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The practical use of surface electromyography during running: does the evidence support the hype? A narrative review

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ABSTRACT

Background/aims: Surface electromyography (sEMG) is a commonly used technique to investigate muscle activation and fatigue, which is non-invasive and can allow for continuous measurement. Systematic research on the use of sEMG in the sporting environment has been on-going for many years and predominantly based on cycling and rowing activities. To date there have been no reviews assessing the validity and reliability in sEMG exclusively in running activities specifically during on-field testing. The purpose of this review is to evaluate the use of sEMG in the practical context and whether this be translated to on-field testing.
Methods: Electronic literature searches were performed using the Cochrane Library, PUBMED, CINAHL and PeDro without restrictions on the study date to identify the relevant current English language literature.
Results: 10 studies were relevant after title and content review. All the studies identified were all level three evidence based. The general trends of the sEMG activity appear to correlate with running velocity and muscle fatigue seems almost always the consequence of prolonged, dynamic activity. However, these changes are not consistently measured or statistically significant throughout the studies raising the question of the accuracy and reliability when analysing sEMG measurements and making assumptions about the cause of fatigue.
Conclusions: An agreed consensus when measuring and analysing sEMG data during running activities particularly in field testing with the most appropriate study design and reliable methodology is yet to be determined and further studies are required.

What is known

- Surface electromyography (sEMG) is widely used in the sporting environment to assess for muscle fatigue.
- A number of methods and techniques are available to measure changes in EMG signals.

What this review adds

- This is the first review of the use of sEMG exclusively to running exercises with on-field testing.
- Multiple techniques and methods are being used with inconsistent results.
- Caution is required when interpreting the reliability of the recorded results.
- Further research is necessary.

INTRODUCTION

Muscle surface electromyography (sEMG) is a commonly used technique for measuring muscle activation. Systematic research on the use of sEMG in the sporting environment has been on-going for many years[1] and predominantly based on cycling activities.[2] To date there have been no reviews assessing the validity and reliability in sEMG exclusively in running activities. The purpose of this review is to evaluate the use of sEMG in the practical context and whether this can be translated to on-field testing.

EMG has been increasingly used to investigate muscle activity and fatigue as this is non-invasive and can allow for continuous measurement. By investigating changes occurring in the EMG signal, muscle activation can be inferred by certain EMG signal changes; either in the time and/or amplitude of the EMG signal or in frequency domains.[3] A number of parameters have been used to investigate changes in the amplitude and frequency domains of the EMG signal. These include mean and median frequency to investigate changes in the frequency spectrum of the EMG signal as well as root mean square and integrated EMG to determine amplitude changes.[4] Muscle fatigue developed during isometric contractions increases the EMG signal amplitude and the power spectrum towards lower frequencies.[5–7]

Surface v fine wire EMG

EMG can be categorised into either surface or fine wire. Fine wire EMG (fEMG) involves placing electrodes and recording electrical activity intramuscularly, whereas sEMG measures the electrical signal of the muscle recorded from the surface of the skin overlying the muscle. Intramuscular recording of muscle electrical activity using fEMG is appropriate for the study of the physiology and pathology of individual motor units, whereas sEMG is better suited for investigation of the temporal pattern of activity and fatigue of whole muscles or muscle groups.[8] sEMG is non-invasive making it is more appropriate than fine wire in the sporting environment. This may minimise discomfort, risk of infection, and allows for frequent and even live repetition of assessments. Various types of expensive sEMG measuring equipment have been developed often without clarity of their exact use or reliability during on field-testing. This is a review of sEMG activity literature related exclusively to running exercises.

METHODS

Electronic literature searches were performed using the Cochrane Library, PUBMED, CINAHL and PeDro without restrictions on the study date to identify the relevant current English language literature. One reviewer (RW) conducted the literature search and retrieved the abstracts. The methodological quality of the studies included and the abstracts of the reviews identified using this search were inspected by two authors (RW, RS). Those meeting the inclusion criteria were retrieved and read in full. A low number of studies relevant to the research question were identified.

The inclusion criteria and related MeSH terms searched were adult human studies, athletes, running, sport, exercise, endurance, exhaustion, fatigue, training, fitness, track, treadmill testing, EMG and sEMG. Exclusion criteria included cycling, rowing, static, resistance, isometric, concentric, eccentric and isokinetic exercises. Fifty-five papers were identified from PubMed. Ten studies were relevant after title and content review. Key words included runner, run, sport, exercise, endurance, fatigue, exhaustion, treadmill, training, fitness, fit long distance, EMG and surface EMG. The outcome measures included impulse, electrical potential, muscle motor unit, motor unit action potential, electrophysiological activity, EMG signal and mean power frequency.

RESULTS

Two reviewers (RW and RS) independently identified studies to be included in the review, with no disagreements. Fifty-five papers were identified. Following application of the inclusion criteria, 10 studies were found to be eligible for appraisal. Using the Oxford Centre of Evidence-Based Medicine, all the studies identified were of levels 3a and 3b.

CRITICAL APPRAISAL

The Critical Appraisal Skills Program for cohort studies was used to review all the studies.[9] [10] Study design, methods and outcomes were extracted and tabulated in online supplementary table provided. All studies included running activities with participants being athletes and football players at a professional and amateur level. Running activities varied between each study with athletes being tested on different surfaces ranging from outdoor to indoor track surfaces over varying distances. The studies all measured different muscles groups in the lower limb using surface electrodes placed at different points on each muscle. One study included muscles of the foot and only two studies investigated both legs. All participants in each study were deemed physically fit at the time of testing with no associated injuries. The number of participants in each study was low with the mean number of 9.5 with sample sizes ranging from 4 to 19.

DISCUSSION

From the results outlined in this review, sEMG appears to provide inconsistent results when assessing neuromuscular activity during running. The general trends of the sEMG activity appear to correlate with running velocity and muscle fatigue seems almost always the consequence of prolonged, dynamic activity. However, these changes are not consistently measured or statistically significant throughout the studies raising the question of the accuracy and reliability when analysing sEMG measurements and making assumptions about the cause of fatigue.

Owing to the varying descriptive methodology of each study the results merely indicate that a pattern seems to exist when using sEMG measurements during different running exercises. With each study using participants of different capabilities at different times of the day with different technical equipment, the interpretation of sEMG data and comparison of findings between the different studies becomes very challenging, unreliable and statistically insignificant.

With regards to study design, a clear distinction should be made between running surfaces and the neuromuscular activity should be differentiated depending on whether the context allows changes in velocity and direction (eg, running on a track) or controlled speed and direction (eg, treadmill testing and gradient). Each treadmill study varied in terms of speed and gradient. Only four studies were identified with on-field testing, further indicating the difficulties in the practical and analytical use of this equipment

Responses may differ between muscles groups in each leg and the consideration of stride frequency with an increase in speed or onset of fatigue is a vital part of the assessment of muscular fatigue.[3] These are not consistently measured throughout each of these papers. Each study measures different muscle groups in the lower limb with no consistency in using both legs; only 2 of the 10 studies used both legs. Guidelines are available for the placement and preparation of the surface electrodes[11 12]; these are inconsistently followed in each paper; with recording failure and electrode connections frequently problematic. When interpreting results, the analysis must take into consideration the 'cross-talk' effect of detecting signals form more than one muscle leading to inaccurate signals. These differences and complications make comparable interpretation of data extremely difficult with questionable accuracy and reliability when interpreting results. The results further suggest that muscles may fatigue at different thresholds seen by decreasing, minimal or no sEMG activity, which may depend on athlete calibre, certain local muscle measurements, velocity, distance, mechanism and origin of the onset of fatigue, whether peripheral or central. This is inconsistently tested, measured and remains poorly understood in the literature.

The low number of studies identified reflects the logistical challenges of study methods involving participants running, particularly during field testing, the cost of expensive sEMG equipment, the rapid changes in technology of the equipment over the past 30 years and complexity of accurate analysis. Given the potential impact of previous injury on sEMG response, which is not clear in these studies, it seems prudent to initially measure uninjured legs, on a standardised flat surface while running in straight lines. Both limbs and major muscle groups would need to be measured with greater detail on each participant, such as measurements of muscle mass/volume, fitness for example, VO2 max or lactate threshold to account for confounders and bias.

These confounding factors make the measurement and mathematical analysis very challenging, leading to potentially inaccurate or false results. The low number of participants in each study makes them significantly underpowered. Furthermore, a very high number of participants are required to achieve sufficient power for conclusions to be made and this may restrict future research. These limitations make it difficult to determine fatigue measurements and have a relatively high risk of selection bias. No general consensus on a reliable and comparable methodology or optimal statistical analysis for assessing and analysing sEMG activity exists.

SUMMARY

Despite the commercial applications and use of expensive sEMG equipment in the sporting environment, there are many important limitations with this technique when it is used during running. The variety of methods and equipment for processing sEMG data limits the ability to interpret and compare data. sEMG measurements seem to demonstrate inconsistent, non-statistical changes in lower limb sEMG activity and much larger cohorts of athletes must be studied with comparable sEMG methods and statistical analysis to produce more reliable and valid results. This may be difficult to achieve in practice, especially when investigators wish to include professional athletes.

There is currently no consensus on how to measure and analyse the sEMG data produced during running activities. This technique may have the potential to predict fatigue, recovery and prevent injury but until these limitations are addressed and results better understood the commercial application of sEMG remains uncertain in this context.

Contributors All authors stated contributed to data collection, analysis and interpretation. RW initiated the idea and performed the first review of the literature with initial tabulated rests. RS performed another literature review and tabulated further results with analysis and write-up of the results providing concise discussion and conclusions. GW reviewed the tabulated results and provided further analysis of results.

Competing interests None declared.

Provenance and peer review Not commissioned; externally peer reviewed.

Data sharing statement No additional data are available.

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Study	Demographics	EMG Equipment and Techniques	Design	Methods	Outcomes
1.Nummela et al 1993	Age range 20-28(25+/-3yrs) Mean Height 1.83+/-0.06m Mean Weight 73+/- 6kg All male	Bipolar surface electrodes Constant electrode distance 20mm on each muscle belly Electrode places marked for each day EMG transmitter fixed with belt to waist. Extra load 1.8kgs EMG activity was amplified and recorded telemetrically)	10 sprinters 400m runners/hurdlers All male EMG successfully recorded in7/10 participants Outdoor track 4x leg muscles of the right leg Gastrocnemius medialis GAm Biceps Femoris BF Vastus Lateralis VL Rectus Femoris RF	Two 400m runs performed separately on two successive days on outdoor track Day One: subjects ran a maximal 20m, with a flying start over 40m followed by a 400m time trial with maximum effort. Day Two: subjects ran sub-maximal 20m runs with a flying start at the average speed of the first 100m during the 400m run on the previous day. The maximal and sub-maximal 20m runs were run 3-5 times and the 400m only once. Non-smoothed EMG signals were rectified, integrated and averaged (AEMG) for three phases of running: the pre-activation (50ms prior to ground phase), braking and propulsion phases.	The role of central and peripheral fatigue was evaluated by comparing maximal sprint running in fatigued and non-fatigued conditions. AEMG of RF increased significantly during the submaximal 20m run to the end of 400m during in the braking phase ($p<0.05$) no significant changes were seen in the other three muscles. Comparison of the two maximal conditions, maximal 20m and the 400m AEMG of GAm and BF were significantly greater during non-fatigued condition in the propulsion phase ($p<0.001$) and ($p<0.05$) respectively. The AEMG of all the muscles differed significantly between the different runs in the braking ($p<0.01$), the propulsion ($p<0.05$) and the pre-activation phase ($p<0.05$). The increase in AEMG was 28% in the braking phase and 8% in the propulsion phase. There was a significant difference in the EMG activity in BF and GAm in the propulsion phase between fatigued 400m run and non-fatigued and maximal 20m-run. The AEMG of RF and VL did not differ between these two conditions
2.Nummela et al 1992	Mean age 23.7 S.D 3.5 Mean Height 186cm S.D 5 Mean BM 75kg SD 7 All male Mean Training years 6 SD 2	Bipolar surface electrodes Constant electrode distance 20mm Placed longitudinally over motor point of muscles EMG transmitter fixed with belt. Extra load 3kgs	6 sprinters All male Gastrocnemius medialis GAm, biceps femoris,BF rectus femoris, RF vastus lateralis,VL One Leg: Right Leg Only GAm and VL used in final analysis Mean Training years 6	Two days of 200m on indoor track Day One: subjects ran a maximum speed test over 200m and 400m Day 2:subjects 100m and 300m with 20m flying start on each day. A rest period of five hours between runs was allocated on each day. Before the 400m sprint and immediately after each run, the subjects performed drop jumps	EMG recordings were measured during all runs and drop jumps. A loose sole with a special switch was used to determine contact times during all runs. EMG and EMG:running velocity ratio increased progressively with running distance. EMG activity was greatest in both muscles during the ground reaction phase of the 400m sprint ($p<0.05$). Both the EMG:force ratio in drop jumps and EMG:running speed ratio increased during the second half of the 400m, suggesting primary cause of fatigue in the 400m sprint is related to skeletal muscle and not centrally.

		Wired system EMG signals stored on magnetic tape	SD2	from a height of 39cm.	
3.Mastalerz et al 2012	Mean age 24+/-2yrs Mean BM72+/-2.2kg Mean Height177+/-1.3cm All male	Self adhesive, disposable, surface electrodes Skin shaved, cleaned with isopropyl alcohol,abraded with coarse gauze Electrode placement Validated by Winter et al 8mm diameter, 20mm intraelectrode distance SEMG signal amplified and recorded telemetrically	4 professional 400m runners Rectus Femoris RF Biceps Femoris BF both legs	Subjects ran a 400m run at four different intensities timed at every 100m on an indoor athletic tartan track. Need to add more here	Mean power frequency (MPF) increased by 23.6% biceps femoris (BF) and 19.5% rectus femoris (RF) in left leg compared with 17.5% (BF) and 12.5% (RF) in right leg. During the run with maximum intensity, a 30% difference between left and right BF and 11% for RF fatigue was observed in the first 25 seconds and decreased to 3% for BF and 9% for RF after the 25th second of the testing. Increases in fatigue measured by EMG activity were only seen in highest velocity run. Greater fatigue was noted in the left limb compared to the right during the 400m run on the tartan track. The differences between both legs and the more substantial load on the BF is likely due to the result of the curving part of the track. This effect was also observed in RF but not as significantly.
4.Paavolainen et al 1999	Mean Age HC23.8+/-3.6 LC 24.3+/-2.8 Mean BM HC68.5+/-6.2 LC 71.3+/-6.0 Mean Height HC178.9+/-6.1 LC180.1+/-4.3	Beckman miniature skin electrodes Skin dry shaved, rubbed with sandpaper, cleaned with alcohol Electrodes positioned longitudinally over belly of the muscle Intra-electrode distance of 20mm EMG signals amplified and recorded telemetrically	19 athletes 9 high calibre (HC) and 10 low calibre(LC) runners/orienteers Indoor Track Vastus lateralis Vl, Rectus Femoris RF,Biceps Femoris BF, Gastrocnemius medialis GAm measured One Leg: Right leg 19 elite cross-country runners Background Training years	10k using a 200m distance on an indoor track with a 9.4m long force platform system consisting of five 2D and 3D force plates. At the beginning of the 10k and after running 3,5,7 and 9km all subjects ran a 200m constant velocity lap at a speed of 4.5km/s. The athletes ran 20m before and 20m after the 10K at maximal speed.	In the maximal 20m runs the average integrated EMG (IEMG) of VL, BF and GA during the pre contact and contact phases were 28.5-57.2% lower ($p<0.001$) from the 20m after to the 20m before. The IEMG:force ratio of the total contact, braking and propulsion phases decreased by 35.1-13.5% ($p<0.05$-0.001) from 20m before to 20m after. No differences were seen within each group. During the constant velocity the average IEMG activity in VL increased with no changes in BF or GA. No significant changes occurred in the IEMG:force ratio during the constant velocity lap. The EMG measurements for RF during the constant velocity laps and the after lap were successful for only 11/19 subjects leaving only the remaining three muscles for testing. The decreased IEMG:force ratio under these experimental conditions may not only be peripheral but have a central origin.

			HC 9.1+/-3.2 LC9.0+/-2.4		
5.Rahnama et al 2006	Mean age21.4+/-3.1yrs Mean BM74.5+/-8.5kg Mean Height1.77+/-0.06m	Two elcectrodes per muscle Bipolar surface electrodes 20mm diameter Skin shaved, washed with alcohol, lightly abraded 20mm intraelectrode distance RF midway between ASIS and superior border of patella BF:Long head, midway between ischial tuberosity and lateral condly of femur TA over greatest area of muscle bulk Gastrocnemuis, lateral head over greatest area of muscle bulk	10 amateur soccer players Treadmill testing Rectus femoris, RF,Biceps Femoris BF,Tibialis Anterior,TA, Gastrocnemius measured One leg	Soccer specific intermittent exercise protocol. This included walking, jogging, running and sprinting. The speeds of these were 6km/h, 12km/h, 15/km/h and 21km/h respectively. The total time was 90mins with a 15 minute interval. Each half was 45 minutes -22 minutes in duration, followed by 1 minutes rest and then a second 22 minutes, to simulate a soccer match. Two sessions were carried out using fatigue and control sessions. During the first session the subjects performed a warm-up including soccer specific stretching exercises and running at low speed on treadmill.	The EMG activity was recorded for 5 s at of the speeds 6,12,15 and 21 km/h. All tests were carried out at the same time of day to remove circadian variables. During the first session the subjects performed a warm-up including soccer specific stretching exercises and running at low speed on treadmill. The subject then performed the EMG measurement treadmill protocol for the soccer specific exercises. During the second session, a control test was performed where the same warm was conducted followed by the EMG measurement protocol. The subjects then rested for 45 minutes before repeating the protocol. They had another 45 minute before the final EMG measurements were taken. Each muscle showed a statistically significant increase in EMG activity as speed increased in each condition (exercise and control) (p<0.001).RF (p<0.05), BF (p<0.01) & TA (p<0.05) all decreased activity at each fatigue state, but not GA. After simulation of soccer on treadmill, EMG activity in major lower limb muscles was less than before. This decrease suggests that exercise had an effect on muscle activity even when work rate was sustained.
6. Patras et al 2011	All male Mean Age 24.8+/-5.3 Mean BM77.3+/-7.5kg Mean Height 177+/-5.3cm	Pre-gelled Skin shaved and rubbed with abrasive paper 20mm fixed intra-electrode distance 10mm diameter	14 amateur soccer players All had ACL reconstructed knees Treadmill testing Vastus Lateralis Both Legs	In the first visit to the laboratory, the players performed a GXT test to volitional exhaustion to determine VO_{2max}, lactate threshold. Testing was performed after a warm up of 3 minutes walking at self-selected speed followed by 5 mins jogging at 8km/hr. The incremental test began at speed of	EMG levels for the intact leg strongly correlated with lactate threshold (r=0.77, p=0.001 and velocity at 4mM (r=0.68, p=0.008). Final EMG for the reconstructed leg had moderate relationship with lactate threshold (r=0.47, p=0.09 and velocity at 4mM (r=0.52, p=0.06) which was not statistically significant. The EMG response of the intact leg showed a strong relationship to endurance markers, whereas reconstructed leg

			All with bone patella bone graft-18.5+/-4.3 months before testing Return to sports 6months after reconstruction following widely accepted criteria	10km/hr and increased by 2km/hr every 3 minutes. In the second visit EMG activity was recorded from vastus lateralis (VL) bilaterally during 10min run for 15 secs at 3rd & 10th minute.	did not demonstrate relationship, which may indicate that injury and surgery modify ability of local muscles to tolerate high intensity running.
7. Gefen et al 2002	2 male: 25, 17 2 female:28, 17	Shaved skin, scrubbed with alcohol Surface electrode discs 9mm No exact placement stated	4athletes Treadmill Testing Gastrocnemius lateralis, GAl and medialis GAm, Soleus S, Tibialis anterior TA, Extensor Halucis Longus EHL, Peroneus longus PL One Leg	Marching in athletes was included because a similar method was used to the other studies and importantly the treadmill velocity for the test was 8km/hr, which is the speed of a slow jog or run and faster than a quick walk (~6.5km/hr). The treadmill marching distance was of 2km with 30 inversion/eversion motions of the foot performed pre and post exercise with and without shoes.	The most prominent decrease in EMG signal bursts due to fatigue occur in the LGA and PL muscles which were shown to decrease by 20%. Reductions of 15-20% in duration of signal bursts were observed in MGA and S. The maximum median frequency, MF decrease was recorded for the PL and GAl, fatigue was evident in these muscles after 10 minutes. Due to small numbers single subject designed statistics were designed to test the significance of the substantial drops in of the peroneus longus. Significance was set to 5%. For this analysis marching tasks were divided into three stages of equal duration of approximately 5 minutes. The averaged MF values were recorded at each stage and compared showing a statistical significant drop in in the PL muscle p<0.01from the first stage, the mid-point and to the end. The reductions in activity and decrease in MF of PL and GAl explain changes in gait/force production seen with fatigue.
8.Hanon et al 2005	Mean age26.8+/-5.13 MeanBM65.4+/-2.2kg Mean Height 179.9+/-3.72cm	Bipoloar configuration 10mm diameter Skin scraped No exact placement stated	9 trained athletes Treadmill testing 6 muscles GM,BF, VL, RF, TA, GaS One leg All male, well trained 5-7 sessions per week	Treadmill testing with incremental running tests, increasing in speed every four minutes for twenty minutes, with one minute rest intervals between each. One leg was used for EMG recordings with isometric contractions of each muscle used prior to testing Burst EMG and distance integrated EMG (iEMG), readings were during flight (f) and contact (c) phases.	On the burst scale, an increase in iEMG between start and end was shown for BF-contact and RF-contact. RF-flight before the end p<0.05. For the distance scale GA was the only muscle not to show an increase in iEMG between the 20m at the start and the 20m at the end. The iEMG increased significantly during the last stage for both VL and TA. For BF-f+c and RF-c this increased significantly during middle and penultimate stages. Different muscles exhaust earlier and are different at different speeds with GA, VL at lower speeds BF and RF and higher speeds. The hip mobilising muscles BF and RF were seen to fatigue

					earlier than the other muscles. This is consistent with the linear increase of stride length and speed and explains the resulting fatigue.
9. Mizrahi et al	Calisthenics twice per week Mean Age: 30.1+/-5.1 Mean height: 173.9+/-7.3cm Body Mass 70.4kg+/-9.2Kg	No documented skin preparation Two pairs of small bipolar disposable Ag/AgCl snap sur- face electrodes 10mm diameter No exact placement stated	22 males Treadmill Testing Gastrocnemius and quadriceps Right leg EMG successfully recorded in 12 subjects	Each subject was subjected to an incremental load on the treadmill with an increasing speed to determine his anaerobic threshold which was determined non-invasively as the onset of initial increase in each of the ventilatory equivalent for oxygen (WVO2) and ventilatory equivalent for carbon dioxide (VE/VCO2) The running speed was initially 1 m/s and was increased every 30 sec by increments of 0.22 m/s until the point of anaerobic threshold determination. According to PETCO2 by the end of the 30 min of running on the treadmill all subjects were divided into two groups. Surface electrodes were placed over the quadriceps and gastrocnemius muscles of the right leg.	One group ($n = 10$) had a significant decrease ($p < 0.05$) of PETCO2 and it was defined as the fatigue group. The other group ($n = 12$) did not show a significant change of the amount of PETCO2 at the end of the test and was defined as the non-fatigue group. The average speed for the fatigue group (2.76 ± 0.29 m/sec) was not significantly different from the non-fatigue group (2.75 ± 0.48 m/sec). Only twelve of the subjects were instrumented with the surface electrodes for EMG evaluation due to procedural constraints. The mean, root mean square, mean and median frequency were calculated. In the fatigued gastrocnemius group there was a decrease in the time domain, but it was not statistically significant. No change was noted in the frequency domain results. The gastrocnemius data for the non-fatigue group also do not indicate a significant variation with time. As for the case of the gastrocnemius, the data of the quadriceps muscle did not vary significantly with time during the running tests.
10. Mizrahi et al	Mean age 24.2 SD, 3.7 Mean height 175.5 SD, 5.9 cm, leg length 90.0 SD, 3.0 cm Body mass 73.2 SD, 8.3 kg	Two bipolar Ag/AgCl electrodes 10mm diameter Placed 2cm apart in centre of rectus femoris muscle belly No skin preparation documented	14 males, student population Treadmill Testing Recreational runners 8-10km/week Quadriceps Right leg	There were two running tests, separated by at least one week to ensure fatigue-free initial conditions: one level running and the other at a decline angle of -4°. The running tests were performed on a treadmill. Prior to the running tests, the anaerobic threshold was determined for each subject by monitoring the respiratory data (as per study 9) in level running. Running was at a speed exceeding	Surface electrodes were placed on the quadriceps of the right leg. Five hemispherical markers of 2 cm diameter were used for optional motion capture for the kinematic segments of the lower limb. The markers were attached to the right leg in the sagittal plane to the greater femoral trochanter, the lateral condyle of femur, the lateral malleolus, below the lateral malleolus and opposite to the head of the fifth metatarsal. The average speed in both level and downhill running for all the 14 subjects was 3.53 m/s. Metabolic fatigue was not reached in downhill running. No

				the anaerobic threshold speed of each subject by 5% and lasted 30 min. Before the test, a 15 min warm up running on the treadmill was per- formed.	significant changes in either iEMG or mean power frequencies MPF were noted in level running despite the fact that the anaerobic threshold was exceeded in this case and metabolic fatigue did develop. In downhill running, Statistically significant increases during running were noted in the quadriceps iEMG from the 20th min and onwards and in the MPF from the 15th min and onwards.