Journal of Electromyography and Kinesiology 30 (2016) 216–230

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Review

Detecting fatigue thresholds from electromyographic signals: A systematic review on approaches and methodologies

Peter Ertl *, Annika Kruse, Markus Tilp

University of Graz, Institute of Sport Science, Austria

ARTICLE INFO

Article history:
Received 14 April 2016
Received in revised form 26 July 2016
Accepted 1 August 2016

Keywords:
Electromyographic threshold
Muscular fatigue
Aerobic-anaerobic transition
Cycling ergometer
Incremental exercise
Constant workload
Review

ABSTRACT

The aim of the current paper was to systematically review the relevant existing electromyographic threshold concepts within the literature. The electronic databases MEDLINE and SCOPUS were screened for papers published between January 1980 and April 2015 including the keywords: neuromuscular fatigue threshold, anaerobic threshold, electromyographic threshold, muscular fatigue, aerobic-anaerobictransition, ventilatory threshold, exercise testing, and cycle-ergometer. 32 articles were assessed with regard to their electromyographic methodologies, description of results, statistical analysis and test protocols. Only one article was of very good quality. 21 were of good quality and two articles were of very low quality. The review process revealed that: (i) there is consistent evidence of one or two non-linear increases of EMG that might reflect the additional recruitment of motor units (MU) or different fiber types during fatiguing cycle ergometer exercise, (ii) most studies reported no statistically significant difference between electromyographic and metabolic thresholds, (iii) one minute protocols with increments between 10 and 25 W appear most appropriate to detect muscular threshold, (iv) threshold detection from the vastus medialis, vastus lateralis, and rectus femoris is recommended, and (v) there is a great variety in study protocols, measurement techniques, and data processing. Therefore, we recommend further research and standardization in the detection of EMGTs.

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* Corresponding author at: Mozartgasse 14, 8010 Graz, Austria.
E-mail address: peter.ertl@uni-graz.at (P. Ertl).

http://dx.doi.org/10.1016/j.jelekin.2016.08.002
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1. Introduction

Surface EMG offers versatile applications in various fields of science (e.g. biomechanics, physiology). The most common applications are: (1) the determination of activation of muscles, which can provide the timing sequence during an exercise, e.g. walking or running (2) the EMG-force relationship, which allows analysing the contribution of both individual and groups of muscles, and (3) the EMG signal as an index of fatigue (DeLuca, 1997). Additionally, EMG signals reflect peripheral and central properties of the neuromuscular system (Farina et al., 2004a, 2004b, 2004c). Different signal processing methods in the time and frequency domain allow further analysis of muscle activation such as the amount of effort or fatigue during physical activity. Besides these classical applications, EMG has also been used to detect the aerobic and anaerobic thresholds in groups of both athletes and non-athletes. Threshold detection, typically obtained by the measurement of heart rate, lactate accumulation or ventilation parameters during incremental tests on a cycle ergometer, is used to acquire information about the changes in the metabolic processes. Such information can be used to plan and control the physical training. Due to the different methods available (heart rate, lactate accumulation or ventilation parameters) there are numerous denominations (aerobic threshold (AT), anaerobic threshold (AnT), ventilator thresholds (VT1, VT2), lactate turn points (LTP1, LTP2), Onset of Blood Lactate (OBLA), maximal lactate steady state (MLSS), hear rate turn points (HRTP1, HRTP2)) for the two prominent thresholds in the literature. For the sake of clarity, in the present paper we will use the terms first and second metabolic threshold as synonyms for the aerobic and anaerobic transition points, respectively. Similar to these standard measurements, different approaches have been presented to determine these thresholds by means of EMG. Specific behaviour of the EMG signal during incremental (e.g. onset of nonlinear increase in EMG signal) or constant workload test (highest power output without increase in EMG signal) was interpreted as electromyographic threshold (EMGT). The term EMGT will be used for thresholds detected by EMG measurements throughout this paper.

Muscular thresholds determined from EMG signals have been detected during incremental as well as constant work load tests. Although several explanations for their physiological causes have been formulated in the last decades, there is still no general consensus in the scientific community. Most researchers agree that the accumulation of H^+ ions is critical, causing the reduction of the intracellular pH (Enoka and Stuart, 1992). Bearden and Moffatt (2000) alternatively describe the possibility of an insufficient Na^+/K^+ pump, which leads to a disrupted excitation-contraction coupling regardless of intracellular pH and consequently leads to fatigue since the recruitment of additional motor units is required. Nielsen et al. (2001) suggested that the accumulation of lactic acid during exhaustive exercise is less due to muscular fatigue, but serves as a protector against fatigue (Nielsen et al., 2001). According to Moritani and deVries (1978), an increased EMG signal during exhaustive exercises refers to additional motor unit recruitment. This should compensate the loss of contractility due to decreased conductivity as a result of peripheral fatigue (Briscoe et al., 2014). Candotti et al. (2008) report a correlation between the lactate accumulation and the percentage of type II fiber recruitment after the non-linear increase of the integrated EMG (iEMG) signal. This non-linear increase of iEMG is referred to changes of the recruitment patterns of different muscle fibers especially the increased recruitment of fast twitched fibers (Glass et al., 1998). Alternatively some authors (e.g. Farina et al., 2007; Sbriccoli et al., 2009) suggested that the muscle fiber conduction velocity (MFCV) could indicate the fiber type distribution changes during dynamic cycling activities (Farina et al., 2004b, 2004c; Sbriccoli et al., 2009; Pereira et al., 2013). The consequence of recruiting additional fast motor units is a faster fatigue process of the involved muscles because of the increased lactate and H^+ concentration (Hofmann et al., 1994). It follows that more active muscle fibers lead to an imbalance between lactate removal sites and lactate production sites (Svedahl and MacIntosh, 2003). This may explain the increase of the EMG signal due to the increased recruitment of motor units during incremental exercise.

Different EMG parameters were used to detect EMGTs in the literature. While some analysed the amplitude of the Root Mean Square (RMS) values of the EMG signal (Camata et al., 2009; Hug et al., 2003b; Hug et al., 2006a, 2006b; Jammes et al., 1998; Jürimäe et al., 2007; Lucía et al., 1999; Pitt et al., 2015; Smirmaul et al., 2010) or the integrated EMG (iEMG) (Candotti et al., 2008; Gassi and Bankoff, 2010; Hofmann et al., 1994; Jürimäe et al., 2007; Matsumoto et al., 1991), others conducted a frequency domain analysis by calculating the mean power frequency (MPF) (Helal et al., 1987) or median frequency (MDF) of the signal (Hug et al., 2003a). Some studies also investigated the muscle fiber conduction velocity MFCV during cycling (Farina et al., 2004a, 2004b, 2007; Sbriccoli et al., 2009; Lenti et al., 2010; Stewart et al., 2011; Pereira et al., 2013).

Different scientists also applied different approaches/protocols to detect these aerobic-anaerobic transition points. Several researchers observed breaks in linearity of different EMG parameters during incremental exercise on a cycle ergometer and defined them as Electromyographic Threshold (EMGT) (Camata et al., 2009; Candotti et al., 2008; Hug et al., 2003b, 2006a, 2006b; Jürimäe et al., 2007; Lucía et al., 1999; Pitt et al., 2015), physical working capacity at the fatigue threshold (PWC_{FT}) (Bergstrom et al., 2013), Mean Power Frequency Fatigue Threshold (MPF_{FT}) (Camic et al., 2010), Fatigue Threshold-EMG (FT-EMG) (Gassi and Bankoff, 2010), Integrated EMG Threshold (IEMGT) (Glass et al., 1998), MFCVT (Pereira et al., 2013) or EMG-AT (Electromyographic Anaerobic Threshold) (Hofmann et al., 1994). Others applied several constant work load trials on a cycle ergometer to determine the so-called Electromyographic Fatigue Threshold (EMGFT) (Gassi and Bankoff, 2010; Graef et al., 2008; Housh et al., 1995; Matsumoto et al., 1991; Moritani et al., 1993; Smirmaul et al., 2010) or Neuromuscular Fatigue Threshold (NFT) (Fontes et al., 2012).

Compared to the classic approaches, the detection of EMG thresholds has the advantage that it provides muscular-specific, in contrast to systemic, thresholds non-invasively. However, the results of EMG measurements highly dependent on the measurement itself and the subsequent signal processing methods. Despite a significant number of publications about the EMG threshold detection since 1970, no golden standard has been established so far. Therefore, the aim of this review was to investigate the different EMG threshold methods concerning their methodological approaches and the validity of their results. The specific purpose of the present review was to (1) identify all the relevant papers in the databases SCOPUS and MEDLINE, (2) highlight all the important findings and recent developments, and (3) assess the formal quality of every study using a self-developed quality assessment protocol.

2. Method

2.1. Search strategies (1)

To identify literature related to the electromyographic threshold detection during dynamic exercise with well-defined intensities on a cycle ergometer, the authors conducted a systematic electronic database search using SCOPUS and MEDLINE (1980–2015). Table 1 shows the results of the search steps of the systematic approach. The results from the databases (n = 370) were exported into a citation manager (Citavi) and further analysed.

2.2. Inclusion and exclusion criteria (2)

In order to decide which studies should be used for further analysis, one reviewer (PE) checked all the titles and excluded "a priori" all the irrelevant studies from the search results by screening the titles. In a second step, the same reviewer checked the keywords and included all the titles which contained one of the following: EMG threshold, RMS, fatigue threshold, frequency, cycle ergometer, integrated EMG, metabolic thresholds, dynamic measurements. In a third step, the reviewer further excluded titles which included at least one word describing one of the following exclusion criteria: Mechanomyographic, isometric, treadmill protocol, patients, static measurements. In a fourth step, a second reviewer (AK) controlled all the decisions made. Disagreements concerning exclusion or inclusion were discussed with a third reviewer until a consensus was reached. Subsequently, abstracts of the remaining studies (87) were further analysed in detail by two reviewers (PE, MT) to assess their importance for this systematic review. A flow chart of this process is shown in Fig. 1.

2.3. Quality assessment (3)

Since no formal criteria for the investigated topic have been published so far, we adapted existing quality assessments (QA) from similar studies (Downs and Black, 1998; Hermens et al., 2000; Merletti, 1999; Murley et al., 2009). We refer to the detailed protocol attached in Appendix A.

Two reviewers (PE and MT) performed their quality assessment of 43 papers independently. The assessment protocol contained items about the general study design (e.g. description of the participants, description of the results, statistical analysis) and the EMG methodologies (e.g. description of electrodes, EMG parameters, skin preparation, orientation and placement, fixation method, measurement of the impedance, assessment of baseline noise, filter and sampling frequency). If authors did not include information about sampling frequency or filter cut offs, the study was excluded during the QA. Further formal assessment criteria included information about the exercise protocol, determination of other threshold parameters, warm-up programmes and the subject's position during the test. A total number of 23 questions had to be answered during the QA. While six questions were rated with 0, 1 or 2 points, 17 questions were rated with 0 or 1 point, resulting in a maximum score of 29 points. If the separate quality assessment of two reviewers (MT and PE) differed by three or more points, the assessment was discussed by the reviewers to obtain a consensus and a final score. Studies were rated with "low", "good", and "very good quality" when they achieved 40–59%, 60–79%, and 80–100% of maximum possible points, respectively. Studies that reached less than 40% were rated with "very low quality".

2.4. Statistical analysis

The ratings of the reviewers were analysed with SPSS Version 22.0.0.0 (© IBM 2013, Chicago, IL, USA). Mean and standard deviations of scored points were calculated. The objectivity of the quality assessment was assessed by calculating the intraclass-correlation-coefficient ICC (2,1) between the results of both reviewers.

3. Results

3.1. Quality assessment

The mean score for the studies after the quality assessment (QA) was 18.05 ± 3.13 out of 29 possible points. The mean ICC between the results of the two reviewers that assessed the quality of each study was 0.90 (range 0.80–0.95). This indicates "very good" agreement (Vincent and Weir, 2012). Values above 0.9 are classified as high.

3.2. Identification, selection and quality of studies

Altogether 43 original studies that met the inclusion criteria were detected from which 11 were excluded during the quality assessment based on limited information about the measurement procedures. Thus, 32 original studies were analysed in detail and the results are presented in Table 1. One study was rated with "very good quality". Most studies (n = 21) were of "good quality", while 8 studies were of "low quality" and 2 studies were of "very low quality". The most common reason for not achieving the highest standards was limited information about the EMG measurements as well as missing information about statistical tests, e.g. test for normal distribution or detailed description of results (e.g. missing effect size).

3.3. Subjects and protocols

The number of subjects in the studies varied from 5 to 49. Twenty-three studies had only male subjects, 1 study had only female subjects and 6 studies included both male and female subjects. The training status of the subjects included healthy untrained subjects (Briscoe et al., 2014; Camic et al., 2010; Hug et al., 2003a, 2004, 2006a; Jammes et al., 1997, 1998; Kang et al., 2014;

Table 1
Search steps in electronic databases.

	Search steps in electronic databases	Hits (Medline)	Hits (Scopus)
1.	"electromyographic threshold" OR "EMG threshold" OR "surface electromyography" OR "EMG"	81.246	105.471
2.	"ventilation" OR "ventilatory" OR "lactate" or "VT" OR "LT" or "fatigue" AND "threshold"	480	2241
3.	"neural drive" OR "RMS" OR "root mean square" OR "iEMG" OR "integrated" OR "frequency"	179	1.397
4.	"Cycle" OR "cycle ergometer" OR "cycling" OR "exercise"	110	1.063
5.	"exercise test" OR "incremental"	70	300

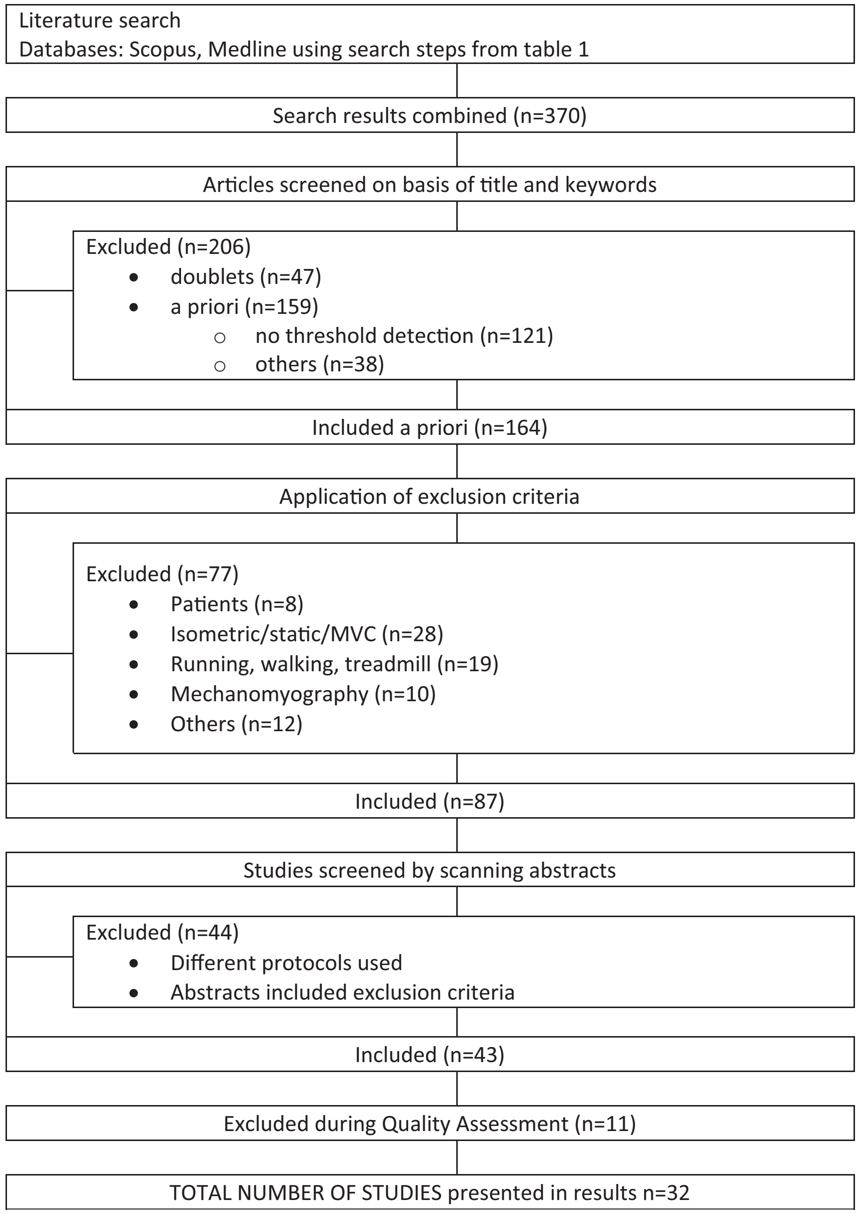

Fig. 1. Search strategy flow-chart.

Matsumoto et al., 1991; Mello et al., 2006; Moritani et al., 1993), recreational athletes (Bearden and Moffatt, 2000; Bergstrom et al., 2013; Camata et al., 2009; Candotti et al., 2008; Fontes et al., 2012; Gassi and Bankoff, 2010; Glass et al., 1998; Hug et al., 2003a, 2006b; Jürimäe et al., 2007; Kendall et al., 2010; Moritani et al., 1993; Pitt et al., 2015; Pereira et al., 2013; Pringle and Jones, 2002; Sbriccoli et al., 2009; Taylor and Bronks, 1995; Viitasalo et al., 1985) and elite athletes (Helal et al., 1987; Hug et al., 2003b; Lucía et al., 1999; Viitasalo et al., 1985). One study did not indicate the training status of the subjects (Graef et al., 2008).

Throughout the examined studies, different loading protocols were used to determine metabolic and EMG thresholds. Basically two different study protocols can be distinguished: Authors either used incremental tests until voluntary exhaustion (n = 22) or a so-called neuromuscular fatigue threshold test (EMG_{FT}) including three and four constant workloads (e.g. 250 W, 300 W, 350 W, 400 W) as proposed by deVries et al. (1982) (n = 3). Seven studies undertook a combination of both.

3.3.1. Electromyographic threshold (EMGT)

Due to the diversity of used protocols, parameters and study design, there is a lack of clarity in the literature concerning an accurate definition of the electromyographic thresholds. Some authors (e.g. Lucía et al., 1999; Hug et al., 2003b; Jürimäe et al., 2007) described that similar to the analysis of metabolic parameters, breaks in the linearity of the EMG signal (RMS, iEMG, MFCV) in the time domain of incremental exercise as EMG thresholds (EMGT, MFCVT). Protocols of the incremental tests varied between studies. Most of the studies (14) increased their workload every minute (Camata et al., 2009; Gassi and Bankoff, 2010; Hug et al., 2003a, 2003b, 2006a, 2006b; Jürimäe et al., 2007; Kang et al., 2014; Matsumoto et al., 1991; Mello et al., 2006; Pereira et al., 2013; Pitt et al., 2015; Sbriccoli et al., 2009; Smirmaul et al., 2010). Two minute-protocols were used in five studies (Bergstrom et al., 2013; Briscoe et al., 2014; Camic et al., 2010; Glass et al., 1998; Helal et al., 1987; Kendall et al., 2010) while only two studies (Candotti et al., 2008; Viitasalo et al., 1985) included a three-minute-protocol. Electromyographic thresholds were

Table 2
Description of the analysed studies and results of the Quality Assessment (RF = Rectus Femoris; VM = Vastus Medialis; VL = Vastus Lateralis; GM = Gastrocnemius Medialis; GL = Gastrocnemius Lateralis; TA = Tibialis Anterior; SM = Semimembranosus; ST = Semitendinosus; BF = Biceps Femoris; SO = Soleus; EMGT = Electromyographic Threshold; EMG AT = Electromyographic Anaerobic Threshold; EMGFT = Electromyographic Fatigue Threshold; MFCV = Muscle Fiber Conduction Velocity; MFCVT = Muscle Fiber Conduction Velocity Threshold; PSDF = Power Spectral Density Function; VT = Ventilatory Threshold; LT = Lactate Threshold; RCP = Respiratory Compensation Point; MLSS = Maximal Lactate Steady State; OBLA = Onset Of Blood Lactate; rpm = revolutions per minute; CP = Critical Power; PWC = Physical Work Capacity; FFT = Fast Fourier Transformation; HIIT = High Intensity Interval Training; W = Watt; (+) = good muscular threshold detection quality; (∼) = Intermediate muscular threshold detection quality; (−) = bad muscular threshold detection quality; (⁎) = Thresholds N/A because of different purpose.

No.	Study	Participants	Ergometer protocol; Validation	EMG Data processing	Muscles	Outcomes/Results	Quality
1	Pereira et al. (2013)	8 male healthy subjects 36.0 ± 9.7 years, 76.8 ± 11.9 kg, 178.6 ± 7.9 cm, trainings status: 2 years cycling experience, amateur competitions	Incremental test: 5 min warm up at 60 W, start load 150 W increased by 20 W/min, cadence: 80 rpm; ventilation	MFCV and EMG RMS were estimated for segments of 125 ms duration. Bi-segmental linear regression computer algorithm for estimating SEMGT and MFCVT	VL (+)	Algorithm identified breakpoints in all variables (VT, SEMGT, MFCV) No significant difference among VT, SEMGT, MFCVT ($p = 0.46$) Bland-Altman: MFCVT and VT: 87.5% into limits of agreement. Good concordance between SEMGT and VT as well as MFCVT and VT	Very good quality
2	Bergstrom et al. (2013)	6 male, 4 female moderately trained, recreational athletes 20 ± 1 year, 69.9 ± 12.6 kg, 171.6 ± 9.0 cm	Incremental test: 50 W starting power, increased 30 W/2 min; cadence: 70 rpm; ventilation	RMS values were calculated off-line. PWC_{FT} method from deVries - twelve 10 s EMG samples were evaluated	VL (+)	High correlation between PWC_{FT} and VT1 ($r = 0.847$) and no significant difference between PWC_{FT} and PRCP ($r = 0.84$). PWC_{FT} was greater than VT1	Good quality
3	Camata et al. (2009)	13 male experienced cyclists 27.2 ± 3.9 years,72.4 ± 11.8 kg, 174.2 ± 6.4 cm,	Incremental test: 3 min warm-up at 100 W, increased by 20 W/min; cadence: 90 rpm; ventilation	RMS calculated from 2, 5, 10, 30, 60 s windows. EMG_{TH} was defined as the sudden increase of RMS Break points were identified visually after using average values of RMS	VL (+) RF (+) VM (+)	No significant difference between V_{TH} and EMGT of VL, VM, RF ($p > 0.05$) No significant difference among EMGT VL, VM, RF ($p > 0.05$) 5 s and 10 s windows have stronger correlation to V_{TH} (EMG_{TH} 5 s: 0.73-0.81; EMG_{TH} 10 s: 0.75–0.80)	Good quality
4	Camic et al. (2010)	16 untrained male, 23.4 ± 3.2 years, 81.2 ± 13.2 kg	Incremental test: Start at 80 W increased by 30 W/2 min; cadence: 70 rpm; ventilation	PWC_{FT} and MPF_{FT} calculation was done using the model of deVries et al. (1987); Every 2 min stage, six 10 s EMG samples were recorded. RMS and MPF were calcu-lated within those 10 s win-dows	VL (+)	Significant correlation between MPF_{FT} and VT ($r = 0.67$); MPF_{FT} vs. RCP ($r = 0.72$); VT vs. RCP ($r = 0.89$) No significant correlations between PWC_{FT} and MPF_{FT} ($r = 0.39$), VT($r = 0.37$), RCP ($r = 0.42$)	Good quality
5	Candotti et al. (2008)	24 male recreational cyclists 24.9 ± 3.7 years, 72.4 ± 7.5 kg, 164 ± 1.8 cm	Incremental test:3 min unloaded pedalling, followed by increased by25 W/3 min; cadence: 80 rpm; lactate	RMS value was calculated every 1-s non-superimposing. Breakpoints were defined by mathematical algorithm	VL (+) RF (+)	No significant difference between EMGT and LT ($p = 0.96$) Good correlation between VL ($r = 0.83$) RF($r = 0.87$) and LT respectively	Good quality
6	Fontes et al. (2012)	15 healthy physically active male 23.4 ± 5.2 years 73.6 ± 5.1 kg, 177.8 ± 7.0 cm,	Neuromuscular fatigue test: 3–4 exhaustive constant workload trials on separate days. Workloads: 350, 300, 250, 200 W, Warm up at 50 W for 3 min; cadence: 60 rpm; no additional validation method	RMS calculated of 5 s windows. NFT defined as y-intercept from regression line	VL (∼)	Activation of different muscle fibers NFT is not a reliable method to evaluate aerobic capacity Time window for RMS could be an explanation	Good quality
7	Glass et al. (1998)	10 male experienced cyclists 23.40 ± 3.13 years, 177 ± 0.04 cm, 76.64 ± 8.13 kg	Incremental test: 5 min warm-up period 64 W, increased by 45 W/2 min. cadence: 90 rpm; ventilation	EMG recorded during the last 5 s of each minute. EMG data were integrated for each cycle revolution.	RF (+) VL (∼)	IEMG threshold was detected more consistently from RF than from VL. Moderate correlation between VT and EMGT ($r = 0.68$) No significant difference between VT and EMGT	Good quality

Table 2 (*continued*)

No.	Study	Participants	Ergometer protocol; Validation	EMG Data processing	Muscles	Outcomes/Results	Quality
8	Hug et al. (2003b)	8 professional road cyclists 24 ± 1 years, 182 ± 3 cm, 74 ± 4 kg	Incremental test: starting at 100 W, increased by 26 W/min; cadence: free; ventilation	Computed an EMG power spectral density for 2-s sampling periods using FFT and RMS contained in each 2-s spectrum was calculated; 2 independent observers, non-linear increase in RMS	VL (+) RF (∼) VM (+) SM (+) BF (+) GL (∼) GM (∼) TA (+)	No significant difference between EMGT2 and VT2 A significant difference between VT1 and EMGT1 EMGT2 and VT2 occurred at the same time	Good quality
9	Hug et al. (2003a)	1. (n = 28): 18 male, 10 female 47 ± 13 years, 71 ± 14 kg; 2. (n = 5): 5 male, 26 ± 3 years, 76 ± 5 kg; 3. (n = 6): 5 male, 21 ± 4 years, 69 ± 8 kg; trainings status unknown	Incremental test: 2 min rest period, 2 min 0 W warm up followed by work period started at 20 W increased by 20 W/min; ventilation, lactate	RMS was calculated from the last 20 s of each incremental step. Calculation of power spectrum density; MF (power spectrum), EMG Energies: EL: 10–80 Hz, EH: 90–300 Hz non-linear increase of RMS	VL (+)	Resting values of La, pH, K^+ significantly differ between corresponding values at VTH ($p < 0.001$). Significant increase of La and K^+, significant decrease of pH. 85% of subjects show signs of neuromuscular fatigue Neuromuscular fatigue signs occurred in VL around VTH.	Good quality
10	Hug et al. (2004)	5 untrained male 25.8 ± 1.5 years, 76.6 ± 2.1 kg 7 trained male 21 ± 1.6 years, 71 ± 2.5 kg, healthy, non-smoking	2 tests: 1. Incremental test: 2-min rest period, 2 min warm-up. Start at 0 W, increased by 20 W/min; 60 rpm (b) constant-load test with loading at VT; ventilation	RMS and M-Wave was analysed during warm up, test and recovery time. Non-linear increase of RMS	VL (*)	No significant difference between trained and untrained group Untrained significant increase in M-wave duration and significant decrease in M-wave amplitude. No significant M-wave variations found in trained subjects	Good quality
11	Hug et al. (2006a)	6 healthy men 27 ± 1 years, 180 ± 10 cm, 78 ± 9 kg; trainings status unknown	Incremental test on two separate occasions: 3 min warm-up at 100 W, increased by 25 W/min. cadence: 75–85 rpm; no additional validation method	EMG continuously recorded RMS averaged every 5 crank revolutions. Visually by 2 observers and mathematical algorithm	VL (+) RF (∼) VM (+) SM (−) BF (+) GL (∼) GM (−) TA (∼)	Very good concordance between 2 observers (K = 0.88) identifying EMGT No significant difference and good concordance between visual and mathematical method (ICC: 0.67–0.88) 45(93.7%) thresholds detected visually, 32 (66.7%) with computer algorithm; both methods 32 (66.7%), ICC: 0.86.	Good quality
12	Jürimäe et al. (2007)	49 male subjects 23.8 ± 5.7 years, 182.7 ± 5.3 cm, 79.1 ± 8.6 kg (11 cyclists, 10 handball, 9 kayakers, 8 powerlifters 11 controls)	Incremental test: Start at 50 W increased by 25 W/min; cadence: 60 rpm; ventilation	iEMG was calculated in 10 s intervals; EMGT as the non-linear increase of IEMG	VL (+) VM (+) BF (+) GL (+)	Overall failure for detecting was 9% for VM and 3% for VL Good correlation between VT2 and EMGT VL ($r = 0.81$), EMGT VM ($r = 0.73$); moderate correlation between VT2 and EMGT BF ($r = 0.69$) and EMGT GL ($r = 0.58$). No significant difference between VT2 and EMGT ($p < 0.05$)	Good quality
13	Kang et al. (2014)	69 male Undergraduate/ graduate students Age: 23.4 ± 4.2 years; 173.5 ± 5.1 cm, 72.7 ± 9.8 kg	Incremental test: 2 min warm-up, start a 20 W; increased by 20 W/1 min; uptake; cadence: 60 rpm; ventilation	RMS every 1-s non superimposing window, different filtering time at 9, 15, 20, 25, 30 s; Mathematical method for EMG AT detection	VL (+)	No significant difference between AT values from VT and EMG for 9, 15, 20, 25, 30 s filtering intervals. Very good correlation among all 5 filter intervals within EMG ($r = 0.95–0.99$)	Good quality

(*continued on next page*)

Table 2 (*continued*)

No.	Study	Participants	Ergometer protocol; Validation	EMG Data processing	Muscles	Outcomes/Results	Quality
14	Kendall et al. (2010)	18 recreationally trained College men 22.4 ± 3.2y; 178.4 ± 6.2 cm; 78.5 ± 11.3 kg;	Incremental test (VO2 peak, VT): 5 min warm-up (50 W), increased by 25 W every 2 min; cadence: 70 rpm; EMGFT: Four 2-min cycling bouts at incrementally ascending workloads (75–300 W); ventilation	EMG-amplitude values were calculated from raw-signal EMGFT: rates of rise in EMG amplitude values (EMG slope) EMG slope values for each 4 power outputs plotted to determine EMGFT	VL (+)	Test-retest reliability for EMGFT (ICC: 0.65) Significant difference between VT values before and after 6 weeks of HIIT training ($p = 0.01$) No significant difference between predicted and observed VT values ($p = 0.617$)	Good quality
15	Lucía et al. (1999)	28 competitive male cyclists 24 ± 4y, 177,1 ± 5,2 cm, 67,2 ± 6,0 kg, (16 professional and 12 elite road cyclists)	2 incremental tests on different days: Start at 0 W, increased by 5 W/12 s; cadence: 70–80 rpm; ventilation, lactate	RMS calculated for each 2 s spectrum; Computer algorithm: multisegment linear regression	VL (+) RF (+)	Reliability: ICC between repeated measurement were significant and high ($p < 0.05$). Validity: Good correlation between EMGT2 and VT2 ($r = 0.82$) and OBLA (0.82). Moderate correlation between EMGT1 and VT1 ($r = 0.66$) and LT(0.64)	Good quality
16	Mello et al. (2006)	13 healthy male, 21–32 years, 1.75 ± 0.1 cm 73.9 ± 12.3 kg, regularly trained	Incremental test: start at 12.5 W increased by 12 W/min; ventilation	RMS calculated during 20 ms windows; automatic algorithm (RMS-slope)	VL (+)	RMS-slope identified EMGT in every subject No significant difference between EMGT and AT ($p = 0.18$) RMS-slope allows detecting EMGT values for all subjects.	Good quality
17	Moritani et al. (1993)	8 male and 12 female healthy subjects 21 ± 2.3 years, 163 ± 7.3 cm, 55 ± 6.6 kg, trainings status: from untrained to sport team members	Neuromuscular Fatigue Test 5 min warm up at 50 W. Constant power loading at 400, 350, 300, 275 W for male, 350, 300, 250, 200 W for female; ventilation	12 consecutive periodograms were averaged to calculate RMS, iEMG and MPF iEMG, MPF, RMS indicator of muscle fatigue	VL (+)	Significant correlation between VO_2max and EMGFT ($r = 0.85$, $p < 0.01$); Significant correlation between AT VO2 and EMG equivalent for VO2 (EMGFT VO2) $r = 0.923$, $p < 0.01$; Statistically significant difference between AT VO2 and EMGFT VO2, $p < 0.01$	Good quality
18	Pitt et al. (2015)	23 boys, 11.1 ± 1.1 years, 145 ± 8.6 cm, 37.1 ± 7.5 kg 21 men, 23.4 ± 4.1 years, 181.5 ± 6.3 cm, 75.4 ± 10.4 kg; physically active subjects	2 tests: 1. Incremental test: aerobic capacity (VO_2, VO2pk) 5 min warm-up Boys: start 40–60 W, increased by 15–20 W/min Men: start 80–100 W, increased by 30–40 W/min 2. Neuromuscular fatigue test: 5 min warm up, ramp cycling test Start power output: 35–40% of PVO2pk; cadence: 80 rpm; ventilation	RMS was calculated for each pedal stroke EMGTH determined by computer algorithm	VL (+)	EMGTH was identified in 92.2% in men and 78.3% in boys. EMGTH% Pmax in boys appeared slightly later than in men.	Good quality
19	Pringle and Jones (2002)	7 male, 1 female, 25 ± 3 years, 72.1 ± 8,2 kg, 176 ± 5 cm, Healthy, Involved in regular exercise training,	1 Incremental test: 5 min warm-up at 50 W, increased by 25 W/min. cadence: 90 rpm 9 times within 2 weeks Neuromuscular fatigue test: Power outputs between 75% and 115% of power at VO_2max random order; Lactate, ventilation, heartrate	IEMG values computed every 2 s (EMGFT test) or 10 s (MLSS trials) Power output + increase of VL iEMG for each 2-min trial were plotted, EMGFT defined as intercept on y-axis of linear trend line	VL (∼)	EMGFT could not be determined in 50% of subjects Significant difference between EMGFT and MLSS (W) ($p < 0.05$) Significant difference between EMGFT and CP (W) ($p < 0.01$)	Good quality
20	Sbriccoli et al. (2009)	14 healthy male physically active subjects 31 ± 9 years, 77.2 ± 8 kg, 178 ± 9.2 cm	Incremental test: 8 min warm-up at 70 W, increased by 30 W every minute, cadence: 70 rpm; ventilation	sEMG was recorded during the last 30 s of each exercise step average MFCV was calculated using cross-correlation method	VL (+)	Linear increase of MFCV until and decrease after ventilator threshold was reached, respectively.	Good quality

Table 2 (*continued*)

No.	Study	Participants	Ergometer protocol; Validation	EMG Data processing	Muscles	Outcomes/Results	Quality
21	Smirmaul et al. (2010)	24 healthy subjects: 13 trained cyclists 28.4 ± 6.9 years; 167.1 ± 8.5 cm; 70.3 ± 13 kg 11 non-cyclists: 25.8 ± 4 years; 73 ± 9.1 kg; 175 ± 6.4 cm	Incremental test (ITmax): Starting at 0 W increased by 20 W/min; cadence: 90 rpm; no additional validation method	Mean RMS was calculated of each 5 s window; EMGFT defined visually	VL (+) RF (+) BF (+) ST (+) TA (∼)	Significant difference in detecting EMGFT in VL, RF, BF, ST, TA between cyclists and non-cyclists ($p < 0.05$) EMGFT easier to detect in RF and VL in both cyclists and non-cyclists	Good quality
22	Taylor and Bronks (1995)	20 trained male subjects: 22 ± 3.4 years; 179 ± 5 cm; 77.2 ± 6.4 kg	2 incremental tests within 24–72 h: 5 min warm-up at 30 W. Start at 60 W increased by 30 W/4 min: cadence: 60 rpm; no additional validation method	Integrated EMG Signal (iEMG) was calculated; threshold detection method not specified	VL (+) VM (+) RF (+)	Normalisation process did not affect IEMG Good correlation between test-retest No significant difference between tests ($p = 0.29$)	Good quality
23	Jammes et al. (1998)	15 healthy volunteers 7 well trained cyclists (31 ± 3 years) 8 untrained university students (39 ± 3 years).	4 exercise trials: 1. Incremental test: Increased by 20 W/min. 2. progressive exercise trial max work load = 160 W duration 8 min 3. Two 5 min constant load exercise ventilation, lactate	RMS was averaged for 5 consecutive contractions at the end of each stage. Threshold detection method N/A	VM (+)	Changes in RMS/VO2 ratio correlates with anaerobic threshold (VT and LT) Correlation between SEMG changes and overall increase in oxygen uptake during dynamic exercise	Low quality
24	Bearden and Moffatt (2000)	8 trained male with cycling experience 27 ± 3 years, 177 ± 4 cm, 72 ± 8 kg	Incremental exercise test: 1 W/5 s on electrically braked cycle ergometer:; cadence: 90 rpm; ventilation	RMS, averaged every two thirds of a second. Visual Identification of break points by two blinded investigators	VL (+) BF (+) GL (−)	VO2 threshold appeared simultaneously with an increased neuromuscular activity The appearance of the second break point did not differ between VO_2, RMS or RCT	Low quality
25	Briscoe et al. (2014)	5 male, 6 female healthy subjects 23.6 ± 0.7 years, 71.2 ± 4.8 kg;	4 Tests: 1. Incremental test; 2 min warm up at 50 W, increased by 25 W/2 min cadence: 70 rpm 2. three 2 min Constant workload exercise tests corresponded to 70,100 and 130% of $EMG_{FT;}$ heartrate	Recording of EMG amplitude every 20 s from VL for each stage. The EMG_{FT} was defined as a significant increase in EMG amplitude	VL (+)	Estimation of EMG_{FT} in healthy men and women through a single cycle ergometer test was confirmed as a valid method. EMG_{FT} demarcates between non-fatiguing and fatiguing exercise relative to MU activation	Low quality
26	Gassi and Bankoff (2010)	8 male, amateur cyclists and triathletes 25.25 ± 6.96 years, 73.09 ± 4.42 kg, 182.13 ± 5.05 cm	Incremental test: starting at 100 W increased by 25 W/min; cadence: 80 rpm; ventilation	RMS was calculated within the last 10 s of each period; EMG-FT was detected as break in linearity	VL (+) RF (+)	Useful tool to determine the anaerobic threshold No difference was found among the corresponding intensity between VT and EMGFT of VL and RF	Low quality
27	Graef et al. (2008)	38 subjects 22.6 ± 3.5 years, 177.1 ± 7.1 cm, 77.0 ± 11.0	2 tests: 1. Incremental test: 5 min warm-up, increased by 25 W/min. 2. 24–48 h after, EMGFT Test: 5 min warm-up,4 two min cycling bouts; incremental workloads (75 W-300 W); ventilation	EMG amplitude zero-lag 8th order Butterworth, further processing method not specified	VL (+)	Test-retest reliability for EMGFT protocol (ICC: 0.935) No significant difference between EMGFT and VT ($p = 0.79$), no significant difference between EMGFTVO2 and VT (0.20). strong correlations for power output and metabolic parameters for EMGFT and VT ($r = 0.77$ and $r = 0.75$)	Low quality
28	Helal et al. (1987)	9 male elite competitive cyclists 19.5 ± 0.3 years, 69.2 ± 1.7, 175 ± 1.3 cm	Incremental test: 6 min warm-up period at 100–175 W, increased by 25 W/2 min; cadence: 80 rpm; lactate, ventilation	EMG signal converted into 24 s FFT with time window of 1 s, calculated the MPF and PEMG	VL (∼)	EMG breaking points reflected partially muscle lactate production. Results indicate fiber type recruitment changes (?) during incremental exercise.	Low quality

(*continued on next page*)

Table 2 (*continued*)

No.	Study	Participants	Ergometer protocol; Validation	EMG Data processing	Muscles	Outcomes/Results	Quality
29	Hug et al. (2006b)	6 healthy men 27 ± 1 years, 180 ± 10 cm, 78 ± 9 kg; trainings status unknown	Incremental test on two separate occasions: 3 min warm-up at 100 W, increased by 25 W/min. cadence: 75–85 rpm; no additional validation method	EMG continuously recorded EMG RMS averaged every 5 crank revolutions. Visual detection by 2 observers and mathematical algorithm	VL (+) RF (−) VM (+) SM (−) BF (∼) GL (+) GM (−) TA (+)	No significant difference between test 1 and test 2 EMGTH in VL occurred with 100%, less in RF, SM, GM Mathematical model seems to be more reliable and objective	Low quality
30	Matsumoto et al. (1991)	20 female healthy, college students 18–23y (mean 21 years ± 6.1, 158.3 ± 3.5 cm, 50.9 ± 4.3 kg; untrained till highly trained	Neuromuscular Fatigue Test 5 min warm-up at 50 W Power loadings: 350, 300, 250, 200 W (randomised order) Incremental test: 2 min warm up at 30 W, increased by 30 W every min until exhaustion. Cadence: unknown; ventilation	10 consecutive 6-s iEMG signals for each exercise period	VL (+)	Significant correlation between VT and EMGFT ($r = 0.82$, $p < 0.01$) No significant difference between VT and EMGFT ($t = 0.93$, $p > 0.05$)	Low quality
31	Jammes et al. (1997)	15 healthy subjects: 7 well trained cyclists 31 ± 3 years 8 untrained students 39 ± 3 years	Incremental exercise test: 2 min rest period, start 0 W increased by 20 W/min, ventilation	RMS data averaged for five consecutive contractions	VL (∗)	RMS increased progressively RMS correlates with VO2 VT $r = 0.80$ RMS/VO2 increases significantly for light work loads No correlation between RMS/VO2 and corresponding variations of M wave, pH or lactate during recovery.	Very low quality
32	Viitasalo et al. (1985)	Recreational and competitive athletes, 5 male 21–38 years; 182 ± 2 cm; 74 ± 1.5 kg,	Incremental exercise test: Start at 90 W, increased by 15 W/3 min; cadence: 60 rpm; lactate, ventilation	Integrated EMG signal (IEMG) and Mean Power Frequency was calculated; detection method unknown	VL (+) VM (+) RF (+) GL (−) TA (−) SO (−)	For knee extensor (VL, VM, RF), change of linearity differed significantly ($p < 0.05$) Changes for triceps surae (GL, SO) were not significant. TA did not show systematic pattern MPF and PSDF did not change significantly MPF-load varied among subjects	Very low quality

evaluated visually or automatically (see Lucía et al. (1999), Fig. 1, where a multi-segment linear regression of the root mean square (RMS) EMG signal was applied) in the reviewed studies.

3.3.2. Neuro muscular fatigue threshold test (EMG_{FT})

As an alternative to incremental tests, constant workload tests were used in nine studies to determine the EMG-fatigue threshold (EMGFT). Pringle and Jones (2002) defined the fatigue threshold as the highest power output that can be maintained without an increase in the integrated electromyogram signal (iEMG) over time. According to deVries et al. (1982) the EMGFT was calculated in several steps as follows: In a first step, the subject's iEMG data were integrated over 10 s during the various workloads on a cycle ergometer and were plotted as an increasing function over time. Subsequently, the slope coefficients from the time courses against each of the workloads and fitted with linear regression. In a last step, the fatigue threshold was defined as the y intercept of the regression line in Watts (deVries et al., 1982, see 786 their Fig. 1).

Different protocols were used for the electromyographic fatigue threshold test (EMG_{FT}). It consisted of three (Briscoe et al., 2014; Fontes et al., 2012; Jammes et al., 1998) or four (Graef et al., 2008; Housh et al., 1995; Kendall et al., 2010; Matsumoto et al., 1991) mostly randomised work bouts either on the same day or on different occasions with constant workloads. Different approaches in defining the workloads for the different bouts were applied. Based on the method suggested by deVries et al. (1982), several studies (Fontes et al., 2012; Graef et al., 2008; Housh et al., 1995; Kendall et al., 2010; Matsumoto et al., 1991) used defined power loadings at 275, 300, 350 and 400 W for males and 225, 250, 300 and 350 W for females. Attempts to evaluate the power loadings individually were conducted by other authors (Briscoe et al., 2014; Graef et al., 2008; Jammes et al., 1998; Kendall et al., 2010; Matsumoto et al., 1991; Pitt et al., 2015; Pringle and Jones, 2002) by applying an additional incremental test. Briscoe et al. (2014) and Pringle and Jones (2002) defined the power outputs as percentage of power at VO_2max.

3.4. EMG data processing

Different attempts in processing the raw EMG signal for EMGT determination were observed. The amplitude-based methods analysed either the RMS or the iEMG of the EMG signal. While RMS was used in 20 studies (Bearden and Moffatt, 2000; Bergstrom et al., 2013; Briscoe et al., 2014; Camata et al., 2009; Camic et al., 2010; Candotti et al., 2008; Fontes et al., 2012; Gassi and Bankoff, 2010; Hug et al., 2003a, 2003b, 2004, 2006a, 2006b;

Jammes et al., 1998; Kang et al., 2014; Lucía et al., 1999; Mello et al., 2006; Pereira et al., 2013; Pitt et al., 2015; Smirmaul et al., 2010), iEMG was evaluated in seven studies (Glass et al., 1998; Jürimäe et al., 2007; Matsumoto et al., 1991; Moritani et al., 1981; Pringle and Jones, 2002; Taylor and Bronks, 1995; Viitasalo et al., 1985). Two studies (Graef et al., 2008; Kendall et al., 2010) only indicated the use of the EMG amplitude. Two studies determined the EMG threshold by analysing the MFCV (Pereira et al., 2013; Sbriccoli et al., 2009). Some authors analysed the frequency domain of the EMG signal. They used either the median (MDF) (Camic et al., 2010; Hug et al., 2003a) or mean frequency (MPF) (Camic et al., 2010; Helal et al., 1987; Jammes et al., 1997; Viitasalo et al., 1985) of the signal.

3.5. Investigated muscles

EMG thresholds were detected in at least one muscle in each of the 32 reviewed studies. Most studies aimed to determine the EMG values from the vastus lateralis (VL, n = 31). Other muscles observed were the rectus femoris (RF, n = 10), vastus medialis (VM, n = 8), biceps femoris (BF, n = 6), gastrocnemius lateralis (GL, n = 5), tibialis anterior (TA, n = 5), gastrocnemius medialis (GM, n = 4), semimembranosus (SM, n = 3), and soleus muscle (SO, n = 1). Thresholds could be detected most frequently in VL (28/31), RF (7/10), VM (8/8) and BF (5/6). Thresholds could be detected less frequently in GL (2/5), TA (2/5) and SM (1/3), and could not be detected in GM (0/4) and SO (0/1). Two studies (Hug et al., 2006b; Taylor and Bronks, 1995) analysed the test-retest reliability of the EMG thresholds on two different occasions and found no significant differences in the results.

3.6. Comparison to metabolic threshold values

Most studies validated their EMG-thresholds with lactate (n = 1), ventilatory (n = 19), heartrate (n = 1) or a combination of both lactate and ventilatory (n = 6) thresholds. Five Studies did not compare EMG thresholds with other methods because of different study aims. Authors hypothesised that EMG-thresholds should appear simultaneously to the metabolic thresholds. This relationship was either assessed by correlations, Bland-Altman-plots or tests for differences in mean values.

EMGT were compared with the first threshold in 17 studies (Candotti et al., 2008; Briscoe et al., 2014; Fontes et al., 2012; Gassi and Bankoff, 2010; Glass et al., 1998; Graef et al., 2008; Helal et al., 1987; Hug et al., 2003a, 2004; Jammes et al., 1997, 1998; Kang et al., 2014; Kendall et al., 2010; Matsumoto et al., 1991; Mello et al., 2006; Moritani et al., 1993; Pitt et al., 2015). Eight studies (Camata et al., 2009; Hug et al., 2006a, 2006b; Jürimäe et al., 2007; Pereira et al., 2013; Pringle and Jones, 2002; Sbriccoli et al., 2009; Smirmaul et al., 2010) compared the EMGT with the second threshold and seven studies (Bearden and Moffatt, 2000; Bergstrom et al., 2013; Camic et al., 2010; Hug et al., 2003b; Lucia et al., 1997; Taylor and Bronks, 1995; Viitasalo et al., 1985) compared EMGTs with the first as well as the second threshold.

When EMG thresholds were detected and were compared with metabolic thresholds, then high correlations were found in nine studies (Bergstrom et al., 2013; Candotti et al., 2008; Graef et al., 2008; Jammes et al., 1997; Jürimäe et al., 2007; Kang et al., 2014; Lucía et al., 1999; Pereira et al., 2013; Pringle and Jones, 2002; Taylor and Bronks, 1995) and medium to high correlations were found in five studies (Bearden and Moffatt, 2000; Camata et al., 2009; Glass et al., 1998; Jammes et al., 1998; Pitt et al., 2015). However, not all studies found a link between metabolic and EMG thresholds. Pringle and Jones (2002) could not find a relationship between the EMG_{FT} and the physiological parameter (MLSS) tested. They also reported that it was not possible to determine the EMGFT within 50% of the tested subjects (Pringle and Jones, 2002). Hug et al. (2003b) reported significant differences between EMGT1 and the first ventilator threshold despite no significant difference between the EMGT2 and the second ventilatory threshold. A summary of the results is presented in Table 3.

4. Discussion

The purpose of the current paper was to identify relevant publications on the detection of EMG thresholds, to analyse their methodologies and results and to assess their formal quality. This should illuminate if and under which conditions the EMG threshold detection is a reliable and valid tool for the aerobic-anaerobic transition points evaluation.

4.1. Quality assessment

Results of EMG measurements rely heavily on the measurement methodology used and data processing. Therefore, the focus of the quality assessment was placed on these topics and studies were excluded when important information (e.g. filter design, sampling frequency, threshold detection) was missing. As a consequence some important early and classic studies (Airaksinen et al., 1992; deVries et al., 1982; Hofmann et al., 1994; Pavlat et al., 1993; Hänninen et al., 1989; Housh et al., 1995; Mateika and Duffin,

Table 3
Applied protocols, increments and investigated muscles (first number indicates the number of studies where thresholds were detected successfully; second number indicates the total amount of studies on the respective muscle).

Protocols	Increments	VL	RF	VM	BF	GM	GL	TA	SM	ST	SO
Incremental test											
1 min protocol (n = 13)	10–25 W (n = 12)	11/11	2/4	4/4	3/4	0/2	2/3	1/3	0/2	1/1	
	26–50 W (n = 2)	2/2	0/1	1/1	1/1	0/1	0/1	1/1	1/1		
2 min protocol (n = 4)	10–25 W (n = 1)	1/1									
	26–50 W (n = 3)	2/3	1/1								
3 min protocol (n = 2)	10–25 W (n = 2)	2/2	2/2	1/1		0/1	0/1				0/1
4 min protocol (n = 1)	26–50 W (n = 1)	1/1	1/1	1/1							
Others (n = 2)	5 W/12s (n = 1)	1/1	1/1								
	1 W/5s (n = 1)	1/1			1/1			0/1			
Constant test											
Defined loadings (n = 3)	75–400 (n = 3)	2/3									
Power loadings depended on incremental test (n = 7)	Loading at VT (n = 4)	3/4		1/1							
	Loading in percentage of VO2max (n = 3)	1/2									

1994; Miyashita et al., 1981; Nagata et al., 1981; Tyka et al., 2010) had to be excluded during QA. We would like to point out that we recommend these excluded studies and studies regarding MFCV (Van der Hoeven and Lange, 1994; Taylor et al., 1997; Farina et al., 2004a, 2004b, 2004c, 2007; Lenti et al., 2010; Hunter et al., 2011; Kilen et al., 2012; Stewart et al., 2011) for further reading. Due to the rigorous assessment of EMG methodology only one study could be assessed as "very good quality". However, two thirds of the studies were assessed as "good quality" and only two studies were assessed with "very low quality" implying that valid information on EMGTs can be retrieved in this review.

4.2. Investigated subjects and study protocols

Most of the studies undertook their investigation with athletes. It has been suggested that professionals are more capable of recruiting additional motor units (Hug et al., 2003b; Lucía et al., 1999). Moreover, Jürimäe et al. (2007) concluded, that the EMGT could be used in both athletes of various sports background and performance levels including as well as non-athletes and professional athletes.

It is known that the workload increments and stage time of protocols may affect the results of metabolic threshold detections (Heck, 1990; Hofmann et al., 2004). Therefore, in the present study we subdivided the analysed publications with regard to both the incremental workload as well as the stage time to detect possible differences. Table 4 illustrates the use of different ergometer protocols and lengths of stage time including the results on the investigated muscles. It appears that thresholds can be detected frequently by using one minute (n = 12) protocols with 10–25 W (n = 11) increments, in vastus lateralis (n = 11). This finding is in good concordance with the studies of deVries et al. (1987) and Bergstrom et al. (2013), who recommended smaller increments for precise CP, PWC_{FT}, and EMG_{FT} estimation. However, other incremental protocols, with stage times of up to three minutes, have also shown consistent findings although fewer studies are available. Similarly, the different types of constant workload tests were successful in detecting neuromuscular thresholds. However, the vastus lateralis was the only investigated muscle during constant work load tests and some authors described difficulties with EMGFT. Fontes et al. (2012) reported significantly higher power at EMGFT than the critical power (CP) which should be related to the first metabolic threshold. They concluded that the EMGFT method does not allow estimating the aerobic capacity (Fontes et al., 2012). This finding of an overestimated CP by the NFT method was also reported by Pringle and Jones (2002) and (deVries et al. (1982) and could be due to additional muscles involved in the activity. Graef et al. (2008) suggested favouring constant work load tests because incremental tests are more dependent on motivational aspects of the participants due to maximal workload which could therefore influence the muscular threshold.

4.3. Investigated muscles

The reviewed studies revealed that muscles react differently on incremental cycling exercises. The determination of EMG thresholds was consistent in the VL, VM, and RF muscles. EMG signals of other, smaller leg muscles did not show EMGTs as consistently (see Table 3). This reflects that the quadriceps femoris is the major muscle group involved during cycling tests and therefore prone to neuromuscular fatigue (Hug et al., 2003a). Only Helal et al. (1987) reported difficulty in detecting thresholds in the VL. Reasons for the absence of EMGTs in VL were explained by different motor programmes of muscle recruitment or differences in fiber distribution of VL between subjects (Hug et al., 2003b). They also observed a significant difference between VT1 and EMGT1and concluded that some involved muscles fatigued during cycling earlier than others (Hug et al., 2003a, 2003b). It appeared that the involvement of VL during incremental work load was not essential in some subjects. Similarly, Pringle and Jones (2002) also refer to the possibility that other muscles (e.g.: gluteus maximus) contribute proportionally more to the rise of lactate and therefore EMG thresholds in some muscles cannot be detected. It was furthermore hypothesised that a constant pedalling rate might explain the absence of fatigue (Hug et al., 2003b) as it was shown that fatigue in different leg muscles depend on pedalling rate (Takaishi et al., 1996), possibly due to the different involvement of muscle fiber types (Glass et al., 1998; Housh et al., 1995). Smaller muscles of the lower leg (e.g. GM, GL, TA) seem to be less involved during cycling (Smirmaul et al., 2010) and therefore do not show signs of neuromuscular fatigue.

4.4. Investigated thresholds

Among all reviewed studies there seems to be a consensus that the first non-linear EMG increase refers to an additional recruitment of motor units (MU) due to a compensation mechanism based on a reduced contractility (Bearden and Moffatt, 2000; Candotti et al., 2008; Gassi and Bankoff, 2010; Glass et al., 1998; Graef et al., 2008; Hug et al., 2003a; Kang et al., 2014; Kendall et al., 2010; Lucía et al., 1999; Matsumoto et al., 1991; Mello et al., 2006; Moritani et al., 1993; Nagata et al., 1981; Taylor and Bronks, 1995; Viitasalo et al., 1985). A second non-linear increase of the EMG signal could indicate a recruitment of different muscle fiber types (Lucía et al., 1999). Accordingly, after the second non-linear increase, ATP (Adenosintriphosphate) resynthesis in type I muscle fibers seems to be inadequate. This triggers the recruitment of type IIa and type IIb muscle fibers which consequently leads to a metabolic acidosis (Lucía et al., 1999) due to an insufficient oxygen supply to the muscles (Jürimäe et al., 2007; Mäestu et al., 2006). Pringle and Jones (2002) however, pointed out that surface EMG cannot differentiate between increased recruitment, firing rate or muscular failure in contracting muscles (Pringle and Jones, 2002) although each of these processes would lead to an increase in the EMG signal.

Authors of the reviewed studies compared emerging EMG thresholds with corresponding metabolic first and second thresholds. In 17 studies (Candotti et al., 2008; Briscoe et al., 2014; Fontes et al., 2012; Gassi and Bankoff, 2010; Glass et al., 1998; Graef et al., 2008; Helal et al., 1987; Hug et al., 2003a, 2004; Jammes et al., 1997, 1998; Kang et al., 2014; Kendall et al., 2010; Matsumoto et al., 1991; Mello et al., 2006; Moritani et al., 1993; Pitt et al., 2015) authors compared the EMG threshold with first metabolic thresholds. Seven studies (Bearden and Moffatt, 2000; Bergstrom et al., 2013; Camic et al., 2010; Hug et al., 2003b; Lucia et al., 1997; Taylor and Bronks, 1995; Viitasalo et al., 1985) determined the first and second EMG threshold and compared them with the respective metabolic values. Eigth studies (Camata et al., 2009; Hug et al., 2006a, 2006b; Jürimäe et al., 2007; Pereira et al., 2013; Pringle and Jones, 2002; Sbriccoli et al., 2009; Smirmaul et al., 2010) determined only the second threshold. Hug et al. (2006b) explained these differences in the literature as a consequence of different study protocols (including workload increments), different pedalling cadence, or performance level of subjects. The choice of the pedalling cadence (free vs. fix cadence) seems to strongly affect the EMG threshold (Hug et al., 2003b, 2006b; Jürimäe et al., 2007; Lucía et al., 1999). Lucía et al. (1999) used a fixed cadence during incremental tests and was able to detect EMGT2 in all cases. In the studies of Hug et al. (2003b, 2006b), and Jürimäe et al. (2007), subjects were able to select a free cadence and EMGT2 was not always observed. Both methods, fixed as well as freely chosen cadence, have their limitations. When

Table 4
Checklist for assessing the study quality.

Checklist for measuring study quality (Ertl, Penasso, Tilp)	
	The questions of the checklist are standing below and should only be answered with YES or NO (except for question 2, 3, 4, 7, 9, 15) Answers with YES are getting 1, and with NO, 0 points If the article doesn't allow you to answer clearly either way, you have to assign 0 points
1	Is the hypothesis/aim/objective of the study clearly described?
2	Description of the participants (Artero et al., 2011): 0 == less items than required for grade 1 1 == at least age, sex and anthropometry (height, weight) 2 == Items required for grad 1 plus additional information (e.g.: sport, fitness level, etc.)
3	Description of the results (Artero et al., 2011): 0 == less results presented than required for grade 1 1 == p value 2 == p value + η
4	Statistical analysis 0 == *t*-test 1 == *t*-test or ANOVA with verification of the requirements 2 == alpha error-correction on *t*-test and η2
5	Are the main outcomes to be measured clearly described in the Introduction or methods section? If the main outcomes are first mentioned in the results section, the question should be answered "no". 0 == no 1 == yes
6	Are the main findings of the study clearly described?
7	Description of the electrodes. 0 == less items than required for grade 1 1 == description of the material and type of electrode (e.g. Al/AgCl, etc. Merletti, 1999)
8	Was the skin preparation described (e.g. alcohol applied to clean skin, skin abrasion, shaving of hair, etc.)? 0 == no 1 == yes
9	Question about the placement and orientation of the electrodes on the muscle 0 == only the muscle is described 1 == electrode location 2 == items required for grad 1 plus orientation over muscle with respect to tendons
10	Was the fixation method of the sensors/cables/transmitters described (tape, hook and loop etc)? 0 == no 1 == yes
11	Was the interelectrode distance described? 0 == no 1 == yes
12	Did they test the impedance previously? 0 == no 1 == yes
13	Did the authors make a quality assessment of the signal (baseline noise, etc.) 0 == no quality assessment of the signal 1 == assess the signal quality by evaluate the baseline noise 2 == calculate the Signal-to-noise-ratio
14	Question about the filter used in data-processing. 0 == if only stated that the authors used a filter (If not noted exclusion criteria for the whole study) 1 == filter + cut off frequency 2 == filter + cut off + at least one more detail (e.g. bandwidth, order, type)
15	Did the authors use the an amplitude (RMS or iEMG) or frequency based method for detecting the electromyographic threshold? For using RMS or iEMG, it is important to know the calculation window respectively the interval! 0 == if not used or minimum requirements are not declared 1 == Reasonable selection of calculation windows
16	Was the sampling frequency described? (absolutely necessary criteria for an accurate quality assessment – if not mentioned exclusion criteria) The minimal acceptable sampling frequency (=fs) is at least twice the highest frequency cut off of the bandpass filter e.g. if a bandbass filter of 10–400 Hz was used, minimal fs should be at least 800 Hz (400×2)
17	Was the ergometer protocol described (e.g. increments)? 0 == no 1 == yes
18	Was the subject's position during the measurements described (e.g.: individual adjustments of the ergometer)? 0 == no 1 == yes
19	Was the method described how the authors determined the systemic (aerobic-anaerobic) transition points from HR,LT, VT? 0 == no 1 == yes

(*continued on next page*)

20	Was the method clearly described how the authors detected the EMGT (Visually, mathematical and description of reliability of the method?)? 0 == no 1 == yes
21	Was the evaluation of the EMG thresholds anonymised? 0 == no 1 == yes
22	Was the study approved by an ethic committee? 0 == no 1 == yes
23	Did the authors describe the warm up program? 0 == no 1 == yes

cycling at a fixed cadence the required exercise intensity is reached by increasing muscular effort to overcome the increasing resistance. As a consequence, this leads to a greater recruitment of fast motor units and possibly facilitates threshold detection at EMGT2 (Jürimäe et al., 2007). However, in sports practice increased exercise intensity is rather accomplished by increasing both the muscle power as well as cadence (Jürimäe et al., 2007; Lucía et al., 1999). Regarding the performance level of athletes, it is noticeable that all reviewed studies which evaluated the first EMGT or EMG_{FT} had either moderately trained or untrained but healthy subjects. This indicates that the prediction of the first metabolic threshold by EMG methods is reliable in moderately trained or untrained subjects. Moreover, Lucia et al. (1997) used the EMGT1 to predict VT in groups of patients with orthotropic cardiac transplantation to assess the improvement of training programmes in rehabilitation. Hug et al. (2003b) and Lucía et al. (1999) suggested that EMGT2 can only be determined in professional athletes/cyclists due to their capability of recruiting a sufficient number of motor units. However, Jürimäe et al. (2007) was able to determine EMGT2 in professional cyclists but also in subjects of various sports background as well as in subjects who did not actively participate in sports. Nevertheless, Jürimäe and co-workers postulated that an EMGT2 can only be detected when subjects reach intensities near RCP (Jürimäe et al., 2007). Based on these results, it seems that the EMGT1 can be used to estimate the first metabolic threshold in patients (Lucia et al., 1997), recreational athletes (Candotti et al., 2008; Gassi and Bankoff, 2010; Glass et al., 1998; Graef et al., 2008; Hug et al., 2003a; Kang et al., 2014; Kendall et al., 2010; Matsumoto et al., 1991; Mello et al., 2006; Moritani et al., 1993; Taylor and Bronks, 1995) as well as in athletes or well-trained subjects (Bearden and Moffatt, 2000; Bergstrom et al., 2013; Camic et al., 2010; Hug et al., 2003b; Jürimäe et al., 2007; Lucía et al., 1999; Viitasalo et al., 1985). However, the requirement to reach high intensities during incremental tests seems to limit the determination of EMGT2 for the estimation of the second metabolic threshold to at least well-trained individuals (Jürimäe et al., 2007). Additional to amplitude and frequency parameters it could be shown that the MFCF has the potential to estimate the muscular response during increasing fatiguing cycling (Pereira et al., 2013; Sbriccoli et al., 2009). According to the findings of Pereira et al. (2013), the nonlinear increase in MFCV, i.e. the MFCV threshold, is an accurate parameter to estimate VT in a group of trained cyclists. Their results were supported by Sbriccoli et al. (2009) who reported that following an initial increase, MFCV decreased when the ventilatory threshold was reached by the subjects, suggesting some kind of fatigue threshold (Sbriccoli et al., 2009). However, results might be limited due to high standard error of measurement (~10%) and in the assessment of different populations (Pereira et al., 2013). Lenti et al. (2010) pointed out, that the proportion of type II fibers in a group of older subjects is reduced and thus, might influence the MVFC threshold detection.

4.5. EMG recording and data processing

Various EMG measurement and data processing methods were used in the reviewed publications which made the comparisons challenging. To increase quality and enhance reproducibility for EMG threshold detection we suggest following the SENIAM recommendations (Hermens et al., 2000) and the standards for reporting EMG data from Merletti (1999) (e.g.: placement, skin preparation, electrodes, data processing, filtering). Camata et al. (2009) argued in their study that the results of RMS calculation vary depending on the chosen length of the time windows which affect the detected EMG thresholds substantially. Based on their results, they suggest implementing either five or ten second time windows to calculate the EMG threshold from RMS EMG (Camata et al., 2009). In general, it appears that thresholds computed with the amplitude-based methods (RMS, iEMG) are more consistent than techniques based on the frequency using MPF or MDF (see Table 2).

5. Conclusion

Forty-three studies on the detection of muscular thresholds could be found of which 32 studies satisfied the quality criteria. Studies that analysed EMG signals of the rectus femoris, vastus lateralis or vastus medialis muscles were mostly of good quality and reported consistent determination of neuromuscular thresholds. Findings with regard to lower leg muscles (gastrocnemius medialis, gastrocnemius lateralis, tibialis anterior) are however, inconsistent. Incremental protocols including one-minute stages with increments between 10 and 25 W appeared to be appropriate to detect threshold compared to other protocols used. Constant work load tests according to deVries et al. (1982) and Moritani et al. (1993) could be a safe alternative to detect EMG threshold to predict the aerobic capacity (VT), especially for clinical populations (deVries et al., 1982) as well as untrained subjects, since motivational aspects and discomfort during the tests can be reduced or eliminated (Graef et al., 2008). Among the different EMG parameters used in the different studies, root mean square EMG (RMS) and the integrated EMG (iEMG) seem to be most appropriate in order to detect electromyographic thresholds. When using RMS, Camata et al. (2009) recommend five to ten second time windows.

Within the reviewed studies, there is consensus that the EMG methodology could be an additional non-invasive tool to detect the aerobic-anaerobic transition points. Based on the findings of Jürimäe et al. (2007) it can be noted that the electromyographic threshold detection is not a sport-specific measure and can be detected in highly professional road cyclists, recreationally trained subjects but also in non-athletes.

However, the review also revealed a great variance in measurement and data processing in EMG-threshold detection which makes comparisons difficult. Although Hermens and co-authors have developed the SENIAM recommendations in 2000, there is a strong need for developing new ideas concerning EMG data processing as proposed, e.g. by Merletti et al. (2016). Based on the current findings on EMG threshold detection, we suggest the use of one-minute protocols with 20 W increments. According to the literature, we further recommend the investigation of the vastus lateralis (VL) or rectus femoris (RF) and the application of either 5 or 10-s RMS windows, as EMG thresholds are more consistent. Due to the conflicting opinions in the literature, concerning the subject's training status (untrained, recreationally trained, professional athletes) it is not possible to provide an elaborate recommendation at the moment. We propose further research in the field of EMG data processing towards a more accurate and contemporary approach to standardize the EMG threshold methodologies.

Despite the great number of factors influencing the myoelectric signal, it appears possible to detect thresholds indicating fatigue for specific single muscles. This cannot be achieved through classic metabolic methods (e.g.: ventilatory, lactate, heartrate), which produce the overall, systemic response of all muscles. However, further research needs to be undertaken to clarify intracellular processes and their impacts on the EMG course especially at both thresholds (EMGT1 and EMGT2) in order to be able to implement the EMG threshold method as an independent non-invasive tool to detect the aerobic-anaerobic transition points.

Conflict of interest

There are no conflicts of interest.

Acknowledgement

We thank our colleagues from the Institute of Sport Science Graz who provided expertise that greatly assisted the research. We thank Dr. Sigrid Thaller for assistance and for comments that improved the manuscript. We also like to show our gratitude to Harald Penasso for helping us developing the quality assessment protocol.

Appendix A

Table 4

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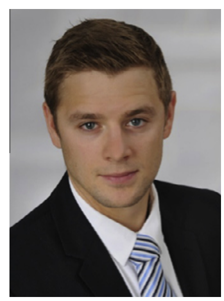

Peter Ertl is a Ph.D. student at the Institute of Sport Science Graz at the University of Graz. He received his Master degree in Sport Science from the University of Graz in 2014. Since 2014 he is working in the research group "Biomechanics, Training and Movement Science" of Univ. Prof. Dr. Markus Tilp. His current research interests include testing and training, electromyography, muscle physiology, neuromuscular fatigue and muscle fatigue.

Annika Kruse is Ph.D. Fellow at the Institute of Sports Science of the University of Graz. She received her Master degree in Sports Science from the University of Kiel/Germany, and since 2014, she has been working in the research group "Biomechanics, Training, and Movement Science" of Univ. Prof. Dr. Markus Tilp at the University of Graz. Her current research interests include muscle and tendon properties in health and disease, spastic cerebral palsy, ultrasonography, ultrasound elastography, electromyography, functional strength training, stretching.

Markus Tilp is full professor and Head of the Institute for Sports Science at the University of Graz. He earned his Ph.D. for Sports Science at the University Graz in 2003 and was guest professor at the Human Performance Laboratory at the University of Calgary, Canada in 2007/08. His research interests are the plasticity of the muscle-tendon unit, movement science, training science, biomechanics, notational analysis, and sports games.