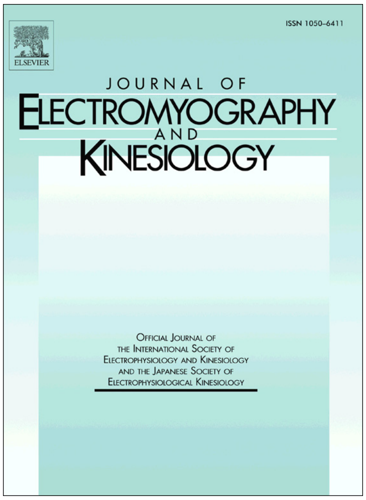
Accepted Manuscript



Muscle mechanical properties of strength and endurance athletes and changes after one week of intensive training

Rauno Á.P. Simola, Christian Raeder, Thimo Wiewelhove, Michael Kellmann, Tim Meyer, Mark Pfeiffer, Alexander Ferrauti

PII: S1050-6411(16)30045-1
DOI: http://dx.doi.org/10.1016/j.jelekin.2016.05.005
Reference: JJEK 1975

To appear in: *Journal of Electromyography and Kinesiology*

Received Date: 2 December 2015
Revised Date: 3 May 2016
Accepted Date: 20 May 2016

Please cite this article as: R.A. Simola, C. Raeder, T. Wiewelhove, M. Kellmann, T. Meyer, M. Pfeiffer, A. Ferrauti, Muscle mechanical properties of strength and endurance athletes and changes after one week of intensive training, *Journal of Electromyography and Kinesiology* (2016), doi: http://dx.doi.org/10.1016/j.jelekin.2016.05.005

Title of the article

Muscle mechanical properties of strength and endurance athletes and changes after one week of intensive training

RAUNO Á. P. SIMOLA[1], CHRISTIAN RAEDER[1], THIMO WIEWELHOVE[1], MICHAEL KELLMANN[2,3], TIM MEYER[4], MARK PFEIFFER[5], ALEXANDER FERRAUTI[1]

[1]*Department of Training and Exercise Science, Faculty of Sports Science, Ruhr-University Bochum, Germany*

[2]*Department of Sport Psychology, Faculty of Sports Science, Ruhr-University Bochum, Germany*

[3]*School of Human Movement Studies and School of Psychology, The University of Queensland, Brisbane, Australia*

[4]*Institute of Sports and Preventive Medicine, Saarland University, Saarbrücken, Germany*

[5]*Institute of Sports Science, Johannes-Gutenberg University, Mainz, Germany*

Correspondence to:
Rauno Álvaro de Paula Simola
Ruhr-University Bochum, Faculty of Sports Science
Department of Training and Exercise Science
Gesundheitscampus Nord, Haus-Nr. 10
44801 Bochum, Germany
E-Mail: raunosimola@hotmail.com
rauno.depaulasimola@rub.de

Tel.: +49 234 32 22965
Fax.: +49 234 32 14775

Abstract: The study investigates whether tensiomyography (TMG) is sensitive to differentiate between strength and endurance athletes, and to monitor fatigue after either one week of intensive strength (ST) or endurance (END) training. Fourteen strength (24.1 ± 2.0 years) and eleven endurance athletes (25.5 ± 4.8 years) performed an intensive training period of 6 days of ST or END, respectively. ST and END groups completed specific performance tests as well as TMG measurements of maximal radial deformation of the muscle belly (Dm), deformation time between 10% and 90% Dm (Tc), rate of deformation development until 10% Dm (V10) and 90% Dm (V90) before (baseline), after training period (post1), and after 72 hours of recovery (post2). Specific performance of both groups decreased from baseline to post1 ($P < 0.05$) and returned to baseline values at post2 ($P < 0.05$). The ST group showed higher countermovement jump ($P < 0.05$) and shorter Tc ($P < 0.05$) at baseline. After training, Dm, V10, and V90 were reduced in the ST ($P < 0.05$) while TMG changes were less pronounced in the END. TMG could be a useful tool to differentiate between strength and endurance athletes, and to monitor fatigue and recovery especially in strength training.

Keywords: tensiomyography, strength training, endurance training.

1. Introduction

Strength and endurance athletes are noticeably different from each other in physiological, morphological, and performance aspects (Costill et al., 1976; Hawley, 2009; Lattier et al., 2003). Albeit neural aspects (e.g., number and type of motor units recruited) play a significant role during the execution of different types of physical activity (Sale, 1987), muscle contractile properties (e.g., intrinsic muscular qualities) are key determinants of performance in both strength and endurance athletes (Costill et al., 1976; García-García et al., 2015; Lattier et al., 2003; Loturco et al., 2015). Accordingly, sprinters have a faster fiber type dominance, which favours a powerful muscle contraction in comparison with endurance runners, which in the other hand show higher proportion of slow fiber type (Costill et al., 1976).

There is evidence that the functional differences observed between athletes from sports of distinct physiological requirements are partly due to genetic endowment, as well as to training specific adaptations (Lattier et al., 2003). Endurance training stimulates several metabolic adaptations in trained muscle fibers, such as increased mitochondrial content, slower rate of glycogen utilization and greater reliance on fat oxidation. In contrast, resistance training promotes muscle hypertrophy and increases maximal strength (Hawley, 2009). Thus, it can be assumed that short-term intensive endurance and strength trainings lead to different muscular contractile responses.

In the applied field, there is an intense demand for sensitive and practical tools that would help to predict athletic performance in different types of sport (García-García et al., 2015; Loturco et al., 2015) and to understand the effects of intensive training periods (Kellmann and Günther, 2000). A large amount of the procedures commonly available are either invasive or motivation dependent, and might induce fatigue (Bosco et al., 1983; Breil et al., 2010; Fry et al., 1994). In this context, an alternative method, such as the tensiomyography (TMG), allows muscular function evaluation through the assessment of different mechanical properties.

The TMG is a method based on the radial deformation of the muscle belly and the time it takes to occur during a twitch contraction evoked by electrical stimulation. It may provide an additional advantage in the applied field to detect between-group differences in cross-sectional comparisons (e.g., talent detection) and within-group changes in longitudinal assessments (e.g., after training and rest periods), as it allows a non-invasive evaluation of the contractile properties (Carrasco et al., 2011; de Paula Simola et al., 2015; Hunter et al., 2012) without producing additional fatigue, and examines muscle in isolation (García-García et al., 2015; Loturco et al., 2015). The TMG mechanical properties have been used to investigate the effects of different types of physical exercise, such as strength (de Paula Simola et al., 2015; García-Manso et al., 2012; Hunter et al., 2012) and endurance (García-Manso et al., 2011), besides estimating the fiber typer composition in skeletal muscle (Simunic et al., 2011). Nonetheless, information concerning differences in TMG mechanical properties of typical endurance and strength/power athletes is spare (Loturco et al., 2015). Furthermore, as far as we know, no study has examined the specific TMG response characteristics after intensive training periods.

Therefore, the purposes of the present study were: (1) to investigate whether the TMG mechanical properties are able to differentiate between strength/power and endurance athletes; and (2) to monitor the specific changes in contractile properties after either one week of intensive strength (ST) or endurance (END) training.

2. Methods

2.1. Participants

The ST group consisted of fourteen male athletes (age: 24.1 ± 2.0 years; weight: 78.9 ± 6.9 kg; height: 180.2 ± 5.1 cm; body mass index: 24.3 ± 1.8 $kg\cdot m^{-2}$; 1RM in the parallel squat exercise: 1.3 ± 0.2 $kg\cdot BW^{-1}$; CMJ: 44.1 ± 4.8 cm; $\dot{V}O_{2max}$: 57.4 ± 5.2 $ml\cdot min\cdot kg^{-1}$) experienced in strength training for at least three years with minimum of two strength training sessions per week. The inclusion criterion was the achievement of at least 120% of their body weight in 1RM in the parallel squat. The END group was composed of eleven well-trained male cyclists (age: 25.5 ± 4.8 years; weight: 69.7 ± 6.1 kg; height: 179.8 ± 6.0 cm; body mass index: 21.5 ± 1.4 $kg\cdot m^{-2}$; CMJ: 36.2 ± 4.4 cm; $\dot{V}O_{2max}$: 60.6 ± 6.6 $ml\cdot min\cdot kg^{-1}$; training amount, approx. 10000 $km\cdot yr^{-1}$). As inclusion criterion, the participants had to accumulate at least 5000 km cycling training a year and competition experience at least at national level. The participants provided their written consent to participate in the study, which was approved by the local Ethics Committee of the Ruhr-University Bochum.

2.2. Design

The ST and END groups carried out a supervised and intensive training period of six days, which consisted of eleven training sessions of strength and endurance, respectively

(Figure 1). During the week before the training period, a health examination and one familiarization session were undertaken. Furthermore, in both groups, all baseline measurements including anthropometry, TMG, a countermovement jump test (CMJ), and an incremental cycling test to voluntary exhaustion to determine the maximal oxygen uptake ($\dot{V}O_{2max}$) were performed.

Before (baseline) and after training weeks (post1), as well as after 72 hours of recovery (post2), the specific functional capacities of both END and ST athletes were assessed in order to evaluate the influence of training periods on their respective fatigue status. For that, a 40-km cycling time trial (TT_{40}) and the CMJ were defined as the gold standard performance tests in the END and ST groups, respectively. At all measurement times, TMG measurements were followed by the specific gold standard performance tests.

Prior to the baseline measurements, participants were asked to refrain from strenuous exercise for at least 48 hours, and to arrive at the laboratory in a fully recovered state. At the day before and at baseline test day, participants completed a food diary and were instructed to replicate their nutrition habits as closely as possible before the testing days. All the measurements were conducted at the same time of day (± 1 hour).

[Figure 1 about here]

2.3. Training interventions

Both training periods were designed to induce fatigue via different neuromuscular and metabolic pathways and incorporate a broad range of strength and endurance methods used in the applied field. For all details about the training interventions, see Figure 2.

ST Training: The ST training consisted of accented lower-body completed by upper-body and core training. After a standardized 10 min warm-up, the following three different strength training protocols were applied: Multiple Sets (MS), Eccentric Overload (EO), and Flywheel (FW) (de Paula Simola et al., 2015).

END Training: The END training was composed of high volume moderate-intensity training (MIT), constant high-intensity training (CHIT), and high-intensity interval training based on Wingate sprints (HIIT) (Skorski et al., 2015). Training sessions were conducted outside on the participants' own bicycles and mean percentage of maximum heart rate for the

CHIT, HIIT, and MIT was 73.3%, 91.8%, and 71.3%, respectively.

[Figure 2 about here]

2.4. Measurement procedures

Tensiomyography (TMG): TMG constitutes a specific electrical stimulator (TMG-S2), the TMG-OK 3.0 software, as well as a displacement sensor tip (Figure 3) with a spring constant of 0.17 $N \cdot mm^{-1}$, which was positioned perpendicular to the muscle belly (TMG-BMC, Ljubljana, Slovenia). The measuring location was carefully determined as a point of maximal muscle belly displacement during voluntary knee extension. The TMG mechanical properties assessed were Dm, Tc, V_{10}, and V_{90} (Figure 4). Whereas Dm is equivalent to the maximal radial deformation of the muscle belly, Tc is the deformation time between 10% and 90% Dm. V_{10} and V_{90} can be understood as the rate of deformation development until 10% Dm (10%Dm/Δtime) and 90% Dm (90%Dm/Δtime), respectively (Figure 4). These constitute the main parameters in this trial because of high sensitivity and reliability scores (ICC = 0.92 to 0.94, CV = 4.9 to 9.9%) (de Paula Simola et al., 2015). Dm is commonly associated to the muscle belly radial stiffness and tendon mechanical properties (García-García et al., 2015; García-García et al., 2013; Rodríguez et al., 2002; Simunic et al., 2011). In addition, this property has been considered a measurement of activation of the muscle fibers (Carrasco et al., 2011; de Paula Simola et al., 2015; Hunter et al., 2012) and exercise-induced muscle damage (Hunter et al., 2012). Tc, V_{10}, and V_{90} refer to the time and velocities of the muscle radial deformation, which in turn indicate the time and velocities of muscle fibers contraction, respectively (de Paula Simola et al., 2015).

The muscle vastus lateralis of the dominant lower limb was analysed during a twitch contraction evoked by individual maximal electrical stimulation over the muscle belly of 1 ms duration. Maximal electrical stimulation and Dm were found by progressively increasing the electric current by 20 mA, each time separated by 10-second intervals. The average value from two maximal twitches was used for further analyses. The vastus lateralis was assessed in a supine position and an internal knee angle of 120° was kept by using supporting pads. Two electrodes (5 x 5 cm) were placed five cm distally and five cm proximally to the sensor. The positions of the electrodes and the sensor were marked and kept constant during the complete experimental period.

[Figure 3 about here]

[Figure 4 about here]

Parallel squat one repetition maximum (1RM): 1RM in the parallel squat exercise was assessed in the ST group only at baseline, functioning as an inclusion criterion and an individual calculation of the subject's training loads, by means of a smith rack machine (TechnoGym Multipower, Italy). The hypothetical 1RM was determined by the formula proposed by Brzycki (Brzycki, 1993). After warm-up recommendations, the subjects were instructed to position into a shoulder bride stand, and the barbell was placed on the trapezius muscle and posterior deltoid muscle. In the parallel squat, the knees are flexed until the inguinal fold is in a straight horizontal line with the top of the knee musculature. A laser imager and an acoustic stimulus served to standardize the range of motion of approx. 105-110°. The test was stopped when subjects were unable to raise the barbell in a range of five to ten maximum repetitions with a proper technique or without the help of a supervisor.

Countermovement jump (CMJ): Two maximal CMJ were performed on a contact platform (Haynl Elektronik, Germany) without arm swing interspaced with 30 seconds (Bosco et al., 1983). Jump height based on flight time (jump height = $g \cdot$flight time^2.8^{-1}, where g is the acceleration due to gravity) were recorded and the mean height was calculated for later analysis (Bosco et al., 1983). Although maximal voluntary contractions have been recognized as gold standard measures of force capacity, the CMJ test was used in this trial because of its high reliability (ICC = 0.92, typical error = 1.86) and great usefulness for neuromuscular assessment in the applied field (Raeder et al., 2016). The reliability scores found for CMJ are comparable with values found for maximal voluntary contractions (Raeder et al., 2016). Additionally, the CMJ performance is strongly correlated to maximal strength and power in multijoint exercises of the lower limbs (Nuzzo et al., 2008).

40-km cycling time trial (TT_{40}): The TT_{40} was performed in an electromagnetically braked cycle ergometer (Cyclus 2 by RBM elektronik-automation GmbH, Leipzig), which has been shown to produce valid indices of power output (Reiser et al., 2000). Ambient laboratory temperature was kept between 18.4 and 22.4 °C. The appropriate cycling movement was obtained through a proper adjustment of each subject’s racing bike on the ergometer and an electrical fan was positioned approx. 0.5 m in front of the subject for cooling. A flat 40 km time trial profile was created using the Cyclus 2 software and utilized for all trials. After a standardized warm-up, participants were instructed to complete the distance as fast as possible; and visual feedback on the distance covered, power, pedal cadence, and heart rate (HR) were available during each trial. HR was monitored and recorded using Polar ProTrainer 5 (Polar Electro, Kempele, Finland).

Incremental cycling test: The incremental cycling test was performed on the same cycle ergometer used for the TT_{40}. The lactate threshold was also determined for training prescriptions (Stegmann et al., 1981). Gas exchange parameters ($\dot{V}O_2$ and $\dot{V}CO_2$) were measured continuously using an automated online metabolic cart (Meta Lyzer 3; Cortex, Leipzig, Germany). The test started with an initial 50 W and the power was increased by 50 W every 3 min until voluntary exhaustion. Gas calibration was completed before each test day, and the volume calibration was conducted before each test following the instructions provided by the manufacturer. The highest mean value for 30 s was defined as the $\dot{V}O_{2max}$, and HR was monitored and recorded using Polar ProTrainer 5 (Polar Electro, Kempele, Finland). Capillary blood samples for the determination of blood lactate concentrations were taken from the hyperemized left earlobe and samples were immediately hemolyzed. Analysis was carried out using an enzymatic-amperometric method (Super GL, Greiner, Flacht, Germany). Ambient laboratory temperature was kept between 18.4 and 22.4 °C.

2.5. Statistical analyses

Data are presented as the mean ± standard deviation

(SD). These data were analysed using the Statistical Package for the Social Sciences 18.0 Software (SPSS Inc., USA). The Kolmogorov-Smirnov test was used to check the normality of the data distribution. Differences between groups at the baseline measurements (anthropometry, TMG, CMJ, and $\dot{V}O_{2max}$) were verified with independent *t*-tests. A one-way repeated measures ANOVA was performed to compare the gold standard performance tests (CMJ, TT_{40}) between trials. A two-way mixed analysis of variance (ANOVA) (2 types of training x 3 measurement times) was used to determine the effects of the different training types over time on the TMG parameters. When a significant F value was found, Bonferroni's post hoc test was applied. Cohen's d effect sizes between groups at baseline and between measurement times for identified statistical differences for TMG variables were determinate. Effect sizes of 0.2, 0.5, and 0.8 were considered small, medium, and large differences, respectively. Statistical significance was set at $P < 0.05$.

3. Results

Baseline measurements revealed higher values of body mass (78.9 ± 6.9 vs. 69.7 ± 6.1 kg; $P = 0.003$) and body mass index (24.3 ± 1.8 vs. 21.5 ± 1.4 $kg \cdot m^{-2}$; $P = 0.001$) for the ST group. Furthermore, the ST group showed superior performance in CMJ (44.1 ± 4.8 vs. 36.2 ± 4.4 cm; $P = 0.002$) and a shorter Tc (20.7 ± 2.4 vs. 25.7 ± 5.2 cm; $P = 0.013$; $d = 1.32$) (Table 1 and Figure 5).

Decreases in CMJ (44.1 ± 4.8 vs. 41.3 ± 3.5 cm, $P = 0.011$) and in TT_{40} performance (65.9 ± 2.6 vs. 68.2 ± 1.9 min, $P = 0.033$) from baseline to post1 were observed in the ST and END groups, respectively (Figure 6). During recovery from post1 to post2, increases in CMJ (41.3 ± 3.5 vs. 44.1 ± 5.1 cm, $P = 0.002$) and TT_{40} performance (68.2 ± 1.9 vs. 65.7 ± 1.9 min, $P = 0.008$) were found.

Reductions from baseline to post1 with large effect sizes (d range between 0.79 and 0.86) for Dm ($P = 0.002$), V_{10} ($P = 0.002$), and V_{90} ($P = 0.003$) were observed only in the ST group (Table 1 and Figure 7). Moreover, the same TMG properties tended to return to baseline values at post2 (Table 1). In the END group, the only TMG parameter that showed a decrease at post1 was Dm ($P = 0.01$; $d = 0.40$). Decrements in V_{10} and V_{90} were shown only at post2 ($P = 0.001$; d range between 0.69 and 0.82).

[Table 1 about here]

[Figure 5 about here]

[Figure 6 about here]

[Figure 7 about here]

4. Discussion

The main findings of the present study were the differences in contractile properties between typical endurance and strength/power athletes; and the specific responses in contractile properties after six days of intensive strength and endurance training.

The differences between groups at the baseline measurement (Table 1 and Figure 5) are consistent with Loturco et al. (2015), who also observed differences in TMG mechanical properties and CMJ performance between elite endurance, and power track and field athletes. These results show that experienced strength/power athletes have an advanced contractile capacity (e.g., time necessary for the muscle fiber contraction) in comparison with endurance athletes. This could be explained by possible differences in muscle fiber types distribution between the two categories of athletes. Regression analysis has shown a high significant correlation (r = 0.878) between Tc and muscle fiber type composition (e.g., proportion of myosin heavy chain I) of the muscle vastus lateralis (Simunic et al., 2011). Additionally, muscle fiber shortening velocity, and therefore performance in strength/power events, is also determined by architectural properties, such as muscle fiber length. It has been shown that elite sprinters have longer fascicle length compared with elite distance runners (Abe et al., 2000). Nevertheless, as far as we know, no study has linked TMG properties to muscle architecture characteristics. However, not all TMG properties were sensitive enough to distinguish between the different categories of athletes. Even though there was an absence of significant difference between groups for Dm, this might suggest how important is the tendon stiffness for both types of athletes, as the mechanical forces can be better transmitted (García-García et al., 2013). Because Tc in the ST group was shorter in comparison with the END group, it was expected that muscle deformation velocity was higher in the ST group. However, significant differences in V_{10} and V_{90} between groups were not observed. As the muscle deformation velocity is calculated by a combination from the muscle deformation and contraction time (velocity = distance/time), it is possible that lower values of Dm observed in the ST group (although not statistically significant) has led to similar muscle deformation velocities (Table 1). Even though neither the composition of fiber types nor the muscle architecture has been measured, we do believe that possible differences in these aspects between groups might contribute to the advanced contractile capacity observed in the ST athletes.

Significant reductions in CMJ and TT_{40} performance at post1 were found, indicating that the training periods induced a specific fatigue in both ST and END groups. Furthermore, both gold standard performance tests values returned to baseline levels after 2 days of recovery (Figure 6). Accordingly, several TMG muscle properties tracked the changes in the gold standard performance tests (Table 1). From baseline to post1, Dm decreased in both groups while V_{10} and V_{90} were reduced only in the ST group (Table 1 and Figure 7). Furthermore, while the ST group showed a tendency to recover during the next two days, it was observed a time delay for changes in V_{10} and V_{90} in the END group (Table 1). Therefore, it is reasonable to claim that Dm, V_{10}, and V_{90} are able to detect fatigue and at least a trend to a recovery state after an intensive ST training period, whereas only Dm seems to be sensitive for fatigue detection after an intensive END training period.

The large effect sizes for Dm, V_{10}, and V_{90} shown after the ST training (Table 1 and Figure 7) point out that this type of training induces a greater influence on TMG properties in comparison with END workloads. This is a plausible result since a close relationship between strength exercises (particularly high intensity eccentric muscle actions) and exercise-induced muscle damage has been well recognized (Howatson and van Someren, 2008). As less motor units are recruited during lengthening muscle actions in comparison to isometric and concentric actions, while producing a great amount of force, damage in cellular structures are yielded (Hunter et al., 2012; Howatson and van Someren, 2008; Howatson and Milak, 2009; Schoenfeld, 2012). In this regard, Hunter et al. (2012) recently demonstrated that the parameter Dm is closely associated with exercise-induced muscle damage. As a preferential exercise-induced muscle damage of type II muscle fibers has been already stated (Hunter et al., 2012; Howatson and van Someren, 2008), a lower number of fast-twitch muscle fibers would be available for contraction by the ST athletes just after the training period, thereby impairing the muscle contractile capacity by means of a reduction in the activation of the muscle fibers (decreased Dm) and contraction velocities as well.

Reductions in Dm were also found after END training (Table 1). Nonetheless, muscle contraction during an exercise such as cycling is almost entirely concentric and mechanical trauma from ground impact forces does not occur (Halson et al., 2003) which a relationship between muscle damage and decrease in Dm becomes difficult to establish. However, the cumulative effects of the endurance training sessions may induce oxidative stress to attenuate the body's antioxidant defense systems and lead to membrane peroxidation (Halson et al., 2003). Thus, it can be speculated that these impairments at the cellular level might lead to an increase in muscle fibers stiffness and a reduction in their activation (decreased Dm) after the END training in the present study.

It has to be pointed out that not all results are easy to explain, which can be partly attributed to some limitations of the study. Eleven induced fatigue-training sessions of a wide range of both strength and endurance-training methods used in the applied field were equally distributed over six days in a week in well-trained strength and endurance subjects, respectively. However, a comparison between completely different training contents seems to be difficult to realize, since it is impossible and impracticable to match strength and endurance workloads when including a variety of specific training methods. Nevertheless, comparisons between the effects of strength and endurance training loads on contractile properties have been done by a variety of authors (Costill et al., 1976; Putman et al., 2004).

Curiously, decrements in muscle contraction velocities in the END group were shown only at post2 (Table 1) with a concomitant return of the group functional capacity to baseline levels (Figure 6). This distinction between electrically evoked muscle performance and functional capacity might be explained by the great importance of the cardiorespiratory system on aerobic exercises performance, as the TT_{40} (Skorski et al., 2015). The delay found for changes in V_{10} and V_{90} is difficult to explain in more detail, but it might be possibly related to low frequency fatigue. This type of fatigue is believed to be a primary source of impairments in muscle performance during lengthening contractions. However, both concentric and eccentric tasks can induce low frequency fatigue, which is characterized as long lasting, and can be defined as a preferential decrease in electrically evoked muscle force elicited at low frequencies (Iguchi and Shields, 2010). Although not fully elucidated, it is believed that the main causes of the low frequency fatigue is a fatigue-induced reduction in Ca^{2+} release from the sarcoplasmic reticulum and increased oxidative stress (Westerblad and Allen, 2002). The results of the present study indicate that monitoring of short-term intensive endurance training by means of changes in V_{10} and V_{90} might be less effective when compared to strength training.

In conclusion, the TMG parameter Tc is able to distinguish between strength/power and endurance athletes; and Dm, V_{10}, and V_{90} are capable of detecting fatigue and indicate a recovery state after an intensive strength training week and a recovery period, respectively. TMG could be a useful tool to differentiate between athletes from sports of distinct physiological requirements (e.g., endurance versus strength/power athletes), and to monitor fatigue and recovery especially in strength/power athletes. The TMG parameters seem to be less sensitive to fatigue detection after an intensive endurance training period. Coaches and athletes should be aware that both short periods of intensive strength and endurance training composed of a broad range of training methods used in the applied field lead to impairments in muscle contractile capacity in well-trained subjects.

Acknowledgments

The present study was funded by the German Federal Institute of Sport Science (RegMan – Optimization of Training and Competition: Management of Regeneration in Elite Sports; IIA1-081901/12-16). The authors gratefully acknowledge CAPES (Brasil) for financial support. The authors would like also to thank the athletes for their participation.

References

Abe T, Kumagai K, Brechue WF. Fascicle length of leg muscles is greater in sprinters than distance runners. Med Sci Sports Exerc 2000;32:1125-1129.

Bosco C, Luhtanen P, Komi PV. A simple method for measurement of mechanical power in jumping. Eur J Appl Physiol Occup Physiol 1983;50:273-282.

Breil FA, Weber SN, Koller S, Hoppeler H, Vogt M. Block training periodization in alpine skiing: effects of 11-day HIT on VO_{2max} and performance. Eur J Appl Physiol 2010;109:1077-1086.

Brzycki M. Strength testing: predicting a one-rep max from repetitions to fatigue. J Physical Education 1993;64:88-90.

Carrasco L, Sanudo B, Hoyo M, Pradas F, Da Silva ME. Effectiveness of low-frequency vibration recovery method on blood lactate removal, muscle contractile properties and on time to exhaustion during cycling at VO_{2max} power output. Eur J Appl Physiol 2011;111:2271-2279.

Costill DL, Daniels J, Evans W, Fink W, Krahenbuhl G, Saltin B. Skeletal muscle enzymes and fiber composition in male and female track athletes. J Appl Physiol 1976;40:149-154.

de Paula Simola RA, Harms N, Raeder C, Kellmann M, Meyer T, Pfeiffer M, Ferrauti A. Assessment of neuromuscular function after different strength training protocols using tensiomyography. J Strength and Cond Res 2015;29:1339-1348.

Fry AC, Kraemer WJ, Van Borselen F, Lynch JM, Marsit JL, Roy EP, Triplett NT, Knuttgen HG. Performance decrements with high-intensity resistance exercise overtraining. Med Sci Sports Exerc 1994;26:1165-1173.

García-García O, Cancela-Carral JM, Huelin-Trillo F. Neuromuscular profile of top level women kayakers, assessed through tensiomyography. J Strength Cond Res 2015;29:844-853.

García-García O, Cancela-Carral JM, Martínez-Trigo R, Serrano-Gómez V. Differences in the contractile properties of the knee extensor and flexor muscles in professional road cyclists during the season. J Strength Cond Res 2013;27:2760-2767.

García-Manso JM, Rodríguez-Matoso D, Sarmiento S, de Saa Y, Vaamonde D, Rodríguez-Ruiz D. Effect of high-load and high-volume resistance exercise on the tensiomyographic twitch response of biceps brachii. J Electromyogr Kinesiol 2012;22:612-619.

García-Manso JM, Rodríguez-Ruiz D, Rodríguez-Matoso D, de Saá Y, Sarmiento S, Quiroga M. Assessment of muscle fatigue after an ultra-endurance triathlon using tensiomyography (TMG). J Sports Sci 2011;29:619-625.

Halson SL, Lancaster GI, Jeukendrup AE, Gleeson M. Immunological responses to overreaching in cyclists. Med Sci Sports Exerc 2003;35:854-861.

Hawley JA. Molecular responses to strength and endurance training: are they incompatible? Appl Physiol Nutr Metab 2009;34:355-361.

Howatson G, Milak A. Exercise-induced muscle damage following a bout of sport specific repeated sprints. J Strength Cond Res 2009;23:2419–2424.

Howatson G, van Someren. The prevention and treatment of exercise-induced muscle damage. Sports Med 2008;38:483–503.

Hunter AM, Galloway SD, Smith IJ, Tallent J, Ditroilo M, Fairweather MM. Assessment of eccentric exercise-induced muscle damage of the elbow flexors by tensiomyography. J Electromyogr Kinesiol 2012;22:334-341.

Iguchi M, Shields R. Quadriceps low frequency fatigue and muscle pain are contraction type dependent. Muscle Nerve 2010;42:230-238.

Kellmann M, Günther K. Changes in stress and recovery in elite rowers during preparation for the Olympic Games. Med Sci Sports Exerc 2000;32:676-683.

Lattier G, Millet GY, Maffiuletti NA, Babaut N, Lepers R. Neuromuscular differences between endurance-trained, power-trained, and sedentary subjects. J Strength Cond Res 2003;17:514–521.

Loturco I, Gil S, Laurino CFS, Roschel H, Kobal R, Abad CCC, Nakamura FY. Differences in muscle mechanical properties between elite power and endurance athletes: a comparative study. J Strength Cond Res 2015;29:1723-1728.

Nuzzo JL, McBride JM, Cormie P, McCaulley GO. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. J Strength Cond Res 2008;22:699–707.

Putman CT, Xinhao X, Gillies E, MacLean IM, Bell GJ. Effects of strength, endurance, and combined training on myosin heavy chain content and fibre-type distribution in humans. Eur J Appl Physiol 2004;92:376-384.

Raeder C, Wiewelhove T, Westphal-Martinez MP, Fernandez-Fernandez J, de Paula Simola RA, Kellmann M, Meyer T, Pfeiffer M, Ferrauti A. Neuromuscular fatigue and physiological responses after five dynamic squat exercise protocols. J Strength and Cond Res 2016;30:953-965.

Reiser M, Meyer T, Kindermann W, Daugs R. Transferability of workload measurements between three different types of ergometer. Eur J Appl Physiol 2000;82:245-249.

Rodríguez LP, López-Rego J, Calbet JA, Valero R, Valera E, Ponce J. Effects of training status on fibers of the musculus vastus lateralis in professional road cyclists. Am J Phys Med Rehabil 2002;81:651-660.

Sale DG. Influence of exercise and training on motor unit activation. Exerc Sport Sci Rev 1987;15:95–151.

Schoenfeld B. Does exercise-induced muscle damage play a role in skeletal muscle hypertrophy? J Strength Cond Res 2012;26:1441-1453.

Simunic B, Degens H, Rittweger J, Narici M, Mekjavic IB, Pistot R. Noninvasive estimation of myosin heavy chain composition in human skeletal muscle. Med Sci Sports Exerc 2011;43:1619-1625.

Skorski S, Hammes D, Schwindling S, Veith S, Pfeiffer M, Ferrauti A, Kellmann M, Meyer T. Effects of training-induced fatigue on pacing patterns in 40-km cycling time trials. Med Sci Sports Exerc 2015;47:593-600.

Stegmann H, Kindermann W, Schnabel A. Lactate kinetics and individual anaerobic threshold. Int J Sports Med 1981;2:160-165.

Westerblad H, Allen DG. Recent advances in the understanding of skeletal muscle fatigue. Curr Opin Rheumatol 2002;14:648-652.

Figure Captions

Figure 1. Schematic illustration of the study design. ST = strength training group; END = endurance training group; 1RM = parallel squat one repetition maximum; $\dot{V}O_{2max}$ = maximal oxygen uptake; TMG = tensiomyography; CMJ = countermovement jump; TT_{40} = 40 km time trial. * gold standard performance test.

Figure 2. Six days intensive endurance and strength training programs and their respective training protocols.

Figure 3. TMG displacement sensor.

Figure 4. Radial twitch response with different TMG mechanical properties (Dm, Tc, V_{10}, and V_{90}).

Figure 5. TMG mean value curves with the contraction times (deformation time between 10% and 90%Dm) of the strength (Tc ST) and endurance training (Tc END) groups at the baseline measurement. Curves are constructed based on the individual raw data and fitted according to different values of muscle belly deformation and their correspondent times. Values are mean ± SD. * $P < 0.05$: significantly different from Tc ST.

Figure 6. Mean percentage changes in CMJ (solid line) and TT_{40} (dashed line) performance relative to baseline. Values are mean ± SD. * $P < 0.05$: significantly different from baseline and post2. CMJ = countermovement jump; TT_{40} = 40 km time trial.

Figure 7. TMG mean value curves of the strength training group at baseline (solid line) and post1 (dashed line) measurements. Curves are constructed based on the individual raw data and fitted according to different values of muscle belly deformation and their correspondent times. Values are mean ± SD. * $P < 0.05$: significantly different from baseline.

Figure 1

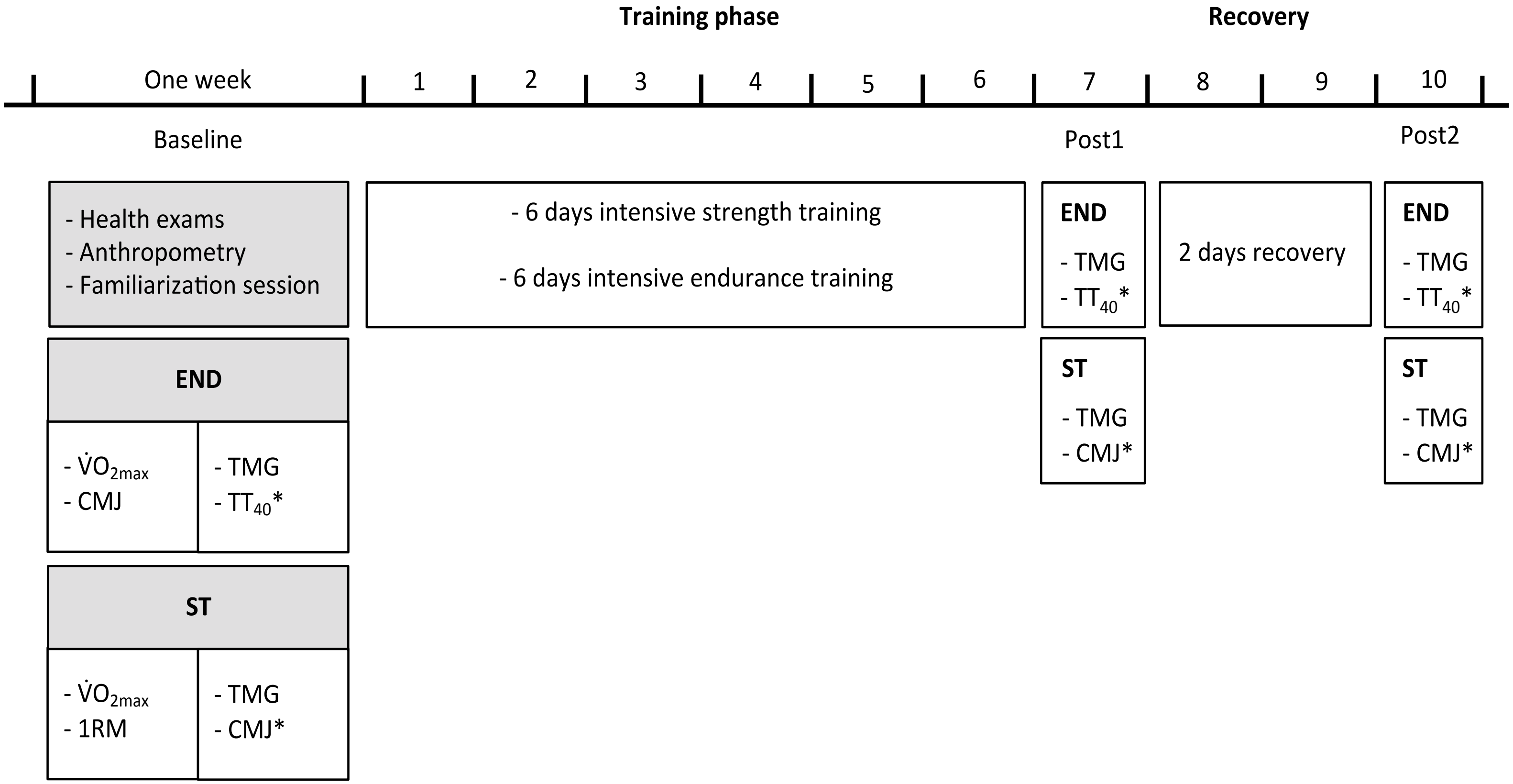
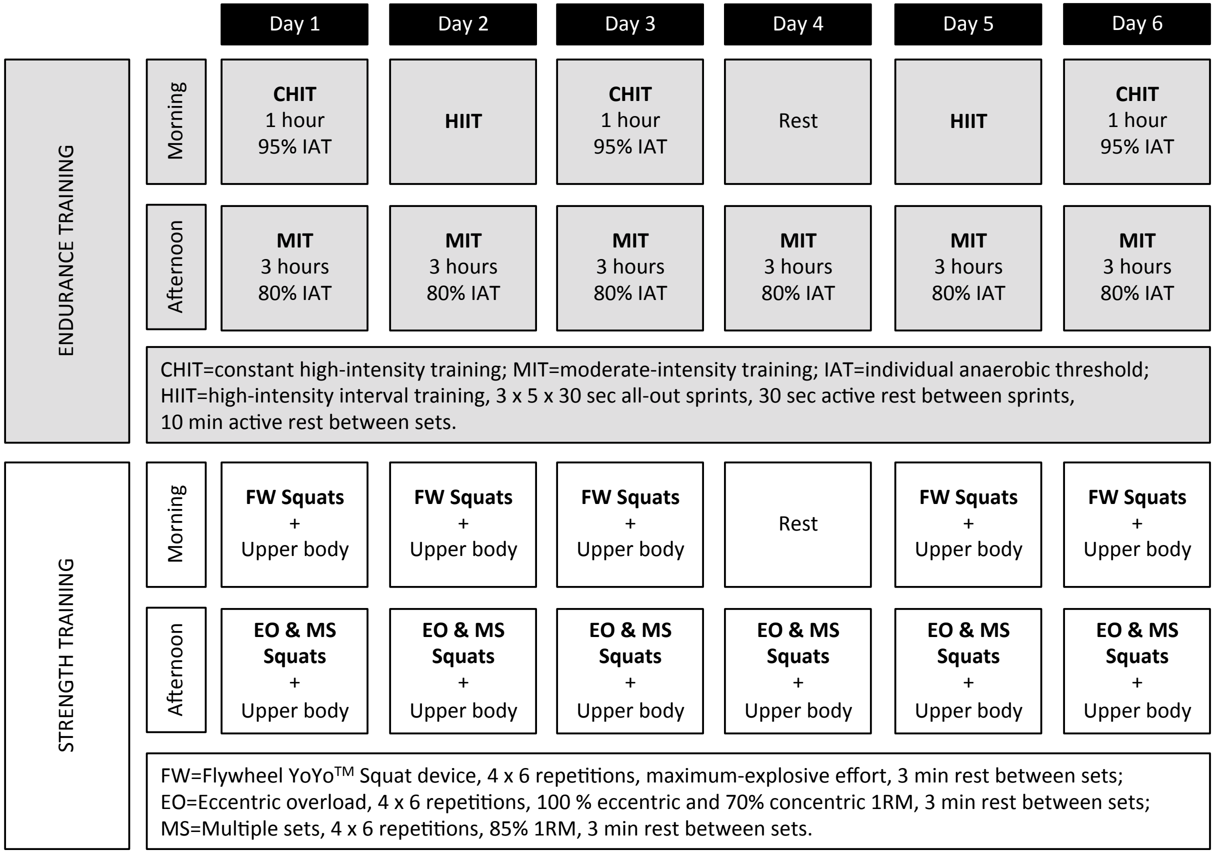

Training phase
Recovery
One week
1
2
3
4
5
6
7
8
9
10
Baseline
Post1
Post2
- Health exams
- Anthropometry
- Familiarization session
- 6 days intensive strength training
- 6 days intensive endurance training
END
- TMG
- TT_{40}*
2 days recovery
END
- TMG
- TT_{40}*
ST
- TMG
- CMJ*
ST
- TMG
- CMJ*
END
- $\dot{V}O_{2max}$
- CMJ
- TMG
- TT_{40}*
ST
- $\dot{V}O_{2max}$
- 1RM
- TMG
- CMJ*

Figure 2



		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
ENDURANCE TRAINING	Morning	**CHIT** 1 hour 95% IAT	**HIIT**	**CHIT** 1 hour 95% IAT	Rest	**HIIT**	**CHIT** 1 hour 95% IAT
	Afternoon	**MIT** 3 hours 80% IAT	**MIT** 3 hours 80% IAT	**MIT** 3 hours 80% IAT	**MIT** 3 hours 80% IAT	**MIT** 3 hours 80% IAT	**MIT** 3 hours 80% IAT
STRENGTH TRAINING	Morning	**FW Squats** + Upper body	**FW Squats** + Upper body	**FW Squats** + Upper body	Rest	**FW Squats** + Upper body	**FW Squats** + Upper body
	Afternoon	**EO & MS Squats** + Upper body	**EO & MS Squats** + Upper body	**EO & MS Squats** + Upper body	**EO & MS Squats** + Upper body	**EO & MS Squats** + Upper body	**EO & MS Squats** + Upper body

CHIT=constant high-intensity training; MIT=moderate-intensity training; IAT=individual anaerobic threshold;
HIIT=high-intensity interval training, 3 x 5 x 30 sec all-out sprints, 30 sec active rest between sprints,
10 min active rest between sets.

FW=Flywheel YoYo^{TM} Squat device, 4 x 6 repetitions, maximum-explosive effort, 3 min rest between sets;
EO=Eccentric overload, 4 x 6 repetitions, 100 % eccentric and 70% concentric 1RM, 3 min rest between sets;
MS=Multiple sets, 4 x 6 repetitions, 85% 1RM, 3 min rest between sets.

Figure 3

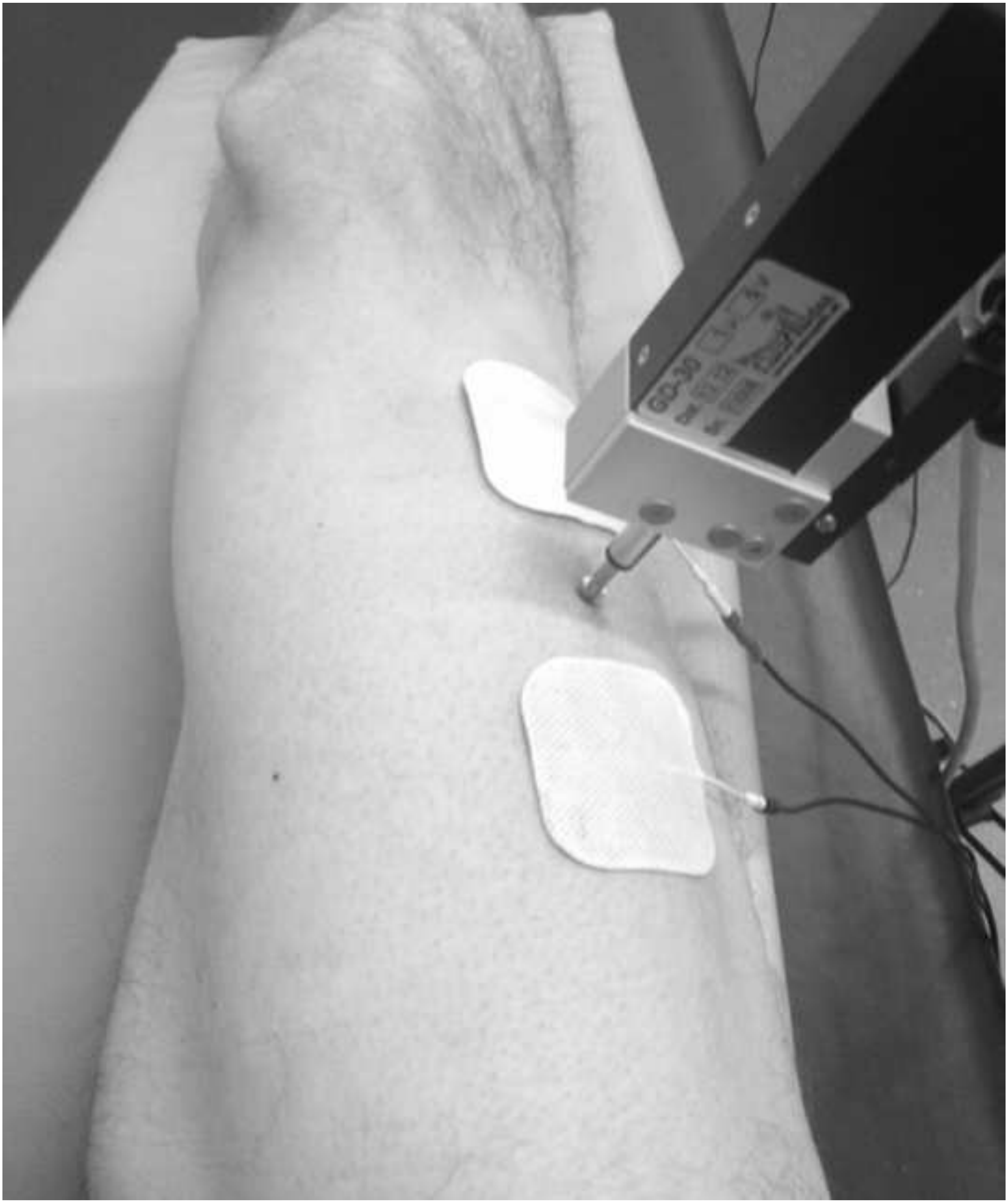


Figure 4

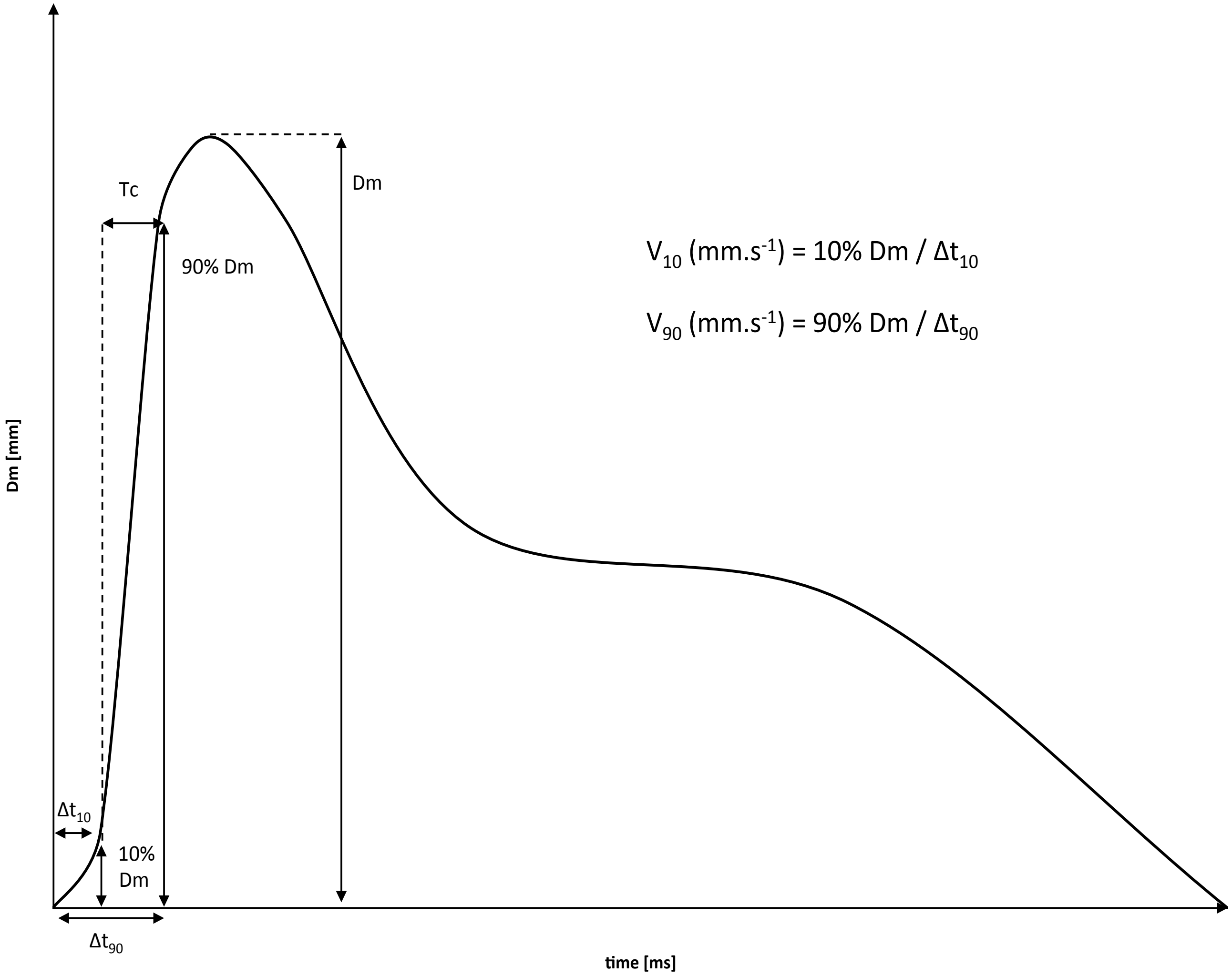

Tc
Dm
90% Dm
V_{10} (mm.s^{-1}) = 10% Dm / Δt_{10}
V_{90} (mm.s^{-1}) = 90% Dm / Δt_{90}
Dm [mm]
Δt_{10}
10% Dm
Δt_{90}
time [ms]

Figure 5

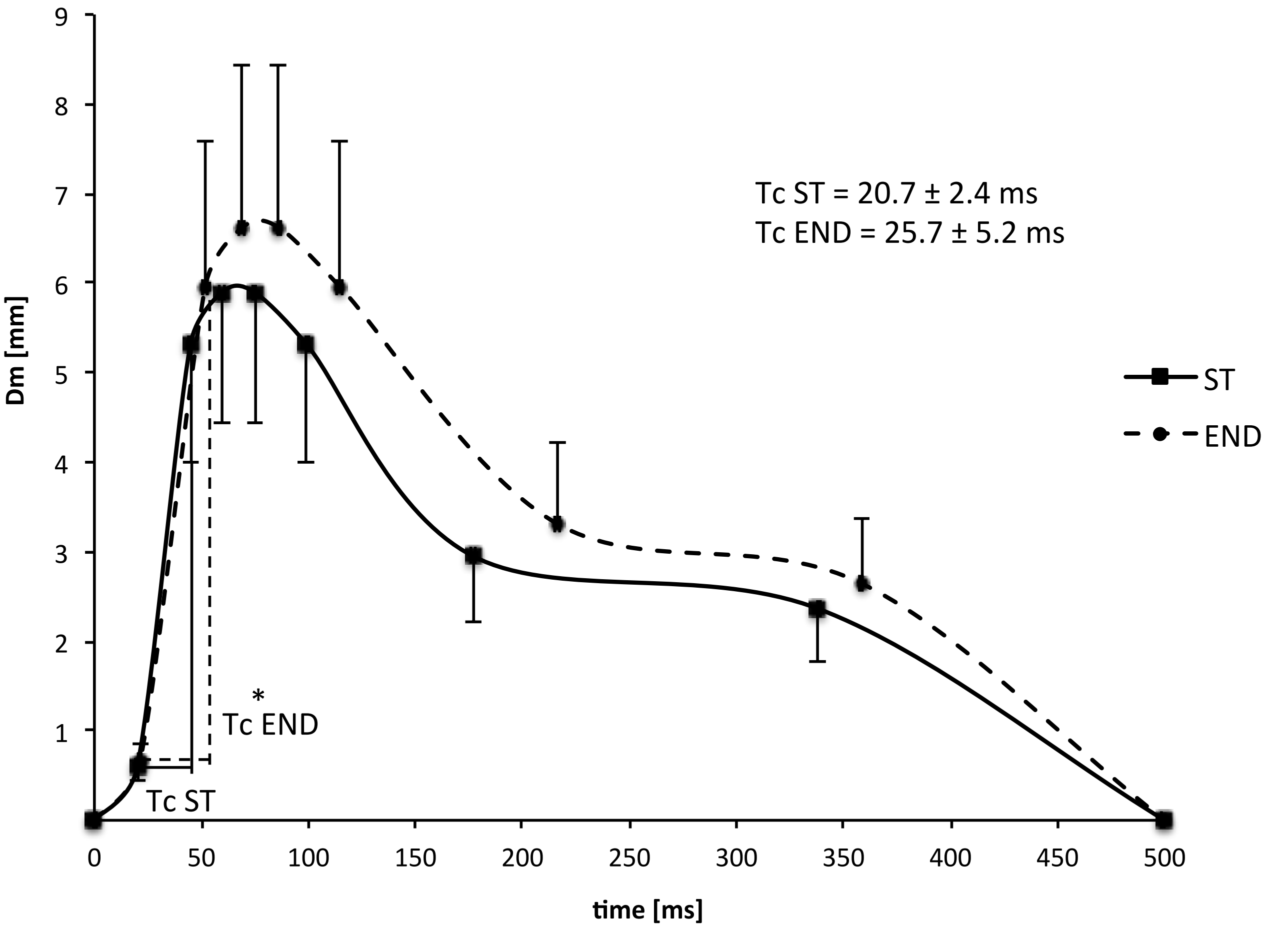

Tc ST = 20.7 ± 2.4 ms
Tc END = 25.7 ± 5.2 ms
ST
END
*
Tc END
Tc ST
Dm [mm]
time [ms]
0
1
2
3
4
5
6
7
8
9
0
50
100
150
200
250
300
350
400
450
500

Figure 6

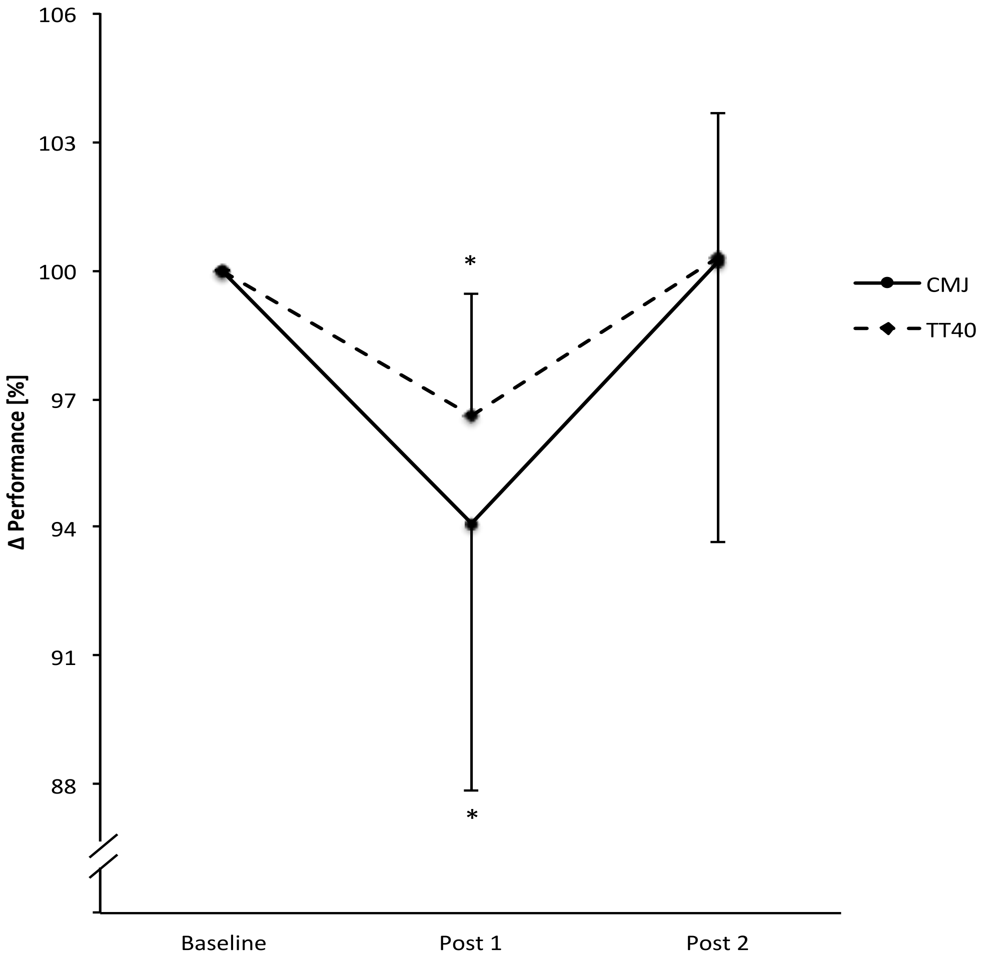
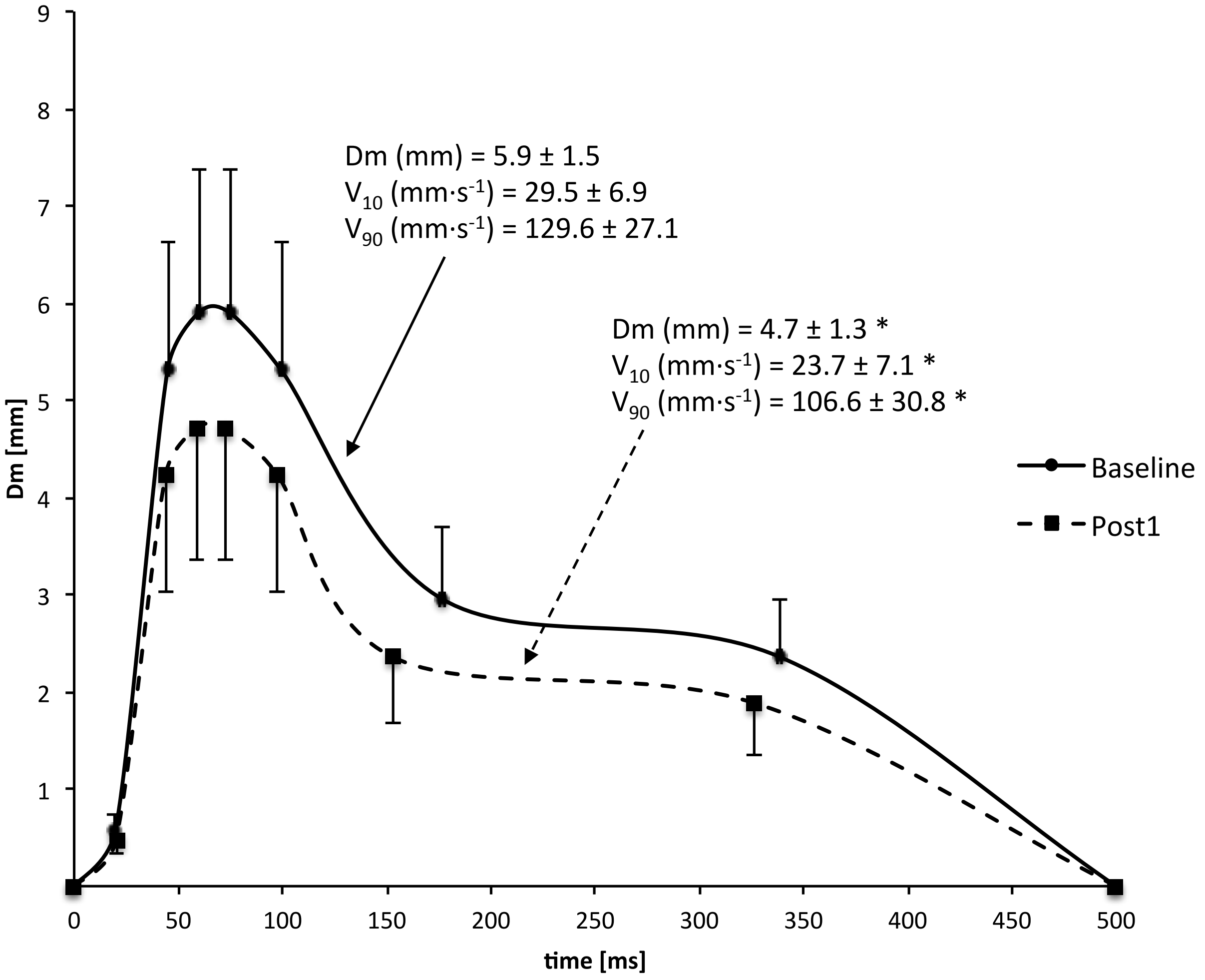

106
103
100
97
94
91
88
Δ Performance [%]
Baseline
Post 1
Post 2
*
*
CMJ
TT40

Figure 7



9
8
7
6
5
4
3
2
1
Dm [mm]
0
50
100
150
200
250
300
350
400
450
500
time [ms]
Dm (mm) = 5.9 ± 1.5
V_{10} (mm·s^{-1}) = 29.5 ± 6.9
V_{90} (mm·s^{-1}) = 129.6 ± 27.1
Dm (mm) = 4.7 ± 1.3 *
V_{10} (mm·s^{-1}) = 23.7 ± 7.1 *
V_{90} (mm·s^{-1}) = 106.6 ± 30.8 *
Baseline
Post1

Table 1. Two-way mixed measures ANOVA for TMG parameters for the ST group ($N = 14$) and END group ($N = 11$). Values are mean ± SD

Test Variable	Group	Baseline	Post1	Post2	Cohen's *d* effect size			ANOVA *p*-value		
					Baseline ST Baseline END	Baseline Post 1	Baseline Post 2	Time	Group	Interaction
Dm [mm]	ST	5.9 ± 1.5	4.7 ± 1.3[a]	5.1 ± 1.3[a]	0.52	0.86	0.57	0.000	0.273	0.051
	END	6.6 ± 1.8	5.9 ± 1.7[a]	5.3 ± 1.6[a]		0.40	0.76			
V_{10} [$mm \cdot s^{-1}$]	ST	29.5 ± 6.9	23.7 ± 7.1[a]	25.2 ± 6.4[a]	0.19	0.83	0.65	0.000	0.572	0.066
	END	31.0 ± 8.7	27.7 ± 7.6	24.5 ± 7.1[a]		0.32	0.82			
V_{90} [$mm \cdot s^{-1}$]	ST	129.6 ± 27.1	106.6 ± 30.8[a]	112.8 ± 28.1[a]	0.02	0.79	0.61	0.000	0.990	0.110
	END	129.0 ± 40.7	116.2 ± 32.6	104.3 ± 31.1[a]		0.35	0.69			
Tc [ms]	ST	20.7 ± 2.4[b]	19.9 ± 2.4[b]	20.8 ± 2.5[b]	1.32	0.33	0.04	0.218	0.001	0.435
	END	25.7 ± 5.2	24.4 ± 3.1	24.3 ± 2.5		0.31	0.36			

[a] $P < 0.05$: significantly different from baseline; [b] $p < 0.05$: significantly different from END.

Rauno Álvaro de Paula Simola graduated from the School of Physical Education, Physiotherapy and Occupational Therapy, Federal University of Minas Gerais, Brazil in 2001. He is currently a Ph.D. candidate at the Department of Training and Exercise Science, Faculty of Sports Science, Ruhr-University Bochum, Germany. His current research interests include neuromuscular adaptations to strength and endurance training.