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# Changes in Strength, Endurance, and Fatigue During a Resistance-Training Program for the Triceps Brachii Muscle

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***Context:*** As a result of the adaptation process, some functional properties show different functions over time during strength training. Muscle strength and fatigue may show different adaptation patterns in reaching the improvement plateau after several weeks of training.

***Objective:*** To follow muscle endurance and fatigue values during resistance training of the elbow extensors in young nonathletes.

***Design:*** Descriptive laboratory study.

***Setting:*** Controlled laboratory.

***Patients or Other Participants:*** Nineteen healthy young nonathletes (age = 21.0 ± 1.1 years; body mass index = 25.2 ± 2.9 kg/m²).

***Intervention(s):*** Triceps brachii resistance training was performed on the isoacceleration dynamometer for 10 weeks (frequency = 5 times a week, 5 sets of 10 maximal elbow extensions, 1-minute resting period between sets).

***Main Outcome Measure(s):*** Measurements of endurance strength and fatigability were conducted using the same equipment, and endurance strength (ES), fatigue rate (FR), and decrease in strength (DS) were defined.

***Results:*** All measured values for triceps brachii strength changed after training (ES increased by 57%, FR decreased by 68%, and DS improved by 59%; $P < .001$). No correlation was found between ES and the fatigability values—FR and DS ($r^2 = 0.37$ for FR and $r^2 = 0.04$ for DS; $P > .05$). The FR and DS trends showed specific functions, which reached a plateau after 4 weeks of training, and we found no further weekly changes in these values as the training continued. As an adaptation to exercise, ES showed a continuous, yet not linear, increase.

***Conclusions:*** Fatigability in the triceps brachii decreased in the first 4 weeks of training. After that period, muscle functional properties improved as a result of increased endurance.

***Key Words:*** conditioning, upper extremity, athletes

**Key Points**

- Fatigue of the triceps brachii muscle decreased during the first 4 weeks of strength training.
- Decreased strength of the triceps brachii muscle during multiple contractions plateaued after 4 training weeks.
- Further improvement in muscle functional properties was a result of increased endurance.

Strength training leads to functional and morphologic adaptations of skeletal muscles.[1–5] Different effects are expected from different intensities, frequencies, and durations of a training protocol. A greater increase in strength is accomplished with maximal loads, a smaller number of repetitions, and shorter rest periods between sessions. More repetitions in a series with smaller loads and longer interseries intervals increase endurance.[6–8] Surely, the adaptation effects are also closely related to age, genetic predisposition, muscle or fiber types, previous training history, and hormonal or other influences.[8,9]

In any case, the objective of a training program is to increase the function of skeletal muscles, which relates not only to maximal muscle strength and power but also to endurance and fatigue. *Endurance* is the ability of a muscle to maintain its function throughout time and multiple contractions. Muscle endurance can be expressed as a strength decrease that represents the development of fatigability during training sessions. *Muscle fatigue*, defined as the inability of a muscle to generate force or power, is an important factor in exercise performance and muscle functional capacity that significantly limits physical performance.[10–12] It is also modified during the training process. A range of mechanisms have been identified that contribute to the decline of performance.[10] Many muscle properties change during fatigue, including the action potential, extracellular and intracellular ions, and intracellular metabolites.

Muscle strength gain is the result of neural and metabolic components, and their domination varies throughout the training process. Decrease in fatigability is also partially influenced by these mechanisms. Different strength measurements show different functions over time as a result of the adaptation process. Only limited data address the dynamics of fatigue change throughout prolonged training activities, especially in a nonathletic population. At the same time, the dynamics of change of different aspects of strength and endurance during training are not well known. Whether some functional properties improve in linear fashion and when the plateau can be reached in different training regimens remain unclear.

Several studies[13–15] have dealt with changes in different muscle strength values as a result of a variety of training protocols. Greig and Siegler[14] investigated the influence of soccer-specific fatigue on peak eccentric torque and showed that eccentric peak hamstrings torque deteriorated as a function of exercise duration throughout the simulated match and after the passive halftime interval. Only a limited number of authors have examined the effects of training on dynamic exercise-induced fatigue in upper- or lower-body muscle groups. Delayed development of exercise-induced leg fatigue as a result of isometric strength training has been demonstrated through the assessment of maximal isometric voluntary contractions. Izquierdo et al[16] examined how a 7-week resistance training protocol affected an exercise-induced fatigue task conducted on the quadriceps muscles (5 × 10-repetition maximum leg presses). Ahtiainen and Hakkinen[17] found decreases in maximal isometric force of knee extensors of 34% and 44%, on average, after 4 series of 12 repetitions in strength athletes and nonathletes, respectively. Data on upper extremities are scarce, and only a few investigators have dealt with training the elbow flexors[9] or extensors[6,18] with a follow-up on training-induced maximal muscle strength and endurance increase in relation to muscle volume change. For example, Roman et al[9] observed that after 12 weeks of heavy-resistance training of elbow flexors in 5 elderly men, the amount of work a participant could perform during a 25-repetition test increased by 41%, together with changes in muscle volume and peak torque. But no follow-up of strength decrease or fatigue changes throughout the training was reported in these studies.

Furthermore, to our knowledge, no researcher has investigated the effects of strength training for elbow extensors on fatigue rate change throughout multiple muscle contractions and time. Therefore, the aim of our study was to determine the value of elbow-extensor exercise-induced fatigue (as a result of a series of multiple consequent contractions) and to evaluate characteristics of the changes during strength training by applying identical training and testing procedures. Another aim was to correlate functions of muscle fatigue throughout 10 weeks of training with endurance strength values.

## METHODS

Our descriptive laboratory study included a pretest-posttest, repeated-measures design with static group comparison. The independent variable was time (pretraining, training weeks, posttraining). Main outcome variables included maximal muscle strength, endurance strength, fatigue rate, and decrease in strength.

### Experimental Approach to the Problem

Triceps brachii strength training was conducted and muscle strength measurements were taken in the Laboratory for Functional Diagnostics. In a protocol of 5 series of 10 triceps brachii muscle contractions, with a 1-minute resting period between series, we were able to precisely measure strength values of each maximal contraction on a daily basis. This allowed us to define muscle endurance and fatigability as a function of muscle strength decrease. We measured and followed these strength values on a weekly basis to find the trend in fatigue rate decrease as a result of strength training. Also, we wanted to investigate possible differences between values that define endurance and fatigability in young nonathletes.

**Table 1. Anthropometric Characteristics of Nonathletes**

| Time | Age, y | Height, cm | Body Weight, kg | Body Mass Index |
|---|---|---|---|---|
| Before training | 21.0 ± 1.1 | 181.8 ± 7.8 | 83.2 ± 11.3 | 25.2 ± 2.9 |
| After training | 21.2 ± 1.0[a] | 181.9 ± 7.6 | 81.9 ± 10.8[a] | 24.7 ± 2.7[a] |

[a] $P < .05$.

### Participants

A group of 19 healthy young men (age = 21.0 ± 1.1 years; body mass index [calculated as kg/m$^2$] = 25.2 ± 2.9) who did not take part in any formal resistance exercise regimen volunteered for this study (Table 1). All participants were nonathlete medical students who were not engaged in any organized physical activity before the study. The testing-training procedure was introduced to the participants 1 day before the training started, so they would be familiar with the procedure. They were always measured in a group so they could observe previous training sessions, which generated a competitive spirit among them. The Institutional Review Board of the Medical School, University of Novi Sad, approved the research protocol. The investigation was performed according to the principles outlined in the Declaration of Helsinki. All participants were given oral and written explanations of the study before they signed a consent form.

### Strength-Training Protocol

Elbow-extensor strength training was performed on an isoacceleration dynamometer (model Dyno; Concept 2, Inc, Morrisville, VT). The protocol lasted for 10 weeks, with a frequency of 5 sessions per week, and each session included 5 sets of 10 maximal contractions (elbow extensions) after a 15-minute general warm-up. A 1-minute resting period was allowed between sets. Each contraction was performed with full elbow extension of both arms simultaneously against resistance to maintain central acceleration during the whole range of movement, as previously reported.[18] The isoacceleration dynamometer allows precise measurement of each contraction workload and strength output. Participants were performing contractions with their perceived maximum effort. Load and strength were measured for each contraction, which allowed exact measurement of individual and total workloads during a series of contractions or throughout the whole training. The strength of each repetition was measured in kilograms and Newtons and was shown on the dynamometer display. As seen in Figure 1, participants were in the sitting bench-press position and were instructed to perform each contraction with maximum effort while being orally encouraged by the investigator (J.P.G.). An adequate and precise movement range was accomplished with constant supervision. The investigator also instructed participants on how to perform contractions correctly and controlled all the movements during the training and testing sessions.

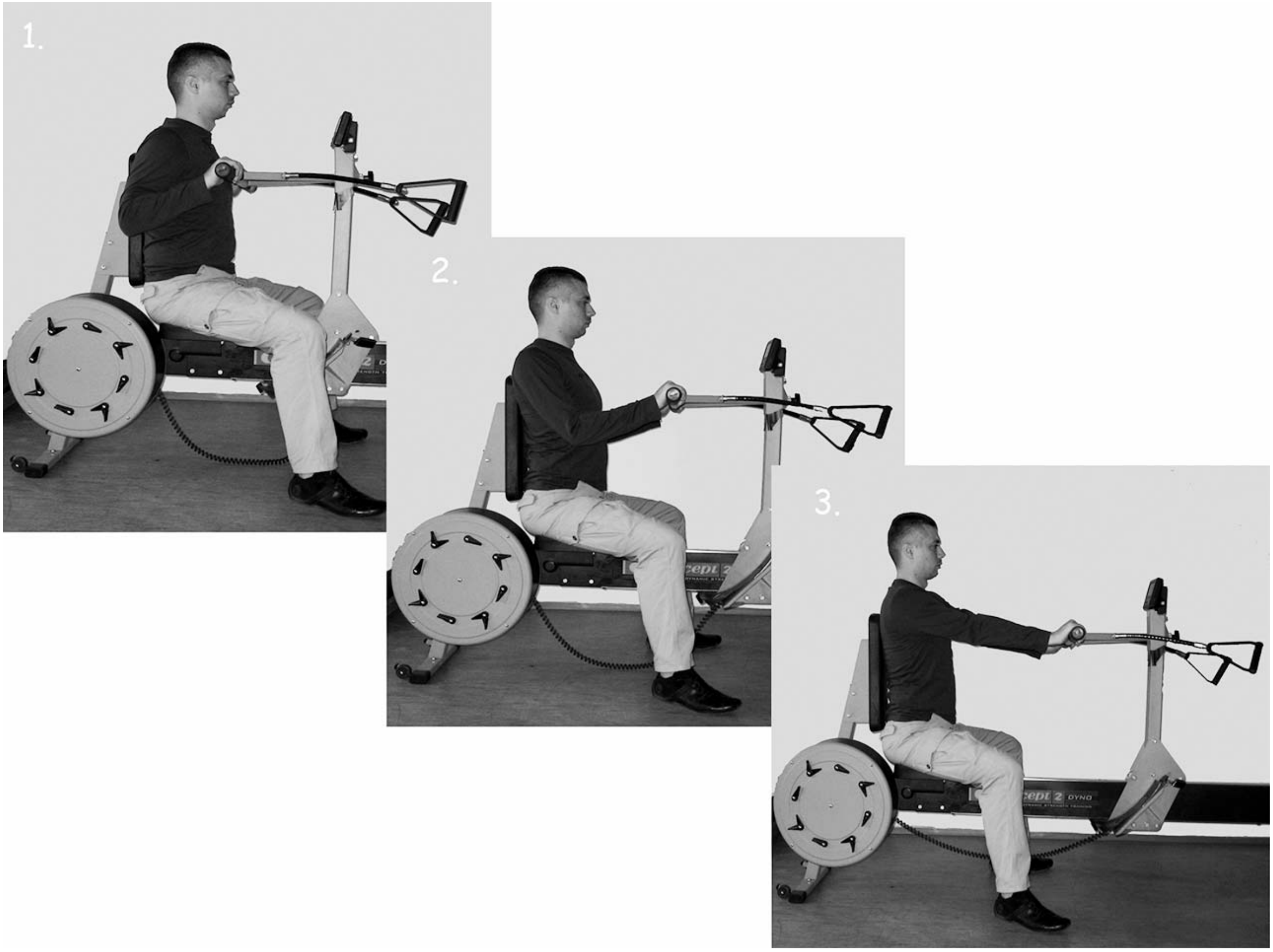


**Figure 1. Phases of elbow-extension movement on the isoacceleration dynamometer during training sessions and strength measurements. Each contraction was performed in a sitting bench-press position, with full elbow extension and direct supervision by an investigator. The strength value of each contraction was recorded and analyzed.**

### Muscle Strength Measurements

A training log was designed for each participant, and every contraction strength value was noted on the first and last training days. To follow strength changes on a weekly basis, every strength value was also recorded on the fifth training day of each week. This protocol allowed us to define and calculate 3 muscle endurance and fatigue values for each participant. In addition to maximal strength, overall daily endurance was calculated from individual maximal strength values of every contraction and therefore defined as *endurance strength*, that is, the capability of a muscle to maintain the highest work values throughout time and multiple contractions. *Fatigue*, or a muscle's inability to maintain its function of multiple contractions over time, was calculated as the maximal strength decline throughout daily sessions. All strength measurements were performed using procedures and equipment identical to those used during the training sessions.

*Maximal strength* was defined as the highest scored result in newtons. *Endurance strength* (ES) was the average value of all 50 daily contractions. Percentage decline of the average value of the fifth series in relation to the first series was defined as the *fatigue rate* (FR). A difference in the average values of muscle strength between the first and fifth training series was defined as a *decrease in strength* (DS).

### Statistical Analysis

All calculations were performed using SPSS (version 10.0; SPSS, Inc, Chicago, IL). Statistical significance was set at $P < .05$. All data were presented as mean $\pm$ SD unless otherwise indicated. The difference in muscle strength values before and after training was analyzed using the paired $t$ test. Differences in measured variables were also expressed in percentages. Repeated-measures analysis of variance was used to assess the significance of weekly changes of strength values. Correlations between different strength measurements were determined using the Pearson correlation coefficient.

## RESULTS

### Triceps Brachii Muscle Strength Values Training Changes

Differences between baseline and posttraining values were found for all measured variables, that is, elbow-

**Table 2. Elbow-Extensor Maximal Muscle Strength and Endurance in Nonathletes Before and After a 10-Week Training Protocol**

| | Before Training | After Training |
|---|---|---|
| Maximal strength, N | 660.0 ± 112.3 | 839.5 ± 125.5[b] |
| Endurance strength, N | 462.3 ± 103.9 | 725.6 ± 117.6[b] |
| Fatigue rate, % | 38.9 ± 8.6 | 12.4 ± 0.7[b] |
| Decrease in strength, N | 229.2 ± 43.2 | 94.8 ± 35.3[b] |

[a] $P < .05$.
[b] $P < .01$.

extensor maximal muscle strength and endurance, as shown in Table 2 ($P < .001$). The ES increased by 57% and FR decreased by 68%. At the same time, DS improved by 59%. A correlation was also noted between FR change and DS ($r^2 = 0.70$), whereas no correlation was discovered between ES and FR or DS ($r^2 = 0.37$ and $r^2 = 0.04$, respectively).

### Triceps Brachii Muscle Strength Values: Trend

The average weekly trends of ES and DS throughout the training program are shown in Figure 2. Similar function is present for the average FR weekly values, with a plateau after 4 weeks of training. The ES improvement trend was different from the fatigability measurements (FR and DS).

We evaluated all values weekly and compared them with the previous week's results. We registered significant changes but not after each week. With regard to ES, changes were not seen after weeks 5 (ES = 592.8 ± 117.6 N), 6 (ES = 598.82 ± 128 N), 9 (ES = 715.2 ± 129 N), and 10 (ES = 714.6 ± 123.1 N).

With regard to FR and DS, changes were noted during the first 4 weeks. During that period, the FR decrease was 10% on average each week, compared with the previous week. At the same time, DS improved by 25% on average (229.2 ± 43.2 N for the first week, 178.1 ± 46.9 N for the second week, 138.4 ± 48.8 N for the third week, and 123.43 ± 43.5 N for the fourth week). However, no weekly changes in these values were demonstrated later during the training process.

## DISCUSSION

Our study was designed to follow changes in certain strength measurements during elbow-extensor resistance training in nonathletes and to analyze the trends of these changes throughout the training process.

As a result of a complex process of muscle adaptation to training, increases in all measured strength values were registered in nonathletes. The ES increased by 57% on average. At the same time, fatigability decreased by 68% when expressed as FR and by 59% when expressed as DS. This decrease is also related to improved muscle functional properties, and together with endurance, it is one of the main results of muscle adaptation after a programmed physical activity.

In our study, after 5 series of 10 maximal elbow extensions, DS was 42% before training and 25% after a 10-week training regimen; this was in line with other research. Ahtiainen and Hakkinen[17] reported a decrease in maximal isometric force of knee extensors of 34% to 44% on average after 4 series of 12 repetitions in strength athletes and nonathletes. Mean force during the first 500 milliseconds of the maximal isometric muscle action decreased by 27% to 39% in both groups.[17] Izquierdo et al[16] recorded a 58% to 62% (before to after training) peak power loss after 5 series of 10 maximal knee extensor contractions and only a 12% to 17% corresponding exercise-induced decline in isometric strength of the same muscle groups in recreationally trained men. Reduction in

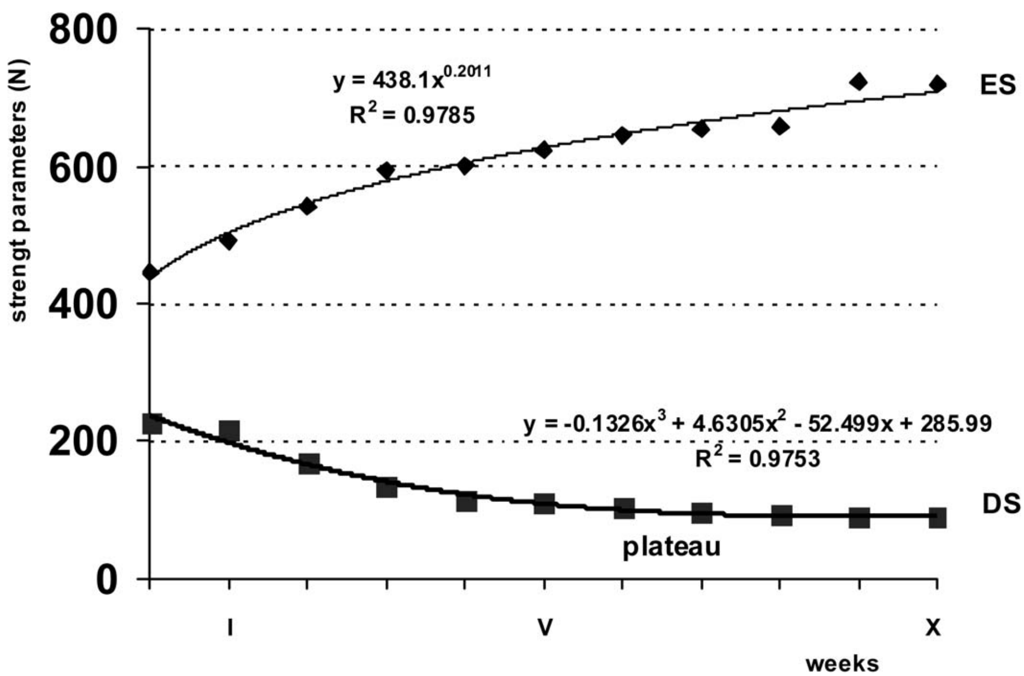


**Figure 2. Weekly averages for muscle endurance strength and decrease in strength during a 10-week strength training. Abbreviations: ES, endurance strength; DS, decrease in strength.**

maximal force and skeletal muscle fatigue after 1 hour of running was 41% in the immobilized leg (for 2 weeks) and 10% in the other leg of young nonathletes.[19]

Interesting findings have been discovered when studying changes in strength measurements on a weekly basis. The ES did not change significantly only in the fifth and the tenth week. However, FR and DS changed only during the first 4 weeks, with no weekly changes from the fifth to the tenth week.

Continuous, long-lasting physical activity led to complex adaptation processes, which resulted in improved functional properties.[20–26] When we analyzed these changes, different aspects of strength showed different trends during the training process. Although ES showed a continuous but not linear increase, FR changes reached a plateau after an initial 4 weeks of improvement. This plateau signified the peak of neural adaptation, as hypertrophy would not influence this value later during the training.[18]

In the first training days and weeks, the neural component of strength gain together with fast metabolic adaptation leads to an increase in muscle strength. Improved endurance in this period could be explained only by strength gain and gradual fatigue decrease. The muscle strength increases as a result of the recruitment of new motor units, synchronized recruitment of engaged units, increased firing rate, and decreased antagonistic reactivation.[1–3] Simultaneously, cellular metabolic control is raised to a higher level, with an improved energy and substrate supply, more efficient energy consumption necessary for the contractions, an increase in the number of receptors to facilitate diffusion, and higher concentration of enzyme molecules in the main metabolic pathways for energy production and other cellular processes (mainly synthesis).[5] Angiogenesis, a process of forming new blood capillaries in engaged muscle tissue, increases the volume of blood supplied to the muscle. This increases the concentration of substrate and energy provided for the muscle as well. At the same time, increased blood flow through a muscle speeds up the elimination of products from metabolic degradation, and consequentially, leads to a faster recovery and delay in fatigue development as a result of lowering the pH value inside the muscle.[10]

All these mechanisms together enable greater strength output through the repeated contractions. Izquierdo et al[16] noticed similar changes in the electromyogram signal before and after training at fatigue when participants exercised with the same relative load, whereas after training, the muscle was able to work more and accumulate more metabolites before task failure.

Muscle fatigue is the temporary inability of a muscle to maintain its function during repeated contractions and is another factor significantly limiting physical performance.[10] A range of mechanisms have been identified that contribute to the decline of performance. Together with the accumulation of intracellular lactate and hydrogen ions causing impaired function of the contractile proteins, effects include ionic changes on the action potential, failure of sarcoplasmatic reticulum $Ca^{2+}$ release by various mechanisms, and the effects of reactive oxygen species.[10] Contrary to muscle strength, which significantly correlates with muscle size, fatigue does not significantly correlate with muscle volume.[1–3,17] Thus, muscle size increase, or hypertrophy, would not influence the fatigue decrease of the engaged muscle, at least not the muscle strength decrease throughout the repeated contractions. Therefore, reaching the fatigue plateau after 4 training weeks suggests the maximal levels of the aforementioned adaptation mechanisms have been attained. Also, training and testing were performed on the same machine, which helped participants learn the movement and improve coordination, thereby gradually improving performance during the first few weeks.

Because fatigue does not correlate with muscle volume, domination of hypertrophy in later training weeks will not influence fatigue.[18] Nevertheless, an increase in muscle mass, that is, hypertrophy, which dominates in the second half of the training, would influence the increase in endurance, as muscle endurance relates not only to neural mechanisms but also to muscle mass.[18]

When we correlated different strength factors, ES of the triceps brachii muscle correlated significantly with its maximal strength but not with FR or DS. In our study, by using a specific multiple-contractions protocol, ES and FR described muscle functional properties in different ways. Previously, ES was reported to highly correlate with muscle volume and FR was related to the influences of other factors that affected muscle strength, such as the neural component.[18] In the present study, FR and DS showed a strong positive correlation, which indicated that only one of those two factors was sufficient for quantitative assessment of muscle fatigability.

A strength decrease throughout subsequent multiple contractions could give new insights into muscle properties not related to muscle size and could help in designing training protocols to improve endurance according to specific sport demands. This factor, related to muscle fatigability, can be improved during the first 4 weeks of training, which is a practical implication of this study. After that, it reaches a plateau, and any further changes in muscle functional properties are mainly due to endurance improvement. The delay in fatigue development over time during maximal training does not behave in the same fashion as the strength increase. In our study, we were able to measure the strength aspect of muscle adaptation to physical activity and to follow its development through training.

New findings regarding specific correlations between some strength factors over time could ensure better quality and precision in designing and planning training protocols and in their tapering in relation to the specific needs for increasing athletes' fitness. Characteristics of training (ie, intensity, frequency, and volume) should be precisely based on the most appropriate combination aimed at delaying fatigue, as this could lead to better results in sports with prevailing endurance activities.

In conclusion, FR and DS trends indicated specific functions that plateaued after 4 weeks of training, and no further weekly changes in these measurements were found as the training continued. The average strength value of multiple contractions (that is, ES) improved throughout training by 57%, as it showed a continuous but not linear increase as a result of adaptation to exercise. Therefore, fatigability decreased in the first 4 weeks of programmed training. After that, the functional properties of muscles improved as a result of increased endurance.

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