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# Relationship Between Physiological Fatigue and Muscular Fatigue Assessed Utilizing Surface Electromyography Wearable Technology

*Original Research*

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## Abstract

**Introduction**: The purpose of the study was to assess the relationship between upper leg muscle fatigue and physiological fatigue during a maximal treadmill running test.
**Methods**: A total of 13, trained athletes participated and were tested for maximal oxygen uptake (VO2peak). Throughout the test, oxygen uptake respiratory exchange ratio (RER), and heart rate (HR) were recorded simultaneously with surface electromyography (sEMG) electrodes utilizing wearable sEMG compression short technology.
**Results**: During the maximal exercise test, there were significant positive relationships between Muscle Load and all physiological measures ($p < 0.001$ for all) and significant negative relationships between sEMG frequency and Muscle Load and all physiological measures of fatigue ($p < 0.001$ for all).
**Conclusions**: Using sEMG wearable compression short technology may be a useful way to measure and monitor muscle strain and fatigue, primarily outside of a laboratory setting.

***Key Words***: fatigue; muscles; wearable technology; maximal oxygen intake

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## Introduction

Wearable microsensor technology enables the remote quantification of various types of exercise training intensities, heart rate intensities, distances, and movement workloads [1-5]. Moreover, the primary method wearable technology quantifies internal stress is to measure heart rate [6]. While heart rate and time engaged in various heart rate training zones are valuable metrics to assess cardiovascular strain, heart rate wearables do not indicate acute muscular strain, neuromuscular fatigue, or even myoelectric manifestations of fatigue during continuous and intermittent high-intensity activities [3,7]. Identifying if relationships exist between cardiovascular and neuromuscular indices of fatigue may improve the way practitioners implement training and recovery strategies for athletes. Furthermore, surface electromyography (sEMG) can measure or identify myoelectric manifestations of fatigue and acute muscle fatigue by recording the muscle fire rates determined by the sEMG mean frequency [8]. As fatigue increases, sEMG frequency of a muscle will likely decrease [8].

Historically, sEMG measurements required a laboratory setting and surface electrodes were strategically placed on the skin and long wires would be connected to stationary computer and monitoring system which would restrict movement and might lead to sEMG noise disrupting the signal. Furthermore, the mode of exercise (i.e., cycling or running) may alter neuromuscular fatigue responses different. Upper leg fatigue cycling on a stationary bike elicits a different rate of neuromuscular fatigue and perhaps alters sEMG frequencies differently than running, which is more sport specific for nearly every sport, except perhaps cycling [9]. The advent of novel wearable sEMG technology allows for running activities to be less restrictive and open the door for fatigue research to be conducted outside of the laboratory [10]. However, prior to field-based research, it may be useful to measure both physiological responses and muscle fatigue with the sEMG during a maximal running test to assess if the sEMG technology capable of detecting decreases in mean frequencies.

Although research is debatable regarding how fatigue influences peak amplitudes, some research suggests that amplitudes may not change when a muscle is exercising in a fatigued state, however, there is usually a decrease in the mean frequency of the sEMG signal [8]. Additionally, it is not well known how physiological responses (i.e., VO2peak, RER, and HR) are related to sEMG frequency and neuromuscular fatigue when running at a maximal or near maximal cardiorespiratory load. Wearable technology has progressed and is capable of measuring sEMG outside of a laboratory setting, sEMG measurements have not been simultaneously related to known physiological responses such as VO2peak, RER, and HR. A thorough understanding between cardiorespiratory fatigue and neuromuscular fatigue is needed to improve external and internal load management strategies for athletes [11]. Therefore, the purpose of the study was to assess the relationship between neuromuscular fatigue measured via StriveTM Sense3 wearable sEMG compression short monitoring system and indices of metabolic fatigue measured via a calibrated metabolic cart during graded, maximal exercise test on a treadmill.

## Methods

### *Participants*

A total of 13 recreationally trained participants (18–30 years old, n=7 females, n=6 males) participated in the study. The criteria for recreationally trained athletes, were as individuals reporting regularly engaged in moderate-vigorous activity (defined by the American College of Sports Medicine), such as running, biking, or weightlifting, 2 or 3 times a week for at least 30-60 minutes per session. Prior to participation, participants completed and passed a health history survey and physical activity readiness questionnaire. All participants were healthy and did not have any contraindications to exercise. Then participants read and signed an informed consent form prior to participation in the study. The university Institutional Review Board approved the laboratory study.

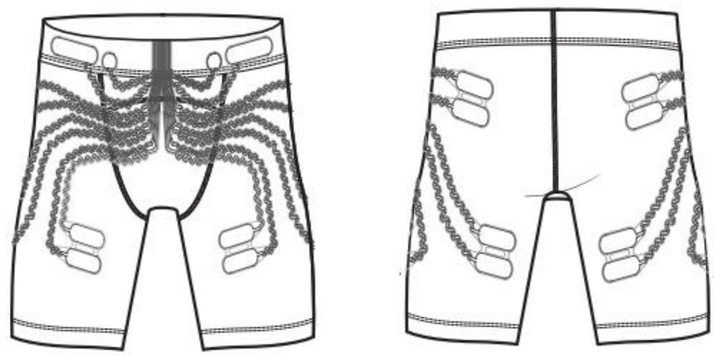
### *Protocol*

After informed consent was given, participants were fitted with a comfortably sized compression short that contained accurate electrode placements on the left and right rectus femoris (RF), biceps femoris (BF) and gluteus maximus (GM). Then, participants were fitted with a heart rate (HR) monitor (Polar Global, Kempele, Finland) and the face mask to measure oxygen uptake. Once the participants was set up with all the equipment, they completed a brief warm-up at a self-selected pace for 10-minutes before the treadmill test. Once each participant indicated they were ready to perform the exercise test, the mask and head strap were appropriately secured and connected to a calibrated metabolic cart with a heart rate monitor synced to the cart. Participants participated in a step-incremental protocol that began with a 2-minute starting phase at 3.5 mph and a 6% grade. Following the first, 2-minute phase, speed increased to 5.0 mph and then increased 0.5 mph every two minutes until the athlete reached volitional exhaustion. The 6% grade stayed constant throughout the test. Once volitional exhaustion was achieved, the treadmill was stopped and participants were instructed to complete a self-selected cool-down. Throughout the exercise treadmill test, the sEMG electrodes within the compression shorts recorded muscle activity. Physiological data such as oxygen consumption (VO2), respiratory exchange ratio (RER), and HR, were measured using 5-second sample rates (Pravo Medics, Truemax 2400, UT, USA) and $VO_{2peak}$ was reported as the highest relative $VO_2$ in $ml \cdot kg^{-1} \cdot min^{-1}$ [12]. Heart rate was reported as beats $\cdot$ $min^{-1}$ (BPM) and $HR_{peak}$ was reported as the highest heart rate achieved at any point throughout the test [12].

### *Assessing Muscle Fatigue*

To assess neuromuscular fatigue in the current study, the wearable StriveTM Sense3 performance monitoring system was utilized [13]. The StriveTM Sense3 wearable includes an sEMG system containing electrodes inside of a pair of compression shorts. Electrodes placement inside the shorts will then fall onto the surface of the left and right RF, BF, GM, (Figure 1). The electrodes are heat-pressed to the inside of the shorts. The skin surface area and the electrodes inside the shorts were dampened prior to the warm-up and exercise test. The StriveTM Sense3 electrode polymer technology does not require skin preparations at the electrode site, only small amount of dampness.

**Figure 1.** StriveTM Sense3 performance monitoring system diagram. Left image is the anterior view, right image is the posterior view.



*Muscle Load and Muscle EMG Frequency*

To determine Muscle Load and frequency, each sEMG measurement was determined by measuring the voltage difference over two sensor pads (e.g., bipolar sensors configuration). The voltages were fed into an analog bandpass filter with cutoffs at 70Hz and 500Hz. Then the voltages were fed into an analog to digital converter which samples at 1024Hz. The signal was digitally processed with a proprietary algorithm that correlates highly to rectifying finite impulse response (FIR) filters which are commonly used to analyze sEMG signals. The output of the proprietary algorithm is described as Muscle Load (expressed as arbitrary units, AU) which indicates an accumulated overall load of the muscles at any given time point throughout the treadmill test. In addition to Muscle Load, sEMG frequency was also measured for the left and right RF, BF, GM [13]. The filtering was completed at 24Hz to provide a detailed sEMG recording without overloading the system processing power [13].

*Statistical Analysis*

Descriptive statistics for all participants (means ± SD) were calculated for age, height, weight, $VO_{2peak}$, RER, $HR_{peak}$ $HR_{avg}$, time to exhaustion, and time above RER = 1.0. Metabolic data ($VO_2$, RER, HR) from the exercise test and Muscle Load and mean frequencies from the sEMG compression shorts were time merged with 5-second sample rates which equated to 1135 data points throughout the total 13 treadmill tests. To assess the relationship between metabolic indicators of fatigue and neuromuscular fatigue, multiple Pearson's Product-Moment correlations (r) were utilized. All statistics were analyzed using IBM SPSS 27.0 (Version 27.0, IBM Inc., Armonk, NY). The criterion for statistical significance was set a priori at $p \leq 0.05$.

**Results**

*Physical Characteristics and Physiological Performance*

Physical characteristics including age, height, weight, and key physiological test results including $VO_{2peak}$, RER, $HR_{peak}$, time to exhaustion, time above an RER ≥ 1.0 were calculated for all participants (Table 1).

The correlation analyses testing the relationship between Muscle Load and physiological test results revealed significant positive correlations (Table 2). An increase in Muscle Load was associated with a subsequent increase in HR, $VO_2$, and RER. The correlation analyses testing the relationship between Muscle Load and muscle frequency measured via EMG compression shorts were significant negative correlations (Table 2). An increase in Muscle Load was associated with a decrease in EMG frequency of both the left and right BF, RF, and Glute muscles in the upper legs. Lastly, the correlation analyses testing the relationship between physiological fatigue ($VO_2$, RER, HR) and muscle frequency revealed significant negative correlations (Table 3). Increases in $VO_2$, RER, HR were associated with decreases in sEMG frequency of both the left and right BF, RF, and Glute muscles in the upper legs.

**Table 1.** Physical characteristics and exercise testing results for all participants.

| | All (N=13) | Male (n = 6) | Female (n=7) |
|---|---|---|---|
| Age (years) | 27.0 ± 6.0 | 28.8 ± 6.4 | 25.4 ± 5.5 |
| Height (cm) | 172.9 ± 11.0 | 183.9 ± 4.1 | 163.4 ± 2.1 |
| Weight (kg) | 74.1 ± 15.6 | 88.4 ± 8.5 | 61.8 ± 6.9 |
| $VO_{2peak}$ ml·kg·min$^{-1}$ | 45.8 ± 4.5 | 47.6 ± 3.0 | 44.3 ± 5.3 |
| RER | 1.06 ± 0.4 | 1.07 ± 0.04 | 1.05 ± 0.03 |
| $HR_{peak}$ (BPM) | 189.7 ± 12.2 | 189.5 ± 14.5 | 189.9 ± 11.0 |
| Time to Exhaustion (minutes) | 8.2 ± 4.0 | 9.1 ± 4.6 | 7.4 ± 3.5 |
| Time above RER ≥ 1.0 (minutes) | 2.7 ± 1.4 | 3.6 ± 1.5 | 1.8 ± 0.9 |

Data are means ± SD.

**Table 2.** Correlations between Muscle Load, physiological data, and EMG frequency data throughout the exercise test. Data consisted of a total of 1135 data points throughout 13 treadmill tests.

| Muscle Load correlated to: | Pearson's *r* | *p*-value |
|---|---|---|
| HR | 0.557 | <0.001 |
| RER | 0.464 | <0.001 |
| $VO_2$ | 0.527 | <0.001 |
| Left RF Frequency | -0.519 | <0.001 |
| Right RF Frequency | -0.547 | <0.001 |
| Left BF Frequency | -0.314 | <0.001 |
| Right BF Frequency | -0.386 | <0.001 |
| Left Glute Frequency | -0.329 | <0.001 |
| Right Glute Frequency | -0.369 | <0.001 |

**Table 3.** Correlations between physiological variables and EMG frequency throughout the graded, maximal exercise test. Data consisted of a total of 1135 data points throughout 13 treadmill tests.

| Heart Rate correlated to: | Pearson's *r* | *p*-value |
|---|---|---|
| Left RF Frequency | -0.140 | <0.001 |
| Right RF Frequency | -0.314 | <0.001 |
| Left BF Frequency | -0.145 | <0.001 |
| Right BF Frequency | -0.186 | <0.001 |
| Left Glute Frequency | -0.148 | <0.001 |
| Right Glute Frequency | -0.212 | <0.001 |
| **RER correlated to:** | **Pearson's *r*** | ***p*-value** |
| Left RF Frequency | -0.272 | <0.001 |
| Right RF Frequency | -0.363 | <0.001 |
| Left BF Frequency | -0.256 | <0.001 |
| Right BF Frequency | -0.216 | <0.001 |
| Left Glute Frequency | -0.278 | <0.001 |
| Right Glute Frequency | -0.239 | <0.001 |
| **$VO_2$ correlated to:** | **Pearson's *r*** | ***p*-value** |
| Left RF Frequency | -0.247 | <0.001 |
| Right RF Frequency | -0.262 | <0.001 |
| Left BF Frequency | -0.195 | <0.001 |
| Right BF Frequency | -0.243 | <0.001 |
| Left Glute Frequency | -0.299 | <0.001 |
| Right Glute Frequency | -0.296 | <0.001 |

**Discussion**

The main findings revealed that sEMG and Muscle Load measured via StriveTM Sense3 performance monitoring system is positively related to physiological parameters of cardiorespiratory fatigue. Accumulated Muscle Load increased with subsequent increases in fatigue as measured by RER, $VO_2$, and HR (Table 2). Furthermore, the negative correlations between HR, RER, and VO2 and sEMG frequency in the left and right RF, BF, and GM suggests upper leg muscular fatigue is occurring to the upper leg muscles. However, it is not known, and unlikely, if the decreases in sEMG frequency imply a maximal rate of fatigue. These findings are consistent with fatigue research suggesting that muscular fatigue results in a reduction in EMG frequency, especially in the upper legs during running exercise [8,9,14,15]. The decrease in sEMG frequency was also negative related to the accumulated Muscle Load, suggesting Muscle Load may be a useful arbitrary metric to quantify overall load throughout vigorous type or maximal activities and sports competition.

As previously mentioned, sEMG research supports the concept that sEMG frequency will decrease as muscles become fatigued [8,15]. While the significant negative correlations (Table 3) between metabolic indicators of fatigue were not very strong in the current study, the lack of corollary strength could be due to muscle synergies of the upper legs adapted to the work being performed during the exercise test prior to any robust sEMG changes in the muscle [8]. Robust alterations in sEMG may occur after longer duration fatigue, which is likely to occur during field and court-based sports. Once muscle synergy's fail to adapt, it is likely that neuromuscular fatigue (i.e., sEMG frequency) becomes more prevalent, thus further hampering sEMG frequency during running [15]. It could also be that muscle deoxygenation occurred rapidly prior to significant neuromuscular fatigue [16]. Contrary the results, Turpin et al. [13] found that fatigue induced declines in neuromuscular activity occurred prior to adaptations in muscle synergies when cycling. Research suggests that neuromuscular fatigue is different between repeated sprint running and cycling and should not be compared [9]. Another plausible explanation for the weak relationships could be due to type 2 error as research has demonstrated that different regions of a muscle may have different firing properties thus may fatigue differently [16-18].

During a maximal exercise protocol, cardiac output is the rate limiting factor in more aerobically fit individuals, meaning that oxygen delivery of the cardiovascular system cannot keep up with the work required of the muscles [12,19]. Thus, muscle fatigue may be less impacted by the brief, albeit, maximal exercise test in the current study. In sports, it is reasonable to suggest that athlete's rarely reach a sustained peak aerobic or anaerobic capacity for a continuous period of time without a subsequent intermittent recovery break [20,21]. Moreover, measuring heart rate during competition is a beneficial way to measure cardiovascular strain, however, heart rate can recover quickly and may not be able to indicate muscle fatigue that accumulates throughout longer duration and intermittent-types of competition [4]. According to the results, measuring neuromuscular fatigue via sEMG may be able to indicate upper leg muscle fatigue and combining sEMG with HR data may be an effective wholistic approach to monitor fatigue during athletic competition. Additional research is needed to assess if the sEMG frequency declines while muscle load increases during longer duration intermittent high intensity sports such as basketball, American football, tennis and others.

While the current study uses a novel wearable garment equipped with sEMG to measure fatigue associated with physiological fatigue, it is not without limitations. First, the average time to exhaustion occurred at 8.2 minutes and the average time exercising above an RER > 1.0 was 2.7 minutes. The majority of athletes, primarily elite athletes, are likely to engage in greater amounts of exercise training duration and at high intensities than the exercise test in the study [4,6,22]. Further, previous research suggests there is a relationship between muscle deoxygenation and neuromuscular activity and deoxygenation likely occurs prior to changes in muscle fatigue [23]. Therefore, it may be that participants in the current study reached cardiorespiratory fatigue before and this was related to myoelectric manifestations of fatigue, opposed to significant muscle fatigue [7]. A longer duration exercise that includes intermittent bouts of high intensity running may be a better way to test if the accumulated Muscle Load is an appropriate way to gauge neuromuscular fatigue throughout sports competition. Next, the mode of exercise (i.e., continuous running to volitional exhaustion) could have limited the relationship between physiological changes and sEMG frequency. Running is a rhythmic exercised, meaning the rhythmic cadence may prevent disruptions in neuromuscular fatigue patterns. The majority of sports, require athletes to engage in countless combinations of sprinting, change of direction movements, jumping, jogging, resting, etc. The variable movements and intensities are likely alter the cardiorespiratory system different than the neuromuscular system. Future studies should attempt to assess cardiorespiratory fatigue and neuromuscular fatigue in settings or exercise protocols that closely mimics sport training.

**Conclusions**

Assessing upper leg muscular fatigue with sEMG compression shorts is associated with physiological fatigue measured with a calibrated metabolic cart during a maximal or near maximal exercise test. Objectively measured muscle strain with sEMG may be advantageous to determining fatigue than simply using accelerometry and global positioning system (GPS) wearable technology as an indicators of stress or workloads. Additional research is warranted to identify if sEMG is a beneficial method of measuring fatigue during continuous and intermittent high-intensity exercise during athletic preparation competition.

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**Conflicts of Interest:** The authors declare no conflict of interest

**References**

1. Sanders, G.J.; Roll, B.; Peacock, C.A. Maximum Distance and High-Speed Distance Demands by Position in NCAA Division I Collegiate Football Games. *J Strength Cond Res* **2017**, *31*, 2728-2733, doi:10.1519/JSC.0000000000002105.
2. Sanders, G.J.; Roll, B.; Peacock, C.A.; Kollock, R.O. Maximum Movement Workloads and High-Intensity Workload Demands by Position in NCAA Division I Collegiate Football. *J Strength Cond Res* **2018**, 10.1519/JSC.0000000000002611, doi:10.1519/JSC.0000000000002611.
3. Sanders, G.J.; Boos, B.; Rhodes, J.; Kollock, R.O.; Peacock, C.A.; Scheadler, C.M. Factors associated with minimal changes in countermovement jump performance throughout a competitive division I collegiate basketball season. *Journal of Sports Science* **2019**.
4. Sanders, G.J.; Boos, B.; Rhodes, J.; Kollock, R.O.; Peacock, C.A. Competition-Based Heart Rate, Training Load, and Time Played Above 85% Peak Heart Rate in NCAA Division I Women's Basketball. *J Strength Cond Res* **2018**, doi: 10.1519/JSC.0000000000002876, doi:doi: 10.1519/JSC.0000000000002876.
5. Vlantes, T.G.; Readdy, T. Using Microsensor Technology to Quantify Match Demands in Collegiate Women's Volleyball. *J Strength Cond Res* **2017**, *31*, 3266-3278, doi:10.1519/JSC.0000000000002208.
6. Stojanovic, E.; Stojiljkovic, N.; Scanlan, A.T.; Dalbo, V.J.; Berkelmans, D.M.; Milanovic, Z. The Activity Demands and Physiological Responses Encountered During Basketball Match-Play: A Systematic Review. *Sports Med* **2018**, *48*, 111-135, doi:10.1007/s40279-017-0794-z.
7. Rampichini, S.; Viera, T.M.; Castiglioni, P.; Merati, G. Complexity Analysis of Surface Electromyography for Assessing the Myoelectric Manifestation of Muscle Fatigue: A Review. *Entropy* **2020**, *22*, 529, doi: https://doi.org/10.3390/e22050529.
8. Ortega-Auriol, P.A.; Besier, T.F.; Byblow, W.D.; McMorland, A.J. Fatigue influences the recruitment, but not structure of muscle synergies. *Front Hum Neurosci* **2018**, *12*, 217, doi:https://doi.org/10.3389/fnhum.2018.00217.
9. Tomazin, K.; Morin, J.B.; Millet, G.Y. Etiology of Neuromuscular Fatigue After Repeated Sprints Depends on Exercise Modality. *Int J Sports Physiol Perform* **2017**, *12*, 878-885, doi:10.1123/ijspp.2016-0200.
10. Lynn, S.K.; Watkins, C.M.; Wong, M.A.; Balfany, K.; Feeney, D.F. Validity and Reliability of Surface Electromyography Measurements from a Wearable Athlete Performance System. *J Sports Sci Med* **2018**, *17*, 205-215.
11. Halson, S.L. Monitoring training load to understand fatigue in athletes. *Sports Med* **2014**, *44 Suppl 2*, S139-147, doi:10.1007/s40279-014-0253-z.
12. Poole, D.C.; Jones, A.M. Measurement of the maximum oxygen uptake Vo2max: Vo2peak is no longer acceptable. *J Appl Physiol (1985)* **2017**, *122*, 997-1002, doi:10.1152/japplphysiol.01063.2016.
13. Davarzani, S.; Helzer, D.; Rivera, J.; Saucier, D.; Jo, E.; Burch, R.F.; Chandler, H.; Strawderman, L.; Ball, J.E.; Smith, B.K., et al. Validity and reliability of StriveTM Sense3 for muscle activity monitoring during the squat exercise. *Int J Kin Sport Sci* **2020, 8, 4**.
14. Turpin, N.A.; Guevel, A.; Durand, S.; Hug, F. Fatigue-related adaptations in muscle coordination during a cyclic exercise in humans. *J Exp Biol* **2011**, *214*, 3305-3314, doi:10.1242/jeb.057133.
15. Hautier, C.A.; Arsac, L.M.; Deghdegh, K.; Souquet, J.; Belli, A.; Lacour, J.R. Influence of fatigue on EMG/force ratio and cocontraction in cycling. *Med Sci Sports Exerc* **2000**, *32*, 839-843, doi:10.1097/00005768-200004000-00017.
16. Vieira, T.M.; Botter, A. The Accurate Assessment of Muscle Excitation Requires the Detection of Multiple Surface Electromyograms. *Exerc Sport Sci Rev* **2020**, doi:10.1249/JES.0000000000000240.
17. Watanabe, K.; Kouzaki, M.; Moritani, T. Region-specific myoelectric manifestations of fatigue in human rectus femoris muscle. *Muscle Nerve* **2013**, *48*, 226-234, doi:10.1002/mus.23739.
18. de Souza, L.M.L.; Cabral, H.V.; de Oliveira, L.F.; Vieira, T.M. Motor units in vastus lateralis and in different vastus medialis regions show different firing properties during low-level, isometric knee extension contraction. *Hum Mov Sci* **2018**, *58*, 307-314, doi:10.1016/j.humov.2017.12.012.

19. Saltin, B.; Calbet, J.A. Point: in health and in a normoxic environment, VO2 max is limited primarily by cardiac output and locomotor muscle blood flow. *J Appl Physiol (1985)* **2006**, *100*, 744-745, doi:10.1152/japplphysiol.01395.2005.
20. Torres-Ronda, L.; Ric, A.; Llabres-Torres, I.; de Las Heras, B.; Schelling, I.D.A.X. Position-Dependent Cardiovascular Response and Time-Motion Analysis During Training Drills and Friendly Matches in Elite Male Basketball Players. *J Strength Cond Res* **2016**, *30*, 60-70, doi:10.1519/JSC.0000000000001043.
21. Losia, M.F.; Bishop, P.A. Analysis of exercise-to-rest ratios during division IA televised football competition. *J Strength Cond Res* **2008**, *22*, 332-340, doi:10.1519/JSC.0b013e31816607b0.
22. Berkelmans, D.M.; Dalbo, V.J.; Kean, C.O.; Milanovic, Z.; Stojanovic, E.; Stojiljkovic, N.; Scanlan, A.T. Heart Rate Monitoring in Basketball: Applications, Player Responses, and Practical Recommendations. *J Strength Cond Res* **2017**, 10.1519/JSC.0000000000002194, doi:10.1519/JSC.0000000000002194.
23. Osawa, T.; Kime, R.; Hamaoka, T.; Katsumura, T.; Yamamoto, M. Attenuation of muscle deoxygenation precedes EMG threshold in normoxia and hypoxia. *Med Sci Sports Exerc* **2011**, *43*, 1406-1413, doi:10.1249/MSS.0b013e3182100261.