Effects of Plyometric and Weight Training on Muscle–Tendon Complex and Jump Performance

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ABSTRACT

KUBO, K., M. MORIMOTO, T. KOMURO, H. YATA, N. TSUNODA, H. KANEHISA, and T. FUKUNAGA. Effects of Plyometric and Weight Training on Muscle–Tendon Complex and Jump Performance. Med. Sci. Sports Exerc., Vol. 39, No. 10, pp. 1801–1810, 2007. Purpose: The purpose of this study was to investigate the effects of plyometric and weight training protocols on the mechanical properties of muscle–tendon complex and muscle activities and performances during jumping. Methods: Ten subjects completed 12 wk (4 d wk⁻¹) of a unilateral training program for plantar flexors. They performed plyometric training on one side (PT; hopping and drop jump using 40% of 1RM) and weight training on the other side (WT; 80% of 1RM). Tendon stiffness was measured using ultrasonography during isometric plantar flexion. Three kinds of unilateral jump heights using only ankle joint (squat jump: SJ; countermovement jump: CMJ; drop jump: DJ) on sledge apparatus were measured. During jumping, electromyographic activities were recorded from plantar flexors and tibial anterior muscle. Joint stiffness was calculated as the change in joint torque divided by the change in ankle angle during eccentric phase of DJ. Results: Tendon stiffness increased significantly for WT, but not for PT. Conversely, joint stiffness increased significantly for PT, but not for WT. Whereas PT increased significantly jump heights of SJ, CMJ, and DJ, WT increased SJ only. The relative increases in jump heights were significantly greater for PT than for WT. However, there were no significant differences between PT and WT in the changes in the electromyographic activities of measured muscles during jumping. Conclusion: These results indicate that the jump performance gains after plyometric training are attributed to changes in the mechanical properties of muscle–tendon complex, rather than to the muscle activation strategies. Key Words: PLANTAR FLEXION, TENDON STIFFNESS, PRESTRETCH, HUMAN, ULTRASONOGRAPHY

It is well known that plyometric training improves jumping and sprinting abilities and other ballistic movements (29,31). Previous studies suggested that the increase in jumping performance after plyometric training was attributed to neuromuscular adaptations, that is, the pattern of motor unit recruitment, muscle activities of agonists and antagonists (3,4,6,21,31,33). For example, Chimera et al. (3) show that the increased preparatory adductor activity and abductor-to-adductor coactivation presented preprogrammed motor strategies learned during plyometric training. They state that plyometric training might reduce the risk of injury by enhancing functional joint stability in the lower extremities. Kyrolainen et al. (21) also report that the preactivity of muscles increased after 4 months of plyometric training, and this change led to increased tendomuscular stiffness. Komi (10) suggests that higher stiffness levels of lower limb muscles during stretch-shortening cycle exercises led to a benefit in terms of the greater amount of stored and reused elastic energy. In fact, Toumi et al. (31) demonstrate that the knee joint stiffness during the eccentric phase of countermovement jump increased significantly for the jump training combined with weight training group, but not for weight training group. However, it is unclear whether these changes in tendomuscular stiffness were caused by the changes in the muscle activities and/or the mechanical properties of muscle–tendon complex itself.

Jumping and sprinting movements induce stretch-shortening cycles in the muscle–tendon complex in the lower limbs, in which lengthening and shortening actions of the muscle–tendon complex are repeated (10). During stretch-shortening cycle exercises, the elastic energy is stored in tendon structures in the lengthening phase and is reused in the shortening phase (10). Recent studies have investigated the relationship between tendon properties and
jump performances in vivo (1,16). We found that tendon stiffness in knee extensors was inversely correlated with the relative difference in jump height between vertical jumps performed with and without countermovement—prestretch augmentation (16). In addition, the stiffness of the human tendon has been shown to increase after resistance training using heavy loads (12,18,27). Kubo et al. (18) report that after isometric squat training, the tendon stiffness in knee extensors increased, and, simultaneously, the prestretch augmentation during vertical jumping decreased. Considering these findings, it is hypothesized that plyometric training would change the tendon properties, making them suitable for stretch-shortening cycle exercises. In addition, the above-quoted findings (12,31) tempt us to assume that there is a difference in the effects on the mechanical properties of muscle–tendon complex and the neural adaptations between plyometric and weight training regimens. If so, the differences in these changes would lead to the differences in the effects on jump performances.

The purpose of this study was to investigate the effects of plyometric and weight training protocols on the mechanical properties of muscle–tendon complex and muscle activities and performances during jumping. These findings would be useful to elucidate the mechanisms of improved performances during the stretch-shortening cycle after plyometric training.

METHODS

Subjects. Ten healthy males (age: 22 ± 2 yr, height: 170 ± 3 cm, body mass: 63 ± 8 kg, mean ± SD) voluntarily participated in this study. They did not have an experience of regular exercise training. Therefore, the obtained results in this study would be different from those from trained subjects. They were fully informed of the procedures to be utilized as well as the purpose of this study. Written informed consent was obtained from all subjects. This study was approved by the office of the Department of Sports Sciences, University of Tokyo, and complied with their requirements for human experimentation.

Training. Subjects performed plyometric training on one side (PT) and weight training on the other side (WT). In each subject, the right and left legs were randomly allocated to the training protocols. They completed 12 wk (4 d wk⁻¹) of plyometric and weight training protocols on the sledge apparatus (VR-4100, Cybex Corp.) with an inclination of 17° from the horizontal position. The subjects lay on the sliding table of this apparatus. The table was designed to slide with minimal friction with a constant load through a steel cable connected to adjustable weights. The measurement of one-repetition maximum was made every 4 wk to adjust the training load. At the end of the training session, the one-repetition maximum increased significantly by 55 ± 11% for PT and 58 ± 13% for WT, respectively (both P < 0.001). In a training session, a subject would train the PT protocol leg first, then the WT protocol leg, and in the next session, the order would be reversed.

For PT, the subjects performed the two kinds of training protocols, that is, hopping and drop jump training. During the hopping jump, the initial position was maximal plantar flexion. Then, the subjects developed the plantar flexion force to maximal dorsiflexion (eccentric muscle action), and rebounded to start plantar flexion until the toe finally lifted away from the footplate of this apparatus (concentric muscle action). The subjects repeated these movements without a pause. During the drop jump, the sliding table of this apparatus was moved to a height of 20 cm from the surface of the footplate of this apparatus to the sole of their foot with the assistance of an experimenter. They were dropped down from a height of 20 cm. After landing on the edge of the footplate of this apparatus, the ankle joint was dorsiflexed until the maximally dorsiflexed position (eccentric muscle action). Then, the subjects started plantar flexion and took off (concentric muscle action). The subjects repeated these movements without a pause. The subjects performed five sets of each exercise (hopping and drop jump) with a between-set rest interval of 30 s, which consisted of unilateral plantar flexion at 40% of the one-repetition maximum with 10 repetitions per set. According to the previous findings (8), maximal mechanical power has been thought to occur at a resistance of 30–45% of the one-repetition maximum.

For WT, the subjects were instructed to lift and lower the load at an approximately constant velocity, taking about 1 s for the concentric action and 3 s for the eccentric action. The exercise was performed over the range of motion from the fully dorsiflexed position to the fully plantar flexed position. The subjects performed five sets of exercise with a between-set rest interval of 1 min, which consisted of unilateral plantar flexion at 80% of the one-repetition maximum with 10 repetitions per set. It is generally known that high intensity (~80% of the one-repetition maximum) exercise is highly effective for gaining muscular size and strength (24).

Jump performance. Three kinds of unilateral maximal jumps using only the ankle joint (squat jump: SJ; countermovement jump: CMJ; drop jump: DJ) were performed on the sledge apparatus. The load used was 50% of the body mass for each subject. Because the body mass of the subjects did not change after training, the load for each subject was the same before and after training. A force plate (Kistler, 9281B, Switzerland) was mounted firmly onto the footplate of this apparatus. A wooden block was attached to the force plate, and the subjects placed the ball of their right foot on the block with the knee fully extended. The vertical component of the ground reaction force (Fz) was recorded from the force platform. Three retroreflective landmarks were placed over the following anatomical landmarks on the right side of the subjects: the fifth metatarsophalangeal joint, the lateral malleolus, and the lateral epicondyle of the knee. During jumping, subjects were filmed from the right (using the right ankle) or left
(using the left ankle) sides in the sagittal plane with a digital high-speed video camera at a sampling frequency of 200 Hz (HSV-500C, Nac, Japan).

Before the experiment the subjects were familiarized with the jumping actions. For all tests, they were instructed to jump to a maximal height. The test was repeated five times per subject, with at least 3 min between trials. For SJ, the subjects initially kept the ankle position maximally dorsiflexed, and supported the load in this position. Then, the subjects started ankle movement until the ankle was fully plantar flexed and the toe lifted away from the wooden block. For CMJ, the initial position was maximal plantar flexion. Then, the subjects developed the plantar flexion force to maximal dorsiflexion (eccentric muscle action), and rebounded to start plantar flexion until the toe finally lifted away from the footplate of this apparatus (concentric muscle action). For DJ, the sliding table of this apparatus was moved to a height of 20 cm from the surface of the footplate of this apparatus to the sole of their foot with the assistance of an experimenter. They were dropped down from a height of 20 cm. After landing on the edge of the wooden block with the ball of the right foot, the ankle joint was dorsiflexed until the maximally dorsiflexed position (eccentric muscle action). Then, the subjects started plantar flexion and took off (concentric muscle action). We excluded the trials in which the knee joint was flexed slightly according to images taken by a high-speed video camera.

Using a public domain National Institutes of Health (NIH) image software package, the ankle joint angle and jump height were measured. Assuming that the displacement of the retroreflective landmark of the lateral malleolus was equal to that of the center of mass, the jump height was defined as the maximum displacement of the retroreflective landmark of the lateral malleolus from the resting position (ankle joint angle was 90°). Three individual jump height recordings excluding the largest and smallest values were averaged. The difference between the heights of CMJ or DJ and SJ, expressed as the percentage of that in SJ, was proposed as an index of prestretch augmentation (15).

The repeatability of the jump height measurements was investigated on two separate days in a preliminary study with six young males. There were no significant differences between the test and retest values of the SJ, CMJ, and DJ heights. The intraclass correlation coefficient (ICC) was 0.91 for SJ, 0.88 for CMJ, and 0.85 for DJ, respectively.

Joint stiffness. Ankle joint torque (TQ) during DJ was estimated from the following equation (9):

\[ TQ = F_z L_1 \cos(A_j - 90) \]

where \( F_z \), \( L_1 \), and \( A_j \) are the vertical component of the ground reaction force, the length from the estimated center of the ankle joint to the ball of the foot (measured for each subject), and the ankle joint angle, respectively (see Fig. 3 in Kawakami et al. (9)).

According to Kuitunen et al. (19), ankle joint stiffness was calculated as a change in joint torque divided by the change in the ankle joint angle during the eccentric phase. As mentioned above, three trial values for jumping heights were averaged.

### Table 1. Mechanical and morphological properties of muscle and tendon for plyometric and weight training protocols.

<table>
<thead>
<tr>
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<th>Before</th>
<th>After</th>
<th>Before</th>
<th>After</th>
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<tbody>
<tr>
<td>Muscle volume (cm³)</td>
<td>576.5 (49.7)</td>
<td>604.8 (51.8)*</td>
<td>579.4 (48.8)</td>
<td>610.8 (51.4)*</td>
</tr>
<tr>
<td>MVC (N/m)</td>
<td>116.0 (23.4)</td>
<td>131.4 (27.5)*</td>
<td>114.5 (24.6)</td>
<td>135.1 (26.0)*</td>
</tr>
<tr>
<td>Activation level (%)</td>
<td>90.7 (9.4)</td>
<td>95.2 (5.6)*</td>
<td>91.2 (8.0)</td>
<td>96.0 (6.0)*</td>
</tr>
<tr>
<td>Coactivation level (%)</td>
<td>12.8 (5.3)</td>
<td>12.6 (4.4)</td>
<td>13.5 (3.9)</td>
<td>14.4 (5.4)</td>
</tr>
<tr>
<td>Twitch torque (N/m)</td>
<td>16.0 (2.2)</td>
<td>16.4 (3.41)</td>
<td>16.6 (2.5)</td>
<td>16.8 (3.4)</td>
</tr>
<tr>
<td>Time to peak torque (ms)</td>
<td>153 (24)</td>
<td>139 (14)*</td>
<td>148 (25)</td>
<td>143 (10)</td>
</tr>
<tr>
<td>Rate of torque development (N m s⁻¹)</td>
<td>106.6 (22.3)</td>
<td>117.8 (16.8)</td>
<td>112.7 (12.3)</td>
<td>117.0 (23.3)</td>
</tr>
<tr>
<td>Maximal tendon elongation (mm)</td>
<td>13.7 (2.3)</td>
<td>15.0 (2.3)*</td>
<td>12.5 (2.3)</td>
<td>11.9 (2.6)</td>
</tr>
<tr>
<td>Tendon stiffness (N/mm)</td>
<td>129.0 (35.8)</td>
<td>154.0 (55.2)</td>
<td>127.9 (25.8)</td>
<td>165.9 (43.7)*</td>
</tr>
<tr>
<td>Elastic energy of tendon (J)</td>
<td>20.4 (7.0)</td>
<td>24.4 (7.9)*</td>
<td>19.9 (6.8)</td>
<td>19.0 (5.9)</td>
</tr>
<tr>
<td>Tendon CSA (mm²)</td>
<td>57.2 (8.1)</td>
<td>59.1 (8.7)</td>
<td>59.0 (7.9)</td>
<td>58.3 (8.4)</td>
</tr>
</tbody>
</table>

Mean (SD). * Significantly different from before training.
The repeatability of the joint stiffness measurements was investigated on two separate days in a preliminary study with six young males. There were no significant differences between the test and retest values of joint stiffness. ICC was 0.86.

Cross-sectional area of muscle and tendon. Measurements of muscle and tendon cross-sectional areas (CSA) were carried out by magnetic resonance imaging scans (AIRIS II, HITACHI Medical Cop., Tokyo, Japan). T1-weighted spin-echo, axial-plane imaging was performed with the following parameters; TR 850 ms, TE 25 ms, matrix 256 × 256, field of view 250 mm, slice thickness 10 mm, and interslice gap 0 mm. The subjects were imaged in a supine position with the knee and ankle kept at 0° (full extension) and 90° (anatomical position), respectively. During the scanning, the subject lay supine with the base of the foot resting on a polystyrene block to maintain an ankle angle of 90°. The number of sections obtained for each subject was 42–47. The muscles investigated were as follows: medial gastrocnemius (MG), lateral gastrocnemius (LG), and soleus (SOL). From the axial image, outlines of each muscle were traced, and the traced images were transferred to a computer for CSA calculation using a public domain NIH image software package. The muscle volume was determined by multiplying the anatomical CSA of each image by the thickness (10 mm). In addition, the measurement of tendon CSA was taken at two positions (one above the calcaneous and the other at 10 mm proximal to the calcaneous). The average CSA at the two positions was calculated as the representative of tendon CSA.

The repeatability of muscle volume and tendon CSA measurements was investigated on two separate days in our previous study with six young males (13). There were no significant differences between the test and retest values of the muscle volume and tendon CSA. ICC was 0.92 for the muscle volume and 0.97 for the tendon CSA.

Muscle strength, resting twitch, and neural activation. The maximal voluntary isometric strength (MVC) of the plantar flexor muscles was determined using an electrical dynamometer (Myoret, Asics, Japan). The subject lay prone on a test bench and the waist and shoulders were secured by adjustable lap belts and held in position. The ankle joint was set at 90° with the knee joint at full extension, and the foot was securely strapped to a footplate connected to the lever arm of the dynamometer. Before the test, the subject performed a standardized warm-up and submaximal contractions to become accustomed to the test procedure.

The repeatability of the muscle strength measurements was investigated on two separate days in a preliminary study with eight young males. There were no significant differences between the test and retest values of joint stiffness. ICC was 0.86.

Resting twitch properties were assessed by supramaximal electrical stimulations. The stimulating lead electrodes were placed on the skin of the right popliteal fossa and oriented longitudinal to the estimated path of the tibial nerve with the anode distal. A high-voltage stimulator (SEN-3301, having a specially modified isolator SS-1963, Nihon-Koden, Japan) generated rectangular pulses (triple stimuli with a 500-μs duration for one stimulus and an interstimulus interval of 10 ms). Maximal twitch contractions were evoked in the resting muscle by progressively increasing the stimulation intensity until increases failed to elevate twitch torque further. The stimulus intensity that elicited peak twitch torque was used throughout the duration of the measurements. Peak torque, time to peak torque, and the rate of torque development were measured as the twitch properties.
During MVC, evoked twitch contractions were imposed by supramaximal electrical stimulations to assess the activation level of muscles. The experimental procedures have been described in detail previously (17). In all subjects, the stimuli increased the force during MVC at the appropriate latency. Shortly (within 1–2 s) after MVC, when the potentiation effect of the contraction still persisted, the same stimulation was given to the muscle at rest (control twitch). The voluntary force at the instant of stimulation was used as the MVC force. The twitch force (difference between peak twitch force and MVC force) was measured, from which the level of muscle activation with voluntary effort (% activation) was assessed from the following equation (twitch interpolation technique; (17)): 

\[
\% \text{ activation} = \left(1 - \frac{\text{twitch force}}{\text{MVC force}}\right) \times 100 \%
\]

where control twitch represents the twitch imposed on the resting muscle after MVC.

**Stiffness of Achilles tendon.** The subject was instructed to develop a gradually increasing force from a relaxed state to MVC within 5 s. The task was repeated two times per subject with at least 3 min between trials. An ultrasonic apparatus (SSD-2000, Aloka, Tokyo, Japan) with an electronic linear array probe (7.5-MHz wave frequency with 80 mm scanning length; UST 5047-5, Aloka) was used to obtain longitudinal ultrasonic images of the medial gastrocnemius muscle. The probe was longitudinally attached to the dermal surface with adhesive tape, which prevented the probe from sliding. To evaluate the elongation of the Achilles tendon, the displacement of the myotendinous junction obtained from the ultrasound images could be corrected for angular joint rotation and contractile tension, since any angular joint rotation occurs in the direction of ankle plantar flexion during an “isometric” contraction (22). To monitor ankle joint angular rotation, an electrical goniometer (Penny and Giles) was placed on the lateral aspect of the ankle. To correct the measurements taken for the elongation of the Achilles tendon, additional measurements were made under passive conditions. Displacement of the myotendinous junction of the medial gastrocnemius muscle caused by rotating the ankle from 90 to 70° was digitized in sonographs taken as described above. Thus, for each subject, displacement of the myotendinous junction obtained from the ultrasound images could be corrected for that attributed to joint rotation alone (22). In the present study, only values corrected for angular rotation are reported.

The measured torque (TQ) during isometric plantar flexion was converted to tendon force \(F_t\) by the following equation:

\[
F_t = \frac{TQ}{MA}
\]

where MA is the moment arm length of the triceps surae muscles at 90° of the ankle joint, which is estimated from the lower-leg length of each subject (15). In the present study, the tendon force and elongation values above 50% of MVC were fitted to a linear regression equation, the slope of which was adopted as stiffness (16). Two trial values for tendon stiffness were averaged. ICC of the two measurements of tendon stiffness for all subjects was 0.91.

The repeatability of the tendon stiffness measurements was investigated on two separate days in our previous study with eight young males (13). There were no significant differences between the test and retest values of tendon stiffness. ICC was 0.89.

**TABLE 2. Ankle angle, angular velocity, and performance during jumping tests for plyometric and weight training protocols.**

<table>
<thead>
<tr>
<th>Ankle angle at the lowest position (°)</th>
<th>Before</th>
<th>After</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>SJ</td>
<td>67.7 (4.7)</td>
<td>67.1 (7.3)</td>
<td>68.5 (4.5)</td>
<td>66.0 (9.9)</td>
</tr>
<tr>
<td>CMJ</td>
<td>68.1 (5.2)</td>
<td>68.2 (7.2)</td>
<td>68.3 (4.3)</td>
<td>67.7 (5.1)</td>
</tr>
<tr>
<td>DJ</td>
<td>68.9 (5.6)</td>
<td>69.4 (6.2)</td>
<td>69.3 (5.0)</td>
<td>68.9 (4.1)</td>
</tr>
<tr>
<td>Angular velocity during eccentric phase (°/s)</td>
<td>96.5 (26.4)</td>
<td>98.1 (27.4)</td>
<td>83.4 (8.5)</td>
<td>75.3 (15.6)</td>
</tr>
<tr>
<td>CMJ</td>
<td>205.6 (33.1)</td>
<td>226.3 (48.1)</td>
<td>198.4 (33.5)</td>
<td>213.4 (46.4)</td>
</tr>
<tr>
<td>DJ</td>
<td>122.7 (25.6)</td>
<td>141.4 (18.8)</td>
<td>126.2 (18.0)</td>
<td>137.0 (31.3)</td>
</tr>
<tr>
<td>Angular velocity during concentric phase (°/s)</td>
<td>153.8 (25.8)</td>
<td>158.1 (19.9)</td>
<td>144.3 (29.3)</td>
<td>155.3 (30.6)</td>
</tr>
<tr>
<td>SJ</td>
<td>81.4 (15.8)</td>
<td>115.4 (43.9) *</td>
<td>71.8 (11.2)</td>
<td>84.6 (18.9)</td>
</tr>
<tr>
<td>CMJ</td>
<td>232.2 (46.5)</td>
<td>314.1 (50.5) *</td>
<td>236.3 (35.5)</td>
<td>24.4 (3.1)</td>
</tr>
<tr>
<td>DJ</td>
<td>23.6 (5.4)</td>
<td>33.8 (5.0) *</td>
<td>24.2 (4.3)</td>
<td>25.5 (3.7)</td>
</tr>
<tr>
<td>Jump height (cm)</td>
<td>12.0 (7.6)</td>
<td>19.1 (12.0)</td>
<td>12.8 (5.0)</td>
<td>8.3 (11.7)</td>
</tr>
<tr>
<td>CMJ</td>
<td>14.7 (8.2)</td>
<td>29.2 (16.6)</td>
<td>17.9 (13.5)</td>
<td>13.1 (14.1)</td>
</tr>
<tr>
<td>DJ</td>
<td>13.0 (7.6)</td>
<td>19.1 (12.0)</td>
<td>12.8 (5.0)</td>
<td>8.3 (11.7)</td>
</tr>
</tbody>
</table>

Mean (SD), * Significantly different from before training.
Electromyographic activity. The electromyographic activity (EMG) was recorded during the measurements of the maximal voluntary isometric strength, tendon properties, and jump performances. Bipolar surface electrodes (5 mm in diameter) were placed over the bellies of MG, LG, SOL, and tibialis anterior (TA) muscles with a constant interelectrode distance of 25 mm. The electrodes were connected to a preamplifier and differential amplifier with a bandwidth of 5 Hz to 500 Hz (model 1253A, NEC Medical Systems, Tokyo, Japan). The EMG signals were transmitted to a computer at a sampling rate of 1 kHz. The EMG was full-wave rectified and averaged for the duration of the contraction (mEMG). During the jumping tests, the mEMG values from MG, LG, SOL, and TA were calculated from the prelanding (defined as 100 ms preceding landing), eccentric and concentric phases, respectively, according to the ankle joint angle. In addition, the mean of mEMG in the MG, LG, and SOL was defined as the mEMG of plantar flexors. During the measurements of tendon properties, the mEMG of TA was measured to investigate the antagonist muscle activity of TA (coactivation level). To determine the maximal activation of TA, a maximal dorsiflexion isometric contraction was performed at the same angle (90° of ankle joint). We normalized the mEMG value of TA with respect to the mEMG value of TA at the same angle when acting as an agonist at maximal effort.

Statistics. Descriptive data included means ± SD. A two-way ANOVA with repeated-measures [2 (groups) × 2 (test times)] was used to analyze the data. The F ratios for main effects and interactions were considered significant at P < 0.05. Significant differences among means at P < 0.05 were detected using a Tukey post hoc test.

RESULTS

The muscle volumes of the plantar flexor muscles increased significantly 4.9 ± 2.3% for PT (P = 0.003) and 5.4 ± 2.8% for WT (P = 0.002), respectively (Table 1). No significant difference in the relative increase of muscle volume was found between PT and WT (P = 0.379). There were no significant differences in the relative increase in the muscle volume among MG, LG, and SOL (Fig. 1). Furthermore, no significant change in the Achilles tendon CSA was found between both the protocols (Table 1).

The MVC value increased significantly by 17.3 ± 21.7% for PT (P = 0.017) and 19.3 ± 13.6% for WT (P = 0.003), respectively (Table 1). There was no significant difference in the relative increase of the MVC value between the two protocols (P = 0.818). The activation level of the plantar flexor muscles assessed by superimposing electrical stimuli increased significantly by 5.6 ± 6.6% for PT (P = 0.019) and 5.8 ± 8.2% for WT (P = 0.049), respectively (Table 1). No significant change in the coactivation level was found after training for PT (P = 0.771) and WT (P = 0.549), respectively (Table 1). Although the twitch torque value and the rate of torque development did not change for both the protocols, the time to peak torque shortened significantly for PT (P = 0.011) but not for WT (P = 0.499) (Table 1).

Both protocols produced no significant differences in the tendon-elongation values at any force-production levels after training (Fig. 2). The maximal tendon elongation and elastic energy increased significantly for PT (tendon elongation P = 0.031, elastic energy P = 0.044), but not for WT (tendon elongation P = 0.374, elastic energy P = 0.681) (Table 1). The relative increases in the maximal tendon elongation and elastic energy were greater for PT than for WT (tendon elongation P = 0.032, elastic energy

FIGURE 3—The relative changes in the jump height of SJ, CMJ, and DJ for plyometric and weight training protocols. The relative increases in the SJ, CMJ, and DJ heights were significantly greater for PT than for WT. ** P < 0.01; *** P < 0.001.
The stiffness of the Achilles tendon increased significantly by 28.9\% for WT ($P = 0.002$), but not for PT (21.7\%; $P = 0.109$) (Table 1). There was no significant difference in the relative increase of stiffness between the two protocols ($P = 0.558$).

Table 2 shows the measured variables during the three kinds of jumping tests before and after training. For both protocols, there were no significant differences in the ankle angle at the lowest position in all the jump tasks. The angular velocities at eccentric and concentric phases did not change after training, except for in the concentric phase of SJ for PT ($P = 0.003$). SJ height increased significantly by 29.8\% for PT and 10.9\% for WT (both $P < 0.001$). The PT protocol produced a significant increase in the jump height of CMJ (37.7\%; $P < 0.001$) and DJ (47.5\%; $P < 0.001$), but the WT protocol did not (CMJ: 6.2\%; $P = 0.096$; DJ: 6.5\%; $P = 0.108$). The relative increases in the SJ, CMJ, and DJ heights were significantly greater for PT than for WT ($P < 0.001$; CMJ $P = 0.001$; DJ $P < 0.001$) (Fig. 3). The prestretch augmentation of CMJ and DJ did not change for PT (CMJ $P = 0.161$, DJ $P = 0.075$) and WT (CMJ $P = 0.231$, DJ $P = 0.182$). However, the relative increase in the prestretch augmentation of CMJ was significantly greater for PT than for WT ($P = 0.028$), and that of DJ did not reach statistical significance ($P = 0.058$).

Table 3 shows the mEMG of plantar flexors and TA during jumping tests. The mEMG of plantar flexors during SJ, CMJ, and DJ increased significantly for both PT and WT (all $P < 0.05$). There were no significant differences in the relative increase in the mEMG of plantar flexors between PT and WT. The mEMG of plantar flexors during the other phases (prelanding and eccentric phases) did not change after training using both the protocols. During CMJ and DJ, no changes in the ratio of mEMG of plantar flexors during the eccentric phase to that during the concentric phase were found for both PT and WT (all $P > 0.05$). No significant changes in the mEMG of TA were observed after training.

The joint stiffness increased significantly from 4.1\% to 6.7\% for PT ($P = 0.047$) for PT, but was unchanged for WT ($P = 0.191$) (Fig. 4).

**DISCUSSION**

The major findings of this study were that 1) the tendon stiffness increased significantly for WT, but not for PT; 2) the joint stiffness increased significantly for PT, but not for WT; 3) the relative increases in the jump heights of SJ, CMJ, and DJ were significantly greater for PT than for WT; and 4) no differences in the changes in the electromyographic activities of the plantar flexor and tibial anterior muscles during jumping tests for plyometric and weight training protocols.
activities of measured muscles during jumping were found between PT and WT.

Previous findings obtained from animal experiments demonstrated that the mechanical and morphological properties of tendons were variable through physical training (2,25,28,30,32,34). Most of these previous studies used endurance exercises as the training protocol, and revealed increases in the ultimate failure load and stiffness of tendons. In contrast, Simonsen et al. (28) report that strength training produced no significant changes in the ultimate tensile strength of the rat Achilles tendon. Further, only a few attempts have so far been made at investigating the influences of plyometric training on tendons (25,30). According to the limited information available, jumping or sprint training protocols produced no significant changes in tendon properties (25,30). With regard to the effect of plyometric training on human tendons, cross-sectional information is available from previous research (11,15). We have reported that the tendon properties of knee extensors were more compliant in sprinters compared with untrained subjects (15). Recently, we have shown that that the tendon properties of knee extensors did not change after repeated drop jump exercises temporarily (14). Furthermore, our previous study has demonstrated that the tendon stiffness of knee extensors increased after 12 wk of isometric training (12).

In addition to this, other types of isometric training (short duration of muscle contraction), characterized as ballistic or explosive, did not increase the stiffness of tendon structures (12). Considering these previous findings using animals and humans (12,14,15,25,30), an exercise protocol that required high force production for a short duration (i.e., ballistic contraction) could not change the tendon properties.

Recent studies have demonstrated that the stiffness of human tendons increased after resistance training using a heavy load (12,18,27). The present results for the WT protocol agreed with these previous findings. However, the training protocol did not induce a significant hypertrophic change in the tendons. A possible explanation would be that the resistance training induced changes in the internal structures of tendons. Namely, the variability of the mechanical quality of tendon structures originates from differences in the cross-link pattern or structure of the collagen fibers (5). On the other hand, according to our recent observations concerning changes in tendon stiffness after training, the increase of tendon stiffness after isometric training (e.g., 58% (12)) tended to be greater than that after isotonic training (e.g., 30% (17); 29% (present study)). Hence, it might be assumed that there was a difference in the effects of the contraction mode on the tendon properties between isometric and dynamic contractions. Unfortunately, the mechanisms which resulted in the increase of tendon stiffness after isometric and isotonic training protocols are unknown. These areas are presently under investigation in our laboratory.

Some previous researchers have suggested that enhanced jumping performance after plyometric training was attributed to neural adaptations, that is, the patterns of motor unit recruitment and muscle activities of agonists and antagonists (3,4,6,21,33). For example, Chimera et al. (3) report that the adductor muscle preactivation and adductor and abductor coactivation both increased after plyometric training. In the present study, however, the relative increases in jump heights were greater for PT than for WT (Fig. 3). If these differences in jump performances were caused by neural adaptations, the changes in the EMG activities during jumping would be different between PT and WT protocols. For all jumping tasks, however, no differences in the increase in mEMG during the concentric phase were found between PT and WT (Table 3). In addition, the mEMG of plantar flexors and TA during the other phases (prelanding and eccentric phases) did not change after training (Table 3). Kyrolainen et al. (20) also have demonstrated that the muscle activity patterns did not change after 15 wk of plyometric training. They state that the increases in the jump height after plyometric training cannot be explained by changes in the muscle activity patterns and/or increased neural input to the muscles. Therefore, these results suggested that the differences in jump heights between PT and WT were not caused by the muscle activation strategies.

In the present study, the maximal tendon elongation and stored elastic energy increased significantly in the PT protocol (Table 1). Thus, the increases in the CMJ and DJ heights for PT would be related to the unchanged tendon stiffness. Hence, it might be assumed that, compared with the WT protocol, the tendon properties would change to be suitable for stretch-shortening cycle exercises after plyometric training. For WT, on the contrary, the jump heights of CMJ and DJ did not change after training. This result could also be explained by an offset of the positive (increase in muscle function) and negative (increase in tendon stiffness) effects on performance during stretch-shortening cycle exercises. This point was already confirmed by our recent study (18). Namely, isometric squat training increased the tendon stiffness of knee extensors and decreased prestretch augmentation during vertical jumping. However, the performance during stretch-shortening cycle exercises cannot be explained by only one factor (tendon property), since this is a complex issue. These discussions require additional data for clarification.

Another finding of this study was that the joint stiffness increased significantly for PT, but not for WT (Fig. 4). This result agrees with the previous findings (29,31). Komi (10) suggests that a higher stiffness level of lower-limb muscles during stretch-shortening cycle exercises facilitated greater amounts of stored and reused elastic energy. In fact, Heise and Martin (7) show a positive correlation between leg stiffness and running economy, concluding that economical runners possessed a running style that was stiffer during ground contact. Furthermore,
Toumi et al. (31) suggest that the high joint stiffness during the eccentric phase might be accomplished by a proper preprogrammed motor command. At the beginning of the study, therefore, it was expected that the increase in joint stiffness would be the result of neural adaptations after training. In the present results, however, there were no significant differences in the changes induced by the two protocols in muscle activities during jumping. Accordingly, we may say that the increase in joint stiffness after plyometric training was caused by changes in the mechanical properties of muscle–tendon complex, and not by neural adaptations. Malisoux et al. (23) report that the passive tension of a single muscle fiber increased after 8 wk of plyometric training. They also stated that plyometric training was effective in improving the cross-bridge mechanics of single fibers. Taking the present findings into account along with these previous findings, it is likely that the increase in joint stiffness after plyometric training is related to the changes in the properties of muscle (active cross-bridge), because of unchanged tendon stiffness.

Recent studies showed that running economy and performance improved after plyometric training (26,29). Spurrs et al. (29) report that plyometric training improved running economy and distance running performance, and thus increased the musculotendinous stiffness of the ankle joint using the oscillation technique. They postulated that the increase in the musculotendinous stiffness of the ankle joint resulted in improved running economy and performance. Taking these previous findings into account, together with our results on the PT protocol, we speculate that tendon stiffness remained unchanged and that joint stiffness increased after plyometric training. These changes in the mechanical properties of muscle–tendon complex would lead to the improved running economy and distance running performance.

In conclusion, tendon stiffness increased by weight training; conversely, joint stiffness increased by plyometric training. Furthermore, jump performance improved by plyometric training, although no differences in the pattern of muscle activities during jumping were found between before and after training. These results indicate that the jump performance gains after plyometric training are attributed to changes in the mechanical properties of muscle–tendon complex, rather than muscle activation strategies.

REFERENCES


