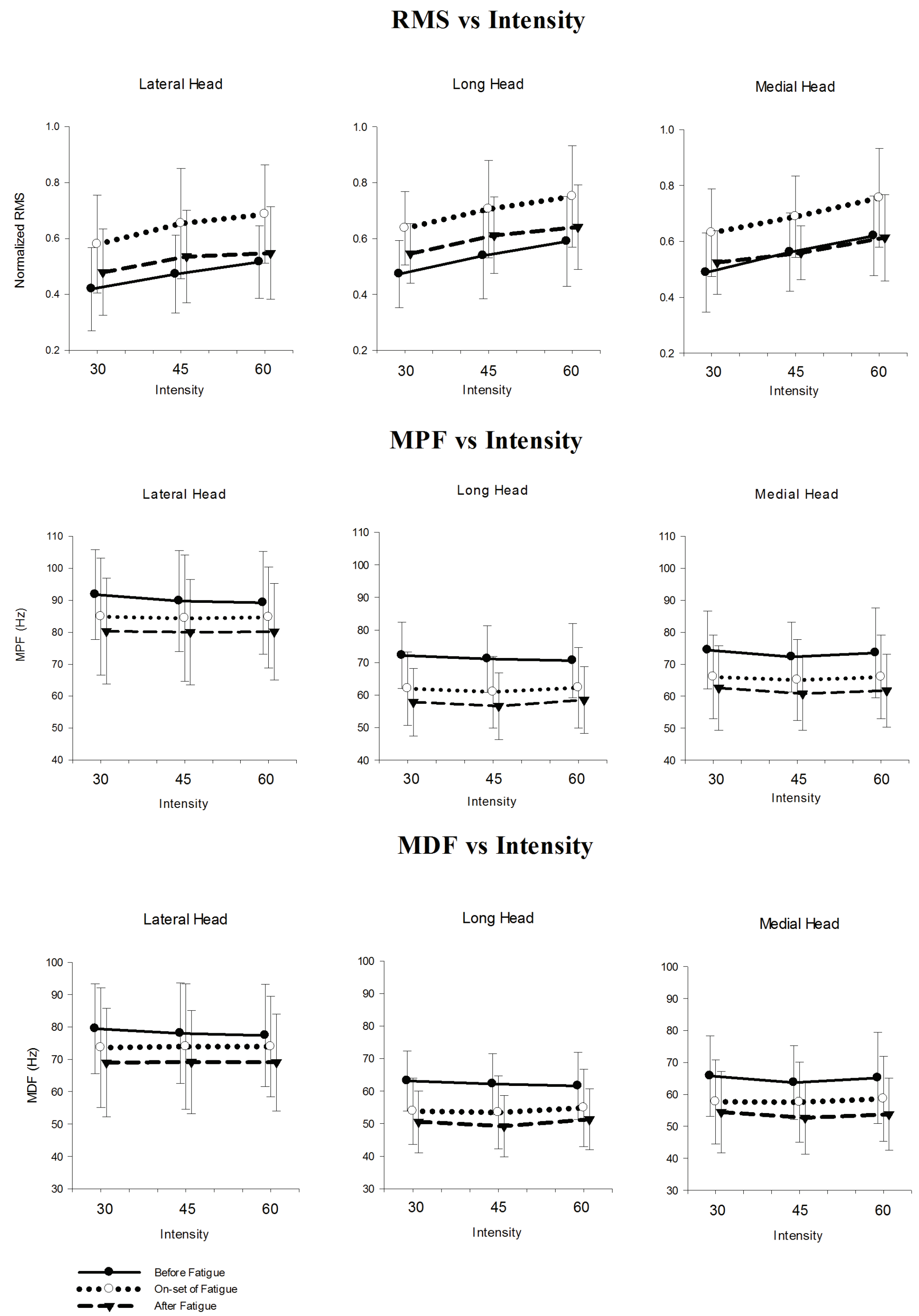

Figure 5. RMS, MPF and MDF as a function of exercise intensity (30%, 45% and 60% MVC) under pre-, onset- and post-fatigue conditions.

expected from this pair of heads. The activation amplitudes (RMS curves in Figure 3) of the three heads revealed that the activation levels of each head exhibited similar trends towards the performed exercise, although the anatomy of the heads are different. This could be attributed to the fact that the motor unit recruitment pattern of synergist muscles was previously reported to be similar[24]. Thus, the long and lateral head pairs and the lateral and medial head pairs should exhibit a similar activation pattern because these two head pairs act as extension and abduction synergists. Surprisingly, the literature does not provide any information for the long and medial head pair, and there is no clear evidence showing whether this pair acts as extension or abduction synergist. However, the results of this study reveal that the ROF and TTF were statistically significant in this pair, which suggests an independent behaviour (non-synergists) in them during the development of fatigue.

The ROF in a particular head was found to be statistically insignificant at different intensities, but the TTF was found significantly different among different intensities. This finding indicated that the motor unit recruitment pattern of a head does not depend on the exercise intensity. These results concur with the results of previous studies on different muscles[18,25]. For all the subjects, we also observed the NTTF to be similar (~64.5% of ET) in each head among the different intensities as well as in all three heads at a particular intensity. We believe this is primarily due to the synergistic behaviour of the heads for the performed exercise.

The TTF of a particular head showed statistical significance ($P<0.05$) among different intensities, but the TTF values of the different heads at the same intensity were statistically insignificant ($P>0.05$). TTF variability (SD) was observed to reduce with increasing intensity (~13 at 30% MVC, ~9.5 at 45% MVC and ~6 at 60% MVC). This finding could be explained by the presence of central fatigue, which is more pronounced at lower intensities[26] and has diminishing effects at higher intensities. In addition, central fatigue is more related to the subject's physiological and psychological conditions at the time of exercise[26,27]. In most cases, with increasing exercise intensity, there is a tendency for subjects to be more focused resulting in reduced central fatigue and subsequently lower variations in TTF.

The RMS, MPF and MDF values of the heads at different intensities under pre-, onset- and post-fatigue conditions provided further insights. At any particular intensity, RMS was observed to be statistically insignificant ($P>0.05$) among the three heads for every investigated condition. This observation points to the fact that the motor unit recruitment pattern is same among the three heads at any particular intensity. However, MPF and MDF were observed to be statistically significant ($P<0.05$) for all the three heads at any intensity under pre-, onset- and post-fatigue conditions, thus symbolizing different motor unit firing rates. Hence, MPF and MDF are more useful parameters to distinguish between non-fatigue and fatigue conditions of the muscle. These observations, when taken together, revealed that the long and medial heads pair exhibited contrasting behaviour from the other two pairs in not only the temporal but also the spectral parameters. The spectral behaviour of the long and medial heads appeared similar among the tested intensities under all the conditions. This might be due to the fact that the long and lateral heads are large sized bi- and mono-articular muscles respectively, whereas the medial head is smaller in size and is mono-articular[20]. Furthermore, the number of fast-twitch fibres in the long and lateral head is almost same whereas it is roughly half of that in the medial head[4]. From a biomechanical point of view, the mono-articular lateral and medial synergist pair is responsible for arm abduction, whereas the large sized long and lateral synergist pair is responsible for elbow extension. These characteristic variations may be the reason why the long and medial head pair exhibit different behaviour as the pair is neither of similar sized muscles nor the anatomy of the two is same.

Percentage change in the RMS, MPF and MDF from pre- to onset-fatigue and from onset- to post-fatigue conditions provide additional insights to the functioning of the TB. The size, dominant fibre type and biomechanical structure of the muscle contributes to the change in the sEMG parameters during isometric exercise[28]. During the pre- to onset-fatigue condition, the medial head shows lowest ΔRMS(%) depicting its smaller size, whereas the lateral and long head observed larger but similar values due to their comparatively larger size, for all investigated intensities. We also found that MPF and MDF showed a different %Δ in all the three heads during the pre- to onset-fatigue condition, affirming that these heads work independently prior to fatigue. Interestingly, for the onset to post-fatigue condition, all parameters showed similar behaviour which suggests that the three heads act as a single unit after fatigue.

One of the concerns of the current study is the use of the RMS slope at low intensities to determine ROF. As demonstrated by several researchers, fatigue is not solely responsible for an increase in RMS at lower intensities, but the recruitment of new motor units might also explain this increment[29,30]. Thus, the increase in RMS observed during contractions performed at 30% MVC, and at 45% and 60% MVC might have different explanations. Nevertheless, this parameter has been used by some researchers to analyse muscles during fatiguing conditions, even at low contractions[23,31]. In addition, the use of sEMG for closely spaced muscles could generate crosstalk[32], but we followed standard and recommended precautionary measures in our experimental protocol to minimize this issue. Moreover, only young and healthy male subjects were selected for this study. As such, the inclusion of subjects from different age groups and gender may provide further insights into the topic.

Conclusion

Although the ROF showed differences among the three heads of the TB, the variation in TTF and NTTF was negligible. The analysis of the three heads during fatiguing isometric contractions based on spectral parameters revealed that the three heads exhibit different behaviours, which indicates that the heads display different motor unit recruitment and firing rate patterns. However, the temporal parameter used in this study could not capture these behavioural changes. No clear conclusion could be drawn with respect to an individual head, and further analyses are required to elucidate the compensation strategies of the three heads. Nevertheless, our results affirm that the lateral and long heads, and the lateral and medial heads act as synergists during extension and abduction, but no such clear relationship was observed for the long and medial heads. The findings of the current study can contribute to the design of rehabilitation training programmes for individual heads of the TB and the training of individual heads in the context of sport activities. Our results can also help roboticist and automation enthusiasts in the design and control of TB related prosthetics for the disabled. Future studies might include the investigation of the three heads during dynamic contractions and the effect of exercise and training on each head of the TB.

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Authors Contributions

Conceived and designed the search experiment - JH, CKL. Performed the search experiment – JH, CKL Contents arrangement - JH, KS, SID. Wrote the paper - JH, KS, SID.

References

1. Hussain J, Sundaraj K, Low YF, Lam C, Sundaraj S, Ali MA. A systematic review on fatigue analysis in triceps brachii using surface electromyography. Biomed Signal Process Control 2018;40(1):396-414.
2. Asraf Ali M, Sundaraj K, Badlishah Ahmad R, Ahamed NU, Islam A. Recent observations in surface electromyography recording of triceps brachii muscle in patients and athletes. Appl Bionics Biomech 2014; 11(3):105-118.
3. Saeterbakken AH, van den Tillaar R, Fimland MS. A comparison of muscle activity and 1-RM strength of three chest-press exercises with different stability requirements. J Sport Sci 2011;29(5):533-538.
4. Elder G, Bradbury K, Roberts R. Variability of fiber type distributions within human muscles. J Appl Physiol 1982;53(6):1473-1480.
5. Ali MA, Sundaraj K, Ahmad RB, Ahamed NU, Islam MA, Sundaraj S. Muscle fatigue in the three heads of the triceps brachii during a controlled forceful hand grip task with full elbow extension using surface electromyography. J Hum Kinet 2015;46(1):69-76.
6. Marri K, Krishna NM, Jose J, Karthick P, Ramakrishnan S. Analysis of fatigue conditions in triceps brachii muscle using sEMG signals and spectral correlation density function. IEEE International Conference on Informatics, Electronics & Vision (ICIEV)2014. p. 1-4.
7. Kholinne E, Zulkarnain RF, Sun YC, Lim S, Chun J-M, Jeon I-H. The different role of each head of the triceps brachii muscle in elbow extension. Acta Orthop et Traumatol Turc 2018;52(3):201-205.
8. Bigland-Ritchie B, Woods J. Changes in muscle contractile properties and neural control during human muscular fatigue. Muscle Nerve 1984;7(9):691-699.
9. Missenard O, Mottet D, Perrey S. The role of cocontraction in the impairment of movement accuracy with fatigue. Exp Brain Res 2008;185(1):151-156.
10. Semmler J, Ebert S, Amarasena J. Eccentric muscle damage increases intermuscular coherence during a fatiguing isometric contraction. Acta Physiol 2013; 208(4):362-375.
11. Søgaard K, Christensen H, Fallentin N, Mizuno M, Quistorff B, Sjøgaard G. Motor unit activation patterns during concentric wrist flexion in humans with different muscle fibre composition. Eur J Appl Physiol Occup Physiol 1998;78(5):411-416.
12. Hussain J, Sundaraj K, Low Y, Lam C, Ali MA. Electromyography-A Reliable Technique for Muscle Activity Assessment. J Telecommun, Electron Comput Eng 2018;10(2-6):155-159.
13. Ikuta Y, Matsuda Y, Yamada Y, Kida N, Oda S, Moritani T. Relationship between decreased swimming velocity and muscle activity during 200-m front crawl. Eur J Appl Physiol 2012;112(9):3417-3429.
14. Stirn I, Jarm T, Kapus V, Strojnik V. Evaluation of muscle fatigue during 100-m front crawl. Eur J Appl Physiol 2011;111(1):101-113.
15. Gates DH, Dingwell JB. The effects of neuromuscular fatigue on task performance during repetitive goal-directed movements. Exp Brain Res 2008;187(4):573-585.
16. Enoka RM, Duchateau J. Muscle fatigue: what, why and how it influences muscle function. J Physiol 2008;586(1):11-23.
17. Fukuda TY, Echeimberg JO, Pompeu JE, Lucareli PRG, Garbelotti S, Gimenes RO, Apolinário A. Root mean square value of the electromyographic signal in the isometric torque of the quadriceps, hamstrings and brachial biceps muscles in female subjects. J Appl Res 2010;10(1):32-39.
18. Sakamoto A, Sinclair PJ. Muscle activations under varying lifting speeds and intensities during bench press. Eur J Appl Physiol 2012;112(3):1015-1025.
19. Ali M, Sundaraj K, Ahmad RB, Ahamed NU, Islam M, Sundaraj S. Evaluation of repetitive isometric contractions on the heads of triceps brachii muscle during grip force exercise. Technol Health Care 2014;22(4):617-625.
20. Davidson AW, Rice CL. Effect of shoulder angle on the activation pattern of the elbow extensors during a submaximal isometric fatiguing contraction. Muscle Nerve 2010;42(4):514-521.
21. Perotto AO. Anatomical guide for the electromyographer: the limbs and trunk. Charles C Thomas Publisher; 2011.
22. Marri K, Swaminathan R. Analyzing origin of multifractality of surface electromyography signals in dynamic contractions. J Nanotechnol in Eng Med 2015;6(3):031002.
23. Perlovitch R, Gefen A, Elad D, Ratnovsky A, Kramer MR,

Halpern P. Inspiratory muscles experience fatigue faster than the calf muscles during treadmill marching. Respir Physiol Neurobiol 2007;156(1):61-68.
24. Laine CM, Martinez-Valdes E, Falla D, Mayer F, Farina D. Motor neuron pools of synergistic thigh muscles share most of their synaptic input. J Neurosci 2015; 35(35):12207-12216.
25. Li X, Shin H, Zhou P, Niu X, Liu J, Rymer WZ. Power spectral analysis of surface electromyography (EMG) at matched contraction levels of the first dorsal interosseous muscle in stroke survivors. Clin Neurophysiol 2014;125(5):988-994.
26. Carroll TJ, Taylor JL, Gandevia SC. Recovery of central and peripheral neuromuscular fatigue after exercise. J Appl Physiol 2016;122(5):1068-1076.
27. Metcalf E, Hagstrom AD, Marshall PW. Trained females exhibit less fatigability than trained males after a heavy knee extensor resistance exercise session. Eur J Appl Physiol 2018:1-10.
28. Christie A, Inglis JG, Kamen G, Gabriel DA. Relationships between surface EMG variables and motor unit firing rates. Eur J Appl Physiol 2009;107(2):177-185.
29. Tarata MT. Mechanomyography versus electromyography, in monitoring the muscular fatigue. Biomed Eng Online 2003;2(1):3.
30. Zhang Y-T, Frank CB, Rangayyan RM, Bell GD. A comparative study of simultaneous vibromyography and electromyography with active human quadriceps. IEEE Trans Biomed Eng 1992;39(10):1045-1052.
31. Doix A-CM, Gulliksen A, Brændvik SM, Roeleveld K. Fatigue and muscle activation during submaximal elbow flexion in children with cerebral palsy. J Electromyogr Kinesiol 2013;23(3):721-726.
32. Talib I, Sundaraj K, Lam CK, Hussain J, Ali MA. A review on crosstalk in myographic signals. Eur J Appl Physiol 2019;119(1):9-28.