Concurrent Strength and Endurance Training: The Influence of Dependent Variable Selection

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ABSTRACT

Twenty-six active university students were randomly allocated to resistance (R, n = 9), endurance (E, n = 8), and concurrent resistance and endurance (C, n = 9) training conditions. Training was completed 3 times per week in all conditions, with endurance training preceding resistance training in the C group. Resistance training involved 4 sets of upper- and lower-body exercises with loads of 4–8 repetition maximum (RM). Each endurance training session consisted of five 5-minute bouts of incremental cycle exercise at between 40 and 100% of peak oxygen uptake (V\textsubscript{O\textsubscript{2}}\text{peak}). Parameters measured prior to and following training included strength (1RM and isometric and isokinetic [1.04, 3.12, 5.20, and 8.67 rad\textsuperscript{-1}] strength), V\textsubscript{O\textsubscript{2}}\text{peak} and Wingate test performance (peak power output [PPO], average power, and relative power decline). Significant improvements in 1RM strength were observed in the R and C groups following training. V\textsubscript{O\textsubscript{2}}\text{peak} significantly increased in E and C but was significantly reduced in R after training. Effect size (ES) transformations on the other dependent variables suggested that performance changes in the C group were not always similar to changes in the R or E groups. These ES data suggest that statistical power and dependent variable selection are significant issues in enhancing our insights into concurrent training. It may be necessary to assess a range of performance parameters to monitor the relative effectiveness of a particular concurrent training regimen.

Key Words: resistance, endurance, training, V\textsubscript{O\textsubscript{2}}\text{peak}


Introduction

Many recreational exercisers and athletes endeavor to enhance strength and endurance simultaneously to improve their performance in domestic and athletic contexts. The rationale for this concurrent training is that the benefits from both endurance and resistance training can be simultaneously acquired. Research over the last 2 decades has shown on some, but not all, occasions that strength or endurance development is actually attenuated by concurrent training (5, 11, 13–16, 18, 23). The studies reporting an inhibition in adaptation suggest that simultaneous acquisition of components of fitness during concurrent training may not be possible.

There have been three commonly advanced arguments in relation to why concurrent training may produce an inhibition in the development of strength or endurance. First, the initial bout of activity causes acute fatigue that compromises the overload achieved in the second bout, and over time the adaptation to the second bout of training is less than if there had been no preceding activity (9). There is some evidence for acute fatigue as a phenomenon, but few data to indicate whether over time the small reductions in overload are sufficient to compromise adaptation (2, 19). There are data to suggest that performing resistance and endurance training on the same day may compromise adaptation when compared with alternate-day concurrent training (19). Second, concurrent training causes neuromuscular adaptations that are distinct from endurance or resistance training (8, 12, 19). Again there is some evidence for this contention (15, 18), although much work is still required to describe these differences. Third, an inhibition in strength or endurance adaptation may be due to overtraining, even though this explanation has typically been rejected (11, 12, 16). The role, if any, that these mechanisms have either in isolation or together in inhibiting adaptation during concurrent training will be clarified over time with more research.

These proposed mechanisms however, do not explain why inhibition of adaptation is only seen in some concurrent training studies. Almost certainly differences in the design of concurrent training interventions, nutritional, and training histories of partici-
pant, and genetic predispositions of the subjects are implicated in this variation between studies (4, 6, 7, 10, 11). Equally, however, other issues may also be involved, for example, inadequate statistical power may explain the absence of differences between conditions within studies (e.g., changes in 1 repetition maximum [1RM]) (20). In addition, the dependent variables selected in some studies may have been insensitive to the effects of concurrent training; hence, little change in adaptation has been reported in some studies. Abernethy and Jürimäe (3) recently demonstrated that some strength indices are more sensitive than others to the effects of resistance training. Conceivably, some strength and endurance indices may be more sensitive to the positive and/or negative effects of different forms of concurrent training. For example, isoinertial, isokinetic, and isometric strength measures monitoring training adaptations on the same muscle group are often poorly correlated, presumably because they are measuring different structural, neural, and/or muscular phenomena (3, 5). The purpose of this investigation was to determine whether concurrent training produced similar 1RM, isometric, and isokinetic strength measures monitoring different adaptations on the same muscle group are often poorly correlated, presumably because they are measuring different structural, neural, and/or muscular phenomena (3, 5). The purpose of this investigation was to determine whether concurrent training produced similar changes in endurance and range of strength and power variables as resistance or endurance training performed in isolation. Critically, we used both parametric and effect size (ES) techniques, which quantify the magnitude or meaningfulness of the effect of independent variable manipulations, to ascertain differences in dependent variable scores across training conditions.

Methods

Experimental Approach to the Problem

The purpose of this study was to determine whether concurrent training produced similar changes in endurance and a range of strength and power variables as resistance or endurance training performed in isolation. We selected a range of strength measures because it has previously been shown that some strength indices are more sensitive than others to the effects of resistance training (3). In doing so, it would also be possible to see whether different strength indices were more sensitive to the positive and/or negative effects of concurrent training. The resistance training in this study was designed to enhance strength, and the intensity and duration of the endurance training was similar to that used in other concurrent training investigations (2, 4, 11).

Subjects

Twenty-six active, university students (11 men, 15 women) were randomly allocated to resistance training (R) (n = 8; 5 men and 3 women), endurance training (E) (n = 9; 3 men and 6 women), and concurrent training (C) (n = 8; 3 men and 6 women) groups. The groups were of a statistically similar age, weight, and height (Table 1). The participants were active students who participated regularly in social and intramural sports but were neither systematically training for a sport nor undertaking resistance training. The experimental procedures complied with the requirements of the National Health and Medical Research Council and were approved by the Medical Research Ethics Committee of the University of Queensland. Training and testing associated with the experiments were conducted within the facilities of the Department of Human Movement Studies at the University of Queensland.

Design

Subjects completed 6 weeks of R, E, or C training. Dependent variables (isoinertial, isometric, and isokinetic strength, \( V_{\text{O2peak}} \), and Wingate test performance) were measured prior to and following the training period. These measurements were performed on 3 separate days (testing day [TD] 1, 2, and 3), with the order of TDs being fixed but not necessarily the order of tests within each TD. Where testing order was randomized for a particular TD, the order was retained for a given subject at subsequent measurement occasions. Strength tests were performed on TD 1, \( V_{\text{O2peak}} \) measured on TD 2, and Wingate test performance assessed on TD 3.

Dependent Variables

Leg strength was measured isoinertially, isometrically, and isokinetically. Isoinertial strength was assessed by measuring 1RM squat on a Plyopower system (PPS Norskew, Lismore, Australia). One RM squat was measured after a warm-up consisting of 8 repetitions with a light load. Subjects then performed a single repetition with a heavier load. The weight was then progressively increased until the subject could not successfully complete 1 repetition. A lift was deemed to be successful when subjects could lower the bar such
that a knee angle of 90° was achieved and then raise the bar back to the upright starting position. Subjects received approximately 4 minutes of rest between each attempt. One RM was usually determined within 4–6 efforts.

Isokinetic leg strength was determined by measuring leg extension torque at a knee angle 0.52 rad from full extension at contractile velocities of 1.04, 3.12, 5.20, and 8.67 rad·s⁻¹ on a Cybex 6000 (Cybex division of Lumex, New York, NY). Isometric strength was determined by measuring peak torque produced during a 5-second isometric knee extension at a knee angle 0.78 rad from full extension.

Wingate test performance was assessed during a 30-second maximal sprint performed on a multigear air-braked cycle ergometer (South Australian Sports Institute, Brooklyn Park, South Australia) fitted with toe clips and straps. Software developed and marketed by SASI (Cycletest version 3.1b) enabled peak power output (PPO), average power, and relative power decline to be recorded during each test (power sampling occurred at 10 Hz). All tests were conducted using a gear ratio eliciting 8.87 flywheel revolutions per pedal crank revolution.

Pre- and postintervention VO₂peak was determined using an established protocol (17). Briefly, each subject began cycling at a workload of 50 W on an electrically braked cycle ergometer (Excalibur, Lode, Netherlands). The workload was then increased by 25 W each minute until volitional fatigue. Gas volumes were measured by a turbine ventilometer (Morgan, Kent, England). Concentrations of expired oxygen and carbon dioxide were measured by a gas analysis system (Ametek, Pittsburgh, PA; SOV S3A/1 and COV CD3A). VO₂peak was determined to be the highest oxygen uptake recorded during the test.

Training Regimens

Training in the R, E, and C conditions was conducted 3 times a week (Monday, Wednesday, Friday) for 6 weeks. The resistance and endurance elements of the C group’s training were the same as training undertaken by the R and E groups, respectively. In the C condition, the endurance element of training immediately preceded free weight activity on all training occasions. Endurance training involved five 5-minute bouts of cycle ergometry, each of which were separated by 5 minutes of passive recovery. Work rates for each minute within each cycle bout corresponded with 40, 60, 80, 100, and 100% of the pretraining VO₂peak, respectively. Exercises incorporated within the free weight training program designed to enhance strength, included the half squat, leg extension, hamstring curl, bench press, lat pull-down, biceps curl, lateral raises, and abdominal crunches. Following a warm-up set, participants completed 3 sets to failure at 8, 6, and 4 RM for half-squats and 10, 8, and 6 RM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>R</th>
<th>E</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1RM squat (kg)</td>
<td>115 (39)</td>
<td>117 (44)</td>
<td>103 (30)</td>
</tr>
<tr>
<td>Isometric 45° (N·m)</td>
<td>189 (68)</td>
<td>197 (63)</td>
<td>185 (61)</td>
</tr>
<tr>
<td>1.04 rad·s⁻¹ (N·m)</td>
<td>121 (50)</td>
<td>123 (29)</td>
<td>125 (39)</td>
</tr>
<tr>
<td>3.12 rad·s⁻¹ (N·m)</td>
<td>108 (42)</td>
<td>99 (23)</td>
<td>101 (41)</td>
</tr>
<tr>
<td>5.20 rad·s⁻¹ (N·m)</td>
<td>74 (32)</td>
<td>65 (23)</td>
<td>74 (32)</td>
</tr>
<tr>
<td>8.67 rad·s⁻¹ (N·m)</td>
<td>69 (38)</td>
<td>40 (26)</td>
<td>49 (28)</td>
</tr>
<tr>
<td>VO₂peak (ml·kg⁻¹·min⁻¹)*</td>
<td>54 (14)</td>
<td>40 (6)</td>
<td>41 (7)</td>
</tr>
<tr>
<td>Peak power output (W)</td>
<td>928 (272)</td>
<td>804 (257)</td>
<td>750 (289)</td>
</tr>
<tr>
<td>Average power (W)</td>
<td>612 (177)</td>
<td>574 (172)</td>
<td>531 (186)</td>
</tr>
<tr>
<td>% Decrement</td>
<td>51 (13)</td>
<td>50 (6)</td>
<td>48 (18)</td>
</tr>
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*p < 0.05 but >0.0167 for differences between the R group and other conditions.

for all other exercises. Training resistances were adjusted as needed to take into account changes in training repetition maxima. All sets for a given exercise were completed sequentially, and interset and interexercise recoveries were between 3 and 4 minutes in duration. All resistance and endurance training sessions were supervised. No other training was completed during the intervention.

Statistical Analyses

The pre- and posttraining dependent variable scores, and the changes in the scores as a consequence of training were described (means and SDs). The data were examined for the presence of outliers and when detected were excluded from subsequent analysis (i.e., 1 posttraining PPO value from the R group; and 1 posttraining VO₂peak value from both the E and C groups) (21). One-way analyses of variance were used to determine whether differences in pretraining and changes in (post-pre) dependent variable scores between conditions were statistically significant (p ≤ 0.05). Where they were unmatched t-tests were used in post hoc analysis. The alpha level was adjusted to reduce the risk of experiment-wise error in these analyses using the Bonferroni correction. ESs were calculated using pooled SDs to quantify the effect that the manipulation of the independent variable had on dependent variable scores (22). ESs of 0.2, 0.5, and 0.8 were accepted as being small, moderate, and large respectively (22).

Results

Prior to training, the differences among the E, R, and C conditions for 1RM, isometric, and isokinetic (with the exception of 8.67 rad·s⁻¹) strength were neither significant (p = 0.86–0.98) nor noteworthy (ESs = 0.0–0.4) (Table 2). Although the differences at 8.67 rad·s⁻¹
were not significant, the ESs suggested that the R group was stronger than the C (ES difference = 0.6) and E (ES difference = 0.9) conditions. The R group had a greater $\text{V}_2\text{O}_2$ peak than the C and E groups (ES differences = 1.2). ES differences suggested that the preintervention PPOs during the Wingate challenge were greater in the R group than the E (0.5) and C (0.6) conditions, although the differences were not significant ($p > 0.05$). Similarly, the R group presented a moderate ES difference to the C group (0.5) in terms of average power. Differences between the groups in terms of power decrement were not significant nor noteworthy.

Six weeks of training produced a variety of strength, aerobic, and anaerobic adaptations for the R, E, and C groups (Tables 3 and 4). When compared with the E group (ES = 0.0) changes in 1RM squat strength were large and significant for the R and C groups. There was also a significant and large difference in $\text{V}_2\text{O}_2$ peak adaptation between the R group (decrement) and E and C conditions. None of the changes in any of the other dependent variables were statistically significant, although ES transformations suggested that this was, for some measures, because of inadequate statistical power (Table 4). Specifically, the R group produced a moderate increment in average power; the E condition produced large increments in isokinetic strength at 5.20 and 8.67 rad-s$^{-1}$, and the C group produced moderate increments in isokinetic strength at 1.04 and 8.67 rad-s$^{-1}$.

**Discussion**

There was no parametric evidence of an attenuation or potentiation of strength, anaerobic, or $\text{V}_2\text{O}_2$ peak development as a consequence of concurrent training (Table 3). However, the ES data indicated that the interaction was more complex than the parametric data would suggest (Table 4). This complexity was evident at 2 levels. First, the mismatch between ES and parametric analyses suggest that interpretation of some previous concurrent training investigations may have been a little too simplistic. The second mismatch in response between so-called like dependent variables (in this study the strength variables) within a condition reinforces the complex neuromuscular interactions underpinning, in this case, strength adaptation. These data add weight to Kraemer's (15) plea for more research to accurately describe and explain the subtle variations in strength and endurance adaptation accompanying concurrent training when compared with strength or endurance training in isolation.

Moderate to large ES changes in dependent variables were not always accompanied by significant changes as indicated by parametric analyses. This suggested that some important differences among the R, E, and C conditions might not have been detected parametrically because of insufficient statistical power resulting from a relatively small number of subjects in each training group (see within columns of Table 4). This does not mean, however, the differences were not real or confined to this investigation (e.g., 20). Rather, it suggests that our interpretation of concurrent training data may not have been as insightful as it could have been. Alternatively, the duration of the study might not have been long enough for all training effects to be realized. Although this argument has merit, significant differences in concurrent training adaptation have been reported after a similar duration of training (11).

Differences in certain dependent variable scores were evident in the R, E, and C groups prior to training. These differences may have influenced the magnitude of change in dependent variables in response to the training interventions. For example, the small increment in isokinetic strength seen in R group at 8.67 rad-s$^{-1}$ may have been due to the fact that this group was stronger prior to training and therefore had less potential for adaptation (Tables 1 and 4). However, this explanation does not explain why the better R group at the commencement of training in terms of PPO also showed the greatest change with training (Tables 1 and 4).
The variation in strength adaptation seen in Table 4 reinforces the existence of complex, neuromuscular interplays underpinning 1RM, isometric, and isokinetic strength development. Previously we have shown that there is greatest transfer from isoinertial training to isoinertial strength indices (i.e., isoinertial strength greater than isometric and isokinetic strength indices) (3). These data are consistent with this assertion, as is evidenced by the within-row variation seen in Table 4 for the various strength indices. The better sensitivity of isoinertial indices to isoinertial training may be attributed to structural similarity and/or neural or muscular adaptation (3, 4). Conversely, the poorer sensitivity of the isometric and isokinetic indices to weight training may be attributed to structural dissimilarity and/or less important neural or muscular adaptations. Unfortunately, our data do not allow us to identify the points of congruence between endurance training and isokinetic strength adaptation at 5.20 and 8.67 rad·s⁻¹.

Many people rationalize that concurrent training will afford them the benefits of both strength and endurance training. The fact that an inhibition in strength or endurance adaptation as a consequence of concurrent training has been reported appears to place in doubt this hypothesis, at least in the contexts of those studies (11, 13, 14). Our data also place in question the notion of a simultaneous acquisition of both strength and endurance with concurrent training. Specifically, only 3 of the 6 dependent variables (1RM, VO₂peak, and isokinetic strength at 8.67 rad·s⁻¹), which were moderately or largely affected by any form of training, produced similar changes in the C group as the R or E conditions (Table 4). If the simultaneous acquisition of both strength and endurance were possible, then we would have also expected to see changes in average power during the Wingate test and isokinetic strength at 5.20 rad·s⁻¹ in the C group as well as R or E groups (Table 4).

Our data suggest that dependent variable selection can influence conclusions made with respect to changes in strength and endurance as a result of concurrent training. However, differences in the design of concurrent training interventions, such as mode, duration, and intensity of training, may influence whether any interference in strength or endurance development is observed. Clearly, the interaction between strength and endurance training is a complex issue, and it may still be possible to design specific concurrent training regimens that can minimize or possibly avoid any interference effects.

Scientists and practitioners alike need to measure changes in strength as a consequence of interventions. This study places in stark relief the question of which dependent variables to measure. We have previously addressed this issue (1). Briefly, we must determine, rather than presume, that there is a relationship between changes in particular dependent variable and changes in a particular movement context (e.g., sports skill or activity of daily living). We cannot discount the possibility that the dependent variables that have been shown to have their adaptation attenuated by concurrent training may have little relationship with “more realistic” movement contexts. Equally, the converse may be true. Although this study did not directly relate dependent variable performance to a particular movement context, the variation in strength ESs seen in Table 4 highlights how important dependent variable selection is in the external validity of concurrent training studies. This is not to say that concurrent training research with high internal validity is not important or required but rather that the generalizability of laboratory data to field contexts should not be presumed.

This study has demonstrated that statistical power and dependent variable selection can impact on the interpretation of concurrent training data. Critical to the further investigation of concurrent training is the refinement of strength assessment procedures to ensure that what we are measuring is meaningful to various movement contexts. Hence, our selection of dependent variables should be based not only on those measures with which modulation has been demonstrated but also must consider the relevance of dependent variables to the activity for which concurrent training is being undertaken.

**Practical Applications**

On occasion parametric analyses may suggest that there is no interaction between strength and endurance activity in the concurrent training context; however, this may simply be due to insufficient statistical power and/or inappropriate dependent variable selection. ES transformations allow us to gauge whether the absence of statistically significant differences is due to insufficient statistical power. The issue of dependent variable selection is more difficult to deal with. One strategy is to measure various aspects of performance in a number of ways (e.g., in this study multiple strength measures were taken). In an applied sporting or recreational context, it is essential that changes in one or more dependent variables meaningfully correlate with changes in the movement context of interest.

**References**

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Abstract The purpose of this study was to investigate effects of concurrent strength and endurance training (SE) (2 plus 2 days a week) versus strength training only (S) (2 days a week) in men [SE: n = 11; 38 (5) years, S: n = 16; 37 (5) years] over a training period of 21 weeks. The resistance training program addressed both maximal and explosive strength components. EMG, maximal isometric force, 1 RM strength, and rate of force development (RFD) of the leg extensors, muscle cross-sectional area (CSA) of the quadriceps femoris (QF), throughout the lengths of 4/15–12/15 (Lf) of the femur, muscle fibre proportion and areas of types I, IIa, and IIb of the vastus lateralis (VL), and maximal oxygen uptake (\(\dot{V}O_{2\text{max}}\)) were evaluated. No changes occurred in strength during the 1-week control period, while after the 21-week training period increases of 21% \((p < 0.001)\) and 22% \((p < 0.001)\), and of 22% \((p < 0.001)\) and 21% \((p < 0.001)\) took place in the 1 RM load and maximal isometric force in S and SE, respectively. Increases of 26% \((p < 0.05)\) and 29% \((p < 0.001)\) occurred in the maximum iEMG of the VL in S and SE, respectively. The CSA of the QF increased throughout the length of the QF (from 4/15 to 12/15 Lf) both in S \((p < 0.05–0.001)\) and SE \((p < 0.01–0.001)\). The mean fibre areas of types I, IIa and IIb increased after the training both in S \((p < 0.05\) and 0.01) and SE \((p < 0.05\) and \(p < 0.01)\). S showed an increase in RFD \((p < 0.01)\), while no change occurred in SE. The average iEMG of the VL during the first 500 ms of the rapid isometric action increased \((p < 0.05–0.001)\) only in S. \(\dot{V}O_{2\text{max}}\) increased by 18.5% \((p < 0.001)\) in SE. The present data do not support the concept of the universal nature of the interference effect in strength development and muscle hypertrophy when strength training is performed concurrently with endurance training, and the training volume is diluted by a longer period of time with a low frequency of training. However, the present results suggest that even the low-frequency concurrent strength and endurance training leads to interference in explosive strength development mediated in part by the limitations of rapid voluntary neural activation of the trained muscles.

Keywords Hypertrophy · Neural activation · Power · Strength · Strength vs. endurance training

Introduction

The specificity of training has been well documented, so that prolonged endurance training enhances aerobic performance by improving maximal oxygen uptake \((\dot{V}O_{2\text{max}},\) oxidative capacity) and increasing muscle aerobic enzyme activities, intramuscular glycogen stores, and capillary and mitochondrial density of the muscles (Holloszy and
Coyle 1984; Åstrand and Rodahl 1986). On the other hand, typical strength training with high loads results in neural and muscle hypertrophic adaptations responsible for improved strength of the trained muscles (Komi 1986; McDougall 1992; Sale 1992; Häkkinen 1994).

The physiological stimuli directed to skeletal muscle as a result of strength training and endurance training are divergent in nature. Actually, it has been suggested that they may even be antagonistic to gains in strength (Hickson 1980; Dudley and Djamil 1985; Hunter et al. 1987; Hortobágyi et al. 1991; Kraemer et al. 1995; Bell et al. 1991, 2000). Under these concurrent training conditions, there would be a limited change in skeletal muscle cross-sectional area (CSA, Bell et al. 1991) and/or a reduced hypertrophy of individual muscle fibres (Kraemer et al. 1995; Bell et al. 2000). More specifically, Kraemer et al. (1995) demonstrated that combined training muted the hypertrophy of type I fibres. However, concurrent training may not impair adaptations in strength, muscle hypertrophy, and neural activation induced by strength training only over a short-term period (McCarthy et al. 2002). To the best of our knowledge no data have yet been reported on neural activation of trained muscles as a result of prolonged combined strength and endurance training. The training-induced adaptations in the neuromuscular system differ according to the specific mode of exercise used for strength training. For example, between maximal strength training regimens versus explosive strength training protocols (Häkkinen et al 1985a, 1985b), this compatibility may be different between endurance training and strength training depending upon the types of strength training utilized. Thus, the degree of the antagonism that occurs as a result of combined strength and endurance training may differ based on the nature of the resistance training program and the target goal (e.g. power versus 1RM strength).

Nevertheless, most studies seem to support the contention that the adaptation to typical strength training is different when combined with endurance training. In addition, the volume and frequency of training may also influence the amount of incompatibility observed. Recently, McCarthy et al. (1995) demonstrated no incompatibility when combined training was only performed 3 days per week. Thus, training frequency and the intensity of each program may influence the level of interference. The physiological basis for this may be linked to an interaction between an elevated catabolic hormonal state leading to a reduced change in skeletal muscle CSA (Kraemer et al. 1995; Bell et al. 2000).

Conversely, other studies have shown a synergistic or additive effect in some muscle adaptations (Sale et al. 1990), or a compatibility in certain adaptations as a result of concurrent strength and endurance training (McCarthy et al. 1995). The compatibility may also have an overtraining aspect to it as well, and untrained individuals may be more susceptible to stress than trained people. Thus, some controversies exist regarding the universal nature the “interference effect” that was initially described by Hickson (1980). Nevertheless, this interference effect may hold true when the overall volume of training is high, so that simultaneous training for both strength and endurance may be associated with large strength gains during the initial weeks of training but with only limited strength development later on.

The training for physical fitness of ordinary people and, for example, the military forces calls for the development of muscle strength and endurance but the requirements for the volume and/or frequency of training in ordinary people are usually lower than in training of athletes for some sports. Therefore, the purpose of this study was to investigate the effects of combined strength and endurance training versus those of strength training alone on both functional and structural adaptations of the neuromuscular system in men during a prolonged training period of 21 weeks, while keeping the overall frequency of training at a low level throughout the experiment. Moreover, the subject groups utilized a strength training program planned not only for maximal strength development but also included to some extent lower-load exercises of an explosive nature, i.e. to execute each repetition of these sets as “explosively” as possible (rapid muscle actions). The focus of this study was on the neuromuscular system, thus we recorded the degree of hypertrophic adaptation and maximal strength development of the trained muscles. We were also interested in examining possible training-induced adaptations in voluntary neural activation of the trained muscles possibly associated with power development.

Methods

Subjects

Thirty-two healthy men from the city of Jyväskylä were recruited for the study. Five subjects dropped out after the first measurements or later during the study period (for various personal reasons) so that in the end 16 subjects [mean age of 38 (5) years and mean height of 179 (5) cm] were left in the strength training (S) group and 11 subjects [37 (5) years and 181 (8) cm] were in the combined strength and endurance training (SE) group. The physical characteristics of the subject groups are presented in Table 1. The subjects were carefully informed about the design of the study with special information on possible risks and discomfort that might result, and subsequently signed an informed consent document prior to the start of the study. The study was conducted according to the declaration of Helsinki and was approved by the Ethics Committee of the University of Jyväskylä, Finland.

Subjects had been previously involved with various recreational physical activities such as walking, jogging, cross-country skiing, aerobics or biking but none of the subjects had any background in regular strength training or competitive sports of any kind. Subjects were not on any medications that would affect physical performance.

Experimental design

The total duration of the present study was 22 weeks. The subjects were tested on five different occasions using identical protocols. The first week of the study (between the measurements at week –1 and at 0) was used as a control period during which time no experimental training was carried out but the subjects maintained
their normal recreational physical activities (e.g. walking, jogging, biking, swimming and aerobics). These activities were similar between the groups. The subjects were tested before and after this control period. Thereafter, the subjects started a supervised experimental training period for 21 weeks in the S or the SE group. The measurements were repeated during the actual experimental training period at 7-week intervals (i.e. weeks 0, 7, 14 and 21).

Muscle strength measurements

The subjects were carefully familiarized with the testing procedures of voluntary force production of the muscle groups tested. Second, during the actual testing occasion, two to three warm-up contractions were performed prior to the maximal test actions. In all tests of physical performance external verbal encouragement was given to each subject.

Isometric force–time curves, maximal rate of isometric force development (RFD), and maximal isometric force of the bilateral leg extensor muscles (hip, knee and ankle extensors) were measured on an electromechanical dynamometer (Häkkinen et al. 1998a). In this test the subjects were in a sitting position so that the hip and knee angles were 107° and 110°, respectively. The subjects were instructed to exert their maximal force as fast as possible during a period of 2.5–4.0 s. A minimum of three trials was completed for each subject and the best performance trial with regard to maximal peak force was used for the subsequent statistical analysis.

A David 210 dynamometer (David Fitness and Medical) was used to measure maximal bilateral concentric force production of the leg extensors (hip, knee and ankle extensors) (Häkkinen et al. 1998a). The subject was in a seated position so that the hip angle was 110°. On verbal command the subject performed a concentric leg extension starting from a flexed position of 70° trying to reach a full extension of 180° against the resistance determined by the loads (kg) chosen on the weight stack. In the testing of the maximal load, separate 1RM (repetition maximum) contractions were performed. After each repetition the load was increased until the subject was unable to extend the legs to the required full extension position. The last acceptable extension with the highest possible load was determined as 1RM. This dynamic testing action was used in addition to that of the isometric one, since the strength training was also dynamic in nature.

A David 200 dynamometer modified for strength testing (Häkkinen et al 1998b) was used to measure maximal isometric torque of the knee flexors. The subject was in a seated position so that the hip and knee angles were 110° and 90°, respectively. On verbal command the subject performed a maximum isometric knee flexion of the right leg. A minimum of two maximal actions was recorded and the best maximum was taken for further analysis.

The force signal was recorded on a computer (486 DX-100) and thereafter digitized and analysed with a Codas TM computer system. EMG was full wave rectified, integrated (iEMG in mV·s) and time normalized for 1 s in the following phases: (1) in the isometric actions for the first 500 ms from the start of the contraction, and (2) for the maximal peak force phase of the isometric contractions (500–1500 ms) to calculate maximal iEMG (Häkkinen et al. 1998a). EMG of the BF acting as an agonist recorded during the maximal unilateral isometric knee flexion was analysed in a similar way as those of the EMGs of the VL muscles of the isometric leg extensions. The highest iEMG value recorded for the right BF muscle was taken for further analysis. The iEMG of the right BF acting as an antagonist was also recorded during the bilateral isometric leg extension action. In order to calculate the antagonist coactivation percentage for the BF muscle during the extension action, the following formula was used: iEMG of the BF during the extension divided by the iEMG of the BF during the flexion, all multiplied by 100 (Häkkinen et al. 1998a, 1998b).

Table 1 Physical characteristics of the subject groups during the experimental period

<table>
<thead>
<tr>
<th>Weeks</th>
<th>Strength group (S) (n = 16)</th>
<th>Strength endurance group (SE) (n = 11)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (kg)</td>
<td>Body fat %</td>
</tr>
<tr>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>0</td>
<td>83.9 (15.0)</td>
<td>20.1 (4.9)</td>
</tr>
<tr>
<td>7</td>
<td>84.6 (15.8)</td>
<td>20.3 (4.9)</td>
</tr>
<tr>
<td>14</td>
<td>85.1 (16.3)</td>
<td>20.6 (5.2)</td>
</tr>
<tr>
<td>21</td>
<td>85.9 (18.1)</td>
<td>20.4 (5.3)</td>
</tr>
</tbody>
</table>

*p < 0.05; ***p < 0.001

Muscle CSA

The muscle CSA of the right quadriceps femoris (QF) was assessed before and after the 21-week experimental training using magnetic resonance imaging (MRI) (1.5-Tesla, Gyroscan S15, Philips) at Keskia-Suomen Magneettikuvauus, Jyväskylä, Finland. The length of the femur (L_f), taken as the distance from the bottom of the lateral femoral condyle to the lower corner of the femoral head, was measured on the coronal plane. Subsequently, 15 axial scans of the thigh interspaced by a distance of 1/15 L_f were obtained from the level of 1/15 L_f to 15/15 L_f as described previously (Häkkinen et al. 2001b). Great care was taken to reproduce the same individual femur length each time using the appropriate anatomical landmarks. All MR images were then exported to a Macintosh computer for the calculation of muscle CSA. For each axial scan, CSA computation was carried out on the QF as a whole and for the final
calculation of the CSA, slices 4/15–12/15 were used (slice 4 being closer to the knee joint of the thigh). CSA (measured in cm²) was determined by tracing manually along the border of the QF.

Muscle biopsy samples were obtained before and after the experimental training period. The samples were obtained from the superficial portion of the VL muscle of the right leg utilizing the percutaneous needle biopsy technique of Bergström (1962). Special care was taken to extract tissue from the same location (close to the prebiopsy scar) and depth each time. Muscle tissue samples were frozen in isopentane cooled with liquid nitrogen and stored at –80°C until analysis. Serial cross-sections (10 μm thick) were cut on a cryostat at –20°C for histochemical analyses. Histochemical staining for myofibrillar adenosinetriphosphatase (ATPase) was used to classify the fibers as I, IIa, IIb and IIc (based on the stability of their ATPase activity at pH 4.2, 4.6, and 10.3, in the preincubation medium) according to Brooke and Kaiser (1970). IIc fibres were, however, so rare that they were not included in the final statistical analyses. Mean fiber areas were calculated from one selected portion of the biopsy sample with the average number of fibers (at pre- and post-training) of 85 and 62 recorded for the S group, and 63 and 52 for the SE group, respectively. A loaded image of stained cross-sections was analysed by the Tema Image-Analysis System (Scan Beam, Denmark). A videoscope consisting of a microscope (Olympus BX 50) and colour video camera (Sanyo High Resolution CCD) was used to calculate the mean fibre areas of each fibre type (Häkkinen et al. 2001a).

Aerobic performance

Maximal oxygen uptake ($\overline{V}O_2\text{ max}$) test was carried out using the Ergoline Ergometrics 806S bicycle ergometer only for the SE group. The intensity was 75 W at the beginning of the test and was increased by 25 W every second minute until exhaustion. Heart rate was monitored continuously, and blood pressure before the test. The oxygen uptake ($\overline{V}O_2$) was measured continuously using the SensorMedics Vmax229. Blood samples were taken from fingertip every second minute to measure blood lactate concentrations and determine aerobic and anaerobic thresholds as described in detailed previously (Aunola and Rusko 1984). Blood lactate was determined using an Eppendorf Ebio 6666 lactate analyser.

Anthropometry

The fat percentage was estimated by measuring skin-fold thickness at four different sites according to Durnin and Womersley (1967).

Strength training and combined strength and endurance training

Strength training

The supervised 21-week strength training was carried out twice per week. Each training session included two exercises for the leg extensor muscles: the bilateral leg press exercise and the bilateral and/or unilateral knee extension exercise on the David 200 machine. In addition, each training session included four to five exercises for the other main muscle groups of the body (the bench press and/or the triceps pushdown and/or lateral pull down exercise for the upper body; the sit-up exercise for the trunk flexors and/or another exercise for the trunk extensors; and the bilateral/unilateral elbow and/or knee flexion exercise and/or leg adduction/abduction exercise). The exercises were so-called free motion machine exercises (David Fitness and Medical). The resistance was determined by the loads (kg) chosen on the weight stack, and the subject actively produced the motion and determined the action velocity by himself, and always performed a full range of motion in each exercise.

During the first 7 weeks of the training the subjects trained with loads of 50% to 70% of the 1RM. The subjects performed 10–15 repetitions per set and performed 3–5 sets of each exercise. The loads were 50% to 60% and 60% to 80% of the maximum during the second 7-week period. In the two exercises for the leg extensor muscles the subjects then performed either 8–12 repetitions per set (at lower loads) or 5–6 repetitions per set (higher loads) and performed 3–5 sets. In the other four exercises the subjects performed 10–12 repetitions per set and performed 3–5 sets. During the last 7 weeks of the training (weeks 15–21) two different load ranges were used in the two exercises for the leg extensors so that the subjects completed 3–6 repetitions per set with the loads of 70% to 80% of the maximum and 8–12 repetitions per set with the loads of 50% to 60%. The total number of sets varied between 4 and 6. In the other four exercises the subjects performed 8–12 repetitions per set and performed 3 to 5 sets altogether.

A major part of the knee extension exercises was performed using the basic principles of heavy resistance training but some (20%) of these exercises were performed with light loads (50% to 60% of the maximum) to meet the requirements of a typical explosive strength training protocol. Each repetition of each set with these light loads was executed as “explosively” as possible (rapid muscle actions) (Häkkinen et al. 1998b).

The loads were individually determined during the training sessions throughout the 21-week training period according to the maximum-repetition method. The overall amount of training was progressively increased until the 18th week at which point it was slightly reduced for the final 3 weeks of the 21-week training period.

Endurance training

Endurance training was also carried out twice per week. Thus, the SE group trained two times a week for strength (using the same program as the S group) and two more times a week for endurance. During the first 7 weeks the subjects trained twice a week for 30 min by bicycle ergometer or by walking to train basic endurance (under the aerobic threshold level), which was determined during the aerobic performance test before the intervention. All subjects applied pulse meters during training in order to maintain the intensity of exercise at the required level. On weeks 8–14 the duration of the first training session of 45 min was divided four loading levels: 15 min below the aerobic threshold level, 10 min between the aerobic-anaerobic thresholds, 5 min above the anaerobic threshold and 15 min again under the aerobic threshold. The second training session took 60 min and the training intensity was under the aerobic threshold level. The focus of the last 7 weeks of training was to improve cycling speed and maximal endurance carried out in a 60-min session as follows: 15 min under the aerobic threshold, 2 × 10 min between the aerobic–anaerobic thresholds, 2 × 5 min above the anaerobic threshold and the final 15 min under the aerobic threshold. The other training session of the week was basic endurance training (under the aerobic threshold) and it took 60–90 min.

Statistical methods

Standard statistical methods were used for the calculation of means, standard deviations (SD), standard errors (SE), and Pearson product moment correlation coefficients. The data were then analysed utilizing multivariate analysis of variance (MANOVA) with repeated measures. Probability adjusted t-tests were used for pairwise comparisons when appropriate. The $p \leq 0.05$ criterion was used for establishing statistical significance.

Results

Physical characteristics

No significant changes took place in the body mass or body fat percentage in the S group during the 21-week
training period (Table 1). However, the SE group showed significant ($p<0.05$ and $0.001$) decreases in the body fat percentage throughout the experimental training period but no significant between-group differences occurred.

Bilateral 1RM leg extension values

No significant changes took place in the bilateral concentric 1RM leg extension action during the 1-week control period, while during the 21-week training period significant increases of 21% [from 184 (29) and 228 (29) kg] ($p<0.001$) and 22% [171 (17) and 209 (24) kg] ($p<0.001$) took place in the 1RM load in the S and SE groups, respectively (Fig. 1). The mean relative increases recorded for S and SE did not differ significantly from each other.

Maximal bilateral isometric leg extension force, RFD and iEMGs

No significant changes took place in the maximal bilateral isometric leg extension force during the 1-week control period, while during the 21-week training period significant increases of 22% ($p<0.001$) and 21% ($p<0.001$) were recorded in the S and SE groups, respectively (Fig. 2). The mean relative increases recorded for S and SE did not differ significantly from each other. No significant changes took place in the maximum iEMGs of the VL muscles of the right and left leg of the bilateral isometric leg extension action during the 1-week control period (Fig. 3a, b). During the 21-week training period significant increases of 26% ($p<0.05$) and 29% ($p<0.001$) took place in the maximum iEMG of the right VL in the S and SE groups, respectively (Fig. 3a). The corresponding iEMG increases for the left VL were 19% ($p<0.05$) and 22% (ns) for the S and SE groups (Fig. 3b).

The maximal RFD (Fig. 4) and average force produced during the first 500 ms remained unaltered during the control period in both groups. Throughout the 21-week training period the S group showed significant increases in RFD ($p<0.01$) as well as in average force during the first 500 ms ($p<0.01$) while no changes occurred in the SE group. The changes between the two groups differed significantly ($p<0.001$). The average iEMG of the right VL muscle during the first 500-ms portion of the isometric action increased significantly ($p<0.05–0.001$) during the training period in the S group, while no significant changes occurred in the SE group (Fig. 5). The corresponding iEMG increase for the left VL during the first 500-ms portion of the action was significant ($p<0.05$ for weeks 7 and 14) only in the S group.

Maximal unilateral knee flexion force, RFD and iEMG

No significant changes took place in the maximal unilateral isometric knee flexion force of the right leg during the 1-week control period, while during the 21-week training period significant increases of 18% ($p<0.05$ for week 7) and 22% ($p<0.01$) were recorded in the S and SE groups, respectively. The two groups showed no significant changes in the maximum iEMG of the BF of the right knee flexion during the 1-week control period. During the 21-week training period insignificant increases of 20% and 13% were recorded in the maximum iEMG of the BF in the S and SE groups, respectively.
The maximal RFD of the knee flexion remained unaltered during the control period in both groups. Throughout the 21-week training period the S group showed significant increases in RFD ($p < 0.01$), while no significant increases occurred in the SE group. The change between the two groups differed significantly ($p < 0.001$).

Antagonist IEMGs

The BF activities of the right leg (relative to maximum agonist values of the BF) during the bilateral isometric leg extension remained unaltered during the 1-week control period in both groups. During the 21-week training period it remained statistically unaltered in S [from 29 (21) to 31 (24)%; $p < 0.05$] but decreased in SE [from 27 (10) to 21 (8)%; $p < 0.05$].

Muscle CSA

The CSA of the QF increased during the 21-week training period throughout the length of the muscle from 4/15 to 12/15 $L_f$ in both S ($p < 0.05–0.001$) and SE ($p < 0.01–0.001$) (Fig. 6a, b). The mean relative increases (mean of 5/12 to 12/15 $L_f$) of the QF of 6% and 9% recorded for the S and SE groups did not differ significantly from each other. Similarly, the significant increases of 7% ($p < 0.001$) and 9% ($p < 0.001$) of the QF at its largest portion ($L_f$ 9/15) recorded for the S and SE groups during the 21-week training period did not differ from each other.
Muscle fibre characteristics

The percentage values for the muscle fibre distribution of the VL muscle did not differ significantly before or after the training period in the S or SE groups (Table 2). However, there were trends for the decreases in the percentage of type IIb fibres in both S (\( p = 0.072 \)) and SE (\( p = 0.089 \)). The mean fibre CSA of type I as well as those of type IIa and IIb increased after the 21-week training period in both S (\( p < 0.05 \) and 0.01) and SE (\( p < 0.05 \) and \( p < 0.01 \)) (Table 3). The relative increases between the two groups did not differ significantly from each other.

Maximal oxygen uptake

\( \dot{V}O_{2\text{max}} \) increased during the 21-week training period by 18.5% (\( p < 0.001 \)) in the SE group (Fig. 7). Maximal power at the maximal performance increased by 17% (\( p < 0.001 \)), and the intensity (expressed in watts) that elicited the aerobic and anaerobic thresholds increased by 16% (\( p < 0.01 \)), and 14% (\( p < 0.01 \)), respectively. No significant changes occurred in the maximal heart rate [191 (8) and 189 (12) beats/min], or in the heart rates at the anaerobic or aerobic thresholds during the 21-week training period.

Discussion

The primary purpose of this study was to investigate the effects of concurrent strength and endurance training in men over an extended training period of 21 weeks. The training volume was diluted by a longer period of time with a low frequency of training. The present subjects utilized a comprehensive resistance training program which addressed both strength and power components of fitness. We monitored the hypertrophy at both the cellular and whole-body levels and combined this with the evaluation of voluntary neural activation measures of the thigh musculature. The primary findings of this investigation were that concurrent strength and endurance training resulted in large gains in maximal strength accompanied with significant enlargements in the CSA of the QF and in the sizes of individual muscle fibres. In addition, increased maximal voluntary neural activation of the trained muscles was also observed. The magnitudes of these increases did not differ from the corresponding changes observed in the group that performed strength training alone. However, the present strength/power training program also resulted in significant increases in rapid force production of the trained leg extensors associated with significant increases in the rapid neural activation of these muscles. No changes took

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**Table 2** Mean (SD) fibre distribution of the vastus lateralis muscle before and after a 21-week strength training period in the strength (S) (\( n = 10 \)) and strength and endurance(SE) (\( n = 8 \)) groups

<table>
<thead>
<tr>
<th>Type</th>
<th>Pre Mean (SD)</th>
<th>Post Mean (SD)</th>
<th>S Group</th>
<th>SE Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I (%)</td>
<td>34 (12)</td>
<td>37 (13)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type IIa (%)</td>
<td>16 (15)</td>
<td>26 (19)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type IIb (%)</td>
<td>50 (16)</td>
<td>36 (13)</td>
<td>35 (12)</td>
<td>41 (14)</td>
</tr>
</tbody>
</table>

---

**Fig. 6a, b** Mean (with standard error) cross-sectional areas (CSA) of the total quadriceps femoris (QF) muscle group at the lengths of from 4/15 to 12/15 of the femur (Lf) in the strength training group (S) (a) and combined strength and endurance training group (SE) (b) before and after the 21-week training period (*\( p < 0.05 \), **\( p < 0.01 \), ***\( p < 0.001 \))
place in these special neuromuscular characteristics when strength training was combined with endurance training.

The present 21-week training period, despite the fact that strength training was performed only twice per week, led to large increases of 21% and 22% in bilateral concentric 1RM strength of the leg extensors in groups S and SE, respectively. Thus, diluting the time given to resistance exercise stimuli did not affect the changes in physically active men. The increases in maximal isometric leg extension forces were also of the same magnitude, namely 22% and 21% in the S and SE groups, respectively. Thus, no significant differences existed in the strength development between the two groups. In general, the magnitudes of the present strength gains were well within the ranges reported to take place during pure strength training using the same volume of training in previously untrained subjects, independent of age and gender (Häkkinen et al. 1998b, 2001a, 2001b). An important conclusion from the practical point of view is that the frequency of strength training in previously untrained adults can be as low as twice a week when the loading intensity of training is sufficient and increased progressively (i.e. periodized) throughout the training period. The strength gains of the lower extremities took place gradually throughout the 21-week training period (Figs. 1 and 2) showing clearly that the strength development was not influenced adversely by the simultaneous endurance training, as some others have found (e.g. Kraemer et al. 1995; McCarthy et al. 1995, 2002). Therefore, the present data do not support the concept of the universal nature of the “interference effect” that has been described by Hickson (1980) in strength development when strength training is performed concurrently with endurance training. However, it should be noted that, compared to the present study, Hickson (1980) used a condensed period of time with a higher frequency (and volume) of training. The interference effect may also hold true when the overall volume and/or frequency of training is higher over a longer period of time, so that simultaneous training for both strength and endurance may be associated with large strength gains during the initial weeks of training but with only limited strength development during the later months of training. As the training for physical fitness calls for the development of muscle strength and endurance, the present findings suggest that this type of systematic training for strength and endurance, even with only two sessions per week, can be beneficial when performed for a prolonged period and can be utilized for various practical applications.

It has been well documented that in previously untrained adults, middle aged and older subjects large increases in maximal strength observed during the initial weeks of strength training can be attributed largely to the increased motor unit activation of the trained agonist muscles (Moritani and DeVries 1979, 1980; Häkkinen and Komi 1983; Häkkinen et al. 1998b, 2001a, 2001b). This concept was well supported by the large increases observed in the maximum iEMGs of the leg extensors not only in the pure strength trained group but maximal strength development was mediated by the increased maximal voluntary activation of the trained muscles to about the same extent also in the concurrent strength and endurance training group. The findings indicate that the contributing role of the nervous system to maximal strength development during the present training period in both groups may have been greatly important. Strength-training-induced increases in the magnitude of the EMG could result from the increased number of active motor units and/or an increase in their firing frequency (Sale 1992; Häkkinen 1994). Thus, the present results do indicate a lack of interference for the SE group in the neural adaptations during the maximal training period.

### Table 3

<table>
<thead>
<tr>
<th></th>
<th>S Group</th>
<th></th>
<th>SE Group</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>Mean (μm²)</td>
<td></td>
<td></td>
<td>Mean</td>
<td></td>
</tr>
<tr>
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<td>6149</td>
<td>(2069)</td>
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<tr>
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<td>(1659)</td>
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<td>(1524)</td>
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<tr>
<td>Type IIb</td>
<td>4836</td>
<td>(1389)</td>
<td>5660</td>
<td>(1909)</td>
</tr>
</tbody>
</table>

Significant difference pre–post training (*p < 0.05; **p < 0.01)

![Fig. 7](image-url)  

**Fig. 7** Mean (with standard error) maximal oxygen uptake (VO₂max) recorded in the bicycle ergometer test in the combined strength and endurance training group (SE) during 21-week training period (**p < 0.0001)**
force phase of the contraction when there is enough time, such as 1–2 s, to activate the muscles maximally to produce the maximal peak force. The coactivation of the BF muscle recorded during the leg extension action was within the normal levels in both groups (Häkkinen et al. 1998a, 1998b), and no drastic changes were observed during the training period. However, the present data did indicate that there was some reduction in the coactivation of the antagonist muscles in the SE group, which may have also contributed to enhance the net strength development of the agonists (Häkkinen et al. 1998b). A plausible explanation of the concurrent training-induced decreases in the antagonist coactivation of the BF muscle group could be related to the important role that the BF (together with the gluteus maximus) has in hip/knee extension and/or flexion during the propulsion and recovery phases of the pedal stroke (Gregor and Rugg 1986).

Measures of fibre area by muscle biopsy and of muscle CSA by MRI were used to examine how much muscle hypertrophy may have contributed to the strength gains observed in the present study. The present progressive strength training program, although performed only twice a week, did lead to significant increases during the 21-week period in the mean fibre areas of type I and of types IIa and IIb in both S and SE groups. The relative magnitude of muscle fibre hypertrophy was similar between the two groups, and well within the enlargements reported previously during pure strength training with two sessions per week in middle-aged men and women (Häkkinen et al. 2001a). However, it is likely that if the training frequency had been higher, greater gains in the fibre size would have taken place, at least in the pure strength training group (Kraemer et al. 1995). It has been suggested that a lack of change in the size of skeletal muscles may be an underlying reason for the depressed gains in maximal strength observed after concurrent strength and endurance training (Bell et al. 1991; Kraemer et al. 1995). This may be partly due to the oxidative stress imposed on the muscle and the need to optimize the kinetics of oxygen transfer because of the addition of endurance training to strength training. However, our findings in adult men suggest that hypertrophy of individual muscle fibres of types I and II is similar between strength training and concurrent strength and endurance training when the frequency of training is low. Therefore, the present strength training stimuli, although performed only twice a week but for a long period of 21 weeks, may allow adaptations due to the extended presentation of the exercise stimuli. However, some caution must be exercised when interpreting the present muscle fibre data, as a relatively low number of fibres were analysed and the biopsy samples were obtained only at one particular position in the thigh (Narici et al. 1996; Häkkinen et al. 2001b). Therefore, we also used the multiple-slice method in the MRI scanning to estimate the accurate muscle CSA changes in all regions of the QF. The present MRI data did show that the increases in the CSA of the total QF took place throughout the length of the femur (from 4/15 to 12/15 Lf) suggesting strongly that the degree of overall muscle hypertrophy was very similar between the S and SE groups. It is also possible that architectural changes, e.g. changes in pennation angle of the muscle fibres, may have taken place during the present strength training period (e.g. Kawakami et al. 1993).

The present strength training program was composed not only of heavy resistance but also, to some extent, of explosive types of exercises for the leg extensor muscles. The exercises were machine exercises but the resistance was determined by the load chosen on the weight stack, and the subject actively produced the motion himself, trying to obtain in explosive exercises as high an action velocity as possible throughout the full range of motion. This type of training regimen has previously been shown to lead to increased explosive force production recorded in both isometric and dynamic actions (Häkkinen et al. 1998b). In addition to the gains in maximal force, the present training also led to considerable increases in the RFD and in the average force during the first 500 ms indicating improved explosive strength of the trained muscles in group S. The increases observed in explosive strength during the present strength training indicate that considerable training-induced changes may have taken place in the voluntary and/or reflexly induced rapid neural activation of the motor units of the trained muscles as shown previously in both middle-aged and elderly men and women (Häkkinen et al. 1998b). Actually, this was supported by the observation that the average iEMG of the VL muscles during the first 500 ms of the isometric action increased significantly during the training period in group S. However, the present study showed that although the pure strength training resulted in significant increases in rapid force production of the trained leg extensors associated with the significant increases in rapid neural activation of these muscles, no changes took place in these special neuromuscular characteristics when strength training was combined with endurance training. This agrees with studies finding that concurrent strength and endurance training performed with a high frequency of training (six to ten training sessions per week) interferes with some indicators of explosive strength development, such as vertical jump (Hunter et al. 1987) and angle-specific maximal torque at fast velocities of contraction (Dudley and Djamil 1985). The present results suggest that the low frequency of concurrent strength and endurance training (four training sessions per week) also leads to interference in explosive strength development, probably mediated by a reduced improvement in rapid voluntary neural activation. Training-induced adaptations in the neuromuscular system are known to differ according to the specific mode of exercise used for strength training; for example, between typical maximal strength training regimens and explosive strength training protocols (Häkkinen et al 1985a, 1985b). Therefore, this specificity, in terms of functional adaptations caused by an explosive type of strength training, seems to play
some role in the degree of the antagonism caused by the present type of combined strength and endurance training. In general terms, the present findings also support well the suggested explanations given by Bell et al. (2000) for the discrepancies between many research results; namely, differences in the type of strength training and endurance training, experimental design, subject sample, design of the training program and the sensitivity of the dependent variable (see Leveritt et al. 1999). Nevertheless, since both maximal muscle strength and RFD, which reflects the ability of the leg extensor muscles to develop force rapidly, are important performance characteristics contributing to several tasks of daily life such as climbing stairs, walking, or even the prevention of falls and/or trips (Bassey et al. 1992; Izquierdo et al. 1999), the optimal construction and/or periodical prioritization of maximal strength and/or explosive strength and/or endurance exercises is important for overall fitness training among adults and especially older people. The role of RFD becomes naturally increasingly important for various athletic purposes.

The present 21-week combined strength and endurance training program did significantly improve aerobic performance capacity, since $V_O^{2max}$ increased by as much as 18.5%. The increase was slightly less than that recorded for maximal strength of the lower extremities but rather similar in magnitude to those increases in aerobic performance reported to take place during combined strength and endurance training in previously untrained men (Hickson 1980; Dudley and Djamil 1985; McCarthy et al. 1995; Bell et al. 1997, 2000). Thus, it seems that the addition of endurance training does not impair the magnitude of increase in aerobic power induced by endurance training alone (e.g. McCarthy et al. 1995; Bell et al. 1997, 2000). This is well in line with the concept that central circulation is the predominant factor that limits maximal aerobic power during exercise with large muscle group involvements. Although strength training may lead to peripheral changes that could be considered antagonistic to aerobic power development, e.g. reductions in muscle mitochondria, capillary, and aerobic enzymes, central circulatory adaptations related to enhancement of aerobic power seem only slightly affected by strength training (Hurley et al. 1984; McCarthy et al. 1995). The present findings also have some practical relevance, as maximal aerobic performance in adult men can be increased by using a frequency of as low as twice per week for endurance, when the training program meets the requirements of progressiveness and individualization, and is based on the true monitoring of each training session. Whether the increases were compromised or facilitated by the simultaneous strength training cannot be determined, because no aerobic measures were taken from the present strength training group, and no separate group training for endurance only was included in the present experimental design.

In conclusion, the present data do not support the concept of the universal nature of the “interference effect” in strength development and muscle hypertrophy when strength training is performed concurrently with endurance training. However, this interference effect may hold true with regard to explosive strength development associated with limited changes in rapid neural activation of the trained muscles. Second, the interference effect may also be true when the overall frequency and/or volume of training is higher than in the present study so that simultaneous training for both strength and endurance may be associated with large strength gains during the initial weeks of training but with only limited strength development during later months of training. As the training for physical fitness calls for the development of muscle strength, power and endurance, the present findings indicate that construction and/or periodical prioritization of maximal strength and/or explosive strength and/or endurance exercises is important for overall fitness training.

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53:260–266


**Introduction**

It is of interest and benefit for competitive and recreational athletes to implement both strength and endurance training into their workout programs. Many perform these training programs concurrently in hopes of achieving the adaptations that are common to both forms of exercise. However, these two methods involve different levels of training volume, intensity and duration. Strength training is defined as a low number of repetitions performed on a load that is of high resistance, producing a maximal or near-maximal contraction. (Dudley et al., 1985; Sale et al. 1990) In contrast, endurance training is defined as repeated sub-maximal contractions with loads of low resistance. (Dudley et al., 1985; Sale et al., 1990) When performed independently, these two distinct forms of training induce for the most part, opposite physiological adaptations within the muscle. Therefore, the adaptation to training that the muscle endures is specific to the training stimulus.

Ultimately, strength training enhances force production of the skeletal muscles trained. (LaChance et al., 1987) The increased force production is accompanied by an increase in muscle cross-sectional area and fast-twitch fibre area (Costill et al., 1979), along with increases in muscle contractile protein. (McDonagh et al., 1976) In contrast, endurance training effectively increases the muscle's oxidative capacity. (Gollnick et al., 1973) This adaptation is accredited to increases in slow-twitch fibre area (Gollnick et
al., 1973), muscle mitochondria and aerobic enzyme activity. (Klausen et al., 1981) Moreover, it is important to note that strength training has little or no effect on increasing $\text{VO}_2\text{max}$ (Hickson, 1980; Hickson et al., 1980) and endurance training has no effect on skeletal muscles ability to increase force production. (Hickson, 1980) These findings display that skeletal muscle adapts in a different and sometimes opposite manner to strength and endurance training. Furthermore, it is then hypothesized that skeletal muscle cannot adapt to the two different types of training stimuli simultaneously. For example, increases in the activity of aerobic enzymes have been shown with endurance training. (Gollnick et al., 1973) However, strength training can decrease the activity of these aerobic enzymes. (Tesch et al., 1987)

The hypothesis that skeletal muscle is unable to concurrently adapt to both strength and endurance training has been the topic of much research. Many studies have investigated the interference of strength training on endurance improvements, as well as the impeding effects of endurance training on strength improvements. Most investigations have concluded that interference is present when both strength and endurance training are performed simultaneously (Dudley et al., 1985; Hickson, 1980; Hortobagyi et al., 1991; Hunter et al., 1987; Kraemer et al., Nelson et al., 1990), with the development of strength being the main adaptation being affected. However, some studies (McCarthy et al., 1995; Sale et al., 1990) have shown no impairment in the development of strength or endurance. Furthermore, some research has suggested that strength development or force production is only impaired at high velocities. (Bell et al., 1991a; Bell et al., 1988; Dudley et al., 1985) While others have suggested that force
production at low velocities is not impaired by training for strength and endurance concurrently. (Bell et al., 1991b; Dudley et al., 1985; Kraemer et al., 1995)

This paper will review literature concerning the interaction of concurrent strength and endurance training. Specifically, the paper will review the effects of strength training on endurance improvements and the interference of endurance training in the process of strength enhancements. This will be done in hopes of providing the reader with a better understanding of the effects of such simultaneous training. This paper will also aim to address any factors involved in their interaction as well as the potential of strength training to improve endurance performance.

**Interaction of Concurrent Strength and Endurance Training**

**Endurance Development**

As previously stated increases in endurance capabilities, most commonly measured by increases in $\text{VO}_{2\text{max}}$, are accomplished by performing repeated sub-maximal contractions with loads of low resistance. (Dudley et al., 1985; Sale et al., 1990) Activities included in this form of training include running, biking, swimming, etc. Many studies have examined the possible interference of strength training on endurance improvements. The majority of which have concluded that there are no deleterious effects of strength training on endurance development. Hickson (1980) trained subjects who were previously not active for at least 3 months for 10 weeks. One group performed endurance training 6 days/wk, while the other performed strength training 5 days/wk in addition to the endurance training. The endurance trained group
showed a 23% increase in VO$_{2\text{max}}$ in l-min$^{-1}$, while the concurrent group showed an 18% increase. The result was that no significant difference in the increase of VO$_{2\text{max}}$ was seen between the two groups. Similarly, Hunter et al. (1987) trained previously untrained subjects for 12 weeks. One group was trained for endurance and another trained concurrently for strength and endurance. The studies results showed near identical improvements in VO$_{2\text{max}}$ for both groups, indicating that strength training has little effect on aerobic development. Moreover, Dudley et al. (1985) showed no significant differences in the development of endurance between one group that trained for endurance and another that trained simultaneously for strength and endurance. These results indicate that training for strength and endurance concurrently does not alter the ability to adapt to endurance training. Complementary results were also seen in studies done by Kraemer et al. (1995), McCarthy et al. (1995) and Sale et al. (1990).

All of the aforementioned studies showed no interference by strength training in the development of endurance abilities. However, the above results conflict with a study performed by Nelson et al. (1990). The study had one group perform endurance training 4 days/wk for 20 weeks, while another partook in strength and endurance training concurrently 4 days/wk for 20 weeks. The results showed that both groups showed significant increases in VO$_{2\text{max}}$ over the first 11 weeks of training. However, after the 11$^{\text{th}}$ week the endurance group continued to show significant increases in VO$_{2\text{max}}$, while the concurrent group failed to show further increases. These results may have been seen because of specific parameters within the study’s design. Nelson et al. (1990) had their groups’ train for 20 weeks, whereas most other studies had subjects’ train for less amounts of time. It should be noted though that Sale et al. (1990) had
subjects train for 22 weeks, yet the design consisted of two 11-week training sessions that was divided by a 3-week break. This difference is study design may account for the opposite findings. It can then be concluded that concurrent training does not impede the development of aerobic endurance.

Strength Development

Performing exercises that involve a low number of repetitions on a load that is of high resistance effectively increases strength. (Dudley et al., 1985; Sale et al., 1990) It is of importance that athletes have high levels of not only strength but also endurance. For this reason many athletes' training programs involve simultaneous strength and endurance training. A number of studies have been conducted to investigate the possible interference effects of performing strength training and endurance training concurrently. Most have shown that concurrent strength and endurance training does in fact have deleterious effects on the development of strength or force production. Nelson et al. (1990) conducted a study on previously untrained subjects in which one group, strength trained 4 days/wk for 20 weeks while another group performed the same routine but also performed endurance on the same days. The results indicated that although both groups showed increases in force production, yet the strength-training group showed greater improvements. The same results were found by Kraemer et al. (1995). Subjects in both the strength and concurrent group showed increases in muscle strength, however the strength only group showed significantly greater increases than that of the concurrent group. Moreover, in a 10-week study by Hickson et al. (1980), subjects in both the strength and concurrent groups showed increases in force production. However, while the strength group increased force
production for the entire 10 weeks, the concurrent group displayed a decrease in the last 2 weeks of the training program. These studies exhibit that training concurrently for strength and endurance has negative effects on the development of strength. Dudley et al. (1985), Hunter et al. (1987) and Hortobagyi et al. (1991) also saw similar results in their studies.

In contrast, several studies have shown no interference in strength development when training concurrently for strength and endurance. In a study by McCarthy et al. (1995), subjects trained for 3 days/wk on alternate days for a period of 10 weeks. A strength group performed strength-training exercises on each of the days, while another group performed the strength-training program in addition to an endurance-training program. The results showed that strength increases in the concurrent group were of the same magnitude of the increases in the strength-training only group. However, McCarthy et al. (1995) noted that performing the programs on alternate days allowed for rest and recuperation, possibly explaining the results of the study. Asfour et al. (1984) showed similar results to McCarthy et al. (1995). The results of Asfour et al. (1984) study, state that an individual’s strength and endurance capacities can be improved concurrently. However, it is important to note that the study by Asfour et al. (1984) lasted only 6 weeks. When compared to other studies that were longer in duration, the results of Asfour et al. (1984) may seem less significant. For example, had the study been continued past the 6-week mark, Asfour et al. (1984) may have seen similar results to that of Hickson (1980), where strength development leveled off after 6 weeks and decreased in the final 2 weeks of training. Furthermore, a study conducted by Sale et al. (1990) divided subjects into two groups; one group endurance-trained both legs
and strength-trained one, while the other strength-trained both legs and endurance-trained only one leg. The results indicated that strength development was not impaired in either group. However, the design of the study may have contributed to the findings. Sale et al. (1990) state that the concurrent form of training used in the study may be considered more a “hybrid” than “pure” form of training, thus producing the dissimilar results to that of most concurrent training studies. Also, Sale et al. (1990) suggest that limitations are present in their study if the interference that occurs between concurrent training takes place at the central and not peripheral level. From the results of all of the above studies it can be conceived that training simultaneously for strength and endurance can impede strength development.

High- vs. Low-Velocity Movements

Several studies have suggested that the impairment of force development seen with concurrent training may only affect movements performed at a high velocity. Kraemer et al. (1995) hypothesized that slow-velocity movements may not be impaired by concurrent training to the same extent that high-velocity movements are after analyzing the results of their study. Dudley et al. (1985) made the same inquiry and concluded that concurrent training reduces the ability to increase strength at high-velocities, but the same effect may not occur at low-velocities. Research by Bell et al. (1988) also suggests that concurrent strength and endurance training impair high-velocity strength gains. Later research conducted by Bell et al. (1991) examined concurrent training, where endurance training was combined with low-velocity resistance training. The results showed that the concurrent training did not impair strength increases. The results of these studies suggest that concurrent training for
strength and endurance may not impair low-velocity movements. Further research detailing the differences experienced by high- and low-velocity movements with concurrent endurance training is needed.

Specificity of Muscle Impairment

It has also been suggested that the impairment to strength development that occurs from concurrent strength and endurance training is specific to the muscle groups involved in the endurance training. This suggestion has been confirmed with research by Hunter et al. (1987), where running was performed for the endurance component, while squats and bench press were two of the exercises performed for the strength component. The results showed that the strength grouped made significantly higher increases in squat 1RM, whereas there was no difference found in the increase of bench press 1RM between the strength and concurrent groups. Similar results were attained by Kraemer et al. (1995), where endurance training involved only the lower extremities. The results of Kraemer et al. (1995) showed increases in 1RM for leg press, military press and bench press for all groups. However, the increases in 1RM for leg press in the strength group were significantly higher than in the concurrent group. These findings, along with the fact that both groups had similar increases in bench press and military press, indicate that only muscles involved in the endurance-training component of concurrent training are affected by the associated strength decline. In conclusion, the findings of both Hunter et al. (1987) and Kraemer et al. (1995) express that the deleterious effects on strength improvements exhibited with concurrent training are limited to the muscle groups involved in the endurance component.
Factors Involved in Interaction

Sequencing of Training

It shows that the sequencing of the training may be of importance when investigating the antagonism of concurrent strength and endurance training. Sale et al. (1990) found that subjects who trained concurrently for strength and endurance on alternate days showed greater strength improvements when compared to subjects who trained concurrently on the same day. These results exhibit that concurrent strength and endurance training on the same day may cause more of and interference than does training for strength and endurance on separate days. Athletes and coaches alike should take note of this fact when developing training programs. Moreover, Collins et al. (1993) devised a study in which one group trained for endurance first and strength second on the same day. The other group performed the same exercises, but strength training was done first and endurance training was completed second. The results showed no differences in the development of strength or endurance between the two groups. Although it deserves mention that Collins et al. (1993) had subjects train on the same day. If compared to the study by Sale et al. (1990), the results of Collins et al. (1993) may be contributed to the fact that both groups trained concurrently on the same day. Further research detailing the differences between same day, opposite day and whether strength or endurance training is performed first is needed to draw further conclusions in this area.
Development vs. Maintenance Phase of Training

Antagonism between strength and endurance training has been seen when both forms of training are performed concurrently. An area that needs further investigation is whether developing strength or endurance first, and then maintaining either adaptation while developing the other is possible. A study by Hunter et al. (1987) compared the strength development of previously untrained subjects to that of prior endurance trained subjects. The untrained group trained concurrently for strength and endurance, while the endurance trained group trained for strength and maintained their endurance capacities. The results found that the concurrent training impaired the strength development of the untrained group, when compared to a strength training only group. Furthermore, the study found that strength development was not impaired in the previously endurance trained group, while the group trained for strength development and endurance maintenance. This fact should also be taken into account by athletes and coaches when devising training programs and attempting to avoid the antagonism of concurrent training. No studies were found in which previously strength trained subjects attempted to maintain strength while developing endurance. However, a study by Bell et al. (1991) investigating the sequencing of training for strength and endurance found that after 5 weeks of strength training followed by 5 weeks of endurance training, some maintenance of strength was present. When the opposite sequence was followed, that is endurance then strength training, the improvements in VO$_{2\text{max}}$ were not maintained. An extension of the study of Bell et al. (1991) might be to add a maintenance phase of the first form of training to the second form of training and analyze the results. For example, 5 weeks of strength training would be followed by 5
weeks of endurance training with the addition of a strength maintenance program, and vice versa. The results of such a study might be useful in avoiding the interference effects of concurrent training.

**Strength Training to Increase Endurance Performance**

It has been shown that training concurrently for strength and endurance does not hinder improvements in VO2max. (Dudley et al., 1985; Hickson, 1980; Hunter et al., Kraemer et al., 1995) Therefore, there seems to be a possibility that strength training can be utilized to improve endurance performance. Hickson (1980) investigated this possibility. The results found that following heavy resistance training on the muscles involved in the endurance performance, short-term endurance performance was enhanced. Marcinik et al. (1991) experienced similar results when strength training endurance athletes for 12 weeks. The results showed that endurance performance was increased and the improvement was related to increased leg strength as well as an elevated lactate threshold. Hickson et al. (1988) investigated further into the potential for strength training to raise endurance performance. Hickson et al. (1988) strength trained endurance athletes for 10 weeks. The results showed a 30% increase in leg strength and short-term endurance performance was also increased. Hickson et al. (1988) noted that this increase would be specifically helpful for endurance events requiring fast-twitch fibre recruitment. An example would be an endurance event that usually concludes with a sprinting component. These findings are in conflict with the results of Bishop et al. (1999), who found that endurance trained females (cyclists) who strength trained for 12 weeks, showed significant increases in squat 1RM. However this did not lead to improved cycle endurance performance in the group of female athletes.
These contrasting results, to the possibility of strength training improving endurance performance calls for further investigation or research on this topic.

**Concluding Remarks**

This paper has investigated the possible “interference” or “antagonism” experienced with concurrent strength and endurance training. It is concluded that strength training has no negative effects on endurance training, while both are performed concurrently. There is the possibility that strength training may improve endurance performance, yet further investigation is needed. In contrast, it seems that concurrent training for strength and endurance has deleterious effects on the development of strength. Furthermore, these negative effects seem to be exclusive to high-velocity movements as well as the muscles involved in the endurance performance. Seeing as both strength and endurance are required for most competitive sports, further research in the area of concurrent training for strength and endurance would be both valid and desired.
References


THE EFFECT OF A CARBOHYDRATE AND PROTEIN SUPPLEMENT ON RESISTANCE EXERCISE PERFORMANCE, HORMONAL RESPONSE, AND MUSCLE DAMAGE

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ABSTRACT. Baty, J.J., H. Hwang, Z. Ding, J.R. Bernard, B. Wang, B. Kwon, and J.L. Ivy. The effect of a carbohydrate and protein supplement on resistance exercise performance, hormonal response, and muscle damage. J. Strength Cond. Res. 21(2): 321–329, 2007.—The purpose of this study was to determine whether resistance exercise performance and postexercise muscle damage were altered when consuming a carbohydrate and protein beverage (CHO-PRO; 6.2% and 1.5% concentrations), Thirty-four male subjects (age: 21.5 ± 1.7 years; height: 177.3 ± 1.6 cm; weight: 77.2 ± 2.2 kg) completed 3 sets of 8 repetitions at their 8 repetition maximum to volitional fatigue. The exercise order consisted of the high pull, leg curl, standing overhead press, leg extension, lat pull-down, leg press, and bench press. In a double-blind, posttest-only control group design, subjects consumed 355 ml of either CHO-PRO or placebo (electrolyte and artificial sweetener beverage) 30 minutes prior to exercise, 177 ml immediately prior to exercise, 177 ml halfway through the exercise bout, and 355 ml immediately following the exercise bout. There were no significant differences between groups relative to exercise performance. Cortisol was significantly elevated in the placebo group compared to the CHO-PRO group at 24 hours postexercise. Insulin was significantly elevated immediately pre-exercise, after the fourth lift, immediately postexercise, 1 hour, and 6 hours postexercise in CHO-PRO compared to the placebo group. Myoglobin levels in the placebo group approached significance halfway through the exercise bout and at 1 hour postexercise (p = 0.06 and 0.07, respectively) and were significantly elevated at 6 hours postexercise compared to the CHO-PRO group. Creatine kinase levels were significantly elevated in the placebo group at 24 hours postexercise compared to the CHO-PRO group. The CHO-PRO supplement did not improve performance during a resistance exercise bout, but appeared to reduce muscle damage, as evidenced by the responses of both myoglobin and creatine kinase. These results suggest the use of a CHO-PRO supplement during resistance training to reduce muscle damage and soreness.

KEY WORDS. cortisol, creatine kinase, insulin, muscle damage, myoglobin, weightlifting

INTRODUCTION

Some of the cornerstone experiments in endurance sport nutrition have demonstrated improved performance, whether as improved time-to-fatigue or in time trial settings, when consuming a carbohydrate and electrolyte supplement during the exercise bout (6, 12, 27). Recent work, however, suggests that these original nutritional guidelines may need to be adjusted. In the past five years, evidence has accumulated suggesting that endurance performance can be further enhanced by consuming a carbohydrate and protein (CHO-PRO) supplement compared to a carbohydrate-only supplement (14, 28).

When examining previous literature on carbohydrate supplementation during resistance exercise, one finds mixed results, with some studies showing no effect on exercise performance (9) and others showing an improvement in performance (10, 11, 19). Supported by these latter studies in which performance was improved, along with the recent findings with endurance exercise that reported improved performance when subjects consumed a CHO-PRO supplement, we set out to examine whether consuming a CHO-PRO supplement during resistance exercise would improve performance. Specifically, the study examined whether supplementing with CHO-PRO before and during exercise would improve the amount of weight that could be lifted during an intense resistance exercise workout. The subjects performed 3 sets of 8 repetitions at their predetermined 8 repetition maximum (RM). The ability to lift more than 8 repetitions on the third set of any exercise was defined as an improvement in exercise performance.

Nutritional supplementation can result in an anabolic hormonal response to both endurance and resistance exercise (5, 17, 18, 21, 23, 33). Supplementing with carbohydrate and protein has been found to reduce the rise in cortisol and epinephrine (21, 23, 30), while elevating insulin during exercise (35) and insulin and growth hormone postexercise (5, 33). Supplementation has also been found to decrease muscle protein breakdown and stimulate muscle protein synthesis postexercise (2, 25, 26). Moreover, their effect on protein synthesis appears to be additive (20, 22). Based on the anabolic response promoted by CHO-PRO supplementation, it could be predicted that such supplementation would reduce muscle damage during an intense resistance exercise workout. Therefore, a second goal of this study was to examine the effect of CHO-PRO supplementation on muscle damage. As indicators of muscle damage, we selected to evaluate plasma myoglobin and creatine kinase (CK) concentrations.

We found consumption of a CHO-PRO supplement did not result in increased exercise performance during the resistance exercise workout compared to that of a placebo. However, during and postexercise, the subjects who consumed the CHO-PRO supplement did demonstrate significantly reduced muscle damage compared to the subjects who consumed the placebo.
322 Baty, Hwang, Ding et al.

Table 1. Physical characteristics of test groups.*

<table>
<thead>
<tr>
<th></th>
<th>Placebo subjects</th>
<th>CHO-PRO subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>21.3 ± 0.7</td>
<td>21.7 ± 2.8</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>177.7 ± 1.4</td>
<td>176.9 ± 1.7</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>80 ± 4.2</td>
<td>74.6 ± 1.8</td>
</tr>
<tr>
<td>Lean body mass (kg)</td>
<td>60.5 ± 1.9</td>
<td>59.9 ± 1.5</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>23.0 ± 2.1</td>
<td>19.4 ± 1.8</td>
</tr>
</tbody>
</table>

* Values are mean ± SEM. CHO-PRO = carbohydrate and protein supplement.

Methods

Experimental Approach to the Problem

To test our hypotheses regarding the effects of a CHO-PRO supplement on a bout of weight lifting, we recruited 36 untrained male subjects to participate in the study. After an adaptation phase of 3 weeks, the subjects were paired according to lean body mass. This was followed by the random assignment of each subject within a pair to either a placebo or CHO-PRO treatment group. The placebo group received an electrolyte and artificial sweetener solution and the CHO-PRO group received a 6.2% carbohydrate-1.5% protein solution (both provided by Pacific Health Laboratories Inc., Woodbridge, NJ). The CHO-PRO supplement was selected because it had previously been found to improve endurance performance and reduce muscle damage during endurance exercise (14, 28). Sixteen subjects received the placebo and 18 subjects received the CHO-PRO drink. Two subjects in the placebo group elected to discontinue the study. On the day of testing, we asked the subjects to complete three sets of each exercise at their 8RM. The first 2 sets consisted of 8 repetitions, and on the third set, the subjects were asked to complete as many repetitions as possible until volitional fatigue. The 2 major dependent variables involved in this study centered on the amount of weight lifted and the blood parameters.

Subjects

Thirty-four male subjects who were either untrained to resistance training or had not participated in resistance training for a minimum of 6 months (age: 21.5 ± 1.7 years; height: 177.3 ± 1.1 cm; weight: 77.2 ± 2.2 kg) were recruited from the local community to participate in this study. The mean physical characteristics of each test group are displayed in Table 1. The study was limited to males to reduce variation in hormonal response to the resistance exercise. All subjects were explained the potential risks and benefits associated with participation in the experiment prior to signing an informed consent, approved by the Institutional Review Board at the University of Texas at Austin.

Procedures

Pre-Screening. Participants reported to the laboratory during the 2 weeks prior to the beginning of the training period to provide background information and health history, to sign consent forms, and to undergo a dual energy X-ray absorptiometry (DEXA) body scan to assess body composition and lean body mass (LBM). Subjects were excluded from the study if they were on any medications that might influence their exercise performance. Subjects were also excluded from the study if they admitted to being on any nutritional or pharmaceutical supplements to enhance muscle mass, strength or athletic performance during the pervious 6 months.

Adaptation and Learning Phase. For 3 weeks, meeting 3 times per week (Monday, Wednesday, Friday, 6:30 AM), the participants underwent adaptive training sessions. Each session was instructed and supervised, with attention paid to proper lifting mechanics and form and appropriate weight selection. The 7 lifts included high pull, flat pull-down, standing overhead press, leg extension, leg curl, leg press, and bench press. These exercises were selected because they incorporated all the large muscle groups of the limbs and trunk, resulting in a major percentage of the total musculature of the body being stressed. The participants’ progress was measured and resistance adjusted via 5RM testing every Friday during the 3 weeks of the adaptation phase.

Diet and Exercise Controls. Following the 3 weeks of adaptation, the participants did not meet the following Monday, to ensure a full and adequate rest and recovery. The subjects were asked to refrain from any resistance work of any kind for the 4 days prior to the testing day. Light aerobic activities were allowed, but complete rest was strongly encouraged, especially on the day prior to testing. Prior to the day of testing, the participants were asked to fast for 12 hours, and the last meal was a standardized meal (Ensure, Abbott Laboratories, Columbus, OH). This was done to minimize the effects on initial blood substrate concentrations and metabolic measurements.

Testing Day (see Figure 1). The testing day occurred on the Wednesday of the fourth week. The subjects arrived and an initial blood sample was drawn (30 minutes pre-exercise). Following this blood draw, the subjects drank 355 ml of their first drink and then rested quietly for 30 minutes. At this time, they received their second blood draw (0 minutes pre-exercise) and consumed 177 ml more of the drink. They then began the lifting session in pairs, in a staggered start, and supervised to insure that every group proceeded through each exercise in a similar sequence. The participants were instructed to lift one warm-up set of 8 repetitions at 80% of their 8RM, then 1 set of 8 repetitions at 100% of their estimated 8RM. For the third set, the resistance was the same as the second set (100% of 8RM), but the subjects were asked to lift as many repetitions until volitional fatigue. Lifts above 8 on the third set were interpreted as an increase in exercise performance. Each pair of participants was given 2 minutes total to complete each set and rest. Typically, each set lasted <20 seconds, followed by a brief time to adjust the partners’ resistance, and then the partner completed his lifts in <20 seconds. Rest intervals between sets thus averaged ~100 seconds per individual. Blood was drawn following the fourth exercise (fourth lift) and the participants drank 177 ml of their drink at this point. Immediately postexercise (0 minutes postexercise), a fourth blood draw was taken and 355 ml of drink provided. The participants remained in the weight room,
resting quietly for 1 hour, after which time another blood draw was taken (1 hour postexercise), and a standardized lunch provided. The subjects were asked to refrain from eating until they returned to the laboratory 5 hours later for a sixth blood draw (6 hours postexercise), after which they could eat freely. A seventh blood draw and postexercise survey were taken 24 hours postexercise (24 hours postexercise). All drinks were provided in absolute volumes rather than as a percentage of body weight to keep the research design as practical as possible.

Measurements

Body Composition. Prior to the adaptation phase of the study, body composition was assessed using the Medical Systems Prodigy Model DEXA unit (General Electric, Madison, WI). This unit is a reliable measure of body composition and is valid to within 1–3% body fat compared to underwater weighing. The machine was calibrated using the calibration block provided by the company (General Electric) every morning prior to each subject being measured. The DEXA is a 3 compartment model design for assessing body composition, dividing the body into bone, fat, and fat-free mass. The total region percentage fat was used to assess the subjects’ body fat level.

Weight-Lifting Capacity. The weightlifting equipment was produced by a variety of manufacturers. Eagle Fitness Systems by Cybex International (Midway, MA) manufactured the hamstring curls machine, leg extension cable machines, and the leg press sled. The latissimus pull-down machine was manufactured by Samson (Las Cruces, NM). Free weights were used for the bench press, high pull, and shoulder press.

Blood Analysis. Blood samples (5 ml) were placed in test tubes (Fischer Scientific, Pittsburgh, PA) cooled on ice, containing 0.2 ml of ethylenediaminetetraacetic anhydride solution (EDTA, 24mg·ml⁻¹, pH 7.4). From each blood draw, approximately 60 µl was removed to analyze blood glucose values using a Basic One Touch blood glucose meter (Life Scan Inc., Milpitas, CA). The validity and reliability of the glucometer were verified prior to its use in the study by comparing values obtained with the glucometer with those from a YSI 23A glucose analyzer (Yellow Springs Instruments, Yellow Springs, OH). Calibration of the glucometer was performed with standards provided by Lifescan, Inc. Each EDTA sample was then separated into 3 chilled 12 × 75 ml tubes, and 0.5 ml was placed in tubes containing 1 ml of 10% perchloric acid (PCA). The sample placed in the PCA tube was then agitated to ensure that the red blood cells were completely ruptured. All collection tubes remained on ice for no longer than 1 hour after which they were centrifuged for 10 minutes at 3,000 rpm at 4°C. Following centrifugation, the plasma was transferred to new 12 × 75 tubes and immediately frozen at −180°C for later analysis. Lactate was determined by enzymatic analysis (13). Cortisol and insulin were determined using a competitive ¹²⁵I radioimmunoassay (MP Biomedicals, Costa Mesa, CA) in which cortisol and insulin were determined using a competitive ¹²⁵I radioimmunoassay (MP Biomedicals, Costa Mesa, CA) in which the plasma hormone competes with its ¹²⁵I-labeled antibody, the greater the plasma hormone concentration. The more ¹²⁵I-labeled hormone displaced from the antibody, the greater the plasma concentration. Following an incubation step, antigen-antibody complexes are isolated by centrifugation and radioactivity counted in a gamma counter (Beckman 5500; Beckman Bioanalytical Systems Group, Fullerton, CA). The percent coefficient of variation (%CV) was 4.22 for insulin and 5.33 for cortisol. Creatine kinase (CK) was determined by enzymatic analysis (Diagnostic Chemicals Limited, Charlottetown, Canada). The conversion of creatine phosphate plus adenosine diphosphate to creatine plus adenosine triphosphate by creatine kinase is linked to several enzyme reactions to produce nicotinamide adenine dinucleotide-reduced form (NADPH). The rate of NADPH is a measure of creatine kinase activity. The rate of NADPH was measured on a Beckman DU640 spectrophotometer (Beckman Bioanalytical Systems Group) at 37°C. The %CV for CK was 2.3. Myoglobin was determined by ELISA (MP Biomedicals, Orangeburg, NY). The test is based on the principle of a solid phase enzyme-linked immunosorbent assay. Mouse monoclonal antimyoglobin antibody is used for solid phase immobilization. Once the myoglobin is immobilized, it is exposed to a second antimyoglobin antibody (goat) with horseradish peroxidase attached. After the myoglobin has reacted with both antibodies, free enzyme-linked antibody is removed by washing and the bound myoglobin is exposed to tetramethyl-benzidine. This reacts with the horseradish peroxidase to form a blue color. The addition of a stop-solution changes the color to yellow. The concentration of the myoglobin is directly proportional to the color intensity. Absorbance is measured spectrophotometrically at 450 nm. All assays were measured in duplicate except creatine kinase, which was measured in triplicate.

Survey

At 24 hours postexercise, the subjects were asked to complete a survey questionnaire that was produced internally by the investigators. The survey was designed to discern some psychological aspects of the study, such as whether the subjects perceived a performance-enhancement from the supplement and whether they had an accurate impression about what supplement they received, as well as some physiological aspects such as fat mass loss at the end of the weight-lifting session and the extent of muscle soreness at the time of filling out the survey. For most questions, the answers were either nominal or ordinal and ranged from 1 to 5.

Statistical Analyses

The study was a double-blind, posttest-only control group design, to test for main and interaction effects (treatment × time). The experimental design was a between-within mixed model design (2 × 7), in which the between-subjects factor was the drink (CHO-PRO or placebo) and the within-subjects factors was timing (blood draws 1–7). Across the time points, the 2 groups differed in the type of drink provided. Statistical significance was set at p ≤ 0.05. All results are presented as means ± standard error of the mean (SEM).

RESULTS

To assess the effect of CHO-PRO supplementation on exercise performance, we provided subjects with a CHO-PRO supplement or placebo before and during exercise on the testing day and asked them to lift to volitional fatigue on the third set of 3 sets, each performed at the subjects’ 8RM. We found that there were no differences in performance between the groups throughout the exercise bout. Exercise performance was similar whether expressed as total weight lifted per exercise (kg) or weight lifted scaled per LBM multiplied by the number of repetitions completed (kg lifted·kg⁻¹ LBM × repetitions) (Table 2).

Results for blood glucose indicated a significant group
<table>
<thead>
<tr>
<th>Exercises</th>
<th>CHO-PRO</th>
<th>Placebo</th>
<th>CHO-PRO</th>
<th>Placebo</th>
<th>CHO-PRO</th>
<th>Placebo</th>
<th>CHO-PRO</th>
<th>Placebo</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>High pull</td>
<td>58.8 ± 2.4</td>
<td>62.5 ± 2.0</td>
<td>48.7 ± 2.0</td>
<td>46.3 ± 2.4</td>
<td>39.3 ± 2.0</td>
<td>39.9 ± 2.2</td>
<td>62.0 ± 2.4</td>
<td>58.7 ± 2.1</td>
<td>65.6 ± 2.1</td>
</tr>
<tr>
<td>Leg curl</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder press</td>
<td>3.9 ± 0.7</td>
<td>4.0 ± 0.9</td>
<td>6.2 ± 0.5</td>
<td>6.5 ± 0.7</td>
<td>5.9 ± 0.7</td>
<td>6.0 ± 0.5</td>
<td>5.9 ± 0.7</td>
<td>5.9 ± 0.5</td>
<td>5.9 ± 0.4</td>
</tr>
<tr>
<td>Leg extension</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Lat pull-down</td>
<td>6.2 ± 0.7</td>
<td>6.0 ± 0.7</td>
<td>11.6 ± 0.4</td>
<td>11.0 ± 0.5</td>
<td>11.0 ± 0.6</td>
<td>10.4 ± 0.6</td>
<td>10.4 ± 0.6</td>
<td>10.4 ± 0.5</td>
<td>10.4 ± 0.5</td>
</tr>
<tr>
<td>Leg press</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Bench press</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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</tbody>
</table>

* Values are mean ± SEM. Weight lifted·kg^1 LBM × repetitions is the weight lifted divided by body mass multiplied by the number of repetitions performed during the third set of an exercise. CHO-PRO = carbohydrate and protein supplement.
levels rose again at 24 hours postexercise, resulting in significantly higher blood cortisol levels in the placebo group.

For the plasma myoglobin response, a significant group × time interaction, a significant main effect for time, and a significant main effect for group were found. There was a significant treatment effect present in the myoglobin response, with the placebo group elevated above the CHO-PRO group. Pre-exercise myoglobin levels were slightly elevated in the placebo group, with significant differences between the placebo and CHO-PRO groups occurring immediately pre-exercise (Figure 6). At the halfway mark of the exercise bout, the placebo group was elevated above the CHO-PRO group ($p = 0.06$). One hour postexercise myoglobin levels were 25% higher in the placebo group compared to the CHO-PRO group ($p = 0.07$). The placebo group had significantly elevated myoglobin levels compared to the CHO-PRO group at 6 hours postexercise ($p < 0.05$), but by 24 hours postexercise, the myoglobin levels were no longer significantly different and were back to baseline values.

For both groups, the general trend was for CK to rise from 30 minutes pre-exercise through 6 hours postexercise, after which the levels fell slightly (Figure 7). There was a dramatic increase in CK levels at 6 hours postexercise in both groups. While CK levels in the placebo group were elevated for the length of the study above those in the CHO-PRO group, these differences reached significance only at 24 hours postexercise.

Survey Data

The survey data showed significant differences between groups to one of the questions, and there was evidence of trends in other questions (Table 3). When asked, “Did the drink affect your performance?” there were significant differences in how the groups replied. A 1 value was coded, “Improved Performance”, a 2 was, “No Change to Performance”, and a 3 was, “Decreased Performance”. Significantly more subjects (n = 10) in the CHO-PRO group thought that the drink improved their performance compared to placebo subjects (n = 3). When asked, “How did you feel upon completing the workout?” with a 1 value being “Strong” and a 6 value being “Very Weak, Sick, Nauseous”, the CHO-PRO group tended to report being less tired immediately postexercise. Subjects in the CHO-PRO group answered on average 2.9, compared to 3.7 for the placebo group. The last 3 questions were asked only to those subjects who participated in the second session of the study. When asked, “Do you presently feel sore, 24 hours after exercise?”, 90% of the CHO-PRO subjects reported being less than or moderately sore, while only 56% of the subjects fed the placebo reported being less than or moderately sore. To the question regarding which drink they thought they received, 3 of the placebo subjects thought that they had received the placebo, 5 subjects were unsure, and 1 thought that he had received the CHO-PRO supplement. Six of the subjects within the CHO-PRO supplement group believed that they had received the CHO-PRO supplement, 3 reported that they were unsure what they received, and 1 reported that he thought he had received the placebo. When asked how certain they were of their answer to which treatment they received, both groups averaged 3.2, where a 3 was coded “Moderately Certain” and a 4 was coded “Unsure”.

![Figure 5](image1.png) **Figure 5.** Plasma cortisol levels for subjects receiving a placebo or carbohydrate and protein (CHO-PRO) supplement at the time points indicated for figure 1. Group means ± SEM are presented at each time point. * Represents significant difference ($p \leq 0.01$) between treatment groups at the corresponding time point.

![Figure 6](image2.png) **Figure 6.** Plasma myoglobin levels for subjects receiving a placebo or carbohydrate and protein (CHO-PRO) supplement at the time points indicated for figure 1. Group means ± SEM are presented at each time point. * Represents significant difference ($p \leq 0.05$) between treatment groups at the corresponding time point. † $p < 0.06$. § $p < 0.07$.

![Figure 7](image3.png) **Figure 7.** Plasma creatine kinase levels for subjects receiving a placebo or carbohydrate and protein (CHO-PRO) supplement at the time points indicated for figure 1. Group means ± SEM are presented at each time point. * Represents significant difference ($p \leq 0.05$) between treatment groups at the corresponding time point.
Table 3. Responses to 24-hour postexercise survey regarding feelings upon completion of the workout.

<table>
<thead>
<tr>
<th>How did you feel upon completing the workout?</th>
<th>Placebo</th>
<th>CHO-PRO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of scores</td>
<td>Percentage</td>
</tr>
<tr>
<td>1 (Strong)</td>
<td>1</td>
<td>6.25%</td>
</tr>
<tr>
<td>2 (Strong, but tired)</td>
<td>4</td>
<td>25.00%</td>
</tr>
<tr>
<td>3 (Tired)</td>
<td>5</td>
<td>31.25%</td>
</tr>
<tr>
<td>4 (Weak)</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>5 (Very weak)</td>
<td>1</td>
<td>6.25%</td>
</tr>
<tr>
<td>6 (Very weak, sick, nauseous)</td>
<td>5</td>
<td>31.25%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Do you presently feel sore, 24 hours after exercise?</th>
<th>Placebo</th>
<th>CHO-PRO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of scores</td>
<td>Percentage</td>
</tr>
<tr>
<td>1 (Not sore at all; fresh)</td>
<td>1</td>
<td>11.11%</td>
</tr>
<tr>
<td>2 (Slightly sore; fairly fresh)</td>
<td>1</td>
<td>11.11%</td>
</tr>
<tr>
<td>3 (Moderately sore)</td>
<td>3</td>
<td>33.33%</td>
</tr>
<tr>
<td>4 (Sore)</td>
<td>4</td>
<td>44.44%</td>
</tr>
<tr>
<td>5 (Very sore; ouch)</td>
<td>0</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Did the drink affect your performance?</th>
<th>Placebo</th>
<th>CHO-PRO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of scores</td>
<td>Percentage</td>
</tr>
<tr>
<td>1 (Improved performance)</td>
<td>3</td>
<td>18.75%</td>
</tr>
<tr>
<td>2 (No change to performance)</td>
<td>13</td>
<td>81.25%</td>
</tr>
<tr>
<td>3 (Decreased performance)</td>
<td>0</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

*N = 33 for the first and third questions and n = 19 for the second question. *p < 0.05 between two treatments. CHO-PRO = carbohydrate and protein supplement.

Discussion

The purpose of this study was to examine the effects of consuming a CHO-PRO supplement compared to placebo prior to, during, and following an acute bout of resistance training on exercise performance and muscle damage. By measuring both hormonal and muscle damage indices postexercise, we hoped to elucidate some of the potential mechanisms for differences seen in the muscle damage responses. We found that a CHO-PRO supplement provided prior to, during, and following an acute bout of resistance training had no effect on exercise performance, but did appear to significantly reduce muscle damage compared to consumption of a placebo at those same times.

In all formats that exercise performance was expressed, whether as total weight lifted or total weight lifted scaled per kg LBM times the number of repetitions, the performances between the groups were remarkably similar. To help explain why no benefit to exercise performance was seen with supplementation, we relied on the review article by Haff et al. (10). They analyzed the confounding results from all of the studies involving CHO-only supplementation and work. There were two factors that Haff et al. (10) highlighted as necessary for a CHO-only supplement to increase exercise performance: (a) the work bout had to exceed 50 minutes in duration, and (b) the exercises had to focus on one main group of muscles, in order to sufficiently deplete muscle glycogen stores. While the exercise bout in our study did last longer than 50 minutes (subjects completed the sequence of lifts in ~60 minutes), the exercises selected during this study incorporated the entire body, not relying solely on one muscle group. While this protocol may not have limited glycogen depletion in selected fiber types (31), it would limit the amount of time each muscle group was used during exercise and thereby limit the influence of substrate availability on performance.

While selected muscle fiber type glycogen depletion could have limited performance, we believe fatigue was most likely due to the built up of local metabolites such as lactic acid and the depletion of high-energy phosphates. Supporting evidence for this assertion comes from the peak lactate values, which were achieved immediately post-exercise. For the CHO-PRO group, peak lactate values were 10.63 ± 0.58 mmol·L⁻¹, and for the placebo group the peak lactate response was 10.18 ± 0.69 mmol·L⁻¹. Given the design of our study, with the rather short rest periods of ~1.5 minutes between sets, it is highly likely that local lactate concentrations rose with each sequential set within an exercise. By the third set of each exercise, the concentration of lactic acid and possibly depletion of creatine phosphate stores within muscle would have prevented the subjects from completing more repetitions.

As exercise performance was not different between groups, any difference found in muscle damage between groups would likely be due to an intervention effect and would not have been confounded by increased work in one group. The major finding of our study was that muscle damage as indicated by muscle enzyme release was significantly reduced postexercise when a CHO-PRO supplement was consumed prior to, during, and immediately postexercise compared to placebo. Subjects who received the CHO-PRO supplement as opposed to the placebo, reported less muscle soreness, also suggesting reduced muscle damage. We used the 24-hour postexercise survey to assess muscle soreness in the subjects. Muscle soreness is known to typically reach its peak between 24 and 48 hours postexercise. While there were no significant differences between the groups, 90% of the CHO-PRO subjects reported being less than or moderately sore, while within the placebo group, only 56% of the subjects reported being less than or moderately sore, and the remaining 44% reported being sore or very sore. Again, while our survey results did not reach significance, they were similar to the results seen by Flakoll et al. (7) in that supplementing with CHO-PRO reduces reported muscle soreness compared to placebo.

To sufficiently quantify muscle damage we used both plasma myoglobin and creatine kinase (CK) levels as indices of muscle damage, due to their different time courses in muscle release. Myoglobin, with a smaller molecular mass of 17 kDa, is both released quicker from damaged muscle and disappears more readily (through renal ex-
Myoglobin was significantly elevated in the placebo group immediately prior to exercise, and while it was statistically significant, it was not physiologically significant, and this initial discrepancy did not influence later differences observed in the study. As myoglobin is a faster appearing index of muscle damage, it was not surprising that elevations approaching significance in myoglobin ($p = 0.06$ and $0.07$, respectively) were observed half-way through the exercise bout (fourth exercise) and at 1 hour postexercise in the subjects receiving placebo compared to those receiving the CHO-PRO. Significance was reached at 6 hours postexercise, with the placebo subjects having elevated myoglobin over the subjects receiving the CHO-PRO, but this difference was eliminated by 24 hours postexercise. These differences carried over to an overall significant treatment effect in the myoglobin response to exercise, with those subjects receiving the placebo having elevated myoglobin compared to those subjects receiving the CHO-PRO supplement.

Comparatively, creatine kinase has difficulty entering the microvascular endothelium directly because of its larger molecular mass of 80 kDa. Instead, creatine kinase is thought to be picked up by the lymphatic system before entering the bloodstream. Due to this longer route, creatine kinase has a longer latency period before appearing in the bloodstream, typically 24–48 hours postcentric exercise, with peak levels occurring 96–120 hours postcentric exercise (24, 29).

Elevated CK levels 24 hours postexercise have been postulated to be caused by elevated cortisol (16, 18). In a study by Kraemer et al. (16), which compared resistance loads and rest intervals in 6 different resistance exercise protocols, they were able to find a correlation of 0.84 between the peak cortisol response 5 minutes postexercise and the peak CK concentration 24 hours postexercise. A similar relationship was found in a second study (18), where they had subjects perform 4 sets of 10 repetitions at the subjects’ 10RM of both upper and lower body exercises. This protocol was repeated over 3 consecutive days; the largest cortisol response occurred postexercise on the first day, and the largest CK response was seen immediately postexercise on the second day. Cortisol is a strong catabolic hormone, and Kraemer et al. (16, 18) postulated that it was the catabolic effects of cortisol, which caused the large muscle damage, resulting in high CK in the bloodstream the following day.

Similar to the two studies by Kraemer et al. (16, 18), cortisol levels were elevated at 0 and 1 hour postexercise, as well as during exercise, in our study. While the levels were above baseline at these time points, the elevation was not significantly different between the two treatment groups. The only time that cortisol was significantly different between treatment groups was at 24 hours postexercise, when the placebo group was significantly elevated over the CHO-PRO group. The creatine kinase response mirrored the cortisol response; there were no significant differences in CK levels between the groups until 24 hours postexercise, when the placebo group had significantly elevated CK levels compared to the CHO-PRO group. With no significant differences between groups immediately postexercise and significant elevations in CK at 24 hours postexercise, it is difficult to argue that the potentially greater muscle damage in the placebo group was due to the catabolic effects of cortisol in our study. We believe that the significant elevation in cortisol at 24 hours postexercise in the placebo group, which was accompanied with a significant elevation in CK at the same time point, was in response to the elevated muscle damage and not its cause. The finding that myoglobin was elevated during placebo when there were no differences in cortisol would also suggest that cortisol was not responsible for muscle damage. Most likely, muscle damage was due to mechanical stress, resulting in the tearing of individual muscle fibers and increased muscle degradation.

However, significant differences between treatment groups for insulin were seen during and following exercise. Insulin was significantly elevated immediately preexercise, after the fourth lift, and 0, 1, and 6 hours postexercise in the CHO-PRO group compared to the placebo group. We would argue that it is potentially the anabolic effects of insulin that are responsible for the differences in muscle damage seen between the 2 groups postexercise.

Research indicates that insulin acts both through increasing rates of protein synthesis and by decreasing rates of protein breakdown to reduce muscle damage following resistance exercise (1, 3, 26). Biolo et al. (3) have shown that insulin is strongly anabolic postexercise and can reduce muscle protein breakdown. Prior to exercise, the researchers started infusion of several tracer amino acids, and then had the subjects complete a bout of resistance exercise. Following the exercise bout, they infused insulin for 3 hours. Insulin infusion significantly reduced protein breakdown. Separate findings by Gelfand et al. (8) regarding the action of insulin support these findings. They infused insulin for 2 hours in resting subjects and found a significant reduction in the rate of protein breakdown.

By reducing the amount of protein degradation resulting from resistance exercise and limiting muscle damage, it would be possible to limit the amount of efflux out of the muscle of both myoglobin and CK. If insulin also increased the rate of protein synthesis, this could enhance the rate to tissue repair and limit the amount of CK leakage, but this process would probably be too slow acting to affect the response of myoglobin, given its small size and quick time response compared to CK.

It is also possible to increase skeletal muscle protein synthesis independent of increasing plasma insulin by providing appropriate amino acids following exercise. Biolo et al. (2) infused amino acids following a resistance exercise bout and reported a large increase in protein synthesis compared to rest. In a study by Tipton et al. (32) consuming 40g of essential amino acids (EAs) post-resistance exercise training nonsignificantly increased protein synthesis, but did significantly increase net protein balance compared to a placebo feeding, and Borsheim et al. (4) found that feeding subjects 6 g of EAs at 1 and 2 hours postresistance exercise significant increased protein synthesis and net protein balance. Moreover, Miller et al. (22) found significant increases in protein synthesis when subjects were fed 0.087 g·kg$^{-1}$ of EAA following a bout of resistance exercise.
Reports of the largest increases in protein synthesis come from studies that incorporate both the elevation of insulin along with provision of amino acids. In the above study by Miller et al. (22), increased synthesis rates when fed amino acids only was not as robust as when supplementing with a mixture of carbohydrate and essential amino acids. In fact, protein synthesis rates were additive for the carbohydrate and amino acids supplement compared with the carbohydrate-only and amino acids-only supplements. Levenshagen et al. (20) and Koopman et al. (15) observed similar results. Following a 60-minute bout of cycling exercise, Levenshagen et al. (20) provided subjects with placebo, a CHO supplement, or a CHO-PRO supplement. Leg protein synthesis rates following CHO-PRO supplementation improved 600% compared with placebo and 400% compared with CHO-only supplementation. Koopman et al. (15) were able to demonstrate a significantly reduced whole body protein breakdown and a significantly increased whole body protein synthesis by feeding subjects a CHO-PRO or CHO-PRO-leucine supplement in comparison to providing a CHO-only supplement following a resistance exercise bout. Furthermore, van Loon et al. (34) found a significant negative correlation between the insulin response and plasma levels of select amino acids after subjects cycled for ~90 minutes of interval-based activity and were fed CHO-only or CHO-PRO supplements postexercise. The greater the insulin response to the feedings, the greater the protein synthesis response, as evidenced from the decrease in plasma amino acids.

The major findings of this study were that providing a CHO-PRO supplement before and during a resistance exercise session does not increase work capacity, but does appear to significantly reduce muscle damage, as evidenced by responses of both myoglobin and creatine kinase. The muscle damage could potentially have been reduced by suppressing the cortisol response to exercise, but probably was more influenced by the CHO-PRO supplement-induced elevation in plasma insulin during exercise and the first 6 hours of recovery. It is possible that an elevation in plasma amino acids could have stimulated protein synthesis and thereby reduced muscle damage as well.

**PRACTICAL APPLICATIONS**

It is the goal of competitive athletes to train at high-intensity exercise bouts as frequently as possible, to maximize and optimize both the training stress and the adaptation response. By consuming a CHO-PRO supplement similar to the one used in our study at a similar schedule during exercise, athletes can significantly reduce the amount of muscle damage produced in a given resistance exercise bout. By minimizing the amount of muscle damage created, athletes should be able to reduce the length of the recovery phase following exercise, and allow the athlete to participate in the next high-intensity exercise bout in a shorter period of time. Reducing muscle damage, enhancing the recovery process and reducing stress of exercise are also important considerations for individuals just starting an exercise training program or who regularly engage in resistance training. Therefore, a recommendation for CHO-PRO supplementation can be made for novice lifters, and individuals who are actively engaged in a resistance training program. One should, however, be cognizant of the amount of carbohydrate being consumed around their workout and factor this amount into his or her overall dietary plan.

**REFERENCES**


Acknowledgments

We would like to thank the many subjects that participated in this study and the technical help of Kim Beckwith and Lynn Cialdella. This research was funded by a grant from Pacific Health Laboratories, Inc. Bongan Kwon, Ph.D. was a visiting scholar from The Korean National University of Physical Education, Seoul, Korea.

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**Effect of glucose supplement timing on protein metabolism after resistance training**

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Department of Kinesiology and Department of Neurology and Physical Medicine and Rehabilitation, McMaster University, Hamilton, Ontario, Canada L8S 4K1; and Metabolism Division, Washington University School of Medicine, St. Louis, Missouri 63110

**Abstract**

We hypothesized that a CHO supplement consumed immediately after resistance exercise would result in 1) decreased urinary 3-methylhistidine (3-MH) excretion (a marker of MPD), 2) increased muscle [13C]leucine incorporation rate (increased FSR), and 3) decreased urinary urea nitrogen excretion (net positive protein balance).

**Methods**

Subjects. Eight healthy young (aged 20–25 yr) men who had been participating in a resistance training program for at least 1 yr before the investigation (≥2 times/wk) were recruited as subjects (Table 1). The experimental procedures, possible risks, and benefits were explained to each volunteer before written consent was obtained. The study was approved by the McMaster University Human Ethics Committee.

Design. Each subject participated in a placebo-controlled randomized double-blind trial with a postexercise CHO supplement and a placebo (Nutrasweet; Pl) trial. They performed unilateral knee extensor exercise such that the muscles of the nonexercised limb served as a control (exercise (Ex) and rest (Con) leg). One week before the two trials, the subjects’ single maximal repetition (1 RM) strength was determined for knee extension and leg press, and their body density was determined by hydrostatic weighing. In addition, subjects completed 4-day diet records, which were analyzed by using a nutritional analysis software package (Nutritionist III, First Data Bank, San Bruno, CA). From this, a dietary checklist was created for each subject. The diets were isoenergetic, whole body protein synthesis rate (WBPS) and amino acid flux compared with sedentary individuals (23). These inconsistencies may relate to the availability of amino acids and energy status during the hyperinsulinemic state (2).

It appears that, when insulin is combined with increased amino acid delivery, FSR and WBPS are increased (2). The importance of insulin in suppressing or attenuating the increase in MPD after exercise may be of particular importance in the postexercise period (4).

Studies to date have not addressed the potential interaction of resistance exercise and insulin/nutritional state on leucine turnover/protein balance. Because insulin may cause a decrease in MPD, and a possible increase in FSR, and resistance exercise is known to increase FSR, it is possible that insulin could decrease MPD and increase FSR simultaneously after a bout of resistance exercise. If the latter occurs in combination with the increase in FSR due to the exercise (4, 6), the net protein balance would be even more positive, thus resulting in a greater net accretion of myofibrillar protein. The consumption of a carbohydrate (CHO) supplement is a simple method of increasing insulin concentrations after exercise (9, 32).

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**Muscle Growth**

In adult humans results from muscle fiber hypertrophy (11). Hypertrophy is the result of an increased net muscle protein balance (i.e., increased muscle protein synthetic rate (FSR) – muscle protein degradation rate (MPD)). Both FSR (4, 6, 30) and MPD (4) can be stimulated by heavy-resistance exercise in humans. It is also known that amino acid transport is independent laboratories has shown that FSR was increased after resistance exercise (3). Further understanding of the factors influencing net protein balance may allow the ability to maximize FSR and minimize MPD, thus maximizing the rate and amount of muscle hypertrophy.

Research in the area of resistance training and its effects on FSR and MPD is limited. Recent work from independent laboratories has shown that FSR was elevated after a bout of resistance training in humans (4, 6). Net protein balance, although more positive, was still negative after resistance exercise in the fasted state (4). In addition, it has been demonstrated that in the fed state, strength-trained individuals have a net positive whole body protein balance and an elevated whole body protein synthesis rate (WBPS) and amino acid flux compared with sedentary individuals (23). These inconsistencies may relate to the availability of amino acids and energy status during the hyperinsulinemic state (2).

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Studies to date have not addressed the potential interaction of resistance exercise and insulin/nutritional state on leucine turnover/protein balance. Because insulin may cause a decrease in MPD, and a possible increase in FSR, and resistance exercise is known to increase FSR, it is possible that insulin could decrease MPD and increase FSR simultaneously after a bout of resistance exercise. If the latter occurs in combination with the increase in FSR due to the exercise (4, 6), the net protein balance would be even more positive, thus resulting in a greater net accretion of myofibrillar protein. The consumption of a carbohydrate (CHO) supplement is a simple method of increasing insulin concentrations after exercise (9, 32).

We hypothesized that a CHO supplement consumed immediately after resistance exercise would result in 1) decreased urinary 3-methylhistidine (3-MH) excretion (a marker of MPD), 2) increased muscle [13C]leucine incorporation rate (increased FSR), and 3) decreased urinary urea nitrogen excretion (net positive protein balance).
had been achieved (23). Immediately after exercise (−1900; t = 0), a blood sample was drawn, a muscle sample was taken from the vastus lateralis muscle of each leg (post-Ex, post-Con0) by using a suction-modified Bergstrom biopsy needle (Still), and the glucose (1 g/kg) or Nutrasweat drink was consumed. Blood samples (4 ml) were collected every 15 min for the next hour and immediately centrifuged and stored at −50°C. At ~2030 (t = +1 h) a second CHO (1 g/kg) or PI drink was administered. Blood samples were again collected every 15 min for the next 1.5 h and again at ~0400, 0430, and 0500 the next morning. Final biopsy specimens were taken at ~0500 (post-Ex10, post-Con10; −10-h incorporation time). The subjects also collected all urine excreted during the 24-h period (−12 h pre-Ex, −12 h post-Ex) for subsequent creatinine, 3-MH, and urea nitrogen determination. Sample collection began in the morning (0600) of the trial (first urination not collected) and continued through to the following morning (0600). Diets were isoenergetic and isonitrogenous during this collection period. The subjects did not leave the laboratory until the final urine sample was collected.

Analysis. Visible fat and connective tissue were removed from the muscle samples, which were then quenched in liquid nitrogen and subsequently stored at −70°C. The L-[1-13C]leucine enrichment in mixed muscle protein was determined by using gas chromatography/combustion/isotope ratio mass spectrometry (GC/IRMS) as described by Yarasheski et al. (29). Blood was analyzed for plasma glucose [kit 315, coefficient of variation (CV) = 3.9%, Sigma Diagnostics, St. Louis MO] and insulin concentration (radioimmunoassay, CV = 2.9%, Diagnostic Products, Los Angeles, CA). Plasma α-[13C] ketoisocaproic acid (α-KIC) was prepared as the trimethylsilylquinoxalinol derivative. Its isotopic enrichment was determined with the use of electron-impact ionization capillary gas chromatography/mass spectrometry (GC/MS) by using selected ion monitoring of mass-to-charge ratio 233/232. Urinary urea nitrogen and creatinine excretion were determined from aliquots of the 24-h urine collections by using colorimetric methods as described by Tarnopolsky et al. (23) (kits 640 and 555, CV = 4.7 and <1%, respectively, Sigma Diagnostics). 3-MH concentration was determined by using an automated amino acid analyzer and was normalized to the 24-h urinary creatinine excretion (Beckman Instruments, Palo Alto, CA).

Calculations. Muscle FSR was calculated according to the equation

$$FSR = \frac{(L_{em} \times 100)}{(K_{ep} \times t)}$$

where muscle protein FSR is measured in percentage per hour, t is the incorporation time (in h) between muscle samples taken from the same leg, L_{em} is the increment in 13C abundance in leucine from mixed muscle protein obtained...
between the muscle samples removed from each leg, and $K_{ep}$
is the mean plasma $\alpha$-$[13]$C[KIC enrichment for $t = 2.5\text{--}10\text{--}10.5$-h blood samples (corrected for natural abundance of $\alpha$-$[13]$C[KIC in the $t = 0$h blood sample). Leucine flux ($Q$) was calculated by using the reciprocal pool model ($\hat{Q}$), at isotopic plateau

$$\hat{Q} = i[(E_i/E_p) - 1]$$

where $i = \alpha$-$[13]$C[leucine infusion rate ($\mu$mol $\cdot$ kg$^{-1}$ $\cdot$ h$^{-1}$)], $E_i$ is enrichment of the infused leucine, $E_p$ is enrichment of the plasma $\alpha$-$[13]$C[KIC (atom percent excess), and the term “−1” corrects for the contribution of the infused isotope to $Q$. The rate of whole body protein degradation (WBPD) was estimated from $Q$ based on the equation

$$\hat{Q} = B + I$$

where $B$ is the rate of appearance of endogenous leucine, and $I$ is the dietary leucine intake. Because the subjects had no dietary intake of leucine during the infusion, $I = 0$; thus $B = \hat{Q}$.

Statistical analysis. Muscle and blood data were analyzed by using repeated-measures analysis of variance (time $\times$ treatment; GB-STAT version 5.30, Dynamic Microsystems). When a significant interaction occurred, Tukey’s post hoc analysis was used to locate the pairwise differences. Area under the curve (insulin, glucose) was calculated with a custom-made software package. Urine and area under the curve data were analyzed by using paired $t$-tests. $P < 0.05$ was selected as being indicative of statistical significance. Values are expressed as means $\pm$ SE.

RESULTS

There were no differences in plasma insulin concentrations at the beginning ($t = -1.5$ h) and end of the infusion ($t = -10$ h; CV = 2.9%). Plasma insulin concentrations were significantly higher for the CHO compared with the Pl condition at the +0.5-, +0.75-, +1.25-, +1.5-, +1.75-, and +2.0-h time points ($P < 0.01$) (Fig. 1). The area under the insulin curve over the first 2.5 h was 4 times greater for the CHO condition compared with Pl [65.2 $\pm$ 12.1 $\mu$U $\cdot$ ml$^{-1}$$\cdot$ h$^{-1}$ for CHO and 15.2 $\pm$ 2.1 $\mu$U $\cdot$ ml$^{-1}$$\cdot$ h$^{-1}$ for Pl ($P < 0.01$)] (Fig. 2).

Plasma glucose concentrations were not significantly different between CHO and Pl before the beginning of ($t = -1.5$ h) and at the end of the isotope infusion (Fig. 3). At the completion of exercise, plasma glucose levels were greater than baseline values for both the CHO and Pl conditions [6.26 $\pm$ 0.40 to 6.73 $\pm$ 0.54 mmol/l for CHO and 5.70 $\pm$ 0.55 to 6.50 $\pm$ 0.25 mmol/l for Pl ($P < 0.05$)]. Plasma glucose concentration was also significantly higher ($P < 0.01$) at +0.5 and +0.75 h in the CHO condition compared with Pl. The area under the curve for glucose in the first 2.5 h was significantly greater for CHO compared with Pl ($P < 0.01$; CHO = 7.21 $\pm$ 0.43 mmol $\cdot$ h$^{-1}$ $\cdot$ l$^{-1}$ and Pl = 5.88 $\pm$ 0.16 mmol $\cdot$ h$^{-1}$ $\cdot$ l$^{-1}$) (Fig. 4).

Twenty-four-hour urinary creatinine excretion was not significantly different between the two conditions ($n = 7$; 1.76 $\pm$ 0.15 g/24 h for CHO and 1.70 $\pm$ 0.09 g/24 h for Pl). Because these values were not significantly different, the remainder of the urinary results were expressed relative to the creatinine values. 3-MH excretion was significantly lower for the CHO condition vs. PI (Fig. 5A). A similar difference was observed for urinary urea nitrogen ($P < 0.05$; $n = 7$; CHO = 8.60 $\pm$ 0.66 g/g creatinine and Pl = 12.28 $\pm$ 1.84 g/g creatinine) (Fig. 5B).

Plasma $\alpha$-$[13]$C[KIC enrichment at each sampling point is shown in Fig. 6 ($n = 7$). Isotopic equilibrium was achieved for each individual subject (CV = $<10\%$, slope = not significant (NS)) and maintained for the duration of the infusion, as expected from previous work (24).

Compared with the control leg muscle, FSR in the exercised vastus lateralis muscle was elevated by 36.1% in the CHO condition and by 6.3% in the Pl condition (NS; $n = 6$) (Fig. 7).

No significant difference was observed for whole body leucine flux between the two conditions ($n = 7$; 115.37 $\pm$ 5.65 $\mu$mol $\cdot$ kg$^{-1}$ $\cdot$ h$^{-1}$ for CHO and 113.07 $\pm$ 4.05 $\mu$mol $\cdot$ kg$^{-1}$ $\cdot$ h$^{-1}$ for Pl).
DISCUSSION

The purpose of this investigation was to determine the effect of glucose supplementation timing when given immediately after a bout of resistance exercise on FSR, MPD, WBPD, and urinary urea excretion. A glucose supplement of 1 mg/kg (immediately and +1 h postexercise) resulted in a significant increase in plasma glucose and insulin concentrations as seen by others (9, 32). This was associated with less urinary 3-MH and urea nitrogen excretion, with no difference in vastus lateralis FSR or WBPD. The net effect was anabolic and would result in a more positive net muscle protein balance.

Most of the work in the area of insulin and its effects on protein turnover has involved the use of insulin and glucose infusions (3, 13, 14, 17). The present study is the first report in humans of the influence of oral glucose supplementation on post-resistance-exercise protein metabolism and has practical implications for athletes and persons performing therapeutic exercise. The positive effects of supplementation on protein metabolism were achieved from a simple redistribution of the timing of the subject’s habitual caloric intake.

The administration of a CHO drink led to a significant decrease in urinary 3-MH excretion over the day of the study. We interpreted this as a reduction in MPD. This finding is supportive of some (13, 18) but not all (3, 14) previous studies of the effect of elevated insulin on MPD. An advantage of 24-h urinary 3-MH excretion over the arteriovenous balance technique is the length of time over which the determination occurs. The
The decrease in 3-MH excretion was accompanied by significantly lower urinary urea nitrogen excretion, which suggested a reduction in amino acid transamination and oxidative deamination because urinary urea excretion is determined by the concentration of urea in the plasma and the glomerular filtration rate (7). We assumed that the glomerular filtration rate for each subject was similar between trials because dietary energy, protein, fluid intake, and exercise were identical for each condition. Furthermore, there were no differences in creatinine excretion, and both urea and 3-MH were expressed relative to this. Thus, assuming that sweat and fecal loss did not differ between the two trials (19, 25), whole body nitrogen balance would be more positive for the CHO condition.

Differences in WBPD were not observed between conditions. It appears the CHO treatment did not provide enough of a reduction in MPD to influence WBPD. However, FSR contributes ~25% to WBPS (15), and one could estimate that only ~7% of the total muscle mass was active during the exercise. Therefore, changes in MPD may have contributed too little to influence WBPD due to a dilutional effect. A similar protocol with the use of a whole body exercise stimulus (vs. single leg) may have shown an effect of MPD on WBPD. Alternatively, protein degradation in non-skeletal muscle tissue (i.e., splanchnic) may have changed in an opposite direction and attenuated the influence of MPD on WBPD (28).

Furthermore, the WBPD measurements were taken from a-[13C]KIC collected immediately postexercise and near the termination of the infusion (t = +10 h; fasted state). It is probable that for the CHO trial there was a reduction in WBPD during the period of hyperinsulinemia postexercise (~2 h) and for the Pl postbreakfast (2 g/kg CHO) (14). WBPD measurements would have to have been taken for ~3 h after each of these time periods to determine whether WBPD was more sensitive to the effect of insulin in the postexercise period. The 3-MH data and the reduction in urea excretion suggested that this may have been the case.

We found that the rates of FSR remained unchanged in response to the administration of CHO. A trend was observed in that the CHO condition led to a nonstatistically significant 36% increase in the difference between the exercise leg and the rest leg (Fig. 7). A positive effect of insulin on FSR has been described by others (3, 17). One factor that may have attenuated an increase in FSR was the fact that the glucose supplement likely caused a decrease in plasma amino acid availability due to elevated insulin. It has been demonstrated that the positive effect of insulin on FSR is seen predominantly with concomitant hyperaminoacidemia (2, 3, 17). Another factor that may have attenuated a positive response from the postexercise glucose supplement was the fact that the insulin was only significantly increased for ~2 h after the supplementation, whereas the incorporation time was 10 h. Future studies should use methods that can determine FSR over a period of ~4 h (3, 4).

Unforeseen sampling errors led to a decrease in the sample size for the FSR analysis (n = 6). Therefore, a type II error may also explain the lack of significant increase. In addition, the exercise stimulus might not have been sufficient to stimulate an increase in FSR in the vastus lateralis. We have previously reported an increase in FSR by using a greater volume of training in a fusiform muscle (biceps brachii) after training (6). Because the vastus lateralis is a pennate muscle that contributes to both knee stabilization and extension,
the force/unit area may have been less than in our previous study using the biceps brachii. A study of female swimmers also found no effect of resistance exercise on FSR by using a muscle that is difficult to fully activate (posterior deltoid) (26). This same group, however, found an increase in FSR in the vastus lateralis by using an almost identical intensity and volume of resistance exercise (4). It should be noted, however, that the subjects in the latter study were untrained (4), and it is possible that this may partially explain the discrepant results. A third possibility is that our measurement of FSR over a 10-h period immediately after exercise may not have included the time points over which FSR is maximal. We know from previous studies that FSR appears to peak at ~24 h after exercise (12).

In summary, our results indicate that consumption of a 1 g/kg CHO supplement immediately and 1 h after exercise (12) may not have included the time points over which FSR is maximal. We know from previous studies that FSR appears to peak at ~24 h after exercise (12).

REFERENCES


Creatine supplementation nullifies the adverse effect of endurance exercise on the subsequent strength performance

Rodrigo Vitasovic Gomes¹ and Marcelo Saldanha Aoki¹,²

ABSTRACT

Objective: The objective of this study was to verify if creatine supplementation exerts an ergogenic effect during concurrent exercise. Methods: Sixteen female university students were divided into two groups: placebo (P) and creatine supplemented (CRE). The participants received 20 g of placebo or creatine for five days and 3 g for the following seven days in a double-blind design. Before supplementation, the participants were submitted to a 1-RM test in the leg press followed by maximum repetition test (three sets of repetitions-to-fatigue, performed at 80% of the 1-RM and separated from 150 seconds of recovery – P: 1st set: 9.0 ± 2.4; 2nd set: 8.9 ± 2.9 and 3rd set: 8.3 ± 3.3 and CRE: 1st set: 10.2 ± 2.2; 2nd set: 9.8 ± 2.9 e 3rd set: 9.7 ± 3.5 reps). After 12 days of supplementation, the participants were submitted to aerobic test in which they were instructed to cover the maximal distance as possible in 20 min. Subsequently, the participants were submitted to 1-RM test once again followed by the maximum repetition test. Results: No differences were observed in the aerobic task performance and in the 1-RM test. After the aerobic test, a decline on the repetition maximum capacity was observed during the last two sets in P (Reps – P: 1st set: 7.6 ± 2.6; 2nd set: 4.3 ± 2.9*; p < 0.01 and 3rd set: 4.6 ± 2.3*; p < 0.01). This reduction was not observed in CRE (Reps – CRE: 1st set: 10.9 ± 2.9; 2nd set: 9.5 ± 2.7 and 3rd set: 9.0 ± 3.0). Conclusions: There is a hypothesis that the performance of resistance exercise is reduced by a residual fatigue from the previous aerobic exercise bout. One of the peripheral causes of acute fatigue during resistance exercise is related to creatine-phosphate depletion. Probably, the supplementation-induced greater muscle creatine-phosphate content accelerates the recovery and the ATP re-phosphorylation, serving as an additional energetic substrate during concurrent exercise.

INTRODUCTION

In the last decades, several studies have investigated the effect of the concurrent training, in which endurance and resistance exercises are performed concurrently at the same training session.¹ Once athletes and individuals physically active adopt this training strategy, there is a great interest in relation to the interference the former activity would exert on the subsequent one.

Results obtained in our laboratory demonstrated that the endurance exercise (70% of the VO₂max for 45 minutes in treadmill) provokes a reduction on the performance of the subsequent maximum repetition test in the leg press at 45°. Other studies corroborate our findings that the aerobic exercise affects the subsequent strength and power development when endurance exercise is previously performed.¹

In another study, it was observed that the resistance exercise (six series of maximum repetitions in the leg press at 45° with three series at 60% of the 1-RM value and the other three series at 90% of the 1-RM value) did not interfere on the posterior aerobic power performance.⁵ These results are also corroborated by other researches that demonstrated that the aerobic power performance does not seem to be influenced by the previous execution of resistance exercises⁴-⁸.

However, the literature presents conflicting results.¹ Some researches suggest the non existence of interference from the concurrent training on the aerobic power or strength performance.⁸-¹² However, in a study conducted by Nelson et al., it was demonstrated that the performance of concurrent training hinders the aerobic power development. This controversy may be related to the adaptation level to the concurrent training stimulus. It seems that individuals adapted to the concurrent training undergo less interference in relation to untrained individuals.³,¹⁴. Other factors also contribute for the discrepancy of results obtained by researches that analyzed concurrent training such as the exercise protocols used and the organization of their variables (intensity, duration and frequency).¹⁵

Currently, the most consistent data on the concurrent training indicates that this strategy lessens the power and strength gains when compared to the resistance training alone.⁴-⁸

There are two hypotheses to explain this harmful interference from the concurrent training. These hypotheses are related to acute or chronic processes.¹,¹⁸ The chronic hypothesis consists of the idea that after the concurrent training, the muscle would try to adapt itself to both stimuli. However, this is not possible because the endurance training-induced chronic adaptations are frequently inconsistent with adaptations observed during the resistance training. According to the chronic hypothesis, the combination of these two different stimuli could affect the development of these two physical capacities (aerobic power and strength) due to the fact that both induce to different adaptations.¹,⁴,⁵,¹⁰

With relation to the acute hypothesis, it is based on the idea that the former activity would lead to a residual fatigue. This fatigue would hinder the performance of the subsequent activity through alterations on the energetic metabolism (lower substrate availability, acidosis, increase on the ammonia concentration).¹¹

Considering that the acute hypothesis is a possible explanation for the interference observed in the concurrent exercise, two studies using carbohydrate supplementation during concurrent exercises were performed.²,⁸ In both studies, the carbohydrate intake exerted no ergogenic effect²,³.
These results led us to consider that the availability of other energetic substrate would be the limiting factor for the performance of the subsequent resistance exercise. Considering that the creatine-phosphate contributed significantly for the performance of the high-intensity exercise, the objective of this work was to verify the effect of the creatine supplementation on the performance of the concurrent exercise (endurance exercise performed previously to the 1-RM test and the maximum repetition test performed at 80% of the 1-RM value).

METHODOLOGY

Sample

Sixteen female Physical Education students (20.1 ± 1.9 years) from the UniFMU University Center were selected. The practice of strength exercises at least three times a week as well as endurance exercises for at least 30 minutes in alternated or simultaneous days was established as inclusion criterion. Other criterion adopted for the participation in this study was the minimum period of 12 months of previous experience in strength training. The sample selection was performed by means of a questionnaire in which the consumption of other nutritional supplements and controlled substances was evaluated. The experimental protocol was approved by the Ethics Committee in Researches involving human beings (CEPSH) of the Biomedics Sciences Institute – University of São Paulo (Nº 051.00). The experiments were conducted according to specific resolution of the National Health Council (Nº 196/96). All individuals were informed in details on the procedures used and agreed in participating voluntarily in the study, signing a term of free and informed consent and privacy protection.

Determination of 1-RM and maximum repetition capacity

After a quick warm up exercise, the 1-RM value was determined through three increasing attempts in the leg press exercise at 45°. Later, the percentile value equivalent to 80% of the 1-RM value was calculated for the performance of the three maximum repetition sets with intervals of 150 seconds.

Endurance exercise

The exercise protocol adopted consisted of 20 minutes running in delimited track field in which the subjects ran the longest distance as possible in 20 minutes. As the exercise maintained a constant step rhythm during the entire activity, the test started with a command voice “ready, go”, with chronometer turned on simultaneously. The test ended with a whistle sound.

Supplementation protocol

The participants were divided into two groups randomly selected. The creatine supplementation (or placebo) was conducted according to double-blind design. In the first phase (overload), 20 grams a day of creatine (or placebo) were administered, being divided into four doses, during five days. During the second phase (maintenance), three grams of creatine (or placebo) were administered during seven days. The group placebo was used as control during seven days. The group placebo was used as control.

Experimental procedure

Two data collections were performed in distinct days 12 days away from one another. At the beginning of the supplementation protocol, both groups were initially submitted to the 1-RM test and to the maximum repetition test in the leg press at 45° (80% of the 1-RM). Twelve days after supplementation (creatine or placebo), both test (1-RM and maximum repetitions) were once again performed shortly after the 20-minutes running test. Therefore, the objective of this work was to verify the effect of the endurance exercise (running) on the strength development in groups placebo and creatine supplemented for 12 days.

RESULTS

The value obtained in the 1-RM test presented no alteration between groups placebo and creatine, with or without the previous execution of the endurance exercise (table 1). The 1-RM value/body weight ratio also remained unchanged in relation to groups placebo and creatine at the beginning (without the previous execution of the endurance exercise) and at the end of the experiments (with the execution of the endurance exercise) (table 1).

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<tr>
<th>Placebo (n = 8)</th>
<th>Creatine (n = 8)</th>
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<td>1-RM (kg)</td>
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<td>Final</td>
<td>191.4 ± 22.5 60.9 ± 5.6 3.2 ± 0.5</td>
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| Values expressed as average ± standard deviation.

However, in the maximum repetitions test, a decrease on the number of repetitions performed by the group placebo after the performance of the aerobic exercise was observed in the two last sets in relation to the beginning of the experiment [P: 1st set: 9.0 ± 2.4; 2nd set: 8.9 ± 2.9 and 3rd set: 8.3 ± 3.3 vs. P: 1st set: 7.6 ± 2.6; 2nd set: 4.3 ± 2.9*; p < 0.01 and 3rd set: 4.6 ± 2.3*; p < 0.01 (table 2). This response was not observed in the group creatine (CRE: 1st set: 10.2 ± 2.2, 2nd set: 9.8 ± 2.9 and 3rd set: 9.7 ± 3.5 vs. CRE: 1st set: 10.9 ± 2.9; 2nd set: 9.5 ± 2.7 and 3rd set: 9.0 ± 3.0). At the end of the experiment, after the endurance exercise, the average number of maximum repetitions performed by the group creatine in the last two sets was higher than that of the group placebo (table 2).

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Regarding the 20-minutes running test, no difference was observed on the performance of both groups (table 3).
DISCUSSION

The objective of the present study was to test the effect of the creatine supplementation on the adverse effect of the endurance exercise on the subsequent strength development. As previously observed, the performance of the endurance exercise affected the subsequent strength development\(^1,2\).

This impairment could be explained due to the performance of the resistance exercise in adverse metabolic and energetic condition, in case this exercise is preceded by an endurance exercise\(^1,15\). This would occur during strength training performed at the same session and hence characterizing an acute effect. In this context, the muscle would have reduced capacity of developing tension during the performance of the posterior strength training. The possible explanation for this phenomenon was called as acute hypothesis\(^1,15\).

The acute interference hypothesis is supported by the study of Craig et al.\(^6\) who verified that the strength development in the lower limbs was impaired due to the performance of an aerobic exercise shortly before the resistance training. In the same study, it was observed that the lower limbs adaptation was not impaired by the previous endurance training. According to the authors, the legs musculature would not recover from the endurance training and would not perform the resistance training at intensity required to promote the desired adaptations.

The mechanisms responsible for the strength and power impairing in the concurrent training are not yet fully identified\(^1,15,18,19\). A possible candidate is the muscular glycogen depletion, once it is an important energetic substrate for the resistance training\(^20-22\). However, previous evidences obtained in our laboratory demonstrate that individuals who ingested adequate amounts of carbohydrate before exercise and who were also supplemented with carbohydrate during concurrent exercise could not achieve lessening the harmful effect of the endurance exercise on the posterior resistance exercise\(^21\). These results, therefore, made us consider the hypothesis that other energetic substrate could contribute for the performance of the concurrent training (aerobic training performed before the resistance training), the creatine-phosphate (CP).

In the present study, the results observed demonstrate that the strategy of ingesting creatine or placebo did not affect the result of the 1-RM test. Recently, in another study conducted in our laboratory\(^23\), we could verify that the creatine supplementation did not change the maximum load supported in supine, checked through the 1-RM test. However, still in this study, we verified that the creatine intake increased the capacity of performing maximum repetitions at 70% of the 1-RM value. These results are in agreement with results found by other researchers\(^17,24\). Earnest et al.\(^17\) did not observe increases on the 1-RM values for supine after creatine supplementation either. As in our study, Earnest et al.\(^17\) only verified increases on the capacity of performing maximum repetitions at 70% of the 1-RM value.

Despite the energy absolute production during short-duration maximal effort (~6–8 seconds), as in the case of the 1-RM test, be predominantly supplied by the creatine-phosphate degradation, the intramuscular creatine basal content before supplementation would be able to supply this demand. Consequently, the group submitted to creatine supplementation would not present a better performance in relation to the group placebo\(^17,23,26\).

In relation to the capacity of performing maximum repetitions (80%-1-RM) in the group placebo, the endurance exercise promoted a decrease on this parameter in relation to the initial test, as expected. A possible explanation for the reduction on the number of maximum repetitions is that the endurance exercise would promote a depletion of the energetic substrates, thus generating a residual fatigue (acute interference hypothesis)\(^1,15\). On the other hand, in the group supplemented with creatine, the capacity of performing maximum repetitions (80%-1-RM) in the leg press at 45° after endurance exercise was maintained.

The fatigue installation in the resistance exercise seems to be multifactorial, presenting as potential causes the CP depletion, the intramuscular acidosis (increase of H\(^+\) ions) and/or the reduction on the muscular glycogen\(^26\). MacDougall et al.\(^26\) observed that the combination between the CP depletion (62% in relation to the rest situation) and the muscular acidosis (21.3 mmol.kg\(^{-1}\) of wet weight) was the responsible for the fatigue at the 1\(^{\text{st}}\) series of maximum repetition at 80% of the 1-RM value. These authors also reported that after three series of maximum repetitions at 80% of the 1-RM value, the incapacity of maintaining the movement pattern seems to be limited by the increase on the H\(^+\) ions concentration\(^28\). The elaboration of this hypothesis was based on the fact that the CP reduction degree (50% in relation to the rest situation) was smaller than that observed in the 1\(^{\text{st}}\) series (62% in relation to the rest situation). Reinforcing this hypothesis, the lactate production had been higher at the end of the last series (1\(^{\text{st}}\) series – 21.3 mmol.kg\(^{-1}\) wet weight vs 3 series – 27.4 mmol.kg\(^{-1}\) wet weight)\(^28\).

Considering that the fatigue at the 1\(^{\text{st}}\) series may be related with the CP reduction, one may speculate that the higher content of this substrate in the muscle would minimize the CP depletion in the group supplemented with creatine, thus favoring its subsequent re-synthesis for the next series. Furthermore, it is important mentioning the buffering capacity exerted by the ATP-CP system\(^27\). The immediate re-phosphorylation of ADT into ATP through the CP hydrolysis requires one H\(^+\) ion\(^27\). As result, this buffering capacity would lessen the harmful effects of the acidosis\(^25,27,28\), such as the inhibition of enzymes involved in the energetic metabolism\(^25,27\) and the reduction on the sensitiveness of the contractile proteins to ions Ca\(^{2+}\)\(^28\).

Therefore, the increase on the availability of this substrate and its buffering capacity would be responsible for the maintenance of the performance in the subsequent maximum repetitions test in the group submitted to creatine supplementation.

CONCLUSION

According to other results available in literature, the present study demonstrated that the previous performance of endurance exercises affects the subsequent resistance exercise. It was also verified in this study, that the creatine supplementation is able to nullify the adverse effect induced by the endurance exercises on the subsequent performance on the maximum repetitions test at 80% of the 1-RM value. These results suggest that the ATP-CP system contributes significantly for the performance of the concurrent exercise in which the subsequent resistance training is performed at high intensity.

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All the authors declared there is not any potential conflict of interests regarding this article.
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