VALIDITY OF WEARABLE ELECTROMYOGRAPHICAL COMPRESSION SHORTS TO PREDICT LACTATE THRESHOLD DURING INCREMENTAL EXERCISE IN HEALTHY SUBJECTS

RONALD L. SNARR,1 DANilo V. TOLUSSO,2 ASHLEIGH V. HALLMARK,3 AND MICHAEL R. ESCO2

1Department of Health Sciences and Kinesiology, Georgia Southern University, Statesboro, Georgia; 2Department of Kinesiology, The University of Alabama, Tuscaloosa, Alabama; and 3Cardiology Imaging Clinic, The University of Alabama at Birmingham, Birmingham, Alabama

ABSTRACT

Snarr, RL, Tolusso, DV, Hallmark, AV, and Esco, MR. Validity of wearable electromyographical compression shorts to predict lactate threshold during incremental exercise in healthy subjects. J Strength Cond Res 35(3): 702–708, 2021—Determination of lactate threshold (LT) is an important variable in improving cardiovascular endurance and performance. Unfortunately, monitoring LT during exercise uses a costly, invasive blood analysis. Recently, electromyography (EMG) has been deemed a potential method of monitoring exercise intensity and may provide a noninvasive technique to monitor lactate during exercise. The purpose of this investigation was to determine if wearable surface EMG technology, acquired from specialized compression shorts, could estimate the LT work rate during incremental cycling. Thirteen men (n = 9) and women (n = 4) completed a maximal exercise test on a cycle ergometer. Blood lactate was measured every minute, whereas EMG was recorded throughout at the site of the vastus lateralis. Lactate and EMG thresholds were calculated using the Dmax method and compared using a Wilcoxon matched-pairs signed-rank test. Results demonstrated no significant differences between lactate and EMG thresholds in regards to work output (p = 0.83), percent maximal heart rate (p = 0.13; Cohen’s d = 0.43), or percent peak oxygen consumption (p = 0.64; Cohen’s d = 0.09). This confirms that both lactate and EMG exhibit similar properties (i.e., increasing exponential values) during incremental exercise. A possible mechanism includes the rise in blood lactate concentration, which increases motor unit recruitment in an attempt to maintain proper cadence and force output during incremental exercise. Thus, a coincidental, exponential increase in EMG amplitude may occur. Therefore, wearable EMG compression gear may provide a viable field tool for monitoring training intensity and predicting LT work rates.

KEY WORDS electromyography, aerobic training, blood lactate, cycling

INTRODUCTION

Lactate threshold (LT) has been used as a predictive measure of performance, because of its representation of a balance between lactate (La) production and clearance (13). For example, when comparing 2 athletes possessing the same VO2max, the individual with the ability to maintain a higher LT has the greater chance of success during a long-duration competition (21). Thus, LT can be seen as an important predictor of endurance performance and a useful measure in training.

Training at levels at or above LT is useful in increasing cardiovascular endurance and inducing reduced [La] levels for a given power output (10,15). Therefore, the LT is a key determinant in programming aerobic exercise intensity. Weekes et al. (4) demonstrated that athletes were unable to maintain even slight intensities (i.e., 15 W) greater than the level of LT for a duration of 30 minutes. Additionally, training at oxygen uptake levels (i.e., %Vo2peak) deemed below LT has been shown to acquire a typical steady-state response in 2–3 minutes; whereas %Vo2peak intensities above LT have shown a delayed steady-state response and led to early exhaustion of the individual (1,28).

Unfortunately, monitoring [La] during exercise is a costly, invasive blood analysis, which requires either capillary blood samples or an indwelling venous catheter. However, electromyography (EMG) is a potential new method of monitoring exercise intensity and may provide a novel, cost-effective field technique to monitor [La] during endurance training. Surface EMG is a noninvasive measure of the
electrical activity, in microvolts (μV), of skeletal muscle tissue along with alterations in motor unit recruitment. Preliminary research indicates that EMG can be used as a method of estimating LT, as well as ventilatory thresholds, during incremental exercise (7,16,32). As exercise intensity increases, the accumulation and production of by-products, such as La, exert a negative effect on skeletal muscle membrane, potential leading to the need for additional motor unit activation (33). Increased high-threshold fiber recruitment thereby impacts the amplitude of the EMG signal (i.e., increased μV output) over time and has been correlated to both the LT and ventilatory threshold (7,16,32,33).

Hypothetically, a relationship exists between the EMG signal and La production. Increases in the amplitude of the EMG signal depend on changes in motor unit recruitment and the amount of skeletal tissue recruited (2,26). Type I muscle fibers record at low frequencies between 20 and 125 Hz, whereas type II muscle fibers produce signaling at 125–250 Hz. During incremental exercise, a shift in the recorded signal from low to high frequencies (i.e., type I, slow-twitch to type II, fast-twitch fibers) is stated to be the EMG threshold (EMG<sub>T</sub>). Recent research by Candotti et al. (7) demonstrated a positive association (r = 0.87) between EMG<sub>T</sub> and LT, along with the ability of EMG to determine the work rate at which LT occurred in recreational cyclists. Electromyography was sampled over 1-second averages and EMG<sub>T</sub> determined by the intersection of 2 linear regression lines. However, only 1 [La] sample was collected per stage during the exercise trials, which can result in a decrease in the sensitivity of LT analysis, and those initial findings have not been confirmed.

Commercially available devices are currently able to monitor EMG to capture activity of lower-body musculature via compression shorts with specialized electrodes. However, the ability of the EMG, via commercially available compression gear, to predict LT has yet to be investigated. As such, the primary aim of this investigation was to determine if EMG, acquired from compression shorts, can be a valid method of estimating the LT power output during incremental exercise. Based on the previous findings (7,25), it was hypothesized that EMG<sub>T</sub> and LT would display a strong positive correlation. The results of this investigation may provide practitioners and athletes with a noninvasive field method of identifying EMG<sub>T</sub> and LT during training.

**METHODS**

**Experimental Approach to the Problem**

The current study was designed to determine if surface EMG via a new commercially available product could be used as viable source to noninvasively predict LT during incremental aerobic exercise. Thirteen subjects completed an incremental exercise test (VO<sub>2</sub>peak) on a cycle ergometer. Blood lactate was analyzed via fingertip during each minute of the test, whereas EMG was recorded from the vastus lateralis continuously.

**Subjects**

Thirteen male and female healthy individuals participated in this study. Descriptive statistics are displayed in Table 1 for all subjects. The sample size was sufficient according to an a priori power analysis with G Power software (Heinrich-Heine University of Dusseldorf, Dusseldorf, Germany), which determined that 11 subjects would be needed to obtain statistical power at the recommended 0.80 level. Subjects recruited met the following criteria: (a) aged between 18–40 years; (b) currently participating in regular moderate-to-vigorous aerobic training (except cycling) for a minimum of 3 days per week for at least 30 minutes per session; (c) free from cardiovascular, metabolic, or neurological disorders that would otherwise affect the results or negatively impact safety; and (d) untrained cyclists (i.e., performed <2–3 hours per week of cycling). This study was approved by the University of Alabama ethics committee, and before any testing, written informed consent was obtained from each subject.

**Procedures**

Subjects were asked to report to the Human Performance Laboratory for 1 visit. Upon arrival, subjects reviewed and signed an informed consent and medical history questionnaire. After consent, subjects had height and body mass measured. Standing height was measured to the nearest 0.1 cm using a stadiometer (SECA 67310; SECA, Chino, CA), whereas body mass was measured to the nearest 0.1 kg (Tanita BWB-800; Tanita, Arlington Heights, IL). Subjects then performed an incremental maximal cycling test while blood lactate, heart rate, and EMG signals were measured. Before testing subjects were familiarized with all equipment and procedures used in the investigation. All testing was performed on a manually braked cycle ergometer (Monark 484 E; Monark, Dalarna, Sweden). Subjects were provided

**TABLE 1. Descriptive statistics of the study subjects.***

|                | Men (n = 9) | Women (n = 4) | All (n = 13) |
|----------------|------------|--------------|-------------|
| Age (y)        | 23.7 ± 5.6 | 20.8 ± 1.5   | 22.8 ± 4.8  |
| Height (cm)    | 175.7 ± 4.2| 165.0 ± 8.4  | 172.4 ± 7.5 |
| Body mass (kg) | 85.6 ± 10.1| 60.5 ± 6.4   | 77.9 ± 14.9 |
| HRmax (b·min<sup>-1</sup>) | 181.3 ± 13.4 | 181.5 ± 5.5 | 181.4 ± 11.2 |
| VO<sub>2</sub>peak (ml·kg<sup>-1</sup>·min<sup>-1</sup>) | 35.2 ± 5.0 | 32.4 ± 7.3 | 34.6 ± 5.7 |

*HRmax = heart rate maximum (b·min<sup>-1</sup>); VO<sub>2</sub>peak = peak oxygen consumption (ml·kg<sup>-1</sup>·min<sup>-1</sup>± SD).
an initial warm-up on the cycle ergometer at an output of 40 W for a period of 3 minutes. The testing phase began immediately following the warm-up at a work output of 80 W and increased in increments of 40 W every 3 minutes thereafter. An analysis of LT testing protocols was used as the basis for the current research study. Previous research examining various cycling protocols indicated that no significant differences existed when using a 20 W or 40 W increase in stage during incremental testing (30). Cadence was kept at 80 (±5) revolutions per minute. Test termination criteria were (a) subject was no longer able to maintain cadence or (b) volitional fatigue.

During each stage, the following variables were measured: blood lactate, heart rate, \( \dot{V}_O_2 \), and EMG activity. Capillary blood samples (25 μL) were taken via finger prick and analyzed every minute throughout the testing procedures, including rest and warm-up. Lactate concentrations were analyzed via the Lactate Plus Meter (NOVA Biomedical, Waltham, MA). Lactate Plus monitors have been shown to have a SE of the estimate of 0.6 mmol·L\(^{-1}\) and strong correlation of 0.94 when compared with laboratory measures (31). A heart rate monitor (Polar Electro Oy, Kempele, Finland) was placed on the subjects’ chest to accurately assess heart rate during the test. A metabolic cart (TrueOne 2400; ParvoMedics, Inc., Sandy, UT) was used to determine the oxygen uptake at the mouth. Before each test, the metabolic cart was properly calibrated according to the manufacturer’s instructions. \( \dot{V}_O_2 \)peak was recorded as the average oxygen consumption, expressed as ml·kg\(^{-1}\)·min\(^{-1}\), among the last minute of the incremental exercise test.

Surface EMG signals were collected with compression shorts containing built-in surface electrodes (Athos; Mad Apparel, Inc., Redwood City, CA). The compression shorts contain electrodes that are situated over various muscle groups within the lower limbs (e.g., gluteus maximus, quadriceps, and hamstrings). However, based upon the previous literature (7), EMG recordings were only analyzed from the signals obtained at the site of the vastus lateralis. The compression shorts used throughout testing were available in traditional clothing sizes (e.g., small, medium, large, etc.). Before testing, each subject was given various sizes of the shorts to try on so that the researchers could determine the best size and electrode placement configuration based upon the individual (e.g., waist size, no loose areas, and that electrode sites were directly against the skin). Preparation for the skin sites included shaving, abrasion, and alcohol cleansing to reduce impedance of EMG signals. Recordings were deemed viable when impedance was below 5 kΩ. Signals were captured at 1 kHz and a linear band-pass (−3 dB frequencies at 80 and 180 Hz) and notch (removal of 60 Hz noise) filters were applied. Raw myoelectrical signals were quantified in this product using root-mean-square transformation along with a signal conversion from analog to digital. Electromyography signals from the compression gear were averaged at a 10-second window.

### Lactate Threshold and Electromyography Threshold Determination (Dmax Method)

Lactate threshold and \( \dot{V}_O_2 \)\(_{\text{peak}} \) were determined in each subject via Dmax calculations (8). Dmax was defined as the point that yielded the maximal distance from the model fitting [La] and EMG curve, using a third-order polynomial equation, to the line formed by the lowest and highest [La] and EMG values taken during the incremental test (35). The Dmax method has been previously validated as computational method to provide a reliable training threshold during incremental exercise. The Dmax point was computed on a custom-written computer program. The percent of \( \dot{V}_O_2 \)\(_{\text{peak}} \) (%\( \dot{V}_O_2 \)\(_{\text{peak}} \)) and percent maximal heart rate (\%HRmax) were recorded at the LT and \( \dot{V}_O_2 \)\(_{\text{peak}} \) to allow for comparisons between each threshold.

### Table 2. Individual and group mean ± SD values among the subjects for % \( \dot{V}_O_2 \)\(_{\text{peak}} \) and %HRmax values at EMG \(_T \) and LT (n = 13).

| Subject | EMG%\( \dot{V}_O_2 \)peak | LT%\( \dot{V}_O_2 \)peak | DIFF | EMG%HRmax | LT%HRmax | DIFF |
|---------|-----------------|-----------------|------|------------|------------|------|
| 1       | 71.67           | 66.17           | 5.50 | 89.93      | 85.88      | 3.95 |
| 2       | 72.56           | 72.56           | 0.00 | 88.16      | 89.74      | -1.31|
| 3       | 76.06           | 76.97           | -0.91| 85.25      | 85.79      | -0.54|
| 4       | 65.88           | 67.06           | -1.18| 95.74      | 92.02      | 3.72 |
| 5       | 76.04           | 69.36           | 6.68 | 90.34      | 89.20      | 1.14 |
| 6       | 74.24           | 74.10           | 0.14 | 91.35      | 92.43      | -1.08|
| 7       | 78.17           | 76.30           | 1.87 | 92.82      | 90.26      | 2.56 |
| 8       | 86.70           | 83.10           | 3.60 | 97.28      | 88.59      | 8.69 |
| 9       | 81.13           | 76.70           | 4.43 | 94.95      | 90.40      | 4.55 |
| 10      | 69.42           | 75.84           | 6.42 | 83.24      | 84.37      | -1.13|
| 11      | 71.16           | 71.87           | -0.62| 88.64      | 86.36      | 2.28 |
| 12      | 83.37           | 75.60           | 7.77 | 89.33      | 93.82      | -4.49|
| 13      | 63.50           | 71.81           | -8.31| 87.70      | 86.10      | 1.60 |
| **Mean**| **75.26**       | **74.65**       | **0.61**| **88.36** | **88.82** | **-0.45**|
| **SD**  | **6.85**        | **5.79**        | **4.76**| **4.06**   | **2.95**   | **3.36**|
| **95% CI**| **13.5**       | **11.4**       | **9.3** | **7.9**    | **5.8**    | **6.6**|
| \( \rho \)  | 0.64            | 0.13            |      |             |             |      |
| Cohen’s \( d \) | 0.09            | 0.43            |      |             |             |      |

*%HRmax = percent maximal heart rate; EMG\(_T \), electromyography threshold; LT = lactate threshold; DIFF = difference in %\( \dot{V}_O_2 \)\(_{\text{peak}} \) between EMG\(_T \) and LT.*
Statistical Analyses

The data obtained were analyzed using a software package (SPSS version 22.0; IBM, Somers, NY). Because of the staged, ordinal nature of the incremental test, the level of LT and EMG T were compared using the Wilcoxon matched-pairs signed-rank test. A Spearman’s rank order correlation was performed to determine the relationship between LT and EMG T. Additionally, a paired sample T-test was applied to identify any statistically significant %V O2peak and %HRmax at the EMG T, provided by the compression garment for the vastus lateralis muscle, and LT. Individual agreement was examined by calculating the number of times EMG T and LT occurred within the same stage of the maximal exercise test. Significance was set at α = 0.05 for all statistical analyses. Normality of the data was assessed via tests for skewness, kurtosis, Kolmogorov-Smirnov, and Shapiro-Wilk test.

A Cohen’s d statistic (9) was calculated as the effect size of the differences, and Hopkin’s scale of magnitude (18) was used where an effect size of 0–0.2 was considered trivial, 0.2–0.6 was small, 0.6–1.2 was moderate, 1.2–2.0 was large, and >2.0 was very large. The procedures of Bland and Altman (4) were used to evaluate the 95% limits of agreement of the EMG T method compared with the LT.

RESULTS

Thresholds in both [La] and EMG were observed in all subjects in the investigation. Individual data, along with means (±SD) for the %V O2peak and %HRmax at the EMG T and LT are shown in Table 2. The mean blood [La] at the level of LT was 3.6 ± 0.69 mmol·L⁻¹. There were no significant differences observed between the work rates obtained through blood [La] or EMG compression gear (Z = −1.732; p = 0.83). The EMG T, via compression shorts, occurred at the same stage of the incremental test as the blood LT in 11 of the 13 subjects (84.6%). Of the remaining subjects (i.e., 2), EMG T took place one stage higher than LT. Using the Spearman’s rho correlation, there was a significant moderate correlation found between LT and EMG T (r = 0.677; p = 0.01).

The values obtained from both LT and EMG T for %V O2peak and %HRmax were determined to be normal post-analysis; thus, parametric tests were used. In terms of %V O2peak, there were no significant differences between LT and EMG T. Nonsignificant (p = 0.38), small (Cohen’s d = 0.45) differences were seen between male and female subjects for %V O2peak at the level of LT. A significant correlation existed between %V O2peak from both measures (i.e., [La] and EMG) at LT (r = 0.73; p = 0.003). The Bland-Altman procedure suggested that the EMG T displayed a 95% limits of agreement that ranged ±9.3% around a constant error of ±2.0% of V O2peak (Figure 1A), with the upper and lower limits at 10.3 and −8.4%, respectively. There was no correlation between the x- and y-axes of the Bland-Altman plot, suggesting that no proportional bias existed (r = 0.48; p = 0.101).

Percent maximal heart rate did not differ between the LT (88.8 ± 2.95%) and EMG T (90.4 ± 4.06%) (p = 0.13; Cohen’s d = 0.43). Furthermore, the %HRmax values between LT and EMG T showed a significantly moderate correlation (r = 0.58; p = 0.04). The Bland-Altman procedure showed that the EMG T displayed 95% limits of agreement that ranged ±6.6% around a constant error of ±1.5% of HRmax (Figure 1B), with the upper and lower limits at 8.1 and −5.1%, respectively. There was no correlation between the x- and y-axes of the Bland-Altman plot, suggesting that no proportional bias existed (r = 0.37; p = 0.21).
DISCUSSION

The purpose of this investigation was to determine if a field-wearable EMG device in compression shorts was a viable method of estimating LT via changes in the EMG signal. Consistent with previous results of EMGT (7), our findings indicate that EMG predicted the LT during incremental exercise. A key finding was the compression gear showed no significant differences in determining the LT when analyzed via %VO2peak or %HRmax. Therefore, wearable EMG technology, such as the device analyzed in the study, seems to provide a suitable method for estimating the LT within field settings by simply monitoring HR.

Whereas no other EMG technology has been tested to predict LT, a compression sleeve, using near-infrared light-emitting diode technology, worn on the calf (i.e., BSX insight) has recently been shown to provide a reliable method of predicting LT (5). The wearable sleeve provided oxygenation levels and measured threshold work rate at a different location (i.e., gastrocnemius) than the device of the present study. Additionally, Tikkanen et al. (32) used a similar product (i.e., EMG clothing) to predict the ventilatory threshold, via EMG, during running in both athletes and nonathletes. Results demonstrated no significant mean differences between the EMGT and ventilatory threshold in either group. These studies further validate the current study and support the notion that noninvasive wearable technology may have the ability to be useful field measures of training intensities.

In contrast to the current study, Seburn et al. (29) proposed that EMG was not a viable option to monitor the anaerobic threshold, indicating that several criteria must be satisfied before establishing the relationship between blood [La] and EMG. First, nonlinear associations must exist between work rate and muscle activation; however, the results of this study satisfy this notion as a curvilinear relationship existed in all subjects examined. Second, EMG must respond immediately to the small changes in La production and decrements in pH that occur at the level of LT. The results of the current study suggest that this association holds true because both [La] and EMG showed inflection points at the same work rate in 11 of 13 subjects tested.

Results also confirm an exponential rise in blood [La] during incremental intensity exercise; thus, all individuals examined provided a distinct LT. As previously stated, the rise in blood [La] occurs when production exceeds clearance; however, this cannot be simply explained, as this is a multifactorial process. One factor that accounts for this is the decrease in localized lactate-removal sites available in adjacent, nonworking type I muscle fibers. As the intensity of exercise increases, additional motor units are signaled for contraction, leaving fewer lactate-removal sites available for the inter- and intracellular lactate shuttle process to occur, leading to increased [La] (7,14). Another important factor in the production of La is the stimulation of phosphorylase, a key regulatory enzyme in carbohydrate metabolism. Throughout exercise, both elevations in epinephrine and Ca2+/calmodulin from contracting musculature indirectly stimulate phosphorylase to breakdown glycogen to be used during glycolysis to form energy, along with elevated [La] (in times of high intensity). As the recruitment of type II fibers occur during high-intensity exercise, less reliance is placed upon oxidative metabolism, because of the low mitochondrial density of anaerobic muscle fibers leading to an increase in La production (27). Furthermore, a redistribution of blood flow from lactate clearance sites (e.g., kidneys, nonworking skeletal tissue, liver, etc.) that would otherwise alleviate the accumulation of blood La during high-intensity activity impact the rapid rise in blood [La] (7).

The EMG signaling also provided a positive breakpoint, EMGT, which is primarily attributed to the rise in type II muscle fiber motor unit recruitment during an incremental exercise bout. It was noted that independent of one’s training status, thresholds can be observed within the EMG signal (7). Previous research into shorter cycling bouts (i.e., 3 minutes) while monitoring muscular activation revealed that there was a linear relationship between EMG amplitude and the work load being performed (25). However, as the bouts were extended to fatigue, root-mean-square signal amplitudes continually increased. These results support the current study demonstrating gradual increases in EMG amplitude throughout each workload of the incremental test. Additionally, with a change in the muscle fiber membrane potential during times of decreasing pH, the excitation-contraction coupling mechanism may be altered to reduce contraction ability or strength. Thus, a compensatory effect of increased recruitment of various motor units, particularly those with a greater twitch rate, is observed. Motor units with faster twitch rates (i.e., type IIX) alter the EMG signal and result in recordings with a greater amplitude and mean frequency (3).

The cause-effect relationship between the increase in [La] and EMG is not exclusive. Previous investigation into individuals with McArdle syndrome (i.e., glycogen storage disease type V wherein no lactate increase is seen) demonstrated that under fatigue, EMG amplitude changes can occur in the absence of blood [La] increases. This leads to a speculation that neural signaling in the central and peripheral nervous system may act to increase motor unit recruitment in times of increasing fatigue or work load (23). Although, Moritani et al. (24) suggested that decreases in the intracellular pH level, because of the accumulation of [La], increases the need for motor unit recruitment to maintain proper cadence and force output during incremental or fatiguing bouts of exercise. Although this relationship is not solely dependent upon each other, another factor (i.e., potassium concentration), not measured in the current study, may have had an impact on the changes in EMG signal amplitude. Several studies have shown that increasing [K+] have a significant impact on motor unit conduction...
velocity and may affect EMG amplitude via the inhibition of excitation-contraction coupling (6,20). In addition to the EMG recording, it has been previously shown that myosin heavy-chain (i.e., percentage of type I fibers) distribution can be an important determinant of LT and VO2peak (12).

Results of the current study demonstrated that the breakpoint in [La] occurred at a mean %VO2peak of 74.7%. Previous research has also observed means similar to the current study, giving values ranging from 66.1 to 80% (12,17,28). Whereas no endurance athletes participated in this investigation, Green et al. (17) observed no significant differences in the %VO2peak at the level of LT between aerobically and anaerobically trained individuals. However, as expected, they observed that untrained individuals showed significantly lower values of %VO2peak compared with both groups of trained individuals.

Like the current results, Dumke et al. (11) observed values of 91.0 %HRmax during an incremental cycling test at the level of LT, almost identical to 90.4% in this investigation. Additionally, Dumke et al. (11) demonstrated that trained cyclists were able to maintain HR values of 90 and 85% HRmax during timed trials of 30 and 60 minutes, respectively, on separate occasions. These results reinforce the notion that a field metric, such as HR, may be used as training tool for intensity in lieu of blood [La] sampling.

Whereas the present results found no significant differences between EMG and LT in relation to work rate, EMG overpredicted thresholds by one stage in 2 individuals. One possible cause of this occurrence may be the inability of the compression shorts electrodes to conform to the individual. The compression shorts were available in traditional clothing sizes (e.g., small, medium, large, etc.) and were best fitted to the individuals based upon waist size and were assessed for proper fit (i.e., electrodes sites were against the skin, and no loose areas of the clothing were present) before all testing. For instance, differences in limb length of various individuals can alter the placement of the electrodes in or out of the innervation zone, be located atop a completely different muscle, or be positioned as to acquire signal acquisition (i.e., cross talk) from neighboring muscle groups. Therefore, misalignments or maladjustments may have an effect on the ability of the surface electrodes to provide valid information about the musculature being examined. However, the primary usage of this garment will take place in the field setting; thus, the methodology of this study was to ensure that the external validity and practicality of wearable technology was not disrupted.

This study is not without limitations. First, although the Dmax method has determined to be reproducible in test-retest studies (8), initial daily resting blood [La] concentrations may have an impact on the linear slope of the curve by which the polynomial curve is measured against, thereby giving a false sense of work output or LT (35). Although blood [La] measured at the site of the fingertips does not directly reflect local muscular La values, it allows for an overall interpretation of the rate and type of cellular metabolism and accrual of metabolic by-products (19). Another limitation of monitoring thresholds with EMG is the training status of the individual. Whereas no trained cyclists were used in this investigation, previous research indicated that training may impact results. It was noted that trained cyclists have been shown to produce 2 significant breakpoints in EMG signaling during incremental exercise. This occurrence may be attributed to the ability of trained individuals to recruit higher threshold motor units when intensity approaches near-maximal levels, producing a second breakpoint in the EMG recording (22).

In conclusion, results indicated that surface EMG was able to estimate LT work output and showed no significant differences between %HRmax and %VO2peak at the threshold level. Although previous research has used compression shorts interlaced with EMG to predict the ventilatory threshold, this was the first, to the authors’ knowledge, that examined the connection between LT and EMG T. Although most of the research in EMG T has occurred in cycling, future research should examine the effectiveness of EMG to predict LT in various cardiovascular modalities (e.g., running, arm ergometry, etc.). Additionally, future research may be warranted to determine the chronic cardiovascular and physiological adaptations garnered from the prescription of training loads via EMG T.

Practical Applications
The results of this investigation determined that EMG, measured via compression shorts, was a valid method of determining LT work rate. Additionally, no significant differences were seen between the thresholds in EMG and LT expressed as %HRmax or %VO2peak. This finding indicates that EMG compression shorts technology may provide valid real-time measures of muscle activation in a practical and field setting. Practitioners may find this information useful, as monitoring blood [La] in the field can be impractical, time consuming, and may require trained personnel to handle blood sampling. Additionally, the compression shorts are cost-effective, vs. laboratory testing, for team monitoring or individuals. Monitoring LT may be an important determinant of the ability of the athlete or individual to maintain predetermined exercise intensities for extended durations (i.e., 30 minutes or more). Therefore, EMG, monitored via specialized compression gear, may provide a viable option in monitoring training intensity and predicting LT levels because of its ability to provide feedback in real time.

Acknowledgments
The results of the current study do not constitute endorsement of ATHOS compression gear by the authors of the National Strength and Conditioning Association. Funding for this investigation was provided by Mad Apparel, Inc. Funding for this study was provided by Mad Apparel, Inc. (San Francisco, CA).
EMG Compression Shorts

REFERENCES

1. Barstow, TJ. Characterization of VO\textsubscript{2} kinetics during heavy exercise. Med Sci Sports Exerc 26: 1327–1334, 1994.

2. Beneke, R, Leithäuser, RM, and Hütler, M. Dependence of the maximal lactate steady state on the motor pattern of exercise. Br J Sports Med 35: 192–196, 2001.

3. Bergstrom, HC, Housh, TJ, Cochrane, KC, Jenkins, NDM, Lewis, RW, Traylor, DA, et al. An examination of neuromuscular and metabolic fatigue thresholds. Physiol Meas 34: 1253–1267, 2013.

4. Bland, JM and Altman, DG. Statistical methods for assessing agreement between two methods of clinical measurement. Int J Nurs Stud 47: 931–936, 2010.

5. Borges, ND and Driller, MW. Wearable lactate threshold predicting device is valid and reliable in runners. J Strength Cond Res 30: 2212–2218, 2016.

6. Camic, CL, Housh, TJ, Johnson, GO, Hendrix, CR, Zuniga, JM, Mielke, M, et al. An EMG frequency-based test for estimating the neuromuscular fatigue threshold during cycle ergometry. Eur J Appl Physiol 108: 337–345, 2010.

7. Candotti, CT, Loss, JF, Melo, MO, La Torre, M, Pasini, M, Dutra, LA, et al. Comparing the lactate and EMG thresholds of recreational cyclists during incremental pedaling exercise. Can J Physiol Pharmacol 86: 272–278, 2008.

8. Cheng, B, Silva, AE, Laggis, JFL, Barros, RV, and Kiss, MA. Characterization of the blood lactate curve and applicability of the Dmax model in a progressive protocol on treadmill. Eur J Appl Physiol Occup Physiol 41: 1–15, 1979.

9. Cohen, J. Statistical power analysis. Carr Dir Psychol Sci 1: 98–101, 1992.

10. Davis, JA, Frank, MH, Whipp, BJ, and Wasserman, K. Anaerobic threshold alterations caused by endurance training in middle-aged men. J Appl Physiol Resp Environ Physiol 46: 1039–1046, 1979.

11. Dumke, CL, Brock, DW, Helms, BH, and Haff, GG. Heart rate at lactate threshold and cycling time trials. J Strength Cond Res 20: 601–607, 2006.

12. Farina, D, Ferguson, RA, Macaluso, A, and De Vito, G. Correlation of average muscle fiber conduction velocity measured during cycling exercise with myosin heavy chain composition, lactate threshold, and VO\textsubscript{2max}. J Electromyogr Kinesiol 17: 393–400, 2007.

13. Farrell, PA, Wilmore, JH, Coyle, EF, Billing, JE, and Costill, DL. Plasma lactate accumulation and distance running performance. Med Sci Sports Exerc 11: 338–344, 1979.

14. Gladden, LR. Lactate metabolism: A new paradigm for the third millennium. J Physiol 558: 5–30, 2004.

15. Golnick, PD, Buby, WM, and Hodgson, DR. Exercise intensity, training, diet, and lactate concentration in muscle and blood. Med Sci Sports Exerc 18: 334–340, 1986.

16. Graef, JL, Smith, AE, Kendall, KL, Walter, AA, Moon, JR, Lockwood, CM, et al. The relationships among endurance performance measures as estimated from VO\textsubscript{2PEAK}, ventilatory threshold, and electromyographic fatigue threshold: A relationship design. Dyn Med 7: 15, 2008.

17. Green, JM, Hornsby, JH, Pritchett, RC, and Pritchett, K. Lactate threshold comparison in anaerobic vs. aerobic athletes and untrained participants. Int J Sports Med 7: 329–338, 2014.

18. Hopkins, W, Marshall, S, Batterham, A, and Hanin, J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc 41: 3–13, 2009.

19. Jorfeldt, L, Juhlin-Dannfelt, A, and Karlsson, J. Lactate release in relation to tissue lactate in human skeletal muscle during exercise. J Appl Physiol 44: 350–352, 1978.

20. Juel, C. Muscle action potential propagation velocity changes during activity. Muscle Nerve 11: 714–719, 1988.

21. Lucía, A, Hoyos, J, and Chicharro, JL. The slow component of VO\textsubscript{2} in professional cyclists. Br J Sports Med 34: 367–374, 2000.

22. Lucía, A, Sánchez, O, Carvajal, A, and Chicharro, JL. Analysis of the aerobic-anaerobic transition in elite cyclists during incremental exercise with the use of electromyography. Br J Sports Med 33: 178–185, 1999.

23. Mills, KR and Edwards, RHT. Muscle fatigue in myophosphorylase deficiency: Power spectral analysis of the electromyogram. Electron Clin Neuro 57: 330–335, 1984.

24. Moritani, T, Nagata, A, and Muro, M. Electromyographic manifestations of muscular fatigue. Med Sci Sports Exerc 14: 198–202, 1982.

25. Petrofsky, J. Frequency and amplitude analysis of the EMG during exercise on the bicycle ergometer. Eur J Appl Physiol Occup Physiol 41: 1–15, 1979.

26. Pires, F, Silva, AE, Gagliardi, JL, Barros, RV, and Kiss, MA. Characterization of the blood lactate curve and applicability of the Dmax model in a progressive protocol on treadmill. Rev Bras Med Esportes 12: 61–65, 2006.

27. Powers, K. Exercise metabolism. In: Exercise Physiology Theory and Application to Fitness and Performance. New York, NY: McGraw-Hill, 2012. pp. 68–91.

28. Roston, WL, Whipp, BJ, Davis, JA, Cunningham, DA, Effros, RM, and Wasserman, K. Oxygen uptake kinetics and lactate concentration during exercise in humans. Am Rev Respir Dis 135: 1080–1084, 1987.

29. Seburn, KL, Sanderson, DJ, Belcastro, AN, and McKenzie, DC. Effect of manipulation of plasma lactate on integrated EMG during cycling. Med Sci Sports Exerc 24: 911–916, 1992.

30. Soma, EA, Lockard, MM, and Stavrianeas, S. Challenging the accuracy of a single-test lactate threshold protocol in collegiate rowers. Int J Sports Sci 3: 206–213, 2010.

31. Tanner, RK, Fuller, KL, and Ross, ML. Evaluation of three portable blood lactate analysers: Lactate pro, lactate scout and lactate plus. Eur J Appl Physiol 109: 551–559, 2010.

32. Tikkanen, O, Hu, M, Vilavuo, T, Tolvanen, P, Cheng, S, and Finni, T. Ventilatory threshold during incremental running can be estimated using EMG shorts. Physiol Meas 33: 603–614, 2012.

33. Vaz, MA, Zhang, YT, Herzog, W, Guimaraes, ACS, and Macintosh, BR. The behavior of rectus femoris and vastus lateralis during fatigue and recovery: An electromyographic and vibromyographic study. Electromyogr Clin Neuro 36: 221–230, 1996.

34. Weekes, S, Davie, AJ, and Zhou, S. Validation of the Dmax method as a predictor of lactate threshold. Aust J Sci Med Sports: 444–445, 1996.

35. Zhou, S and Weston, SB. Reliability of using the D-max method to define physiological responses to incremental exercise testing. Physiol Meas 18: 145, 1997.