Maximal Mechanical Power during a Taper in Elite Swimmers

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ABSTRACT

TRINITY, J. D., M. D. PAHNKE, E. C. REESE, and E. F. COYLE. Maximal Mechanical Power during a Taper in Elite Swimmers. Med. Sci. Sports Exerc., Vol. 38, No. 9, pp. 1643–1649, 2006. Introduction: Insight regarding the fluctuations in neuromuscular function among athletes during a taper is lacking. Purpose: This study examined the time course of changes in maximal mechanical power (Pmax), torque at power maximum (T), velocity at power maximum (V), and swim performance (m/s) that occur during the taper. Methods: Using an arm ergometer with inertial loading, measurements were made during the week prior to the initiation of the taper (high volume, HV), during the 2- to 3-wk period of the taper (taper), and during the week of peak competition (peak) in 24 male competitive collegiate swimmers. Subjects were divided into groups that tapered to peak performance at either the conference (CONF, N = 13) or national (NAT, N = 11) championship competitions. Results: CONF increased Pmax 10.2% (P < 0.01) and swim performance 4.4% (P < 0.001). NAT increased Pmax by 11.6% (P < 0.01), T by 7.4% (P < 0.02), and swim performance by 4.7% (P < 0.001). Pmax displayed a biphasic increase with approximately 50, 5, and 45% of the total increase occurring during the first, second, and third weeks of the taper, respectively. The biphasic response was the most common response among individual swimmers. Swimming performance was significantly correlated to both power and torque (P < 0.05). Conclusion: In summary, maximal arm power measured using inertial load ergometry increased largely during the first and third weeks after training volume was tapered for peak performance in elite collegiate swimmers. Key Words: SWIM TRAINING, INERTIAL LOAD ERGOMETER, TORQUE, HUMAN PERFORMANCE

A taper can be defined as a period of training lasting a few days to several weeks in which training volume is progressively reduced while training intensity is maintained (19). As training volume is reduced, muscle fatigue is reduced, and positive aspects of physical training are increased or supercompensated. Physiological adaptations following the reduction in exercise training volume, such as increased muscular power, strength, and single muscle fiber size, as well as altered metabolic and contractile properties of single muscle fibers, have been documented (3,9–13,16,19–24,28,30). However, the time course for these adaptations has not been well described. Adaptations during the taper will probably depend on the intensity, duration, and volume of training employed prior to and during the taper as well as the plasticity of the physiological systems being measured.

Swim training is an ideal model for studying the physiological adaptations to taper. Elite swimmers commonly perform a large volume of exercise training (50,000–70,000 m-wk−1, 15) followed by a 2- to 3-wk period of markedly reduced volume taper prior to major competition. High mechanical power is a key component of successful swim performance (2,11,14,15,23,29) and has been shown to consistently improve following a taper (1,3,9,11,13,25) in highly trained swimmers. Specifically, following a 2-wk taper, isokinetic power and tethered swimming power have been shown to increase by 5–25% (3,13,25). However, the time course with which mechanical power increases during a taper has yet to be described.

The first purpose of this study was to gain insight regarding the plasticity of the neuromuscular system by establishing the time course with which elite swimmers enhance maximal arm power (Pmax), velocity at power maximum (V), and torque at power maximum (T) during a 3-wk taper. The second purpose of this study was to better understand how to taper for competition. Based on observations regarding physiological adaptations to detraining, it is our hypothesis that much of the increase in maximal arm power would occur during the early portion of the taper (i.e., the first 7–10 d). Measurements of the aforementioned...
variables were made prior to the initiation of the taper, during the 3-wk taper, and prior to competition. Swimming performance was measured during competition prior to the taper and after taper aimed at eliciting “peak” performance.

METHODS

Subjects. Twenty-four elite male (N = 24, 19.9 ± 0.39 yr, 81.7 ± 1.17 kg, 186.1 ± 1.34 cm) swimmers participated in this study. All subjects were members of the University of Texas at Austin men’s intercollegiate athletics swim team, and procedures were approved according to guidelines of the internal review board of the University of Texas at Austin. Subjects were divided into a conference (CONF) group (N = 13) and a national (NAT) group (N = 11) according to their last meet of the competitive collegiate season.

Inertial load ergometry. The inertial load ergometer for measurement of lower-body maximal power during leg cycling, as described by Martin et al. (17), was modified for the measurement of arm power. This was accomplished by removing the seat and mounting a swim bench to the ergometer frame, the addition of crank handles, the replacement of the 56-tooth chain ring with a 39-tooth chain ring (gear ratio = 2.7857), and removal of the intermediate gear. Flywheel angular velocity and acceleration were determined by an optical sensor and microcontroller-based computer interface that measured time (± 1 μs) and allowed power to be calculated instantaneously every 3° of crank revolution or averaged over one complete revolution of the cranks (17). All powers expressed in this paper are average values over one complete crank cycle. The inertial load of the ergometer used was 3.65 kg m⁻². As described in Martin et al. (17), maximal power was calculated as the product of moment of inertia, velocity, and angular acceleration of the flywheel.

Inertial load ergometer tests. All inertial load ergometer testing was performed during the swimming training sessions. Subjects were randomly rotated out of their normal workout routine by their coach at a time when they were sufficiently warmed up but not too fatigued to perform the power test. Subjects towel dried and placed themselves in a comfortable prone position on the bench with the cranks at 45° past vertical (0° = top dead center of crank revolution, and 180° = bottom dead center of the crank revolution). Bench height and body position were held constant for each subject. Four trials were performed per subject for most tests. During trials 1 and 3, the subject began with his right arm forward on the crank arm, which was placed at the 45° position. Trials 2 and 4 were performed with the left arm forward and the crank arm in the 45° position. Data acquisition for each trial required approximately 3–5 s of maximal effort. Sixty seconds were allotted for a recovery period between trials, which was predetermined to be sufficient to prevent residual fatigue.

Time course for testing. Because the inertial load ergometer test was a novel task for the subjects, a series of three inertial load tests (total of 12 learning trials) were performed by each subject at least 1 wk prior to start of data acquisition.

Testing periods corresponded to a given weekly period of training for each group. CONF and NAT performed high-volume (HV), taper, and peak training, with NAT performing two tapers and two subsequent peaks. Table 1 reports the number of days before each peak competition that the power test was performed. Swimming performance, reported as swim velocity (m s⁻¹), were obtained via the NCAA official results from competitions held on 1/30/04–1/31/04 (HV), 2/25/04–2/28/04 (Big 12 conference championships (PEAK CONF and PEAK1 NAT), and 3/25/04–3/27/04 (NCAA championships (PEAK2 NAT)).

Data calculations. The two highest powers of a given session were averaged and represent the Pmax of the athlete. V and T were calculated by taking the average of the velocities and torques corresponding to the two highest Pmax values. Data from each subject was then expressed as a percentage of his highest maximum power obtained during the course of all testing. Because all subjects did not obtain their highest power during the same test session, the average of all subjects never reaches 100%.

The individual swimmers competed in events of 50–1500 m. Swimming performance was assessed using the same distance and stroke style for a given individual according to their specialty. Data are reported as mean percent of highest values (± standard error of the mean). Mean coefficients of variation (SD/mean) for Pmax, V, and T of CONF were 2.44 ± 0.13, 6.06 ± 0.67, and 7.48 ± 1.11%, respectively. Mean coefficients of variation for Pmax, V, and T of NAT group were 2.64 ± 0.25, 7.03 ± 0.95, and 7.29 ± 1.28, respectively.

Training. Training comprised both swimming and land-based workouts. Swimming training generally consisted of a warm-up, then continuous, more intense swimming, followed by higher intensity (interval training), and ending with a cool-down period. During the weeks prior to the initiation of the taper (HV), twice-daily workouts were performed with a frequency of approximately two to three times per week with the

<table>
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<th>Conference (CONF)</th>
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<td>Days prior to Conference Meet</td>
<td>Days prior to National Meet</td>
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<td>Corresponding Period of Training</td>
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<td>Week 3–T2</td>
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HV, high volume; week 1, first week of taper; week 2, second week of taper; week 3, third week of taper; peak, week of conference championship meet; week 1–T1, first week of first taper, week 2–T1, second week of first taper; peak 1, week of conference championship meet; week 1–T2, first week of second taper; week 2–T2, second week of second taper; week 3–T2, third week of second taper; peak 2, week of national championship meet.
remaining days consisting of one workout per day. During HV and early taper, 10–12 total training sessions were performed per week. As the taper progressed, the twice-daily workouts were gradually removed from the training program, with six to eight training sessions being performed per week from midtaper to peak. Land-based training focused on core and upper-body strength and was performed two to three times per week and was gradually reduced and eventually removed from the training by the second week of the taper. The prescribed training of the subjects was reported by the coaches following the completion of the competitive season; therefore, individual training histories are not reported.

**Individual responses to taper.** To determine individual responses to the taper, each subject was placed into one of the following categories based on his Pmax response during the taper: 1) early—predominant increase occurred during weeks 1 and 2 of taper; 2) late—increase during weeks 2 and 3 of taper was most predominant; 3) biphasic—increases during weeks 1 and 3 were predominant; 4) nonresponder—no increase or a decrease in power during taper; and 5) constant—continual increase in power during taper.

**Statistical analysis.** Repeated-measures analysis of variance (ANOVA) was performed to test significance between trials. Least significance difference test identified the means that were significantly different with \( P < 0.05 \). Correlations were completed using the Pearson product–moment correlation method.

**RESULTS**

**Training and taper.** Prior to the conference championship, CONF tapered their training volume as described in Figure 1. Approximately 20% of the total training volume was high intensity throughout this period of training. During the week of competition, the only high-intensity training performed was during competition (i.e., during qualifying and final heats). Training volume during week 1 was 80% of HV, 73% of HV during week 2, 53% of HV during week 3, and 44% of HV at peak (Figure 1A). NAT performed two tapers during the course of the testing period. The first taper (taper 1; including week 1–T1 and week 2–T1) was performed prior to the conference championship meet (i.e., peak 1), and the second taper (taper 2; including week 1–T2, week 2–T2, and week 3–T2) was performed prior to the national meet (i.e., peak 2) (Fig. 1B). Tapers 1 and 2 cannot be analyzed as distinct tapers because the training during taper 1 might have influenced Pmax power during taper 2. Taper 2 is most appropriately viewed as an extension of taper 1, with the goal of maintaining the increased Pmax gained by taper 1. High-intensity training contributed 15, 20, and 20% of the total training load during HV, week 1–T1, and week 2–T1, respectively. Training volume, expressed as a percentage of the meters swum during the high-volume phase, was 80% for week 1–T1; 67% for week 2–T1; 42% for peak 1; 67% for week 1–T2; 50% for week 2–T2; 42% for week 3–T2; and 34% for peak 2. High-intensity training contributed 10, 15, and 10% of the training volume during week 1–T2, week 2–T2, and week 3–T2, respectively.

**Maximal power.** The lowest Pmax for CONF was recorded during HV training (634 ± 23 W; 87.8 ± 2.2% of maximum) (Fig. 2A). The highest Pmax was observed 21 d post HV at week 3 (699 ± 27 W; 96.4 ± 1.3% of maximum), representing a 10.2% increase above HV (\( P < 0.01 \)). As CONF transitioned from HV to week 1 (661 ± 25 W; 91.7 ± 2.4% of maximum), a significant increase in Pmax of 4.3% was observed (\( P < 0.05 \)). The time course for changes in power of CONF was 45, 7, and 48% of the total increase in Pmax during weeks 1, 2, and 3 of the taper, respectively. The Pmax of NAT was lowest during HV2 (592 ± 31 W; 85.3 ± 3.1% of maximum). The highest Pmax was recorded at week 2–T2 (660 ± 29 W; 95.1 ± 1.3% of maximum), representing an 11.6% increase compared with HV2 (\( P < 0.01 \)). During the transition from HV2 to week 1–T1 (629 ± 37 W; 90.3 ± 2.6% of maximum), Pmax in NAT increased 6.3% (\( P < 0.02 \)). NAT displayed a significant (4.7%) decline in Pmax from peak 1 to week 1–T2 (623.32 ± 32.75 W; 89.7 ± 2.4% of maximum) (\( P < 0.01 \)). However, by week 2–T2 (660.45 ± 29.30 W;
95.1 ± 1.3% of maximum), Pmax was regained to a level similar to that achieved at peak 1 (Fig. 2B). Isolation of taper 1 demonstrates that NAT displayed their highest Pmax 20 d post HV2 at peak 1, similar to CONF. The time course for changes in Pmax during taper 1 were 56, 2, and 42% of the total increase in power during the week 1–T1, week 2–T1, and peak 1, respectively. Given that the time course for gains in Pmax with CONF 45, 7, and 48%, over the first 20–21 d of taper, the averaged response of the two groups was approximately 50, 5, and 45% for the first 3 wk of taper. However, not all individuals displayed a biphasic response to the taper; eight displayed a biphasic response, six displayed an early response, five displayed a late response (Fig. 3), three were nonresponders, and two displayed a constant increase in power during the taper.

**Torque.** No significant differences in T were observed during the testing period for CONF. The lowest T was observed during HV training prior to the initiation of the taper (42.6 ± 1.1 N·m; 88.7 ± 2.4% of maximum). The highest T was recorded at week 3 (45.7 ± 1.6 N·m; 94.5 ± 2.1% of maximum), representing a 7.2% increase compared with HV torque (P = 0.15) (Fig. 4).

Torque (T) of NAT was lowest during HV (41.6 ± 1.6 N·m; 87.9 ± 2.7% of maximum), and the highest T was displayed at week 2–T2 (44.7 ± 1.7 N·m; 94.0 ± 1.5% of maximum), representing a 7.4% increase compared with HV (P < 0.02). T was also increased 5.8% at peak 1 (44.06 ± 1.69 N·m; 92.9 ± 2.4% of maximum) compared with HV (P < 0.01). T increased 3.6% from week 1–T1 (42.52 ± 1.33 N·m; 89.9 ± 2.5% of maximum) to peak 1 (P = 0.05) (Fig. 4).

**Velocity.** No significant differences in velocity at maximal power (V) were observed in CONF during the testing period, with values ranging between 141.4 ± 4.6 and 147.1 ± 5.2 rpm. The largest increase in V (4.0%) occurred from HV to week 2 (P = 0.29).

No significant differences in V were observed for NAT; this group was within the range of 134.6 ± 3.7 and 142.0 ± 4.0 rpm. The largest increase in V (5.5%) occurred from the end of HV to peak 2 (P = 0.09).

**Swim performance.** CONF exhibited a 4.4% increase in swim performance velocity from HV to peak (95.8 ± 0.4 to 100 ± 0.0%; P < 0.05). NAT exhibited a 4.7% increase in swim performance velocity from HV to peak 1 (95.2 ± 0.5 to 99.7 ± 0.01%; P < 0.05) and a 4.5% increase from HV to peak 2 (95.2 ± 0.5 to 99.5 ± 0.3%; P < 0.05) (Table 2). Swim performance velocity (m·s⁻¹) was significantly correlated to absolute maximal power (r = 0.39; r² = 0.15; P < 0.05) and torque (r = 0.32; r² = 0.10; P < 0.05) when all available tests for CONF and NAT were combined. Although the relationship between Pmax and swim performance velocity is not strong, approximately 15% of the variation in swim performance can be explained by Pmax. It should be recognized, however, that conditions were not ideally standardized.
DISCUSSION

This study described the time course for changes in maximal power (Pmax) that occur during a collegiate swimming season, focusing on the period of tapering to peak for conference and national competition. Overall, Pmax increased 11% (P < 0.05), T increased 7% (P < 0.05 for NAT), and V increased 4.5% (NS), whereas swim performance increased 4.5% (P < 0.05) when training volume was tapered over 3 wk. The averaged time course for the increases in Pmax were similar in both CONF and NAT, with approximately 50, 5, and 45% of the increase in power occurring during the first, second, and third weeks of taper, respectively (Figure 2, sigmoidal curves).

A consistent finding in both groups was that Pmax, as well as swimming performance, was lowest during the period of high-volume training. Intense endurance training, as employed by competitive swimmers, decreases the ability to exert maximal muscular power due to muscle fatigue or inhibition of neural and/or intrinsic muscle properties (4,6,8). The taper has been defined as the period of training during which the negative impact of training (i.e., muscle fatigue) is reduced and the positive impact of physical training (i.e., improved physiological function) is increased (19). The magnitude of adaptations that occur during the taper will be a direct result of the training load (volume, intensity, and frequency) in the weeks to months prior to the initiation of the taper and the training load during the taper. Both CONF and NAT displayed their highest Pmax values 3 wk (20–21 d) after the initiation of the taper. The time course of increase in Pmax was remarkably similar in both groups despite the fact that NAT performed a slightly greater reduction in training volume during their taper prior to the national championships compared with CONF (Fig. 1). A taper consisting of more than 3 wk (CONF, 27-d taper from HV to peak 1) did not increase mechanical power beyond what was accomplished during the first 3 wk of the taper. Likewise, NAT displayed their highest Pmax during taper 1, 20 d post HV2. Taper 2 did not display any significant improvement in Pmax beyond what was obtained during taper 1. Based on the training conditions used in this study, it appears that approximately 20–21 d is the appropriate duration of taper to maximize the return of maximal power after HV training.

This report is the first to describe the time course of increase in power during a taper in competitive swimmers. Interestingly, when examining the group response to taper, the time course appears biphasic, with substantially less of the total increase in Pmax during week 2 compared with weeks 1 and 3 (Fig. 2). Reversal of chronic muscle fatigue may require only 1 wk of reduced training volume to become evident, whereas neurological adaptations may require a longer 14- to 21-d period to contribute to the overall increase in mechanical power. Hicks et al. (7) demonstrated that twitch force and EMG activity recovered after 6 d following chronic low-frequency stimulation. Despite the recovered twitch force and EMG, the muscles exhibited enhanced fatigue resistance, absence of twitch potentiation, and prolonged contraction and relaxation times up to 20 d postrecovery. Although the biphasic response of increased power during the first and third week was the most typical individual response as well as the averaged team response, not all individual athletes displayed this biphasic pattern. Approximately 25% of the subjects displayed an early response to taper, whereas 21% displayed a late response to taper. This response did not appear to be dependent on whether the swimmer was a sprinter, middle-distance, or endurance swimmer because early, late, and biphasic responders were present in each category. Most likely, the response of the individual was the result of a multitude of factors that may include (but is not limited to) genetics, nutrition, initial level of training status, and experience. Further research is needed to better understand the time

FIGURE 4—(A) Torque at power maximum of conference group expressed as percent of highest torque. (B) Torque at power maximum of national group expressed as percent of highest torque. * Significantly different from HV1; † significantly different from HV2, P < 0.05.

TABLE 2. Swimming performance expressed as a percentage of individual's fastest velocity while competing in their specialty event of a given distance and swimming stroke.

<table>
<thead>
<tr>
<th>Group</th>
<th>HV</th>
<th>Peak 1</th>
<th>Peak 2</th>
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<tbody>
<tr>
<td>CONF</td>
<td>95.8 ± 0.37%</td>
<td>100.00 ± 0.00%*</td>
<td>99.5 ± 0.30%*</td>
</tr>
<tr>
<td>NAT</td>
<td>95.2 ± 0.50%</td>
<td>99.7 ± 0.09%*</td>
<td>99.9 ± 0.30%*</td>
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* Significantly different from HV, (P < 0.05).
course and contribution of muscular and neurological adaptations in mechanical power during the taper as well as the distinct individual responses to a taper.

Another novel finding was the manner in which NAT responded to two closely timed peaking and taper periods as required by the scheduling of the conference and national competitions in collegiate swimming in the United States. The conference and national competitions for this group of swimmers were spaced 4 wk apart. Due to this competition schedule, changes in Pmax and performance at subsequent peaks (peak 1 vs peak 2) can be described. The manner in which training volume was reduced during taper 1 versus taper 2 in NAT was similar (i.e., progressive reduction); however, taper 2 was 1 wk longer, and the absolute volume of training per week during taper 2 (average: 25,000 m·wk⁻¹) was substantially less than during taper 1 (average: 40,000 m·wk⁻¹) (Figure 1). Despite these apparent differences, remarkably similar outcomes in terms of performance and power were observed. This finding indicates that the taper prior to the conference meet was adequate to increase Pmax and performance in a manner similar to a more prolonged and less dramatic taper prior to the national meet in highly trained male collegiate swimmers. In essence, the taper 2 of NAT was successful in maintaining the form gained by taper 1. Taper 2, as performed by NAT, cannot be evaluated as unique taper because of the cumulative training adaptations that occurred during the taper 1.

Torque for both groups was lowest during high-volume training, as would be expected, considering that high-intensity/high-volume endurance training reduces one’s ability to exert maximal muscle force as previously discussed (4,6,8). Based on the observation that V did not change during the testing period, the increased muscle function is due to increases in T and Pmax. Trappe et al. (25) observed similar results following a 21-d taper whereby pre- and posttaper maximal power as measured isokinetically occurred at similar contraction velocities. Although the magnitude of the increase in T for both CONF and NAT was similar (7.2 and 7.4%, respectively), the increase in T of CONF failed to reach significance (P = 0.15). The lack of a significant increase in T for CONF may be due to a slightly greater variation in T or may be due to the fact that CONF were performing approximately 10,000 fewer meters per week during HV training.

It is clear from these data that Pmax significantly increases with the reduction in training volume. The question still remains as to the magnitude of change that can be attributed to muscular, compared with neurological, adaptations. Trappe et al. (25) reported that isolated single muscle fibers significantly increased their maximal velocity of shortening by 32 and 67% in type I and type IIa fibers, respectively, when competitive swimmers taper. The increased Vmax of the isolated single muscle fibers suggests that the taper-induced alterations in contractile properties can occur independent of central nervous system stimulation and motor recruitment. Adaptations in the contractile properties of isolated single muscle fibers following periods of either increased or decreased activity may be explained by changes in the myosin light chain 3 to myosin light chain 2 (MLC3/MLC2) ratio, changes in the geometric relationship between thick and thin filaments, or via transformation of MHC isoforms along the hybridization continuum (6,25–27). As previously mentioned, Trappe et al. (25) observed that the changes in muscle fiber morphology were manifested in increased torque production when the swimmers’ upper-body power was measured isokinetically. This agrees with the current observation that the increase in maximal power was mostly associated with the increased torque production.

Increases in Pmax associated with the taper and peak could also reflect neurological changes in motor unit activation. Shepley et al. (24) used the interpolated twitch method and showed nonsignificant increases in motor-unit activation following a 1-wk taper in highly trained runners. Based on the findings of this study and Shepley et al. (24), neurological adaptations may require an extended period of reduced-volume training to reach significance, implicating a biphasic increase in Pmax.

The taper proved to be effective at increasing in-water swim performance by approximately 5%. Similar improvements in performance have been obtained from studies of competitive runners, cyclists, and swimmers, with a magnitude of increase from 1 to 8% (1,3,9–13,16,18–22,25). A positive relationship has been established for muscular power and sprint swim velocity (2,11,14,23,29). Likewise, increases in muscular power result in noticeable improvements in swim velocity (3,11,13,19,22,25). In this investigation, mechanical power was measured over 3–5 s of maximal effort, whereas the shortest races performed by competitive swimmers last at least 22 s. Despite this lack of specificity regarding the duration of the Pmax test and in-water swim performance, these variables were significantly correlated (P < 0.05). Therefore, it is apparent from this study and others that the increased neuromuscular power developed following a taper is at least partially responsible for the significantly improved swim performance. The inertial load ergometer enables investigators and coaches to gain insight regarding the maximal mechanical power alterations during a taper, a task that was not previously possible without altering the taper and training of the swimmers. We would not expect changes in Pmax and changes in swim performance to be significantly correlated because Pmax only explained 15% of the variance in swim performance. Under ideal experimental conditions, performance would be standardized via repeated 50- to 100-m swims; however, this level of experimental control is not possible without affecting the taper and training of the swimmers. The degree to which other variables such as lean body mass, years of experience, event specificity, and biomechanical alterations to taper have yet to be determined.

In summary, it is evident that maximal arm power, torque, and swim performance increase as collegiate swimmers taper their volume of training during 3–5 wk to optimize their performance. Maximal power increased
11% as training transitioned from high volume to peak via the taper. The average increase in Pmax was biphasic, with approximately one half of the increase evident during the first week of the 3-wk taper, and 45% of the total increase during the third week of the taper. Based on this observation, a 21-d taper appears to be most effective at increasing performance and power as demonstrated by the time course over the 3-wk period.

REFERENCES