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Research article

Relationship between Electromyogram Spectrum Parameters and the Tension-Time Index during Incremental Exercise in Trained Subjects

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Abstract
The inspiratory muscle tension-time index $T_{T0.1}$ (given by $P_{0.1}/P_{Imax}$ x T_I/T_{TOT}) could be used to reliably assess inspiratory muscle activity during exercise. So far, the correlation between the $T_{T0.1}$ and diaphragmatic activity has not been measured and the $T_{T0.1}$ has not been compared with other measurements of the inspiratory muscle load such as the transdiaphragmatic pressure index or TT_{di}. In this study we hypothesize that the $T_{T0.1}$ measuring the mouth is a noninvasive reflection of the electromyographic activity of the diaphragm. We simultaneously measured $T_{T0.1}$ and surface EMG (SEMG) of 8 trained subjects at rest and during incremental exercise. The curvature of $T_{T0.1}$ and the root mean square (RMS) follow the same trend during the incremental exercise with a significant correlation between $T_{T0.1}$ and surface EMG parameters (RMS; $r = 0.81$ $p < 0.001$ and MPF; $r = 0.80$ $p < 0.001$ respectively). We conclude that $T_{T0.1}$ measured as s an adequate noninvasive method reflects the diaphragmatic activity during incremental exercise in healthy subjects.

Key words: Inspiratory muscle drive, mouth occlusion pressure, fatigue; diaphragm.

Introduction

The overall activity of the inspiratory muscles can be evaluated by different invasive techniques. First the tension-time diaphragmatic index (TT_{DI}) proposed by Bellemare and Grassino (Bellemare and Grassino, 1982; 1983) assesses the activity of the diaphragm during breathing given by $TT_{DI} = P_{DI}/P_{DImax} \bullet T_I/T_{TOT}$ where P_{DI} is the transdiaphragmatic pressure, P_{DImax} the maximal transdiaphragmatic pressure and T_I/T_{TOT} the duty cycle. A more direct measurement is the analysis of the time and frequency contents of the electromyographic signal. Both techniques are invasive and involve the use of gastric and oesophageal balloon and oesophageal electrodes respectively. A simplified non-invasive index obtained from the mouth occlusion pressure ($P_{0.1}$) is proposed as an alternative method. This non-invasive tension-time index, validated during exercise in healthy subjects, is derived from the equation $T_{T0.1} = P_{0.1}/P_{Imax} \bullet T_I/T_{TOT}$, where P_{Imax} is the maximal inspiratory pressure and T_I/T_{TOT} is the duty cycle (Hayot et al., 2000).

The efficiency of the respiratory muscle during exercise is much debated in the literature. Although some authors have argued that respiratory muscle performance does not limit maximal incremental exercise tolerance in healthy trained and untrained adults (Coast et al., 1990; Hayot et al., 2000), heavy submaximal exercise has been shown to impair respiratory muscle performance in humans (Johnson et al., 1993; Mador et al., 1993). To the best of our knowledge, no study has drawn the comparison between these two techniques. The present study was aimed to measure $T_{T0.1}$ and surface EMG of inspiratory muscles of trained cyclists during a maximal incremental exercise, not to assess fatigue, but to check if $T_{T0.1}$ could also be a reliable index of the inspiratory muscle activity and recruitment. We reasoned that the $T_{T0.1}$ could also be a reliable index of the inspiratory muscle activity and recruitment. Though the activity of inspiratory accessory muscle is more and more important to the genesis of increased pressures it was not reflected by EMG_{di}. To assess the overall activity of the inspiratory muscle, as the $T_{T0.1}$, we used the surface EMG (SEMG) and the aim of our study was to determine whether tension-time index reflects the inspiratory muscle activity and recruitment.

Methods

Subjects

Eight trained males cyclist took part in this study. The experimental procedures complied with the ethical standards of the 1975 Helsinki Declaration and approval was received from the appropriate local institutional review board. All qualified participants were familiarized to exercise on the cycle ergometer and instructed to avoid exercise, food, and caffeine for at least 2 h prior to exercise testing. All subjects were assigned to a maximal exercise testing session with tension–time index and SEMG measurements. The anthropometric, spirometry and maximal inspiratory pressures are listed in the table 1. The ATS spirometry interpretation workshop only states that subjects should be "never-smokers, free of respiratory symptoms and disease" (Johannessen et al., 2007; Redlich et al., 2014). Subjects not meeting these guidelines were excluded.

Occlusion pressure

$P_{0.1}$ is the maximum pressure developed during a spontaneous respiratory effort during a 100 ms occlusion at the beginning of inspiration (Kera et al., 2013; Whitelaw et al., 1975). Its timing is such that it is not influenced by the conscious response to occlusion. Moreover, as this index is derived from the ventilatory drive it has the advantage of being independent of the mechanical properties of the lung (Kera et al., 2013). $P_{0.1}$ a valid index of neural output was assessed at the level of functional residual capacity (FRC)

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(Whitelaw et al., 1975). Subjects were asked to breathe quietly, with the nose occluded, through a mouthpiece connected to the pneumotachograph (Fleish Lausanne, Switzerland) with a two-way low- resistance breathing valve (0.9 $cmH_2O·L^{-1}$ s, dead space of 50 ml, model 9340 occlusion valve, Hans Rudolph inc, Kansas City, Missouri, U.S.A). During the exhalation phase of breathing, a balloon was rapidly inflated in the inspiratory limb of the breathing circuit to occlude the subsequent inspiratory flow. It was closed during expiration and automatically opened about 150 ms after the onset of the subsequent inspiration. Mouth occlusion pressure ($P_{0.1}$) was measured with a differential pressure transducer (Druck, LPM 9000 series, ± 50 cmH_2O, Leicester, England). The balloon was inflated with helium from a small gas cylinder, and the valve was controlled manually with a small switch. The subject was asked to continue to breathe normally despite the occlusions. Throughout manoeuvres mentioned previously the subject wore headphones and listened to music to dampen any noise from the switching device controlling the balloon, and could see neither the occlusion valve nor the operator and therefore, was unable to anticipate the airway occlusion. The Lab view interface (Lab view, National Instruments Corporation, Austin, Texas, U.S.A.) that provided a visual feedback was used to identify the onset of inspiration. At rest, manoeuvres were made until five technically satisfactory and reproducible measurements were obtained (variation <10%) (Kera et al., 2013). The highest score was kept for analysis.

Maximal inspiratory pressure

Maximum inspiratory pressure (P_{Imax}) is the force that respiratory muscles are able to generate during an occlusive manoeuvre at prefixed volume (Hautmann et al., 2000). Maximal inspiratory pressure (P_{Imax}) was measured at the functional residual capacity (FRC) (the effect of variation of muscle length on force development should be minimal near FRC where the isometric force length curve of the diaphragm is nearly flat), with a differential pressure transducer (Druck, LPM 9000 series, ± 350 cmH_2O, Leicester, England) using the technique of Black and Hyatt (1969). All subjects had no previous experience of these manoeuvres. Therefore, great care was taken to fully explain the procedures. This was facilitated using an oscilloscope (Gould Inc., Cleveland, OH) that provided a visual feedback to the subjects during the explanations and during the manoeuvres. Subjects breathed comfortably on the experimental apparatus without the airflow resistor. After a steady-state FRC was attained, the inspiratory and expiratory ports were occluded at the end exhalation with a balloon shutter valve, and the subject was asked to perform a maximal inspiratory effort. The shutter valve opened automatically after five seconds, and the highest inspiratory pressure that was sustained for at least 1 s was taken as the P_{Imax}. Manoeuvres were made until three technically satisfactory and reproducible measurements were obtained (variation <10 %) (Harik-Khan et al., 1998). The highest score was kept for analysis.

Derived Parameters

$T_{T0.1}$ was estimated as ($P_{0.1}/P_{Imax}$ x T_I/T_{TOT}). For the $T_{T0.1}$ equation $P_{0.1}$, P_{Imax} and T_I/T_{TOT} were assessed at rest and during exercise. $T_{T0.1}$ is an index of the activity of overall inspiratory muscles. High values of $T_{T0.1}$ correspond to high risk of fatigue, as it was shown by Hayot and coworkers (2000).

Surface electromyography (SEMG) measurements

During maximal exercise testing, the SEMG activities were recorded from the diaphragm and intercostal muscles. Bipolar (20mm inter electrode distance) SEMG recording (silver–silver chloride electrodes with 8 mm active diameter; EA224a model, In Vivo Metrics, U.S.A) was employed. Before electrodes applications, the skin was cleaned by abrasion and sponged with an alcohol–ether–acetone mixture to reduce the inter electrode impedance below 2 kΩ. Electrodes were placed between the 7th and 8th intercostal space, on the right side, 1 cm from the lateral board of the rib cage, and the reference electrode on the wrist.

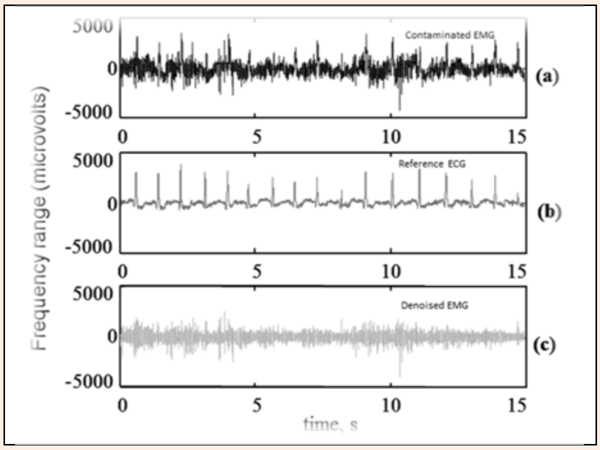

Figure 1. Primary input (SEMG) filtered. (a) Surface respiratory EMG signal contaminated with ECG and power line interference signals, **(b)** ECG signal, **(c)** Cleaned surface respiratory EMG signal.

The myoelectrical activities of respiratory muscles were amplified (differential amplifier) and passed through upper (1kHz) and lower (1Hz) cutt–off filters. Diaphragm electromyography (SEMG) signals recorded by surface electrodes were strongly corrupted by ECG interference. Since ECG signals have large amplitudes and SEMG surface electrodes are positioned adjacent to the heart, SEMG recordings include a large « noise » ECG component. Spectra of the SEMG and ECG signals overlap in the same frequency range. Therefore, simple elimination of the ECG interference by filtering the SEMG signal fails. It is an effective method to separate an interfering signal from a signal of interest when the two signals have overlapping spectra (Akkiraju and Reddy, 1992). It has been also demonstrated that a substantial degree of separation between signals and noise can be obtained in the wavelet domain. In this work, these two well-known denoising techniques were combined to improve the performance of the decontamination procedure. The adaptive filter coefficients were adjusted using information derived from the wavelet coefficients of the two ANC scheme input signals: reference input (ECG) and primary input (SEMG). The estimated noise component provided by the adaptive filter was subtracted from the primary input (SEMG) in order to remove the interferences (Figure 1). The SEMG signals were recorded online using acquisition software (Spatol, Divergent, Compiègne, France). The denoised SEMG signal was analysed by using data computing software (Calvise, Divergent, Compiègne, France). The SEMG signals were sampled in 2048 Hz. The software computed a mean power spectrum density (PSD) by calculating the RMS values of eight consecutive spectra obtained from 0.5–s time windows. The mean PSD was defined by 256 points, in the 0–512Hz frequency bands. The mean power frequency MPF was defined as the frequency that divided the PSD into two regions containing equal power. The RMS and MPF of the PSD were computer calculated in real time.

Protocol

Before each exercise test, we measured the occlusion pressure at rest. The subjects comfortably seated, breathing quietly during 2-3 min. After a stable respiratory ratio was attained, the following parameters were determined from an average of 15 s during 5 min: oxygen consumption (VO_2), carbon dioxide output VCO_2, minute ventilation (V_E), tidal volume (V_T), breathing frequency (f), inspiratory time (T_I) and expiratory time (T_E). Each subject performed at least 10 occlusions at a rate of 2 to 3 per min. Next, the subjects performed maximal inspiratory pressure (P_{Imax}) measurements using the technique of Black and Hyatt (Black and Hyatt, 1969) and then a cycle ergometer (ER 900, Jeager, Germany) and rested for 3 min. This was followed by a 3 min 60 W warm-up period. The workload was then increased in steps of 30 W every 90 s. We have chosen 90 s steps to perform 3 occlusion measurements in the last 45 s. ECG was recorded continuously during maximal exercise testing. The pedalling speed was fixed at 60 rpm throughout the test. Oxygen uptake was determined using an open circuit technique with the CPX system (Medical Graphics Corporation, St. Paul, U.S.A.). The calibration of the flow module was accomplished by introducing a calibrated volume of air at several flow rates with a 3l pump. Expired gas was analysed for oxygen with a zirconium analyser and for carbon dioxide with an infrared analyser. Gas analysers were calibrated before each test using a standard certified commercial gas preparation. The inspiratory airflow, the fraction of expired oxygen (FEO_2) and of carbon dioxide ($FECO_2$) were computer calculated from the last 10 breathing cycles of every minute. Averages were then established for minute ventilation (V_E, $l·min^{-1}$, body temperature pressure saturated [BTPS]), oxygen uptake (VO_2, $l·min^{-1}$, standard temperature and pressure dry [STPD]), carbon dioxide production (VCO_2, $l·min^{-1}$, STPD), respiratory ratio, ventilatory equivalent for oxygen (V_E/VO_2), and carbon dioxide (V_E/VCO_2), and breathing frequency. The exercise was considered to be maximal when three of the following criteria were obtained (Edvardsen et al., 2014; Poole et al., 2008): i) levelling off VO_2 ii) HRmax ≥ 90% theoretical HR max (Hansen et al., 1984) iii) respiratory exchange ratio RER was greater than 1.15 iv) pedal rate < 50 rpm v) volitional exhaustion. Peak VO_2 was defined as the highest VO_2 that could be sustained for at least 30 seconds during the last stage of exercise. At the end of the test, each patient had a 2-minute active recovery and a 3-minute passive recovery. Oxygen uptake (VO_2), carbon dioxide output, respiratory ratio and parameters such as T_I, T_E (expiratory time), T_{TOT}, f (respirator frequency), V_E, and V_T (tidal volume) were continuously measured using the CPX.

Statistical analysis

For statistical treatments, we used the StatView software (Abacus Concepts, Berkeley, California, U.S.A.). All values were expressed as mean and standard deviation (± SD). Linear regression analysis was performed using the least squares method. This analysis was carried out using RMS and MPF as dependent variables and $T_{T0.1}$ as an independent variable. The difference between $P_{Ima,}$ before and ten minutes after the end of the exercise was tested with paired Student's test. A $p<0.05$ was considered statically significant.

Results

Mean anthropometric characteristics and spirometrics data and maximal inspiratory pressure at rest in cyclist subjects are presented in Table 1. Gas exchange and breathing pattern parameters at rest and maximal exercise are listed in the Table 2.

Table 1. Anthropometrics, spirometrics and maximal inspiratory pressure at rest in cyclists subjects. Values are reported as mean (± SD).

Variables		% of predicted value
Age (years)	26 (5)	
Height (m)	1.77 (.05)	
Weight (kg)	69.4 (6.5)	
FVC (l)	5.9 (.3	114 (±2)
FEV1 (l)	4.8 (.4	110 (±5)
FEV1/FVC (%)	81.6 (1.8	108 (±2)
PImax (cmH2O), before	126 (39)	
PImax (cmH2O), after	120 (22)	

FVC = Forced Vital Capacity; FEV1 = Forced expiratory volume in one second; PImax = maximal inspiratory pressure.

Table 2. Gas exchange and breathing pattern parameters at rest and maximal exercise in cyclist subjects. Value are reported as mean (±SD).

	Rest	Maximal exercise
VO_2 ($ml.kg^{-1}.min^{-1}$)	6.2 (.9)	56.7 (8.6)
VCO_2 ($ml.min^{-1}$)	372 (87)	4839 (483)
VE ($l.min^{-1}$)	12.7 (2.6)	151.2 (19.0)
VT (ml)	1004 (117)	3290 (220)
P0.1 (cmH_2O)	1.3 (.2)	27.8 (7.0)
TI/TTOT	.41 (.02)	.47 (.04)
VT/TI ($l.s^{-1}$)	.4 (.1)	5.39 (1.0)
f (bpm)	12 (3)	48 (10)

VO_2 = oxygen uptake; VCO_2 = carbon dioxide output; VE = minute ventilation; VT = tidal volume; P0.1 = occlusion pressure; TI/TTOT = mean inspiratory time to total time of the respiratory cycle; VT/TI = mean inspiratory flow and f = respiratory frequency.

Subjects did not show significant decrease in their maximal inspiratory pressure ten minutes after the end of the exercise compared to rest, respectively 126 ± 39 vs. 120 ± 22 cmH_2O. The tension-time index increased with exercise intensity to reach at maximal effort a mean maximum value of $T_{T0.1} = 0.12$ (Figure 2). At the same time the root mean square (RMS) and the mean power frequency increased with exerted mechanical power output. RMS profile was normalized with respect to the highest value and MPF profile to the initial value, as follows: RMS_i % = (RMS_i/RMS_{max}) x 100 and MPF_i % = (MPF_i/initial MPF) x 100. Results of spectral analysis of SEMG showed homogeneity in RMS and MPF profiles during the maximal exercise between subjects. All showed the same RMS (Figure 5**)** and MPF kinetics profiles (Figure 4b). Both RMS and MPF increased in all subjects during exercise (respectively Figure 3a and 3b).

We found positive linear correlation between RMS and $T_{T0.1}$ ($r = 0.81$, $p < 0.001$; Figure 4).

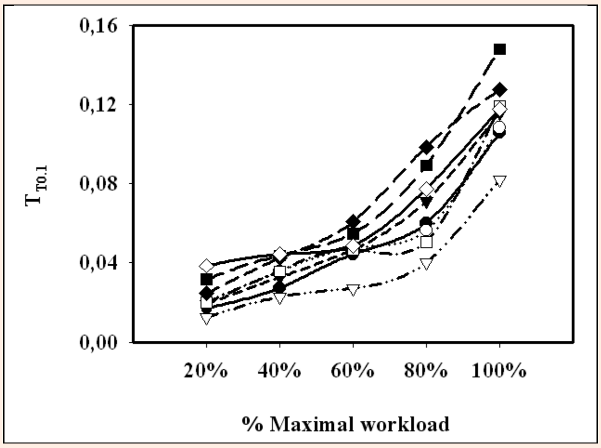

Figure 2. The Tension-time index of the inspiratory muscles TT0.1 for all subjects during incremental exercise.

Discussion

The present study confirms and extends the relationship between inspiratory muscle recruitment by surface EMG and the tension-time index. The main finding of this study was the validation of the noninvasive $T_{T0.1}$ as a good index of inspiratory muscle recruitment.

Inspiratory muscle function can be evaluated by measurement of ($T_{T0.1}$) the noninvasive tension-time index of the inspiratory muscles (Hayot et al., 2000). The tension-time index of inspiratory muscle constitutes a very good mechanical index of O_2 consumption of the respiratory muscles over a wide variety of breathing patterns (Field et al., 1984; Hayot et al., 2000). The noninvasive tension-time index $T_{T0.1}$ (Hayot et al., 2000) had never been compared with surface electromyography. Both root mean square and $T_{T0.1}$ increased during incremental exercise, and were strongly correlated. $T_{T0.1}$ seemed to be a good index to monitor inspiratory muscles activation and inspiratory muscle recruitment during exercise.

The time content of the SEMG established the energy and/or the electric power of the signal. It is well established that the root mean square (RMS) is the best index of the relation EMG/strength. The RMS kinetic is dependent on the number and the firing rate of motor units (MU) (De Luca, 1984).

In the present study, the RMS of the inspiratory muscle of the trained subjects increased with the increase of workload. The increase of RMS was continued from the onset to the end of the maximal testing in all subjects (Figure 4a), indicating the recruitment of additional motor units by the muscle in exercise to maintain a sufficient force level to undertake the workload. Since MPF was shown to be a good index to detect muscle fatigue by lowered frequencies (De Luca, 1984; Gerdle et al., 1990; Petrofsky and Lind, 1980), we suggested that it continuous increase, in all subjects (Figure 4b), demonstrated the non-fatigue of inspiratory muscle in cyclists during a maximal incremental exercise. This result was confirmed by the absence of any difference between P_{Imax} before and 10 min after the end of the exercise (126 ± 39 vs. 120 ± 22 cmH_2O). On the other hand, it is in agreement with previous studies dealing with trained subjects during maximal incremental exercise (Choukroun et al., 1993; Coast et al., 1990).

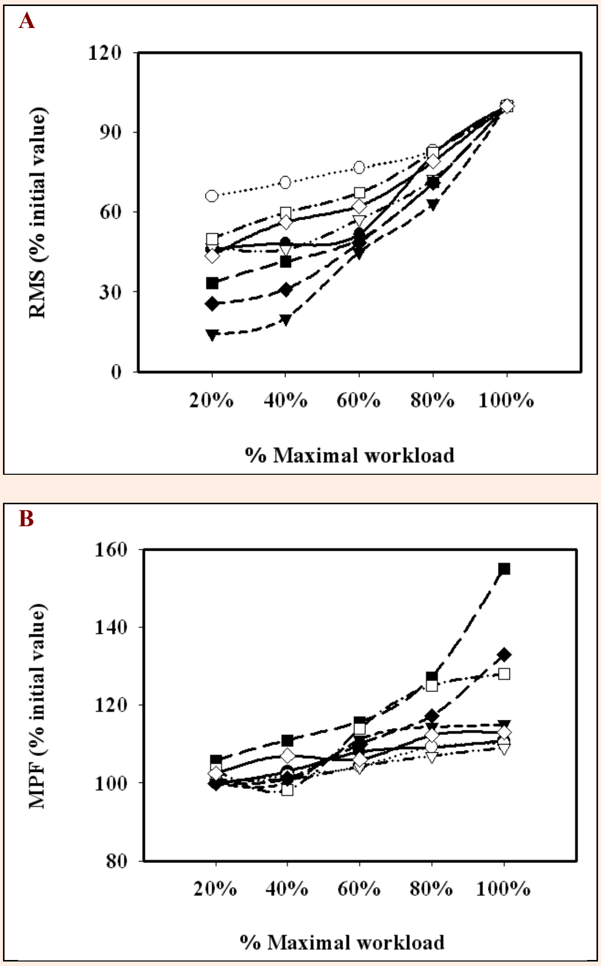

Figure 3. A) RMS kinetics profiles during incremental exercise. B) MPF kinetics profiles during incremental exercise

$T_{T0.1}$ describes the relationship between the force of contraction ($P_{0.1}/P_{Imax}$) and the duration of contraction (T_I/T_{TOT}). The overall inspiratory muscle activity increased progressively (Figure 2) during exercise which provides adequate ventilation. The increase in RMS was concomitant with the increase of the $T_{TO.1}$ for each subject during the maximal testing (Figure 5). We found a positive correlation between the $T_{T0.1}$ and RMS ($r = 0.81$, $p < 0.001$; Figure 4). We proved that the simple $T_{T0.1}$ measured is a good index of inspiratory muscle load. The $T_{T0.1}$ faithfully tracks the EMG activity and hence represents the load on the respiratory system. Even if $T_{T0.1}$ index is a noninvasive method to assess the performance of inspiratory muscles, it seems to be also a good way to be used rather than of SEMG to monitor inspiratory muscle activity and muscle recruitment.

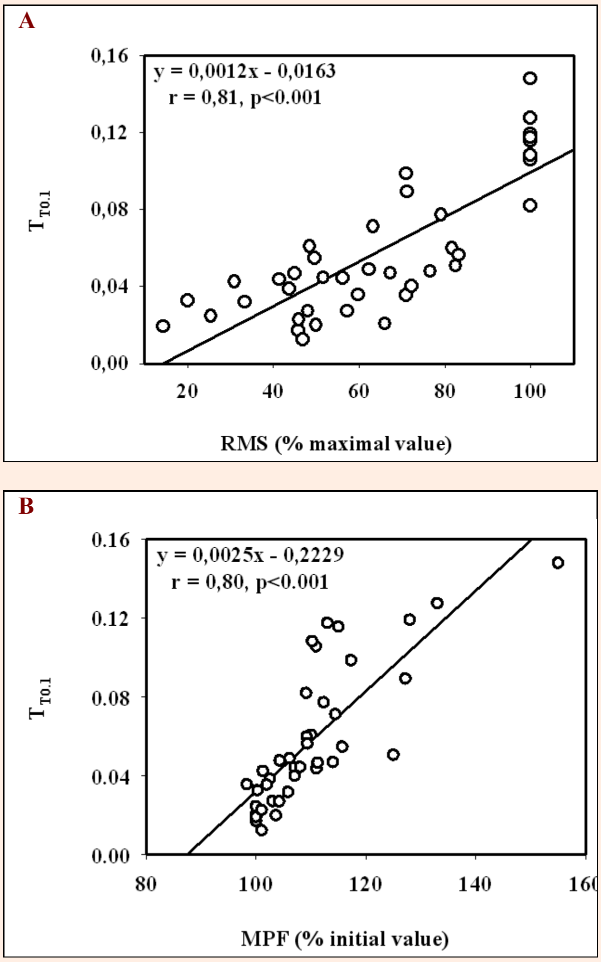

Figure 4. A) Correlation between RMS and TT0.1. B) Correlation between MPF and TT0.1

The most important limitation of our study is the relatively small number of subjects included. This is due to the complexity of the protocol. However, the statistically significant positive associations and correlations between $T_{T0.1}$ and the other indices, render our findings even more meaningful.

Conclusion

In summary, the $T_{T0.1}$ has a good correlation with SEMG parameters to evaluate the inspiratory activity of the respiratory system, at rest and during increased ventilatory demand. We propose that $T_{T0.1}$ could be an easy noninvasive and practical way to evaluate the inspiratory muscle recruitment.

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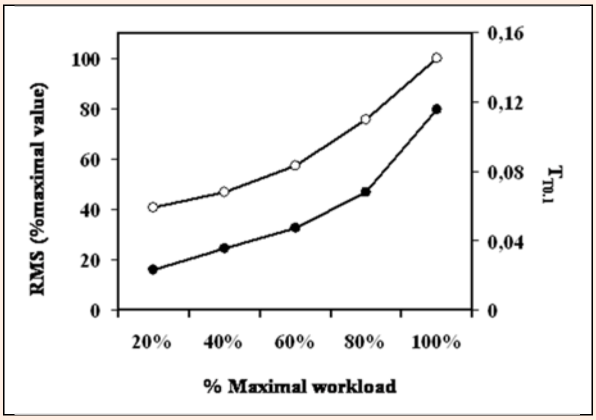

Figure 5. Kinetic of RMS and TT0.1 during incremental exercise.

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Key points

- Overall activity of the inspiratory muscles can be evaluated by different invasive techniques.
- TT0.1 a reliable index of the inspiratory muscle activity and recruitment
- TT0.1 reflects the diaphragmatic activity during incremental exercise in healthy subjects.

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