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Assessment of Muscular Fatigue with Electromyography on Lower Back and Leg Muscles during Continuous Uphill and Downhill Load Carriage Task

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ABSTRACT

Soldiers of Indian Army need to carry moderate to heavy load in complex terrain conditions as their routine activity, which may prove to be highly tiring for leg and back muscles. Soldiers' regular movement at hilly area was simulated in a study consisting of a continuous uphill (UH) and downhill (DH) load carriage task to monitor state of fatigue at back and lower limb muscles. Twelve Indian soldiers walked at a fixed speed on five UH and five DH gradients with three loads (0, 10.7 kg and 21.4 kg). Electromyographic (EMG) recording was carried out throughout the experimentation on four groups of muscles- left and right Erector spinae (ESR and ESL), Vastus medialis (VMR and VML), Gastrocnemius medialis (GMR and GML), and Soleus (SOR and SOL) muscles. Median frequency (MDF) responses of tested muscles were derived from raw (EMG) data. Higher level of muscle fatigue was observed at highest UH inclination as the MDF response in GMR, GML and VMR was lowest at this point. The MDF response were found to be lower at DH gradients as the physical demand of that stage is less than the UH gradients.

Keywords: Electromyography; Median frequency; Load carriage

1. INTRODUCTION

The soldiers of Indian Army generally operate with heavy load in different complex terrains. Climbing up and walking down a hill or mountain with load is a part of the soldier's routine activity. Continuous load march through these difficult terrains causes exhaustion of the physiological system and simultaneously affects the active muscles. The kind of load carriage task performed by the soldiers involves sub-maximal repetitive muscular contraction for long duration which in turn causes undue muscular fatigue. Sub- maximal muscle contraction involves various time dependent physiological and biochemical changes. The force generated by muscle during continuous contraction changes subsequently. These changes may show increase in the integral power or decrease in firing rates of some motor fibers[1,2]. Different mechanisms of fatigue often overlap in their definitions because of the difficulty in isolating one event[3]. Research has mainly focused on localised muscle fatigue as the process of a decline in the force during a sustained activity, which gives a definition of physiological fatigue as the inability to exert any more force or power[4]. Merletti and Parker[5] argue that muscle fatigue can be defined with an engineering approach to fatigue, where fatigue develops over time and is progressive, which defines muscle fatigue as all the physiological changes that occur in the muscle before reaching the inability to exert force.

Electromyography (EMG) measures the electrical activity of localised contracting muscle by summing up the potentials of the recruited motor unit that are stimulating the muscular tissues[6]. There are mainly two important components of myoelectric signals widely used- Root mean square (RMS) for the force generated by the muscle and Median frequency (MDF) for the frequency of contractions to evaluate muscle fatigue[7]. As this is a non- invasive procedure, it reduces the risk of injury and damage to the muscles but the EMG signals gathered from the surface electrodes vary along with the resistance by the skin and subcutaneous fat[8]. Mean frequency (MNF) and MDF are the most useful and popular frequency-domain features[9] and frequently used for the assessment of muscle fatigue in surface EMG signals[10]. Other spectral variables that have been applied in the analysis of EMG signal are total power (TTP), mean power (MNP), peak frequency (PKF), the spectral moments (SM), frequency ratio (FR), power spectrum ratio (PSR), and variance of central frequency (VCF). TTP, MNP, and SM are frequency-domain features that extract the same information as time-domain features based on the energy information. Hence, the discriminant of TTP, MNP and SM in space has the similar pattern as the time-domain features based on the energy information, i.e. integrated EMG (IEMG), RMS, mean absolute value (MAV), and variance of EMG (VAR). Due to the fact that muscle fatigue results in an increase of EMG signal amplitude, time-domain features based on energy information, i.e. IEMG, MAV and RMS, can track this behaviour. Thus, TTP, MNP and SM can also be used as an indicator of muscle fatigue, although EMG signal amplitude, itself, is rarely used to detect muscle fatigue. However, these features can be used in a combination with the spectral analysis

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i.e. MNF and MDF. On the other hand, all spectral features except PSR have the different discriminant patterns in feature space compared with MNF and MDF[11].

The accumulation of biochemical bi-products is termed as the main reason behind the frequency scaling of the power spectrum of myoelectric signals[7]. The interstitial fluid pH changes with metabolic accumulation which reduces the action potential propagation in the muscle fibres. This complex phenomenon is termed as localised muscle fatigue. Mean or median frequency power spectrum is typically used to track progression of fatigue[12]. These myoelectric manifestations of fatigue can be referred to the changes in conduction velocity of muscle fibers, frequency and amplitude[13]. Studies on muscle fatigue applying myoelectric signals have been mainly restricted to exercises exerting constant force during isometric contractions[12]. Whereas a continuous task like load carriage which involves phasic contraction of the active muscles are not evaluated in terms of fatigue analysis. With this background a study had been designed to evaluate the amount of lower back and leg muscles' fatigue (if any) through EMG frequency analysis during continuous uphill and downhill load carriage task by soldiers of Indian Army.

2. MATERIALS AND METHODS

2.1 Participants

Twelve Indian Army (infantry) soldiers [Age- 26.8 (± 3.9) yrs, height- 170.6 (± 3.2) cm and weight 66.2 (± 6.8) kg] participated in the study. A clearance from the Ethical Committee of the author's Institute was obtained prior to the study. Thereafter, soldiers were briefed about the purpose and the risk of the experimentation and their informed consent was obtained after that. The volunteers were proscribed from smoking and alcohol consumption throughout the study period. They were allowed to carry out jogging and light exercise in the morning and had been relieved from night duty during experiment.

2.2 Experimental Protocol

The participants were subjected to treadmill (h/p/cosmos treadmill, Cortex Biophyzik Ltd, Leipzig, Germany) walking for load carriage experiment with the loads mentioned below at a constant walking speed of 3 km.hr^{-1}. The walking speed was selected based on the suggestions on optimum speed in the mountains[14]. Three different magnitudes of loads were employed such as- 10.7 kg consisting of Haversack (HS), Web (Wb) and Rifle (L1); 21.4 kg which consist of Backpack (BP), HS, Wb and Rifle (L2) in existing load carriage ensembles (ELCe, Fig. 1) and without load (No load, NL). Modes, magnitude along with the percentage of body weight and placement of the loads are briefed in Table 1.

There were 10 different uphill (UH) and downhill (DH) gradients used in the study 0, 5, 10, 15, 20, -20, -15, -10, -5 and 0 per cent. The experiments were carried out inside the laboratory with a controlled environment (temperature 20-30˚C and relative humidity 40-60 per cent). The UH walking was performed in an incremental gradient (0- 20 per cent) of TM starting from 0 per cent with a 5 per cent increase after each 6 min of exercise in each gradient followed by DH walking in a decremental gradient (20- 0 per cent). The 6 min duration of the experiment was selected in view of the fact that physiological systems take 3-4 min time to get stabilised during continuous activity of same intensity. The authors gathered experience in this field from their previous studies with similar work intensities and objectives[15,16]. Figures 2 (a) 2(b) show soldier carrying load while walking UH and DH on treadmill. Each participant undergone 30 min UH (6 min each in 0, 5, 10, 15 and 20 per cent gradient) and 30 min DH (6 min each in -20, -15, -10, -5 and 0 per cent gradient) walking continuously to perform 60 min of complete exercise. During the interchange of the gradients the rotation of the treadmill belt was reversed to the opposite direction, the volunteers walked on a different treadmill at 20 per cent gradient for about 10- 15 s. They were immediately shifted to the main treadmill for the completion of the DH walking task.

Figure 1. Existing load carriage ensembles of Indian Army (ElCe).

Table 1. Percentage of body weight with magnitude, different components and placement of loads

Mode	Weight	Components	% of body weight
Existing load carriage ensemble of Indian Army	10.7 kg	Haver sack (HS)- in the waist, Web (Wb)- in front waist region, Rifle- hand	16.2%
Do	21.4 kg	Back pack (BP)- back, HS, Wb, Rifle	32.3%

2.3 Recording of Electromyography

Electromyographic recording was carried out throughout the experimentation on four groups of muscles- left and right Gastrocnemius medialis (GMR and GML), Soleus (SOR and SOL), Vastus medialis (VMR and VML) and Erector spinae (ESR and ESL) muscles. Focus of the study was to see the state of fatigue in the active muscles (lower back and leg muscles) during continuous uphill and downhill load carriage task with the use of EMG. In the present study, soldiers carried various loads for 6 min at each gradient at a given speed during each experiment. Because of a steady state exercise the EMG output of the contracting muscles were assumed to be stable for the given load. Subsequently the time-frequency parameters (MDF) were averaged for a few consecutive cycles i.e. last 120 second because the myoelectric signal at that phase could considered to be quasi-cyclostationary[17].

(a) (b)

Figure 2. Soldier carrying load while walking on a treadmill (a) uphill and (b) downhill.

2.4 Instrumentation

The Delsys Myomonitor sEMG (4.0) system was used for recording of electromyographic signals (Fig. 3). Active bipolar pre-amplified electrodes (n = 8, Delsys) were aligned along the fibres of the muscle under investigation according to the recommendations by SENIAM[18]. EMG raw data was collected though Delsys EMGworks 4.0 acquisition software platform at a frequency of 1024 Hz. Prior to electrode placement, each site was shaved, cleansed with alcohol and gently abraded. To reduce cable movement artefact, cables were secured using elastic bands[19]. EMGworks 4.0 analysis software was used to analyze the recorded data. First the 'Raw EMG' signal plot was created then median frequency (MDF) value was computed on analysis software platform. Finally, the data was exported to excel format. Average of last two min of the MDF data was taken for final analysis.

Figure 3. Delsys Myomonitor sEMG (4.0) system.

2.5 Statistics

Repeated measure ANOVA was applied for EMG parameters as the same group of participants was exposed to all ten gradients (0, 5, 10, 15, 20 per cent, -20, -15, -10, -5, 0 per cent), and three loads in the first study to see over all significance across the conditions. The degree of freedom (df) of the data was checked through Mauchly's test of sphericity for all independent variables and their combinations. The respective 'F' values were taken to check the level of significance. If the sphericity is not assumed, then it was corrected with Greenhous Geisser's correction factor. The corresponding 'F' values were taken as the level of significance. Subsequent to the observed significance level for the various cardiorespiratory and electromyographic parameters; Bonferroni Post-Hoc test was applied to compare between the conditions pair wise. For all the tests, statistical significance was verified at $p \leq 0.05$ level. Statistical Package for the Social Sciences (SPSS 16.0 version) software was used for statistical analysis.

3. RESULTS

Values of electromyographic response (MDF) of lower back and lower limb muscles throughout all loads and gradients are presented in Table 2. Results of the ANOVA with significance level throughout loads, gradients and their interactions including the p values and pairwise comparison are presented in Table 3. Repeated measure ANOVA revealed overall significant change in ESR with load: F (2, 12) = 4.717. The change was almost similar without load and 10.7 kg and maintained about similar value during the rise in gradient (0-20 per cent). It decreased until -15 per cent then started rising while declination changed to 0 per cent. In case of 21.4 kg MDF started to rise with rise in gradient and followed the similar trend of 10.7 kg and without load in downhill gradients. However, the MDF values were much lower in case of 21.4 kg. This was found to be significantly different (overall) with gradient: F (9, 54) = 3.411. Pair wise comparison showed significant interaction between -15 per cent and -5 per cent.

Table 2. Changes in the median frequencies in three pairs of lower limb muscles and one pair of lower back muscle throughout all the gradients and loads

Parameters	Loads	Uphill and downhill gradients									
	(Kg)	0%	5%	10%	15%	20%	-20%	-15%	-10%	-5%	0%
ESR	Nl	58.0 (21.9)	55.4 (18.6)	55.6 (22.9)	60.2 (19.7)	56.0 (21.8)	45.6 (30.3)	46.5 (34.0)	49.7 (32.6)	47.4 (35.4)	53.2 (32.9)
	10.7	57.1 (22.5)	58.0 (20.9)	57.2 (20.2)	56.5 (19.5)	53.2 (17.5)	40.0 (31.2)	39.4 (32.9)	37.3 (26.1)	44.7 (30.6)	49.7 (28.8)
	21.4	28.0 (15.3)	35.9 (19.5)	41.0 (22.8)	39.9 (15.4)	40.7 (13.8)	30.4 (10.1)	31.4 (10.8)	27.9 (8.8)	29.4 (7.7)	37.0 (12.8)
ESL	Nl	60.0 (18.7)	53.8 (16.7)	49.1 (15.8)	58.1 (13.2)	60.3 (13.2)	44.6 (29.3)	46.4 (31.7)	45.9 (33.7)	46.8 (32.6)	57.3 (29.4)
	10.7	56.1 (16.5)	57.0 (15.1)	55.5 (16.4)	58.1 (16.4)	57.5 (15.3)	52.9 (23.9)	49.9 (23.4)	54.3 (22.6)	55.3 (23.1)	64.0 (15.8)
	21.4	39.1 (15.6)	38.4 (11.9)	38.7 (10.9)	40.6 (10.3)	44.4 (9.2)	35.1 (19.6)	30.4 (14.9)	34.8 (22.4)	37.3 (16.4)	31.2 (14.8)
	Nl	66.0 (15.8)	66.7 (11.3)	67.2 (10.5)	67.5 (8.2)	67.9 (6.2)	67.7 (8.0)	68.3 (10.0)	66.4 (10.1)	61.6 (14.1)	56.8 (17.2)
VMR	10.7	73.3 (8.2)	66.7 (7.2)	66.3 (13.4)	69.8 (6.1)	70.4 (7.0)	70.2 (10.7)	69.7 (10.3)	64.1 (16.7)	57.4 (19.5)	55.3 (19.1)
	21.4	65.6 (9.1)	67.4 (14.2)	69.0 (11.4)	72.8 (8.1)	74.3 (9.2)	74.4 (6.2)	72.1 (9.0)	70.9 (8.3)	62.8 (9.6)	55.6 (21.0)
	Nl	69.8 (10.1)	70.8 (10.6)	69.6 (16.5)	67.0 (20.1)	74.2 (15.0)	68.9 (11.4)	65.7 (15.9)	59.5 (17.7)	58.5 (16.7)	62.4 (19.3)
VML	10.7	66.3 (6.2)	63.9 (8.1)	61.7 (8.3)	65.2 (8.3)	64.0 (10.6)	66.8 (9.8)	66.6 (10.5)	67.4 (9.6)	63.8 (10.8)	59.1 (16.6)
	21.4	61.6 (8.1)	60.1 (6.8)	57.2 (12.3)	62.0 (9.9)	65.3 (8.6)	70.9 (7.9)	71.2 (8.2)	66.0 (14.4)	56.8 (13.2)	46.7 (20.6)
	Nl	111.2 (11.4)	101.7 (11.4)	98.0 (10.5)	93.3 (14.9)	96.2 (9.3)	139.2 (12.0)	143.9 (15.6)	137.0 (15.1)	126.2 (12.1)	114.7 (9.6)
GMR	10.7	105.2 (12.6)	102.8 (9.3)	100.3 (10.6)	96.7 (11.3)	91.4 (12.1)	135.1 (16.2)	129.0 (26.1)	131.5 (23.1)	121.8 (19.3)	112.8 (14.5)
	21.4	112.4 (13.5)	105.4 (12.0)	99.9 (10.8)	98.4 (10.5)	96.2 (9.8)	134.5 (12.2)	136.6 (14.5)	130.5 (13.5)	124.0 (14.2)	105.3 (37.2)
	Nl	109.3 (10.0)	101.7 (10.9)	95.5 (12.1)	97.0 (11.3)	95.9 (12.4)	131.3 (13.1)	129.5 (12.5)	122.7 (13.6)	105.3 (18.5)	105.7 (14.9)
GML	10.7	103.2 (8.1)	95.6 (4.9)	94.0 (8.2)	89.7 (6.5)	89.1 (6.7)	133.3 (18.8)	127.0 (13.8)	128.1 (18.4)	117.9 (18.3)	92.7 (23.7)
	21.4	110.1 (13.0)	101.0 (12.1)	97.5 (11.4)	94.8 (9.6)	92.5 (9.6)	131.8 (17.6)	132.9 (17.6)	124.8 (19.3)	114.5 (18.2)	100.2 (34.9)
	Nl	112.9 (27.7)	99.9 (25.1)	104.2 (23.3)	103.5 (11.0)	94.1 (21.0)	110.5 (38.9)	126.8 (28.8)	127.7 (31.5)	122.4 (37.7)	125.2 (28.7)
SOR	10.7	100.7 (25.6)	93.8 (24.6)	104.8 (17.0)	96.8 (10.5)	94.7 (12.9)	104.1 (40.8)	114.3 (19.9)	115.8 (26.2)	114.9 (39.5)	112.5 (31.0)
	21.4	106.8 (23.9)	106.1 (17.6)	103.5 (18.7)	101.9 (15.0)	99.1 (14.2)	124.2 (15.4)	131.1 (14.9)	132.4 (19.1)	128.3 (18.2)	113.5 (39.6)
	Nl	112.9 (15.4)	98.2 (24.2)	90.9 (9.8)	96.7 (15.3)	95.8 (14.0)	124.6 (22.5)	123.8 (21.7)	113.3 (27.7)	112.4 (32.6)	113.2 (23.5)
SOL	10.7	107.4 (16.0)	104.9 (15.4)	105.6 (18.2)	99.1 (16.1)	100.6 (20.1)	109.6 (29.9)	113.1 (21.2)	113.0 (34.7)	115.9 (27.9)	113.1 (25.8)
	21.4	100.9 (18.8)	103.3 (18.9)	101.7 (17.5)	98.3 (19.2)	97.1 (17.0)	114.6 (28.7)	116.3 (24.0)	115.3 (34.8)	117.4 (30.4)	109.6 (42.3)

Table 3. Results of statistical analysis for the studied muscles across all the gradients, loads and their combination

Dependent variables	Independent variables	F value	P value	Overall significance	Pair-wise comparison
ESR	Gradient	0.929	0.508	NS	
	Load	4.717	0.031	*	
	Gradient* Load	0.726	0.726	NS	
ESL	Gradient	3.411	0.002	*	-15 v -5%
	Load	1.409	0.282	NS	
	Gradient* Load	1.031	0.433	NS	
VMR	Gradient	8.628	0.000	*	
	Load	0.785	0.475	NS	
	Gradient* Load	1.182	0.285	NS	
VML	Gradient	6.401	0.000	*	
	Load	2.106	0.159	NS	
	Gradient* Load	2.170	0.007	*	
GMR	Gradient	23.319	0.000	*	0 v 5% 0 v 10% 0 v 15% 0 v 20% 0 v -20% 5 v -20% 10 v -20% 10 v -15% 15 v -20% 15 v -15% 15 v -10% 20 v -20% 20 v -15% 20 v -10% 20 v -5% -10 v -5% -10 v 0%
	Load	1.296	0.297	NS	
	Gradient* Load	0.982	0.484	NS	
GML	Gradient	115.782	0.000	*	0 v 5% 0 v 10% 0 v 15% 0 v 20% 0 v -20% 0 v -15% 0 v -10% 5 v 15% 5 v 20% 5 v -20% 5 v -15% 5 v -10% 10 v -20% 10 v -15% 10 v -10% 10 v -5% 15 v -20% 15 v -15% 15 v -10% 15 v -5% 20 v -15% 20 v -10% 20 v -5% -20 v -10% -20 v -5% -20 v 0% -15 v -5% -15 v 0% -10 v 0% -5 v 0%
	Load	0.123	0.886	NS	
	Gradient* Load	1.330	0.181	NS	

SOR	Gradient	12.411	0.000	*	5 v -15% 15 v -10% 15 v -5% 20 v -15% 20 v -10% 20 v -5%
	Load	0.465	0.639	NS	
	Gradient* Load	1.337	0.180	NS	
SOL	Gradient	11.417	0.000	*	10 v -20% 10 v -15% 15 v -20% 15 v -15% 15 v -5% 20 v -20% 20 v -15%
	Load	0.272	0.672	NS	
	Gradient* Load	1.527	0.091	NS	

*- Significant, NS- Not significant, $p< 0.05$

10.7 kg and without load showed similar trend of change in ESL. 21.4 kg showed a lower response than the other two load conditions. It changed significantly with gradient: F (9, 63) = 8.628 as per the result of repeated measure ANOVA. Pair wise comparison had shown significant interaction of -15 with -5 per cent; -10 with 0 per cent gradient.

The MDF first increased with increase in gradient (0-20 per cent) then decreased with decrease in gradient (20-0 per cent) in case of VMR. On the other hand, VML had shown a disorganised pattern of change with several loads and gradients. VML had overall significant difference with gradient: F (9, 63) = 6.401 and with the interaction between load and gradient: F (18, 126) = 2.170. Bon ferroni Post-Hoc test had shown significant interaction between 10 per cent with -20 per cent and -15 per cent; -15 per cent with -5 per cent; -10 per cent with -5 per cent.

Repeated measure ANOVA had shown overall significant change in GMR with gradient: F (9, 63) = 23.319. Pair-wise comparison revealed significant interaction between 0 per cent with 5, 10, 15, 20 and -20 per cent; 5 per cent with -20 per cent; 10 per cent with -20 and -15 per cent; 15 per cent with -20 per cent, -15 and -10 per cent; 20 per cent with -20, -15, -10 and -5 per cent; -10 per cent with -5 and 0 per cent. The values of MDF of GMR decreased with increase in gradient till 20 per cent. The degree of decrease was -13.5, 13.1, and 13.9 per cent from 0-20 per cent for three loaded conditions. Sharp increase was evident after reaching -20 per cent (30.9, 32.4, 28.5 per cent from 20 to -20 per cent). The values continued to decrease till 0 per cent gradient. However the values were higher in 0 per cent than 20 per cent.

GML changed significantly (overall) with gradient: F (9, 63) = 115.724. Bon ferroni Post-Hoc analysis showed significant interaction of 0 with 5, 10, 15, 20, -20, -15 and -10 per cent; 5 with 15, 20, -20, -15 and -10 per cent; 10 with -20, -15 -10 and -5 per cent; 15 with -20, -15 -10 and -5 per cent; 20 per cent with -15 -10 and -5 per cent; -20 per cent with -10, -5 and 0 per cent; -15 per cent with -5 and 0 per cent; -10 per cent with 0 per cent; - 5 per cent with 0 per cent. In case of GML MDF decreased 12.2, 13.7 and 15.9 per cent from 0-20 per cent for the loaded conditions. It increased 26.9, 33.2, and 28.9 per cent from 20 to -20 per cent for the same.

The result of repeated measure ANOVA showed significant change of SOR with gradient: F (9, 54) = 12.411. Bon ferroni Post-Hoc analysis had shown significant interaction between 5 per cent with -15 per cent; 15 per cent with -10 and -5 per cent; 20 per cent with -15, -10 and -5 per cent. The SOR followed the same response as GMR. There were 19.5, 9.9, and 25.9 per cent for without, 10.7 kg and 21.4 kg load from 20 per cent to -20 per cent). Almost similar trend was followed by SOL. SOL changed significantly with gradient: F (9, 63) = 11.417. Post-Hoc analysis showed significant interaction between 10 per cent with -20 and -15 per cent; 15 per cent with -20, -15 and -5 per cent; 20 with -20 and -15 per cent. MDF in EMG response was lesser in DH gradient in comparison to SOR. It increased 30, 8.9 and 18 per cent from 20 to -20 per cent for without, 10.7 and 21.4 kg load.

4. DISCUSSION

In the present study the electrical functions of active group of muscles were evaluated in terms of MDF to assess the state of fatigue and muscle recruitment pattern during UH and DH load carriage task. The leg muscles like gastrocnemius medialis showed a steady decline in MDF with inclination of the slope of path with all three loaded conditions. The decline is much pronounced with higher gradient and load conditions. The decline in MDF was 13.5, 13.1 and 14.4 per cent with 0, 10.7 and 21.4 kg, respectively from 0 to 20 per cent in GMR and 12.2, 13.7 and 15.3 per cent with 0, 10.7 and 21.4 kg respectively from 0 to 20 per cent in GML. The MDF increased in these muscles with the switch in slope of treadmill path in opposite direction (20 to -20 per cent). There were 30.9, 32.4 and 28.5 per cent increase in GMR and 26.9, 33.2 and 29.8 per cent increase in GML with 0, 10.7 and 21.4 kg loads. At the final 0 per cent gradient of the task the MDF response were lower than -20 per cent. Median frequency decreased after -10 per cent and continued till 0 per cent. These responses were 3.2 and 7.3 per cent higher with 0 and 10.7 kg in GMR from initial 0 to final 0 per cent gradient. 6.3 per cent in GMR with 21.4 kg and 3.3, 10.2 and 8.9 per cent decrease in MDF was observed in GML from initial 0 to final 0 per cent gradient. Almost similar trend was seen with right vastus medialis muscle. Highest MDF values were achieved at -20 per cent with and without loads in case of VMR. Right vastus medialis had shown decline in MDF with decline in gradient. The decrease in MDF was 13.9, 24.6 and 15.1 per cent lower at final 0 per cent than that of initial 0 per cent. Least MDF values were observed at -0 per cent in case of VML. Median frequency response of SOR followed similar pattern as gastrocnemius with and without load. SOL, ESR and ESL had shown disorganised pattern of frequency response with three loads and 10 different gradients.

Frequency domain is the key feature or gold standard for assessing the muscle fatigue and recruitment of motor unit. Stulen and De Luca[20,21] had shown, that median frequency- the frequency at which the power density spectrum is divided into two parts of equal energy provides a reliable estimate of spectral frequency transitions when noise accompanies the EMG signals. According to Roy and De Luca[22] the rate of force variation depends on changes in muscle length, movement of skin over muscle and problems of signal stationarity during dynamic contraction. The muscle fatigues with excess accumulation of lactate inside its fibre. This reduces the recruitment of no. of muscle fibres which in turn affects the conduction velocity of the contracting muscle that causes reduction in the frequency domain (e.g. MDF) of muscle contraction. Current knowledge indicates that by correctly analysing the EMG signal, detected painlessly and non-invasively outside the body, researchers can quantitatively measure and monitor the number of biochemical bi-products accumulated in an individual muscle in terms of reduction in MDF during a sustained contraction[23]. These statements were not verified on dynamic real time conditions where phasic contractions are prevalent to raise its base of applicability. Such kind of task (load carriage in UH and DH gradients) is attempted in the present study to be evaluated in terms of muscular fatigue analysis.

Stulen and De Luca[21] performed a mathematical analysis to investigate the restrictions in estimating various parameters of the power density spectrum. The MDF parameter was found to be one of the most reliable, and this was found to be less sensitive to noise. Decrease in MDF and increase in amplitude was observed with given exercise[24]. The findings confirmed the state of fatigue in all the muscles tested. Measurement of frequency parameters during dynamic contractions requires techniques that retain the temporal information. During the past decade time–frequency analyses techniques have evolved in the field of electromyography, as they have in the realm of other bio-signals such as ECG and EEG. Constable[25], *et al.* investigated the change in the frequency content of EMG signals during high jumps. Roark[26], *et al.* investigated the movement of the thyroarytenoid muscles during vocalisation had successfully applied EMG signal in this area. In both these applications muscles contracted dynamically and briefly. There are other studies where decrease in frequency was observed which resulted in fatigue could be explained as central or peripheral in nature[27-29]. These observations corroborated with the decrease in the frequency during UH load carriage by Indian soldiers of the present study.

The task given to the soldiers in the present study lasted about an hour. Vastus medialis generally assist the extension of leg. Gastrocnemius helps in plantar flexion of the foot and is mainly activated during leg flexion. It also provides the main power for walking during terminal stance phase[30]. Soleus is also known as plantar flexor of ankle especially during bent knee position[31]. Erector spinae helps in adjustment of posture during uphill walking. As the back load increases the inclination of trunk rises to keep the COM above the feet[32]. Silder[33], *et al.* studied the effect of three gradients, without load on vastus medialis and soleus muscles. They observed similar pattern of rise in activation of both the muscles at UH gradients. It is understood that excess activation of muscles caused by continuous UH walking will ultimately lead to fatigue and overexertion injuries. Effect of long duration load carriage on neuro-muscular fatigue was assessed by Grenier[34], *et al.* by estimating frequency changes in vastus lateralis and soleus muscles. After 21 h of simulated military mission peripheral fatigue was observed in recorded muscles with low frequency changes. EMG amplitude of gastrocnemius, soleus, rectus femoris, vastus lateralis, semimembranosis, biceps femoris, left and right erector spinae, and triceps brachii were recorded during an UH and DH load carriage task with or without hiking poles. The activities of gastrocnemius, biceps femoris, rectus femoris, and vastus lateralis muscles had decreased with use of hiking poles. Whereas the activity erector spinae muscles had mininmum change during the task[35]. Fouad[36], *et al.* reported that the Army personnel who are often engaged in physical activity show excitatory response of all muscles as an adaptive response to higher load, gradient and speed for adjusting to posture and walking. The response of GMR, GML, SOR and VMR muscles of the soldiers in the present study suggests these muscles are heavily used in a load carriage task that requires UH walking. At 20 per cent UH gradient, the MDF response was lowest which indicates higher level of muscle fatigue. At -20 per cent MDF in GMR, GML, and VMR were highest for all loads compared to other gradients which indicates maximum no of muscle fibre recruitment[23]. At the final gradient, the MDF was much lower in these three muscles. The soldiers reached the plains i.e. 0 per cent gradient after continuous DH walking for 24 min. At this juncture, the physical demand to continue load carriage is supposed to be very less. In such a situation, the dominant leg muscles (GMR, GML and VMR) needed less no of muscle fibre recruitment to withstand the comparatively easier work load. Thus, a lower degree of MDF response was observed. However, most of the muscles had had a lower MDF at -0 per cent than 0 per cent except SOL and SOR. This can be attributed to less no of fibre recruitment at the end of a 60 min load carriage task.

5. CONCLUSIONS

The present study was comprised of a dynamic load carriage task, which required carrying three magnitudes of loads in a treadmill with UH and DH walking at different gradients. The MDF values were minimum at 20% gradient while carrying 32 per cent of body weight for gastrocnemius and vastus medialis muscles. This suggested maximum fatigue at this point which might have occurred due to soldiers' ability to recruit less no of muscle fibres while carrying out the task. At -20 per cent the work load had decreased and MDF was highest for all loads compared to other gradients. The MDF response decreased at subsequent DH gradients and was very low at 0 per cent as simultaneous reduction of physical work demand in this phase which might have required lesser no. muscle fibres' recruitment. The soleus muscles also showed similar trend with nominal deviations. The state of fatigue in erector spinae muscles could not be understood in this experimental set up. Measurement of fatigue by estimation of blood lactate level and finding out several causes of occurrence of injuries due to load carriage event could have been attempted to judge realistic consequence of such a task. The data of this article can be used for prevention of extra fatigue and subsequent injury while planning for long duration road march at hilly, uneven terrains for soldiers and other occupational backpackers.

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