Intended rather than actual movement velocity determines velocity-specific training response

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BEHM, DAVID G., AND DIGBY G. SALE. Intended rather than actual movement velocity determines velocity-specific training response. J. Appl. Physiol. 74(1): 359-368, 1993.—Eight men and eight women trained 3 days/wk for 16 wk by doing attempted ballistic unilateral ankle dorsiflexions against resistance that either rendered the resultant contractions isometric (one limb) or allowed a relatively high-velocity (5.23 rad/s on an isokinetic dynamometer) movement (other limb). Training sessions consisted of five sets of 10 contractions of each type. Training produced the same high-velocity-specific training response in both limbs (P < 0.001). Peak torque increased most at 5.23 rad/s (38%) in comparison to lower velocities (0, 0.26, 0.52, 1.04, 1.55, 3.02, and 4.19 rad/s). Both limbs also showed similar increases in voluntary isometric rate of torque development (26%) and relaxation (47%) and in evoked tetanus rate of torque development (14%). A similar decrease in evoked twitch time to peak torque (6%) and half-relaxation time (11%) was also observed. Thus, all of these training responses, previously associated specifically with high-velocity resistance training, were produced by a training regimen that prevented an actual rapid movement through a range of movement. The results suggest that the specific alterations in muscle contractile properties associated with high-velocity movements, the most rapidly performed movements, are termed ballistic. In relation to the present study, an example of a ballistic movement would be a human subject dorsiflexing the ankle joint as rapidly as possible through the joint range of movement. Ballistic movements differ from slower movements in that ballistic movements 1) are initiated differently by the brain (8, 2) are characterized by a brief high-frequency discharge of the involved motor units (7, 3) may involve selective activation of high-threshold motor units (13), and 4) involve a characteristic pattern of agonist and antagonist discharge (1, 11). A feature of the most brief and rapid ballistic movements is that they are preprogrammed; that is, once the central command is dispatched to the motoneurons, the ensuing motor unit discharge cannot be modified on the basis of a new command or proprioceptive feedback. Thus, it has been shown that when the intent is to make a ballistic movement, the motor unit discharge is the same whether the involved limb is unimpaired and free to move rapidly, in which case the associated agonist muscle contraction is concentric (shortening), or whether the limb is restrained so that little or no movement occurs, in which case the agonist muscle contraction is isometric (8). The last mentioned feature of ballistic movements raises the following question. Would the velocity specific response to training with attempted ballistic movements be the same, regardless of the nature of the ensuing mechanical event (isometric or concentric contraction), or is an actual rapid movement through the range of motion necessary? The response would be expected to be the same if 1) the neural adaptations to high-velocity training are produced by practicing and, consequently, enhancing the ballistic motor command and high-frequency motor unit discharge characteristic of ballistic contractions, or 2) the specific alterations in muscle contractile properties depend mainly on the high-frequency stimulation the muscle receives and the high rate of force development of the ensuing muscle contraction, regardless of its type based on tetanic contractions electrically evoked at different shortening velocities and evoked isometric twitch contractile properties (9). Another study showed, on the basis of electromyographic (EMG) recordings, that neural adaptations could be involved. Explosive jump training (vs. conventional weight training) produced an earlier onset of motor unit activation in voluntary isometric contractions (15).

In relation to strength training performed with high-velocity movements, the most rapidly performed movements are termed ballistic. In relation to the present study, an example of a ballistic movement would be a human subject dorsiflexing the ankle joint as rapidly as possible through the joint range of movement. Ballistic movements differ from slower movements in that ballistic movements 1) are initiated differently by the brain (8, 2) are characterized by a brief high-frequency discharge of the involved motor units (7, 3) may involve selective activation of high-threshold motor units (13), and 4) involve a characteristic pattern of agonist and antagonist discharge (1, 11). A feature of the most brief and rapid ballistic movements is that they are preprogrammed; that is, once the central command is dispatched to the motoneurons, the ensuing motor unit discharge cannot be modified on the basis of a new command or proprioceptive feedback. Thus, it has been shown that when the intent is to make a ballistic movement, the motor unit discharge is the same whether the involved limb is unimpaired and free to move rapidly, in which case the associated agonist muscle contraction is concentric (shortening), or whether the limb is restrained so that little or no movement occurs, in which case the agonist muscle contraction is isometric (8). The last mentioned feature of ballistic movements raises the following question. Would the velocity specific response to training with attempted ballistic movements be the same, regardless of the nature of the ensuing mechanical event (isometric or concentric contraction), or is an actual rapid movement through the range of motion necessary? The response would be expected to be the same if 1) the neural adaptations to high-velocity training are produced by practicing and, consequently, enhancing the ballistic motor command and high-frequency motor unit discharge characteristic of ballistic contractions, or 2) the specific alterations in muscle contractile properties depend mainly on the high-frequency stimulation the muscle receives and the high rate of force development of the ensuing muscle contraction, regardless of its type.
(isometric or concentric). On the other hand, if rapid and extensive muscle shortening provides a crucial stimulus to the high-velocity-specific training response, then unrestrained rapid ballistic movements would be superior as a training mode in comparison to attempted ballistic movements that are restrained so as to make the ensuing contractions isometric or low-velocity concentric. The purpose of the present study was to determine whether a rapid and extensive muscle shortening was a necessary stimulus to producing a high-velocity-specific training response. Subjects trained both of their legs with attempted ballistic ankle dorsiflexion movements. In one leg the imposed resistance rendered the resultant muscle contractions isometric. In the other leg the imposed resistance allowed the foot to move and the involved muscles to shorten at a relatively high velocity. To test for a high-velocity-specific training response, voluntary strength of ankle dorsiflexion was measured at several concentric contraction velocities. In addition, measurements of evoked muscle contractile properties were made to identify possible high-velocity-specific contractile adaptations to the training.

METHODS

Subjects

Eight male and eight female physical education students served as subjects. The mean age, height, and body mass of the female subjects were 20.9 ± 0.5 yr, 166.6 ± 6.5 cm, and 61.3 ± 4.2 (SD) kg, respectively. The corresponding values for the males were 21.1 ± 0.8 yr, 181.9 ± 9.1 cm, and 81.9 ± 6.4 kg. Subjects were fully informed of the procedures and signed a consent form before participation. The study was approved by McMaster University’s Ethics Committee. One male and one female subject were unable to complete the study because of injuries unrelated to the experiment. Thus, 14 subjects completed the study.

Experimental Design

To examine whether the high-velocity-specific training response depends mainly on the intent to execute ballistic movements, with the associated characteristic neural activation of the involved muscles and rapid rate of force development, or whether rapid and extensive muscle shortening also provides an important stimulus, subjects attempted (ballistic intent) to perform ballistic dorsiflexion movements with both legs in training. However, the foot of one leg was restrained so that the ensuing contraction was isometric. Ankle dorsiflexion of the other leg was opposed by an isokinetic dynamometer that, nevertheless, allowed dorsiflexion to occur up to a set velocity of 5.23 rad/s. This training protocol attempted to ensure a common neural “intent” to make ballistic movements with both limbs but imposed much different actual movement velocities. Our decision to employ a within-subject control, that is, to have the same nervous system activating both experimental legs, was also an attempt to ensure as much as possible a similar motor command to the two legs.

Training Apparatus

A modified “boot” apparatus was used for the leg in which the foot was restrained so that the training contractions were isometric (25). The apparatus allowed the subject to be seated with the thigh horizontal and the knee joint flexed at 90° (1.57 rad). Straps and braces prevented extraneous movement of the upper and lower leg and securely restrained the foot so that any attempt to dorsiflex the ankle joint resulted in an isometric contraction.

For the leg in which the foot was relatively unrestrained, which allowed a rapid dorsiflexion through the range of movement in training, a modified Cybex II (Ronkonkoma, NY) isokinetic dynamometer was used (Fig. 1). The subject was seated in a specially designed chair with restraining straps over the thigh and lower leg to prevent extraneous movement of the upper and lower leg.

The head of the dynamometer, with the attached dorsiflexion foot-holder apparatus, was bolted securely to a wooden platform. The mass and restraining straps of the chair as well as the secure attachment of the dynamometer ensured isolation of the dorsiflexion movement during training. The isokinetic arrangement was designed so that the sitting position of the subject, the positioning of the leg, and the stabilization of upper and lower leg were the same as on the isometric apparatus.

Training Program

Subjects trained for a period of 16 wk. The first 8 wk of training were followed by a 3-wk interruption of training because of the Christmas holidays. Training frequency was 3 sessions/wk with a day of rest between sessions. Subjects executed three (first week), four (second week), and then five (following weeks) sets of 10 maximal attempts of ballistic movements with each leg. A minimum 1-s rest period was allocated between individual contractions of a set with a 2- to 3-min rest period between sets.

Subjects were instructed to attempt to make maximal ballistic dorsiflexion movements with both legs. Specific instructions were for the subjects to attempt to move as rapidly as possible regardless of the imposed resistance. On the isokinetic dynamometer (concentric muscle contractions), the attempt consisted of rapidly dorsiflexing

FIG. 1. Experimental setup for isokinetic testing and training. See text for details.
FIG. 2. Sample isometric (A) and isokinetic (B) training contractions. Antagonist soleus (S) and agonist tibialis anterior (TA) electromyographic recordings are shown below torque recordings.

the ankle, from a starting joint angle of 30° (0.52 rad) plantarflexion \[0° = \text{an ankle joint angle of } 90° \ (1.57 \text{ rad)}\], to engage the resistance mechanism of the dynamometer. Engagement occurred when joint angular velocity had accelerated beyond 5.23 rad/s (300°/s), the velocity set on the dynamometer. These concentric contractions lasted \(\sim 0.5 \text{ s}\) [estimated from duration of tibialis anterior (TA) EMG activity, see Fig. 2] and traversed an angular displacement of \(\sim 50° \ (0.9 \text{ rad)}\).

On the isometric apparatus (isometric contractions), an attempted ballistic movement consisted of contracting as strongly and rapidly as possible against the restraining strap and then quickly relaxing. The restraining strap fixed the foot at a joint angle of 30° [near the optimal point on the dorsiflexion strength curve (25)], that is, the same angle as the starting angle of the concentric contractions done on the isokinetic dynamometer. These isometric contractions lasted \(\sim 0.5 \text{ s}\), similar to the duration of the concentric contractions (Fig. 2). Figure 2 shows examples of isometric and concentric training contractions. In the isometric contraction the time to peak torque (TPT) was 200 ms and the time from the onset of torque to half relaxation was 700 ms. Surface EMG was used to monitor motor unit activity in the agonist TA and in one antagonist (soleus). Both muscles displayed a “burst” of activity of \(\sim 500 \text{ ms}\) in duration in association with the isometric contraction. In the sample concentric contraction, the corresponding TA EMG burst lasted \(\sim 350 \text{ ms}\). In the concentric contraction the onset of torque production was somewhat delayed in relation to the onset of the EMG because the foot had to accelerate to a joint angular velocity of 5.23 rad/s before engaging the resistance mechanism of the dynamometer. In comparison to the isometric contractions, the externally registered torque produced by the concentric contractions was smaller both in magnitude and duration.

In each subject, the dominant foot was randomly assigned to train with either concentric or isometric contractions. The nondominant foot trained with the mode not assigned to the dominant foot. It was arranged so that half of the subjects trained the dominant foot with concentric contractions, whereas the other half trained the dominant foot with isometric contractions. In a training session a subject would train the “isometric” leg first then the “concentric” leg, and in the next session the order would be reversed.

**Measurements**

Both legs of each subject were tested on the isometric and isokinetic apparatus before training (pretest), after 8 wk of training (midtest), and after 16 wk of training (posttest). In each test period for each subject, the order of the isometric and isokinetic testing was randomized.

**Isokinetic measurements.** Isometric and concentric strength were measured on the isokinetic apparatus with the subject positioned as described above for training. Subjects did dorsiflexion contractions through a joint range of 38–70°, depending on their possible range of motion. The starting angle was standardized at 30° of plantarflexion. In random order, test contractions were done at joint angular velocities of 0, 0.26, 0.52, 1.04, 1.55,
3.02, 4.19, and 5.23 rad/s. At each velocity, subjects were instructed to attempt to make maximal effort contractions. Strength was measured as the peak torque (P'T) developed during the contraction. Two trials were given at each test velocity with the best trial taken as the measurement. Rest periods of ~1 min were allowed between contractions to prevent fatigue and ensure a maximal contraction at each velocity. Torques were recorded and read from a high-frequency response recorder (model 17401A, Hewlett-Packard, San Diego, CA).

Voluntary isometric performance. Isometric performance was measured on the isometric apparatus with the subject positioned as described above for training. Subjects were instructed to perform maximal contractions with the greatest possible rate of torque development and relaxation. Two test contractions were made with a 1- to 2-min rest period in between. The best trial was taken as the measurement. The torque signal from the strain gauge of the apparatus was amplified and fed to a microcomputer for analysis (Dataq Software Package, modified by Douglas Oleksuik, McMaster University) of PT, maximum rate of torque development (MRTD), and maximum rate of torque relaxation (MRTR).

Evoked isometric contractile properties. The experimental setup was the same as that used for the voluntary isometric contractions. After the skin was prepared with alcohol and conducting gel, disposable stimulating electrodes were placed over the peroneal nerve's superficial location posterior to the fibular head (anode) and the proximal border of the TA (cathode). Twitch contractions were evoked with square-wave pulses (0.05 ms) delivered from a Grass S11 stimulator. A series of stimuli of increasing intensity were delivered until a maximal twitch response was obtained. Maximal twitch responses were analyzed for PT, TPT, MRTD, MRTR, and half-relaxation time (HRT). The compound muscle action potentials (M-waves) associated with the twitch contractions were recorded with surface EMG electrodes (7-mm-diam cup electrodes) placed 3 cm apart over the belly of TA. Tetanic contractions were then evoked with 1-s trains of stimuli at 100 Hz. Tetanic contractions were analyzed for PT, TPT, MRTD, and MRTR.

Statistics

The data were analyzed by analysis of variance (ANOVA). Voluntary isometric data were analyzed using a three-factor ANOVA with repeated measures on the last two factors [2 (gender) × 2 (training modes) × 3 (test times)]. A four-factor ANOVA was used to analyze the isokinetic data with repeated measures on the last three factors [2 (gender) × 2 (training modes) × 3 (test times) × 8 (test velocities)]. Similarly, a three-factor ANOVA was used to analyze the evoked contractile property data with repeated measures on the last two factors [2 (gender) × 2 (training modes) × 3 (test times)]. F ratios for main effects and interactions were considered significant at P < 0.05. The analysis revealed that gender did not interact with the time or training mode factors. Therefore the results for the men and women were pooled for presentation. Significant differences among means at P ≤ 0.05 and P < 0.01 were detected using Tukey post hoc tests. Descriptive statistics include means ± SD or means ± SE.

RESULTS

Isokinetic Torque Measurements

On the basis of previous research, we expected that the concentric training would produce a high-velocity-specific training response. A high-velocity-specific training response was in fact observed; strength increases were greatest at or near the training velocity of 5.23 rad/s. In regard to the isometric training, the question was whether the attempt to make rapid movements and the associated high rate of force development was sufficient to induce a high-velocity-specific training response or whether actual rapid movements through the range of movement were necessary. Our data indicated that the isometric training produced the same high-velocity-specific response as the concentric training. On the basis of these data, an actual rapid movement through the range of movement was not necessary to produce a high-velocity-specific training response.

Figure 3 shows the high-velocity-specific training response with the data collapsed across training mode (results for isometric and concentric legs were pooled).

On the basis of the significant velocity by time interaction (P < 0.001), which indicated that the magnitude of training-induced increases in torque varied at different velocities, post hoc comparisons of mean values were made. Absolute and percent increases in PT were greatest at the highest velocity tested (training velocity) and were progressively smaller at lower velocities. Thus, at the midtest, significant increases of 11.4, 11.7, 14.3, 19.4, and 21.3% were observed at velocities of 1.04, 1.55, 3.02, 4.19, and 5.23 rad/s, respectively. The corresponding pre- to posttraining increases were 12.7, 11.0, 16.3, 23.9, and 37.7%. At these velocities in which significant increases occurred, virtually all of the increase had occurred by the midtest. Only at the highest velocity (5.23
rad/s) was the mid- to posttest increase (13.5%) significant ($P < 0.05$). At the three lowest velocities tested there were no significant increases in torque after training. On the contrary, at 0 rad/s the posttraining value was 7.2 and 6.7% lower than the mid- and pretest values, respectively ($P < 0.05$).

Figure 4 shows separately the training response in the isometric- and concentric-trained legs. There was no mode time nor mode time velocity interaction, indicating that the training response to the two modes of training was similar. Both legs showed a similar high-velocity-specific training response.

Because the interactions were not significant no post hoc mean comparisons were made. The lack of significant interactions notwithstanding, Fig. 4 shows that the overall response in the isometric-trained leg may have been greater than in the concentric-trained leg.

**Voluntary Isometric Performance**

On the basis of previous research we expected the high-velocity concentric training to cause a small increase in isometric PT and relatively large increases in MRTD and MRTR. We found this pattern of results. In regard to the isometric training, the question was whether the attempt to make rapid movements and the associated high rate of force development would produce the same results. The same results were found for the isometric training; that is, there were no significant mode time interactions in these measures. Consequently, the results were collapsed across training mode for presentation.

$PT$, $PT'$, measured on the isometric apparatus, increased after training (main effect for time, $P = 0.003$; Fig. 5). Mid- and posttest mean values exceeded pretest values by 6.5 ($P < 0.05$) and 9.6% ($P < 0.01$), respectively. The increase between the mid- and posttests was not significant.

$MRTD$. MRTD increased after training (main effect for time, $P < 0.001$; Fig. 5). Mid- and posttest mean values exceeded ($P < 0.01$) pretest values by 29.9 and 25.7% ($P < 0.01$), respectively. The decrease between the mid- and posttests was not significant.

$MRTR$. MRTR increased after training (main effect for time, $P < 0.001$; Fig. 5). Mid- and posttest mean values exceeded ($P < 0.01$) pretest values by 54.9 and 46.5% ($P < 0.01$), respectively. The decrease between the mid- and posttests was not significant.

**Evoked Contractile Properties**

On the basis of previous research (9) we expected that high-velocity concentric training would likely cause a decrease in twitch PT, TPT, and HRT; MRTD and MRTR would be expected to increase. Peak tetanic torque would be expected to show a small increase, with larger increases in MRTD and MRTR. The present results partly fulfilled these expectations. Twitch TPT and HRT decreased, but there were no changes in PT or MRTD and MRTR. Tetanic rate of torque development increased but $PT'$ and $MRTR'$ did not change. In regard to the isometric training, the question was whether the attempt to make rapid movements and the associated high rate of force development would produce the same results. The same results were found for the isometric training; that is, there were no significant mode time interactions in these measures. Consequently, the results were collapsed across training mode for presentation.

Tetanus contractile properties (Fig. 6). PT and MRTR were not altered by training. In contrast, training caused a significant (main effect for time, $P = 0.002$) increase in MRTD). The posttest value exceeded the pretest value by 14.4% ($P < 0.01$). The increases between pre- and midtest (0.1%) and between mid- and posttests (4.9%) were not significant.

Twitch contractile properties (Fig. 7). There were no significant changes in twitch PT, peak-to-peak M-wave amplitude, MRTD, or MRTR with training. In contrast, $PT'$ and HRT were affected by training (both main effects, $P < 0.001$). In TPT the posttraining mean value was smaller than both the mid- (8.9%, $P < 0.01$) and pretest (6.2%, $P < 0.05$) values. The difference (3%) between the pre- and midtest values was not significant. In HRT both the mid- (11.5%) and posttest (11.9%) values were smaller than the pretest value ($P < 0.01$); there was no difference between mid- and posttest values.

**DISCUSSION**

The velocity-specific training response we observed after high-velocity concentric training done on an isokinetic dynamometer was typical of that reported previously (2, 4, 10, 19, 21); that is, strength increases were greatest at the training velocity (highest velocity tested). Similarly, the changes we observed in voluntary isometric performance, namely, relatively greater increases in rate of torque development and relaxation than in PT, were similar to those found previously in response to...
“explosive” training (15). We found the same high-velocity-specific training response after isometric training, in which the isometric contractions were the product of attempted ballistic movements that had been externally restrained to prevent movement. These isometric contractions were characterized by a rapid rate of torque development and relaxation and a short duration. If ve-
Velocity specificity

Velocity of training were defined in terms of the actual velocity of the training movement, then our isometric training would be classified as low-velocity (indeed, zero velocity) training. On this basis our isometric training results are in contrast to previous studies that show that training with isometric or low-velocity concentric contractions increases low-velocity strength but causes little or no increase in high-velocity strength (2, 4, 9, 10, 19, 21, 28). We believe that our isometric training was unique in producing a high-velocity-specific training response because of the way it was performed: attempted ballistic movements with high rate of force development. By contrast, in typical isometric or low-velocity concentric training, no emphasis is put on a rapid rate of force development or an attempt to move as rapidly as possible; therefore, a low- rather than high-velocity-specific training response is produced.

We interpret the results of our isometric training as indicating that an actual high-velocity movement in training exercises is not necessary to produce a high-velocity-specific training response. Instead, the key training stimuli appear to be either one or both of 1) the motor
command and characteristic motor unit activation pattern associated with attempted high-velocity movements, and 2) the high rate of force development of the ensuing muscle contraction, regardless of its type (isometric or concentric). This interpretation is based on the assumptions that 1) the motor command and pattern of motor unit activation in the concentric- and isometric-trained legs was similar; 2) the isometric training setup was successful in preventing movement of the foot and rendering the training contractions isometric; 3) any "cross-training" effect that may have occurred using the within-subject training model did not significantly affect the pattern of results observed; and 4) the dorsiflexor muscles are similar to other human muscles in their responses to low- and high-velocity strength training. Each of these assumptions will now be considered.

To ensure as much as possible the same motor command and pattern of motor unit activation in the isometric- and concentric-trained legs, a within-subject training model was used in which, for each subject, the same nervous system was activating both isometric- and concentric-trained legs. The subjects were also instructed to make the same attempted ballistic movements with both legs, regardless of the resistance encountered. We had no way of assessing directly whether the brain's motor command to isometric- and concentric-trained legs was the same. In some subjects we monitored the motor unit activation associated with the two training modes by recording surface EMGs from the dorsiflexor agonist tibialis anterior and the antagonist soleus. An example of the recordings is shown in Fig. 2. The amplitude and duration of the EMG bursts appeared to be similar in the two training modes, but from these recordings we could not determine whether the same motor units were recruited or whether they discharged with the same firing rates.

Previous research has indicated, however, that the motor unit discharge pattern is similar in attempted ballistic movements, whether actual movement is allowed or prevented (8).

How successful was the isometric training setup in preventing movement of the foot and ensuring isometric contractions? The straps used to restrain the foot were successful in restricting movement to a few degrees or less of joint excursion in comparison to the 40-70° excursion associated with the concentric training. Ensuring "true" isometric contractions is problematic. Even if we had been successful in preventing any foot movement and even if the origin and insertion of the dorsiflexors remained fixed, it is probable that in the isometric training contractions actual shortening of the contractile component (sarcomeres, myofibrils, fibers) occurred at the expense of the series-elastic component. This phenomenon has been demonstrated in mammalian skeletal muscle (12). The joint position used for the isometric training (30° of plantarflexion) placed the dorsiflexors on stretch (25), an arrangement that would have reduced but not eliminated shortening of the contractile component at the expense of the series-elastic component. Therefore, there is the possibility that in addition to a high rate of force development, a small amount of rapid muscle shortening may also have been part of any mechanical stimulus to high-velocity-specific contractile adaptations in the isometric-trained leg. However, the extent of the shortening was far less, and probably also the velocity of shortening, than occurred in the concentric-trained leg. Thus the practical significance of the study is not diminished with respect to the question of whether a rapid movement through a full range of movement is necessary to effect a high-velocity-specific training response.

The cross-training effect in strength training refers to increases in strength in an untrained limb induced by training of the contralateral limb. An increase in voluntary strength of the untrained limb may not occur (5, 6, 20, 28), but when an increase does occur it is much smaller than in the trained limb (3, 17, 18, 22, 27). The cross-training effect is usually attributed to central nervous system adaptations to training of one limb, which are transferred to the untrained limb, because increases in muscle size (6, 18, 20, 22, 27, 28), muscle fiber size (17, 22), evoked contractile force (14), or muscle enzyme activity (22) have never been observed in the untrained limb in association with the increase in voluntary strength. Further evidence of the importance of central neural adaptations in the cross-training effect comes from a study in which electrical stimulation training of one limb increased voluntary strength in the trained but not the untrained limb. In contrast, voluntary contraction training of one limb did increase strength in the untrained limb (3). In the present study we sought to make the motor command and motor unit activation pattern similar in the training of the isometric- and concentric-trained legs. If we were successful, any "central" cross-over would be of little significance. If we were unsuccessful and there was a large difference in the motor command and motor unit activation pattern in the training of the two legs, and if these central factors were entirely or largely responsible for the high-velocity-specific training response, then the velocity-specific response would have been more pronounced in the concentric-trained leg. We found the same response in both legs, making it unlikely that the high-velocity-specific response in the isometric-trained leg was simply the result of central neural adaptations transferred from the concentric training of the other leg. On the basis of the previously cited studies showing no evidence of peripheral muscle adaptations in contralateral untrained muscles, we also discount the possibility that the similar velocity-specific training response in the two legs and the similar evoked contractile property alterations were the result of a cross-training effect.

Our fourth and final assumption was that human dorsiflexor muscles respond to low- and high-velocity strength training with the same velocity-specific responses observed in other muscles such as quadriceps (2, 4, 10, 19, 21, 23, 26, 28) and adductor pollicis (9, 14). The concentric training results confirmed the assumption. In contrast, the isometric results did not confirm the assumption. Isometric training of the dorsiflexors produced a high rather than low-velocity-specific training response. We believe that the high-velocity-specific response to isometric training in the dorsiflexors was caused by the attempted ballistic movements used in the training, and that if conventional isometric or low-velocity concentric training had been used, a typical low-ve-
velocity-specific training response would have occurred. We considered this assumption to be reasonable because we had no reason to believe that the dorsiflexors would behave differently than other muscle groups. The design of the study was based on this assumption. We must concede, however, that we can cite no evidence that conventional isometric training (i.e., relatively slow rising contractions to peak force) of the dorsiflexors produces the typical low-velocity-specific training response. On the other hand, there is some evidence that conventional low-velocity weight training of the dorsiflexors tends to increase rather than decrease evoked twitch TPT and HRT (16). This issue would be resolved definitely by an experiment in which responses to conventional and ballistic isometric training were compared in the dorsiflexors.

Both muscular and neural adaptations could be responsible for the high-velocity-specific training response. Some adaptation within the muscles occurred in the present study, based on the observed increase in evoked twitch MRTD, and decrease in evoked twitch time to PT and HRT (i.e., a briefer twitch contractile response). These adaptations are similar to those reported previously in response to high-velocity dynamic training of adductor pollicis but differ from the response to isometric training of the same muscle, in which no attempt was made to develop force rapidly. The response to the latter type of isometric training included no change in twitch contraction time and a much smaller increase in tetanic rate of force development (9).

The similar adaptive changes in evoked contractile properties in the isometric- and concentric-trained legs could be interpreted in two ways. 1) The high velocity specific training stimulus to muscle consists solely of the high-frequency motor unit firing pattern associated with attempted ballistic movements; the nature of the ensuing mechanical event is of no consequence. 2) If a mechanical stimulus is also important, a condition that greatly restricts or prevents rapid movement but allows force to be developed rapidly is as effective as a condition that allows a high-velocity movement through a full range of motion.

Our results have implications for the training of athletes. It would appear that athletes could improve high-velocity strength performance by attempting rapid movements against high resistance, which causes the actual velocity to be low (e.g., attempting to lift very heavy weights rapidly). A potential advantage of this approach to training is that the contractile forces produced are much greater than those obtained with attempted ballistic movements against little or no resistance. Given that the stimulus to contractile protein synthesis is positively related to the force of contraction (24), the high-resistance method of training would be more successful in causing hypertrophy. Hypertrophy may enhance high-velocity performance, particularly in movements in which considerable inertia must be overcome at the onset of movement (e.g., jumping). On the other hand, training contractions characterized by rapid force development to relatively high peak force may be more likely to cause muscle injuries such as strains and tears. Therefore, caution should be exercised in employing this type of training. It should be introduced into the training program with gradual progression.

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