Objectivity and Validity of EMG Method in Estimating Anaerobic Threshold

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Key words
- filtering intervals
- ventilator threshold
- electromyographic signals
- V-slope

Abstract

The purposes of this study were to verify and compare the performances of anaerobic threshold (AT) point estimates among different filtering intervals (9, 15, 20, 25, 30 s) and to investigate the interrelationships of AT point estimates obtained by ventilatory threshold (VT) and muscle fatigue thresholds using electromyographic (EMG) activity during incremental exercise on a cycle ergometer. 69 untrained male university students, yet pursuing regular exercise voluntarily participated in this study. The incremental exercise protocol was applied with a consistent stepwise increase in power output of 20 watts per minute until exhaustion. AT point was also estimated in the same manner using V-slope program with gas exchange parameters. In general, the estimated values of AT point-time computed by EMG method were more consistent across 5 filtering intervals and demonstrated higher correlations among themselves when compared with those values obtained by VT method. The results found in the present study suggest that the EMG signals could be used as an alternative or a new option in estimating AT point. Also the proposed computing procedure implemented in Matlab for the analysis of EMG signals appeared to be valid and reliable as it produced nearly identical values and high correlations with VT estimates.

Introduction

An incremental exercise is commonly used in exercise physiology and sports medicine to evaluate exercise duration capacity and muscle metabolism based on measurements of heart rate, lactate production, and oxygen uptake. During exercise, muscles eventually reach a point at which the activities of the muscle become anaerobic, called anaerobic threshold (AT). Ventilatory threshold (VT) characterized by a non-linear increase in a minute ventilation has been widely used since the mid 1980's as an estimate of AT due to the availability of a computer program, V-slope, which detects AT point by respiratory gas exchange [1].

In recent years, however, an alternative method using electromyographic (EMG) signs of neuromuscular fatigue has been proposed and widely accepted in related literature in an attempt to estimate AT. Several previous studies compared, for example, the values of AT estimated by both integrated EMG (iEMG) and VT [4,6,19,24], while others compared global EMG activity (root mean square, RMS) and VT [9–12,16]. With affirmative results, some researchers in the field suggested that EMG estimation of AT point can be perceived as a theoretically more valid method as it directly utilizes the signals generated by metabolic acidosis from muscle tissues [9,11,12]. Furthermore, in terms of the practicality of experimental installation, EMG, which requires attaching only electrodes on the muscle, is considered to be much easier and less burdensome for subjects than VT, which requires subjects to bear the discomfort of wearing respiratory apparatus in an experimental setting.

An estimate of AT point by gas exchange is usually obtained in an objective manner using a well-known computer program, V-slope software, which computes a linear (least square) regression slope for each of VO_2 and VCO_2 curves and detects a crossing-point of the 2 regression slopes as an estimate of AT point. In contrast, however, the determination of AT point using EMG in the previous studies appeared to rely mainly on the subjective judgment of researchers, mostly via a visual inspection on graphical plots of EMG data, although some predetermined criteria (i.e., ≥10% of values when compared to the previous ones) were considered in their decision-making. Jansen et al. [13] and Hanon et al.

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[6] analyzed the data obtained from only the last 30 s of each stage, whereas Jammes et al. [11], and Hug et al. [9] used only the last 20 s of each stage.

The data generated by either EMG signals or gas exchange, when manipulated accordingly, has a non-linear shape of density distribution in reality. Thus, a filtering interval is introduced in an attempt to convert the non-linear shape of data distribution into a linear-like shape. In other words, the total data collected up to the point of all-out is segmented into parts using a filtering interval, and a mean value of the data within the range of a filtering interval is taken as a representative value of the segment. It is generally understood that the wider filtering interval is applied to the data, the more linear-like shape of data distribution is produced. It was noticed that the filtering intervals (i.e., data collection techniques based on indirect calorimetry for expired gas analysis) employed in the previous studies ranged from a minimum of 9 s to a maximum of 60 s [3,22], with the 30-s interval being the most frequently used [23]. The filtering interval in the V-slope software is set at 9 s as a default. However, some researchers recommended that a 15 to 60-s filtering interval can be used since the 9-s interval often leads to a severe non-linear shape of data distribution [5,20–22].

A digital filtering estimation of AT implemented in the V-slope software has been widely practiced during the last 2 decades, and the theoretical rationale of the computing procedure has been adequately demonstrated [1]. As such, it has served as the "gold standard" for measuring AT in the field. While estimating AT point using EMG is a traditional method, it has lately been viewed as an alternative and valid method [9–11]. As mentioned before, however, the previous studies that compared the values of AT point estimated by both EMG and VT methods had some shortcomings in terms of validation procedures. For example, determining AT by EMG was rather subjective compared to using VT, and a filtering time interval applied to EMG data was inconsistent with that of VT, which together may result in an inevitable discrepancy between 2 estimates of AT in subsequent comparative analyses. Therefore, the purposes of this study were to verify and compare the performances of AT estimates among different filtering intervals (9, 15, 20, 25, 30 s) and to investigate the relationship and agreement of AT estimates obtained by both VT and EMG methods.

Materials and Methods

▼

Subjects

Total 69 male undergraduate/graduate students (age: 23.4 ± 4.2 years, height: 173.5 ± 5.1 cm, weight: 72.7 ± 9.8 kg, % body fat: 15.9 ± 5.5, VO_2max: 44.47 ± 7.05 mL/kg/min) participated in this study. Students not involved in general recreational exercise over 2 times per week over the previous 6 months were selected for this study and were allowed to pursue general recreational exercise 2 times per week during the experimental period. All participants signed a written consent for this study protocol. All participants were relatively more heterogeneous in their % body fat (0.35) than weight (0.13) and height (0.03) when compared using the coefficients of variation (CV = SD/M) as a reference point. This study was approved by the Institutional Review Board for human subjects' protection at Yongin University. This study was also performed in accordance with the ethical standards of the IJSM [7].

Procedures

The exercise protocols outlined by Hug et al. [9], Jammes et al. [11], and Takaishi et al. [24] were used in this study. In brief, the subjects were acquainted with the equipment and experimental procedures prior to testing and also instructed to avoid any intense training before the testing day. To minimize bias for evaluating threshold point, we used the included pedal straps to fix the participants' feet to ergometer pedal during all testing sessions. The test exercise was then conducted following a 2 min warm-up.

Testing was started at a work load of 20 W and was increased by 20 W every 1 min until the maximal oxygen uptake (VO_{2max}) was reached [9,10]. During cycling exercise, the pedaling rate was kept around 60 cycles per minute (rpm), and a pedal frequency meter was used to maintain this cadence by providing visual feedback. Borg RPE scale was also used at each exercise stage to determine burnout. All subjects had a practice trial to indicate a mark on the scale before the actual testing, and were sufficiently instructed in using the RPE scale.

Subjects were instructed beforehand to fast for at least 12 h. The air-conditioned laboratory was set to a temperature of 24–25 °C and 50–55 % relative humidity. During the tests, gas exchange data were collected continuously using an automated breath-by-breath system (Quark b^2; Cosmed, Italy) and analyzed with 50 Hz duty amplitude at $Zr0_2$ to obtain O_2, CO_2 and N_2. The collected data stored in a PC were further manipulated to compute minute ventilation (VE), O_2 consumption and CO_2 production. Total time taken to the all-out for each subject was segmented with an initial filtering interval of 9 s, which was used in V-slope software (Beaver 1), and subsequent attempts were made to employ 15, 20, 25 and 30-s filtering intervals to the same data of each subject for the estimation of AT.

The EMG signal of the vastus lateralis muscles was taken from bipolar (20 mm center-to-center, 1 × 1 cm of diameter) Ag-AgCl surface electrodes (Noraxon, USA). The electrode was positioned parallel to the lower 2/3 of the line running from the anterior supra iliac spine to the lateral side of the patella on the dominant side of the body. A ground electrode was attached over the C7 vertebra. Each electrode spot was marked with an oil pen and secured with surgical tape after the skin was shaved and cleaned with alcohol to ensure that the electrode remained at the same spot during the test movement. The EMG signal was recorded continuously during test and amplified with a frequency band ranging from 10 to 2 000 Hz (Noraxon Telemyosystem 900, USA; common mode rejection ratio: 100 dB at 60 Hz; differential input impedance: 10 MΩ; gain: 2 000; base-line noise < 1 μV) and then converted from analogue to digital with a sampling frequency of 1 000 Hz. The EMG was subsequently processed by rectification and smoothing (Root Mean Square – 100 ms). Raw EMG data was filtered by full wave rectified and band pass filter (Butterworth, 3rd order, 20–400 Hz). Then numeric value of RMS was calculated during every 1-s non-superimposing window. Total data for each subject, expressed in the linear envelope form, was segmented into parts with a filtering interval of 9, 15, 20, 25 and 30 s, respectively. These filtering intervals were synchronized with the breath-by-breath system at a sampling frequency of 1 000 Hz. This synchronization was done specifically to compare and validate the performance of EMG estimates of AT under the same conditions of each filtering interval.

V-slope method

The detection of AT involves the analysis of behavior of VCO_2 as a function of VO_2 during progressive exercise test when exceeding the lactate threshold (LT) is accompanied by the buffering of lactic acid by [HCO3-] with a consequent increase in VCO_2. This results in a transition in the relationship between the VCO_2 and VO_2, which is the underlying element in all methods of anaerobic threshold detection by gas exchange as also implemented in the V-slope method.

AT point estimation using EMG method

Least squares fitting method among simple linear regression model was used for AT point estimation using EMG data. Least squares fitting method was applied to different filtering times (at 9, 15, 20, 25, and 30 s) based on analyzed raw EMG data. Using least squares, simple linear regression equation was estimated between A and B sections (▶ **Fig. 1**). The largest increased point in simple linear regression slope was then found between 2 sections. Therefore, AT point using EMG data was set as a point having the largest increase, and then simple linear regression slope was calculated. The program Matlab (version 6.5) was used for all data processing, and the results were conducted by choosing the robust fit option the in linear least squares model dialog. Modified least squares fitting method for calculating VO_2 transitions [15,26] was used for estimating AT by using raw EMG data. Different filtering time (at 9, 15, 20, 25, and 30 s) was calculated from raw EMG data to be reconciled with VO_2 results as EMG data/1 s.

Statistical analysis

Descriptive statistics for all measured variables were computed, and repeated measures ANOVAs were used to compare the mean values of dependent variables (computed time taken to reach AT, hereinafter referred to as "AT point time") within the filtering intervals and between the 2 estimation methods. Pearson's correlation coefficients were computed to examine the linear relationship of AT point estimates. Bland-Altman plot was also applied to assess agreement between the measures of 2 methods [2]. The 95 % confidence intervals for the mean difference and the variability of difference scores between 2 measures were computed. SPSS 18.0 for Windows (Chicago, IL, USA) was used for all statistical analyses with a significance level (α) set at 0.05.

Results

▶ **Table 1** presents the mean (standard deviation) values of AT point time obtained by 2 different methods in each filtering interval along with those of the cumulative absolute (mL/min) and relative oxygen uptake (mL/kg/min) upto the AT point. The results of a (2 × 5) ANOVA with repeated measures on both factors revealed that both main effects ('methods' and 'filtering intervals') were not statistically significant: $F_{(1, 68)} = 0.64$, $p = 0.43$; $F_{(4, 272)} = 1.95$, $p = 0.10$), respectively. Furthermore, there was also no significant interaction effect found between the 2 independent variables [$F_{(4, 272)} = 1.96$, $p = 0.10$]. Close examination of ▶ **Table 1** indicates that the point mean values of AT point time obtained by VT for 20, 25, 30 s appeared to be somewhat larger than those by EMG, but the difference was not big enough to be statistically significant in all 5 filtering intervals. In general, the mean values of AT point time obtained by VT become larger as the filtering interval gets wider. However, the mean and standard deviations obtained by EMG method were very similar in magnitude and stable across all 5 filtering intervals.

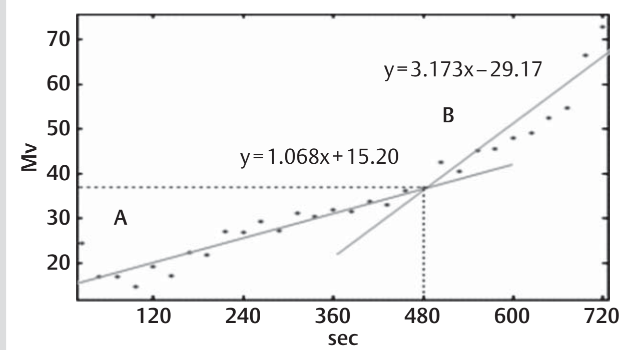

Fig. 1 AT point evaluation through least squares fitting method using vastus lateralis muscle raw EMG data during exercise.

Table 1 Estimated values of oxygen uptake and EMG at anaerobic threshold point based on each filtering time.

Filtering interval time	Absolute oxygen uptake, mL/min	Relative oxygen uptake, mL/min/kg	VT time, sec	EMG AT time, sec
9 s	2 041.70 (456.66)	28.39 (6.77)	508.17 (102.25)	510.78 (115.08)
15 s	2 053.15 (468.32)	28.55 (6.70)	511.74 (106.61)	511.09 (114.22)
20 s	2 080.39 (462.76)	28.97 (6.87)	518.55 (101.54)	511.88 (114.60)
25 s	2 109.32 (472.57)	29.35 (6.95)	521.59 (103.72)	512.68 (114.21)
30 s	2 074.33 (479.90)	28.88 (7.06)	519.86 (105.67)	513.91 (112.59)

Values presented as mean (SD)
VO_{2max}; 3197.23(445.33) mL/min, 44.47 (7.05) mL/kg/min
VT time; time taken to AT-time by VT
EMG AT time; time taken to AT-time by EMG

The relationship between 2 measures in estimating AT point time was examined using Person's correlation coefficients presented in ▶ **Table 2**. The correlation coefficients between 2 measures in each filtering interval, presented in the diagonal, ranged from $r = 0.89$ to 0.94 ($p < 0.05$), indicating reasonably acceptable trend between the 2 measures. This is more so for the wider filtering intervals (i.e., 25 and 30 s). The correlation coefficients among 5 intervals within EMG, presented above the diagonal in ▶ **Table 2**, ranged from $r = 0.95$ to 0.99 ($p < 0.05$) with an average of $r = 0.97$ and were higher in general than those of VT which ranged from $r = 0.89$ to 0.97 ($p < 0.05$) with an average of $r = 0.93$ (see below the diagonal). It can be also noticed that the correlation coefficients among the filtering intervals of 20, 25, and 30 s were somewhat higher than those of other pairs of intervals in both methods. Overall, the estimated values of AT point time computed by EMG method were more consistent across 5 filtering intervals and demonstrated higher correlations among themselves when compared with those values obtained by VT method.

Bland-Altman plots are presented in ▶ **Table 3** and ▶ **Fig. 2** as further analysis to examine the agreement between the VT and EMG methods in estimating AT point time. ▶ **Fig. 2** shows a plot for the VT and EMG with the average value of 2 methods being

Table 2 Correlation matrix of AT point-time measures by VT and EMG methods in each filtering interval.

VT	EMG				
	9 s	15 s	20 s	25 s	30 s
9 s	0.900	0.968	0.956	0.973	0.970
15 s	0.910	0.899	0.973	0.952	0.949
20 s	0.887	0.932	0.890	0.964	0.969
25 s	0.919	0.928	0.949	0.913	0.987
30 s	0.930	0.927	0.940	0.966	0.940

Lower diagonal is a correlation matrix for VT and upper diagonal is that for EMG
Lower correlation coefficient means r value of 9, 15, 20, 25, and 30 s among VT values
Upper correlation coefficient means r value of 9, 15, 20, 25, and 30 s among EMG values
Diagonal correlation coefficient means r value of same filtering time value between VT and EMG

Table 3 Limits of agreement and coefficients of variation based upon filtering interval time.

Filtering interval time	The lower and upper limits of agreement	Variability between 2 measures expressed in terms of CV (%)
9 s	− 101.1 ~ 95.9	19.3
15 s	− 97.8 ~ 99.1	19.2
20 s	− 95.7 ~ 109.0	19.9
25 s	− 82.7 ~ 100.5	17.7
30 s	− 69.1 ~ 80.1	14.5

on the X-axis and the difference being on the Y-axis for the filtering interval at 9 (A), 15 (B), 20 (C), 25 (D), and 30 (E) seconds. The lower and upper limits of agreement for the 9 to 30-s intervals, calculated as $[M_d \pm (1.96) \times SD]$, showed a range of −101.1 to 95.9 (9-s), −97.8 to 99.1 (15-s), −95.7 to 109.0 (20-s), −82.7 to 100.5 (25-s), and −69.1 to 81.0 (30-s), respectively. The variability between 2 measures expressed in terms of CV, computed as $[1.96 \times (SD_d / M_G) \times 100]$ for each of 5 intervals, was 19.3% 19.2%, 19.9%, 17.7%, and 14.5%, respectively; where SD_d = standard deviation of the difference scores and M_G = grand mean of 2 measures. In addition, for all 5 comparisons, 94–96% of the individual values were within the limits of agreement. In general, the examination of Bland-Altman plots showed that both the 95% confidence intervals for the mean difference were narrower and the variability in percentage points became smaller as the filtering interval became wider.

Discussion

AT has been commonly estimated by VT method [1], and its computational procedures are implemented in the well-known computer program called V-slope. The present study attempted to investigate the performance of a new measurement method in estimating the point of AT occurrence during incremental aerobic exercise using EMG signals. The data generated by either EMG signals or gas exchange were transformed into a linear-shape distribution using a filtering interval of 9, 15, 20, 25, and 30 s. The estimates of AT point time obtained by EMG method were evaluated through comparison with those values obtained by VT method. The experimental protocols employed in the current study were outlined by Hug et al. [9], Jammes et al. [11], and Takaishi et al. [24]. The mean values of oxygen uptake at the VT point obtained in this study were reasonably close to those values published in the related research [1]. Both EMG signals and VO_2 amplitude are non-linear in nature, and the amplification of amplitude changes dramatically as exercise intensity and time increase. Some researchers in previous studies have indicated that the calculation of gas exchange parameters obtained from breath-by-breath systems might cause some noise generating fluctuations between breaths. Therefore, they recommend using an average or a smoothing filtering method for VO_2 data in order to attain more accurate oxygen uptake values [1, 14, 25].

Accordingly, a filtering procedure was applied in order to convert non-linear data into linear data in this study. An entire amplitude generated by either EMG signals or VT for each subject was segmented independently by 5 filtering intervals, and the mean values of AT point times were compared within each method and between 2 methods. The mean values of AT point time obtained by VT for 20, 25, 30 s were found to be similar to each other and somewhat larger, and showed higher correlations among themselves than those for narrower intervals. The present data obtained by VT method support the recommendation of previous researchers to use a wider filtering interval rather than 9-s interval. The AT point times estimated by EMG method were also found to be very similar each other, stable in magnitude, and highly correlated across all 5 filtering intervals. Furthermore, the mean value of each sample interval was also deemed to be very comparable with that of VT.

In the previous studies, the determination of AT using EMG appeared to be reliant primarily on the subjective judgment of researchers, mostly via a visual inspection of graphical plots of EMG data [9, 10]. In contrast, the present study has developed a computing procedure using a regression approach implemented in Matlab and applied this program to compute and locate the point of AT occurrence in EMG data. Therefore, for a clinical measurement perspective, the EMG estimation procedure of AT employed in the present study can be considered to be a more objective and reliable technique than the subjective and visual inspection of EMG data. The objectivity of the new estimation procedure is supported partly by the fact that the results found in this study demonstrated considerably higher correlations (r = 0.94 in 30-s) than those (r = 0.60 to 0.82) reported in the previous studies [4, 9, 10, 16, 19, 24].

As most previous studies have acknowledged, the results of our study also demonstrated the importance of filtering intervals when evaluating VO_2max or VO_2 peak by indirect calorimetry [8, 14, 17, 18, 22, 23]. In addition, our study has further revealed that filtering intervals were also essential for evaluating maximal aerobic power and AT point. Therefore, we suggest that the EMG estimation introduced in this paper could be considered not only as a valid and objective measure, but an easy-to-use method in evaluating AT point. We also expect that the EMG method could be easily applied to practical fields when assessing the effective gauge of physical fitness for normal population and athletes, as well as for patients with cardiorespiratory disease.

Conclusion

It is generally understood that if a new measurement technique in clinical measurement sufficiently agrees with an established technique, then the new method may be used as an alternative

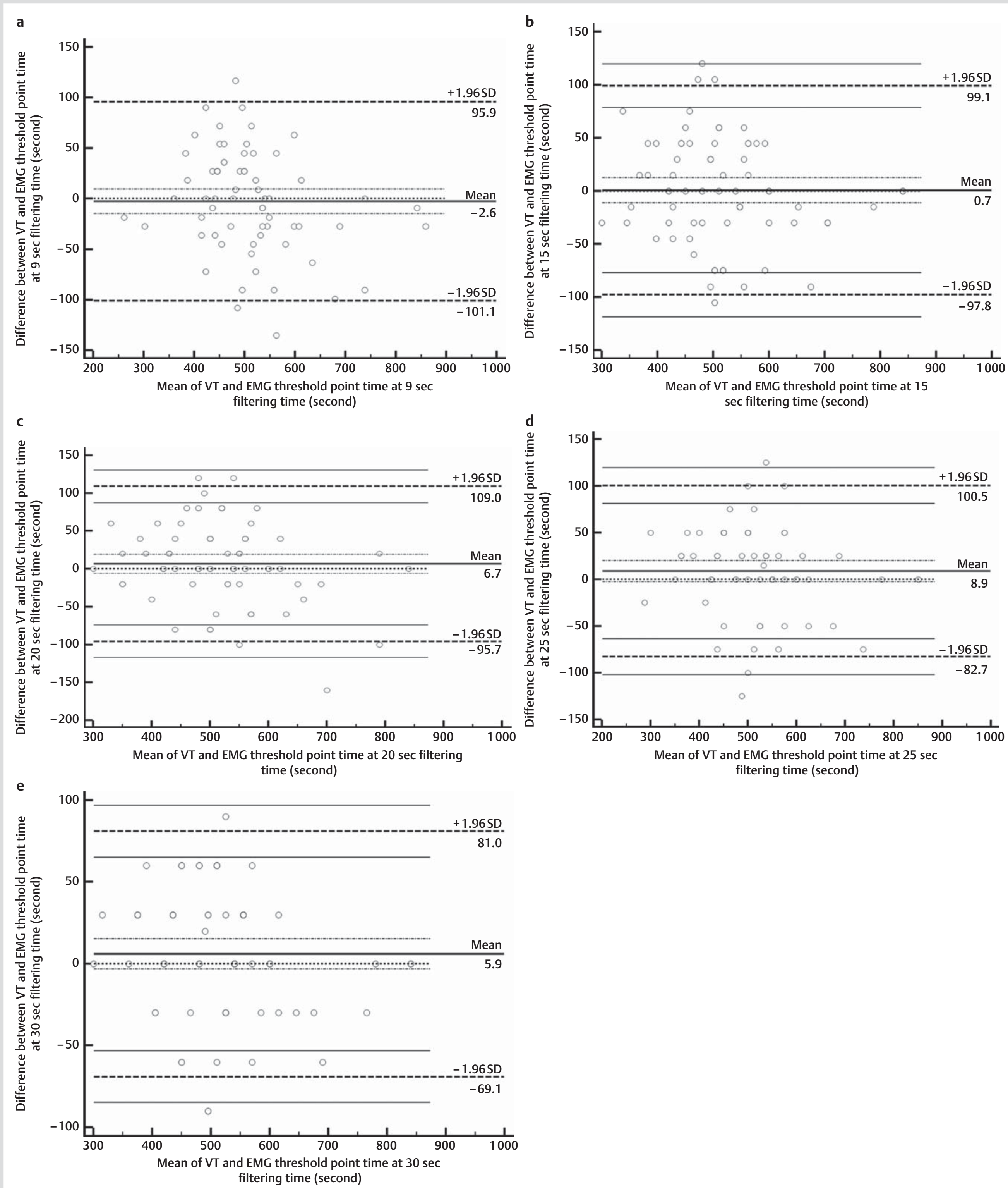

Fig. 2 Bland-Altman plot for the VT vs. EMG threshold point at 9-s filtering time **a**, VT vs. EMG threshold point at 15-s filtering time **b**, VT vs. EMG threshold point at 20-s filtering time **c**, VT vs. EMG threshold point at 25-s filtering time **d**, and VT vs. EMG threshold point at 30-s filtering time **e**. Unit of X and Y axis is second and solid line represents the mean difference (bias) between time sec of VT and EMG threshold point. Upper and lower broken lines represent the 95 % limits of agreement (mean difference ± 1.96 S.D. of the difference).

or replacement to the traditional one. What we found in the present study suggests that the EMG signals can be used as an alternative or a new option for estimating AT point. The proposed computing procedure implemented in Matlab for the analysis of EMG signals also appears to be valid and reliable as it produced nearly identical values and high correlations with VT estimations. The proposed computing procedure for EMG signals utilized the same statistical regression approach as that in the V-slope program. Gas analysis by V-slope is currently in commercial use and broadly employed by researchers. However, there is no computer analysis program available for EMG signals despite the wide understanding of its advantages in clinical settings over VT.

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Conflict of interest statement: We have no conflict of competing interests to disclose.

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