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Comparison of Plyometric Training With Two Different Jumping Techniques on Achilles Tendon Properties and Jump Performances

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Abstract

Laurent, C, Baudry, S, and Duchateau, J. Comparison of plyometric training with two different jumping techniques on Achilles tendon properties and jump performances. *J Strength Cond Res* XX(X): 000–000, 2020—This study compared the influence of 10 weeks of plyometric training with 2 different jumping techniques on Achilles tendon properties and the height achieved in drop jumps (from 20, 40, and 60 cm) and countermovement jumps (CMJ). Subjects were allocated to 2 training groups (n = 11 in each group) and 1 control group (CON, n = 10). One training group kept the knees extended (KE) during ground contact, whereas the other training group flexed the knees to ~80–90° (KF). Achilles tendon stiffness was assessed with ultrasonography, and jump performance was derived from force platform recording. Training increased jump height ($p < 0.01$) in both groups. The increase for the 20-cm drop jump was greater ($p < 0.05$) for the KE group (11.3%) thanfor the KF group (6.3%), with no statistical difference between groups for the 40- and 60-cm drop jumps. Contact time during the 20-cm drop jump decreased (~8%; $p < 0.01$) after training, with no difference between the training groups. The increase in CMJ height was greater ($p = 0.05$) for the KF group (17.5%) than for the KE group (11.8%). Achilles tendon stiffness increased (32%; $p < 0.001$) for the KE group but not for the KF group (11%; $p = 0.28$). There was a positive association ($p < 0.001$) between the changes in tendon stiffness and jump height for 20-cm drop jump in both KE group ($r^2 = 0.49$) and KF group ($r^2 = 0.62$). None of these parameters changed in CON group. In conclusion, the extent of increase in jump height (20-cm drop jump and CMJ) and in Achilles tendon stiffness after training differed between the 2 jumping techniques.

Key Words: countermovement jump, drop jump, plyometric exercise, stretch-shortening cycle, tendon properties

Introduction

In many sporting activities, a common pattern of muscle action during movements is the stretch of an active muscle before performing a shortening contraction (i.e., stretch-shortening cycle (20)). The stretch-shortening cycle increases positive work and power output compared with an isolated shortening contraction (7,18,21).

Plyometric exercises are classically used in the training programs of athletes involved in power events as a means to increase explosive force (27,31). These exercises are thought to enhance the efficacy of the stretch-shortening cycle by increasing muscle-tendon loading during the eccentric phase or by decreasing the duration of the transition between the eccentric and concentric phases (6,16,31). A popular plyometric exercise used to increase vertical jump height is called "drop jump." It involves a vertical jump that is performed immediately after a dropping down from an elevated surface. A few weeks of plyometric training can increase vertical jump height when tested by performing drop jumps (2,9,15,25,34,39), which translates to improvements in such athletic events as sprinting and jumping (for a review, see Ref. 31).

Despite the effectiveness of such training exercises, the underlying adaptations are poorly understood (31). A few studies have suggested that neural factors, as estimated by surface electromyography (EMG), can contribute to the increases in performance after training with plyometric exercises (2,39). In contrast, Kubo et al. (24) found increases in jump height and ankle joint stiffness during the ground contact phase of drop jumps after 12 weeks of plyometric training without any change in EMG activity of the plantar flexor muscles, suggesting that in their study, the improvement in performance was mainly located in the muscle-tendon complex (24).

Insight into the adaptations experienced by the muscle-tendon complex can be gained by analyzing training-related changes in tendon stiffness as assessed with ultrasonography (41). Contrary to conventional weight training (22,23) and eccentric training (10,12) that both increase tendon stiffness, contrasting results have been found after plyometric training. Some groups have observed an increase in Achilles tendon stiffness after 6–14 weeks of plyometric training (5,11), whereas others have not found changes in Achilles tendon stiffness after similar training durations (13,24). In addition to difference in mechanical loading (dropping height) and training volume (total number of jumps and number of jumps per session) (34,41), one possible explanation for the divergent outcomes between these studies could be the proportion of jump exercises performed in each session with the knees flexed (KF) or extended (KE) during the ground contact phase. Consistent with this possibility, Bobbert et al. (3) reported that reductions in the amount of knee flexion during ground contact (i.e., bounce-type drop jump) increases the peak resultant reaction forces at the knee and ankle joints and the force

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transmitted by the Achilles tendon relative to those observed during larger knee-flexion jumps (i.e., countermovement jump [CMJ] drop jump). Because the CMJ technique may be more effective than bounce drop jump at increasing vertical jump height (32), these 2 techniques may involve different adaptations in Achilles tendon properties.

The main objective of our study was to compare the influence of training with 2 different jumping techniques on the gains in vertical jump height and the mechanical properties of the Achilles tendon. According to the training principle of specificity, it was hypothesized that Achilles tendon characteristics and jump height would adapt differently for the 2 jumping techniques. We expected greater adaptations in Achilles tendon properties and drop jump performance for the KE group but greater increases in CMJ height for the KF group.

Methods

Experimental Approach to the Problem

An intervention study was designed to compare the influence of the jumping technique adopted during plyometric training on the Achilles tendon properties and performance in drop jumps and CMJ. Two training groups and 1 control group were constituted. The training program involved 10 weeks of plyometric exercises with 1 of the 2 jumping techniques. One training group (KE) performed all jumping exercises while keeping the KE during the ground contact phase and tried to minimize contact time (bounce-type jump) (3). The second training group (KF) executed the jumping exercises by braking the downward movement after ground contact by quickly flexing the knees to ~80–90° (full knee extension $= 0°$) as occurs in a CMJ (CMJ drop-type jump) and to jump as high as possible with the KE phase performed as quickly as possible (32). The control group (CON) was tested at the beginning and end of the 10-week interval and instructed not to change their daily levels of physical activity between the 2 testing sessions. Jump performance was determined by measuring jump height and contact time for drop jumps performed from 3 different heights (20, 40, and 60 cm) and jump height reached during CMJ, whereas Achilles tendon stiffness and cross-sectional area (CSA) were assessed by ultrasonography recordings.

Subjects

Thirty-two subjects, aged between 19 and 26 years, volunteered for the study were first assigned to the CON group ($n = 10$; 5 women) or 1 of the 2 training groups ($n = 11$; 5 women in each group) based on their availability to participate in the entire training program. Subjects selected to participate in the training program were randomly allocated to 1 of the 2 training groups (KE or KF). Subjects' height and mass did not differ ($p > 0.05$) between the groups and were, respectively, 180.5 ± 5.8 cm and 68.7 ± 14 kg for the KE group, 180.9 ± 10.5 cm and 69.7 ± 10.8 kg for the KF group, and 177.0 ± 9.6 cm and 69.3 ± 9.8 kg for the CON group. All subjects were physically active (students in sport science and physiotherapy), but none of them were previously involved in regular strength or plyometric training programs. Approval for the project was obtained from the local ethics committee. Each subject was informed of the experimental risks and signed an informed document before participating in the study. All procedures used in this study conformed to the Declaration of Helsinki.

Procedures

Training. Each training session began with a warm-up (~15 minutes) included cycling, callisthenic exercises, and jumps (squat and CMJ) and ended with a few static and ballistic stretching exercises. The main part of a training session included two-legged hopping and drop jump exercises from heights of 30–40 cm (Table 1). The exercises were similar for the 2 training groups but differed in the prescribed amount of knee flexion (see above). The exercises comprised vertical jumps for which participants hopped on the spot (stationary hopping) or jumped down and up onto a box or bench (drop jumps on the spot). The drop jump exercises slightly varied by changing subject position relative to the box or bench (subject placed in front or beside the box or straddling the bench). Drop jump exercises were also executed with small displacement (forward or lateral) onto 5 successive boxes and during forward displacement along the length of a long bench with the subject straddling or jumping down and up side-to-side the bench. Each training session included 6–8 of these exercises with the subject performing sets of 10 repetitions of each exercise (Table 1). The rest period between sets of a given exercise and between 2 different exercises was ~1.5 and 3 minutes, respectively.

As Ramirez-Campillo et al. (34) reported that high volume of plyometric training is needed to improve jump performance, progressive overload principle was incorporated into the training program by gradually increasing every week the number of jumps performed in a session from 200 in the first week to 400 in the last week of training (Table 1). This was accomplished by first increasing the number of sets per exercise (from 3 to 5) and then increasing the number of exercises (from 6 to 8). Participants performed 2 training sessions each week, separated by at least 48 hours, as this frequency seems to be optimal for moderately trained individuals (9,34). Training duration lasted 10 weeks to ensure substantial changes in performance (31,38) and tendon properties (41). All sessions were supervised by an experienced coach to control for the correct execution of the exercises and the involvement of the subjects. All the subjects completed the 10-week training program.

Testing. Before beginning training, each participant attended a familiarization session that introduced the experimental protocol. Subjects were tested before and after the 10-week training period with the posttraining evaluation session performed 2–3 days after the last training session to avoid a confounding effect of residual fatigue.

Performances were tested during drop jumps from 3 different heights: 20, 40, and 60 cm. Subjects performed the jumps with their hands on the hips and were instructed to react as quickly as possible at ground contact with minimal knee flexion. We preferred this jump technique because it maximizes the contribution of the Achilles tendon (3), and the jumps are less variable from trial to trial than with greater amounts of knee flexion. Jump height was also recorded during a CMJ to assess more specifically training-related adaptations when greater knee flexion was used during jumps. The CMJ started from a standing position from which the subject moved downward to ~80–90° knee flexion and then immediately performed a fast upward movement to jump as high as possible. The magnitude of knee flexion was controlled by an elastic rope placed below the pelvis. Subjects were instructed to keep their hands on the hips during the entire CMJ. Subjects performed 5 repetitions of each jump with ~20–30 seconds of rest between the jumps.

Table 1
Training program (sets × repetitions).*

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10
Stationary hopping	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10
DJ on the spot										
Front	3 × 10	4 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10
Beside	3 × 10	4 × 10	4 × 10	4 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10
Straddling	3 × 10	3 × 10	4 × 10	4 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10	5 × 10
DJ with displacement										
Forward	3 × 10	3 × 10	3 × 10	4 × 10	4 × 10	4 × 10	5 × 10	5 × 10	5 × 10	5 × 10
Lateral	3 × 10	3 × 10	3 × 10	4 × 10	4 × 10	4 × 10	5 × 10	5 × 10	5 × 10	5 × 10
Forward straddling						3 × 10	3 × 10	3 × 10	4 × 10	5 × 10
Forward side-to-side								3 × 10	4 × 10	5 × 10
Total jumps	200	220	240	260	280	310	330	360	380	400

*DJ = drop jump.

The vertical ground reaction force was recorded with a custom-made force platform (70 × 50 cm) that involved 4 load cells (sensitivity: 0.5 $\text{mV}\cdot\text{N}^{-1}$; linear range: 0–10 kN; Model 1320; Sensor Techniques Limited, Cowbridge, United Kingdom). The force signal was acquired on a computer at a sampling rate of 200 Hz (Model MP 100), and the data were analyzed with the AcqKnowledge software (Biopac System Inc., Santa Barbara, CA). The validity of the force platform in measuring the contact time and flight time was assessed by simultaneously comparing drop jumps performed from 40-cm height in 20 subjects with a commercially available system (Optojump; Microgate, Bolzano, IT). Pearson's correlation coefficients (r) between these 2 recording systems was >0.99 for both contact time and flight time. Intrasubject reliability was assessed by a test-retest procedure on 20 subjects in sessions that were separated by a few (<5) days. The intraclass correlation coefficients for the drop jumps (40 cm) were 0.91 for contact time, 0.97 for jump height, and 0.95 for the coefficient of reactivity, and it was 0.89 for jump height during the CMJ.

Plantar flexion torque during submaximal and maximal voluntary contractions (MVCs) was measured while the subject lay prone on a table. The left foot was secured by 3 straps to a foot plate equipped with an adjustable heel block, and the medial malleolus was aligned with the axis of rotation of the footplate (1). The ankle ergometer was equipped with a force transducer (sensitivity: 0.6 $\text{mV}\cdot\text{N}\cdot\text{m}^{-1}$; linear range 0–1100 N; model TC 2000–500; Kulite, Basingstoke, United Kingdom), and signals were recorded with the same acquisition system used for the force platform. The isometric torque produced by the plantar flexor muscles was calculated by multiplying the recorded force by the ratio between the foot lever arm (distance between the center of the medial malleolus and the first metatarsal) and the ergometer lever arm (distance between the axis of rotation and the connection of the transducer with the footplate). The test-retest correlation coefficient tested in 10 subjects in separated sessions was 0.88.

Achilles tendon properties were assessed with the subject in the same position as used to measure MVC torque. The ultrasound probe was positioned over the muscle-tendon junction of the gastrocnemius medialis, defined as the convergence of the deep and superficial aponeuroses (28). Longitudinal images were obtained using real-time B-mode ultrasonography (ProSound 75; Aloka, Japan) with a 6-cm width linear-array probe (7.5 MHz) coated with a water-soluble transmission gel to provide acoustic contact. The probe was held in place by a custom-made holster strapped to the leg to ensure a constant orientation and pressure of the probe on the skin. In addition, a metallic marker was placed between the skin and the probe to measure the displacement of the muscle-tendon junction (1). Before assessing tendon elongation, Achilles tendon CSA was measured at rest with the ankle at 90° angle. The ultrasound images were recorded in the transverse plane 4 cm above its insertion on the calcaneus, approximately the narrowest site of the free (distal) portion of the Achilles tendon. Cross-sectional area was measured using a polygon selection tool in the Image J software. The test-retest correlation coefficient, tested in 10 subjects on separate days, was 0.92 for tendon stiffness and 0.80 for CSA.

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Data Analysis. The durations of the ground contact and flight phases following the take-off were measured from the recordings of the force platform. Jump height (h) was calculated from the flight time (Ft) with the following formula: $h = (g \times Ft^2)/8$, where g is the acceleration because of gravity (9.81 $\text{m}\cdot\text{s}^{-2}$). A "reactivity" index was computed by performing the ratio between the maximal height attained during the vertical jump and the contact time (39). This index reflects the ability of the subject to produce high forces in a brief period that characterizes "explosive force" (39). The variables that provided the greatest reactivity index for the drop jumps were used in the statistical analyses.

To determine the MVC torque produced by the plantar flexor muscles, each subject performed at least 3 MVCs with 2 minutes of rest between contractions. If the difference in torque between the 2 greatest MVCs was $>5\%$, subsequent trials were performed until the difference between the 2 greatest MVC torque was $<5\%$. Maximal voluntary contraction torque was set equal to the greatest torques produced during the MVCs.

To assess Achilles tendon properties, the displacements of the muscle-tendon junction, reflecting the elongation of the tendon (28), were recorded during brief isometric contractions (3–4 seconds) performed at 20, 40, 60, and 80% MVC torque in a counterbalanced order across subjects (37). Visual feedback of the torque signal and the target torque was provided to the subject. Care was taken to ensure that the heel remained in contact with the footplate during all contractions. The images were analyzed offline (sensitivity: 10 $\text{pixels}\cdot\text{mm}^{-1}$) by the same investigator with Image J software (National Institute of Health). An index of tendon stiffness was determined from the slope of the torque-tendon elongation relation between 20 and 80% of MVC (37). In a pilot study performed in the same conditions on 7 subjects, we observed a linear relation ($r^2 \geq 0.94$) between the force produced by the plantar flexors and the elongation of the free component of the Achilles tendon between 20 and 100%

MVC when tendon elongation was corrected for ankle joint rotation (19). As our objective was not to calculate the absolute Achilles tendon stiffness but simply to assess the influence of plyometric training on the elongation capacity of the tendon structures, we did not convert the measured torque recorded at the ankle level into plantar flexor force. Cross-sectional area was calculated as the average of 2 measurements for each subject. For all measurements, the analyst was not blinded to the group assignment.

Statistical Analyses

The Gaussian distribution of the data was confirmed with the Kolmogorov-Smirnov test. Drop jump performance (height, contact time, and reactivity index), CMJ height, MVC torque, tendon stiffness index, and Achilles tendon CSA were compared between groups with a 2-way analyses of variance (ANOVAs) (group × time) with repeated measures for time. To gain further insight on differences in training effects, 1-way ANOVAs were performed to compare changes (%) in jump performance between the groups. Tukey's post hoc tests were used when drop height main effect or interactions were found. The coefficient of determination (r^2) extracted from Pearson's product-moment correlations was used to assess the strength of the association between the changes in the slope of the relation between torque and tendon elongation and jump parameters for the 3 drop jumps and CMJ height. Eta squared (η^2) was calculated for significant ANOVAs as an estimate of effect size with small ($\eta^2 = 0.1$), medium ($\eta^2 = 0.25$), and large ($\eta^2 = 0.40$) effects (8). Furthermore, Cohen's *d* was calculated as an estimate of effect size when post hoc test revealed differences in the extent of change between KF and KE groups, with small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$) effects (8). The level of statistical significance was set at $p \leq 0.05$ for all comparisons. Values are expressed as mean and *SD*.

Results

A time main effect ($p < 0.05$; $\eta^2 = 0.22$) indicates an increase in MVC torque, without statistical difference between groups (group × training interaction; $p = 0.21$). The MVC torque increased from 114.5 ± 26.1 to 127.1 ± 28.9 N·m (+13%) for the KE group and from 126.3 ± 27.2 to 133.2 ± 19.3 N·m (+8%) for the KF group, with no change (123.0 ± 32.4 vs. 123.5 ± 37.2 N·m; 0.2%) for the CON group. The gain in MVC torque did not differ between the groups ($p = 0.85$).

A group × time interaction ($p < 0.01$; $\eta^2 = 0.47$) for the 20-cm drop jump and post hoc tests indicated that jump height increased for the KE (+11.3%; $p < 0.001$) and KF (+6.3%; $p < 0.01$) [T2] groups but not for CON group (+2.7%; $p = 0.60$) (Table 2). Furthermore, 1-way ANOVA ($p < 0.01$; $\eta^2 = 0.43$) and post hoc tests indicated that jump height increased more for the KE group than for the KF ($p = 0.05$; $d = 0.71$) and CON ($p < 0.01$; $d = 1.20$) groups. Contact time decreased regardless of the group (time main effect, $p < 0.01$; $\eta^2 = 0.14$), with no difference in the amount of change between the groups (1-way ANOVA, $p = 0.27$). The reactivity index increased (group × interaction, $p = 0.05$; $\eta^2 = 0.23$) for the KE (+22.5%; post hoc test, $p < 0.01$) and KF (+14.3%; $p < 0.05$) groups, but with no difference between the groups (1-way ANOVA, $p = 0.18$).

A group × time interaction ($p < 0.05$; $\eta^2 = 0.23$) fort the 40-cm drop jump and post hoc tests indicated that jump height increased for the KE (+9.4%, $p < 0.01$) and KF (+7.8%; $p < 0.01$) groups but not for CON group (+1.5%; $p = 0.96$) (Table 2). Furthermore, 1-way ANOVA ($p < 0.01$; $\eta^2 = 0.25$) and post hoc tests indicated that jump height increased more for the KE ($p < 0.05$; $d = 0.7$) and KF ($p < 0.05$; $d = 1.3$) groups than for the CON group, with no differences between the KE and KF groups ($p = 0.62$). Contact time and its amount of changes did not vary statistically for any group (all p values ≥ 0.12). The reactivity index increased after training (group × interaction, $p < 0.05$; $\eta^2 = 0.40$) but only for the KF group (+16.6%; post-hoc test, $p < 0.05$). The amount of change did not differ between the groups (1-way ANOVA, $p = 0.11$).

A group × time interaction ($p < 0.001$; $\eta^2 = 0.77$) for the 60-cm drop jump and post hoc test indicated that jump height increased after training for the KE (+8.4%; post hoc test, $p < 0.01$) and KF (+13.6%; $p < 0.001$) groups but not for the CON group (+1.7%; $p = 0.99$) (Table 2). Furthermore, 1-way ANOVA ($p < 0.01$; $\eta^2 = 0.71$) and post hoc tests indicated that jump height increased more for the KE ($p < 0.01$; $d = 0.8$) and KF ($p < 0.001$; $d = 1.9$) groups than for the CON group, with no difference ($p = 0.06$) between the training groups. Contact time did not change for any group (all p values > 0.47). The reactivity index was increased after training (group main effect, $p = 0.05$; $\eta^2 = 0.14$), with no differences between group (1-way ANOVA, $p = 0.45$).

Jump height during CMJ increased significantly after training (group × time interaction; $p < 0.001$; $\eta^2 = 0.76$) for the KE (from 29.0 ± 6.6 to 32.1 ± 6.2 cm; post hoc test, $p < 0.001$) and KF (from 32.9 ± 7.6 to 38.4 ± 7.9 cm; $p < 0.001$) groups but not for the CON group (from 27.8 ± 7.5 to 28.2 ± 7.5 cm; $p = 0.96$). Furthermore, the increase in jump performance was greater for the KF group (+17.5%) than for the KE group (+11.8%; $p = 0.05$; $d = 0.66$), whereas the changes for both training groups being greater ($p < 0.001$) than the CON group (+1.5%).

The index of tendon stiffness increased significantly (group × training interaction; $p < 0.01$; $\eta^2 = 0.45$) after training for the KE group (from 5.0 ± 1.2 to 6.7 ± 2.3 Nm·mm^{-1}; post hoc test, $p < 0.001$) but not for the KF group (from 5.4 ± 1.7 to 6.2 ± 2.0 Nm·mm^{-1}; $p = 0.28$) and CON group (from 5.5 ± 1.6 to 5.5 ± 1.4 Nm·mm^{-1}; $p = 0.99$) (Figure 1A–C). Furthermore, 1-way [F1] ANOVA ($p < 0.01$; $\eta^2 = 0.47$) and post hoc tests indicated that the change in tendon stiffness was greater for the KE group than for the KF ($p < 0.05$; $d = 0.69$) and CON ($p < 0.01$; $d = 1.6$) groups (Figure 1D). Achilles tendon CSA before training was similar across groups (KF: 56.0 ± 9.9 mm^2; KE: 61.8 ± 10.6 mm^2; CON: 61.5 ± 5.3 mm^2) and did not change after training ($p = 0.56$).

For drop jumps performed from 20-cm height, the changes in jump height and index of Achilles tendon stiffness were positively associated for both the KE group ($r^2 = 0.49$; $p < 0.001$; Figure 2A) and the KF group ($r^2 = 0.62$; $p < 0.001$; Figure 2B). Similarly, the increase in reactivity index was positively associated with the increase in tendon stiffness ($r^2 = 0.62$; $p < 0.001$) [F2] for the KE group (Figure 2C) but ($p > 0.05$) not for the KF group (Figure 2D). In contrast, there were no statistically significant associations for drop jumps performed from 40 to 60 cm.

Discussion

The main objective of the current study was to compare the effects of a training program of plyometric exercises performed with 2 jumping techniques that stress the Achilles tendon differently. Our results indicate that the index of Achilles tendon stiffness

Table 2

Jump parameters performed from the 3 drop heights in the control (CON) group and, before and after training for the knees extended (KE) and knees flexed (KF) groups.*

	CON			KE			KF		
	20 cm	40 cm	60 cm	20 cm	40 cm	60 cm	20 cm	40 cm	60 cm
Jump height									
Before (cm)	22.6 (5.0)	24.2 (5.3)	23.6 (6.3)	21.5 (4.7)	21.7 (4.7)	20.5 (4.0)	21.4 (3.3)	22.6 (3.4)	22.5 (3.7)
After (cm)	23.1 (4.9)	24.6 (5.5)	23.9 (5.8)	23.8 (4.8)†	23.5 (4.4)†	22.1 (4.1)†	22.7 (3.8)†	24.4 (3.9)†	25.6 (4.4)†
Gain (%)	2.7 (3.6)	1.5 (1.6)	1.7 (3.9)	11.3 (6.1)‡	9.4 (10.8)	8.4 (6.3)	6.3 (3.6)	7.8 (4.8)	13.6 (7.2)
Contact time									
Before (ms)	200.4 (11.1)	204.1 (13.7)	217.5 (14.8)	218.3 (21.4)	210.1 (17.2)	235.8 (31.5)	211.1 (14.5)	205.7 (20.4)	218.4 (23.9)
After (ms)	199.9 (14.9)	205.8 (13.6)	215.7 (13.2)	201.0 (19.3)	199.8 (12.4)	229.0 (30.1)	195.4 (17.2)	190.0 (19.3)	223.1 (28.1)
Gain (%)	1.0 (3.3)	3.0 (3.5)	1.6 (3.6)	−8.2 (6.4)	−5.8 (3.6)	−3.1 (7.0)	−7.4 (4.0)	−7.8 (6.6)	−2.4 (6.1)
Reactivity index									
Before (cm·ms^{-1})	0.116 (0.034)	0.124 (0.039)	0.114 (0.041)	0.100 (0.029)	0.104 (0.024)	0.87 (0.022)	0.099 (0.020)	0.110 (0.028)	0.105 (0.026)
After (cm·ms^{-1})	0.118 (0.025)	0.121 (0.024)	0.112 (0.026)	0.120 (0.027)†	0.200 (0.023)	0.94 (0.024)	0.114 (0.026)†	0.128 (0.031)†	0.115 (0.031)
Gain (%)	6.6 (16.2)	2.6 (11.7)	4.4 (12.5)	22.5 (14.9)	16.9 (15.4)	12.9 (10.8)	14.3 (9.3)	16.6 (11.4)	13.5 (6.6)

*Data are expressed as mean (*SD*) for 10 subjects in CON group and 11 subjects in KE and KF groups.
†Significant ($p \leq 0.05$) changes after training (group × time interaction, Tukey's post hoc test).
‡Significant difference ($p < 0.05$) with KF.

increased after training to a greater extent for bounce-type drop jumps than for CMJ drop jumps. Although the change in Achilles tendon stiffness was positively associated with the change in jump height in the 2 training groups for the 20-cm drop jump, the average increase in jump height was significantly greater for the KE group than for the KF group. In contrast, the gain in CMJ was greater for the KF group than for the KE group. The absence of differences in the increases in drop jump performance at the 40- and 60-cm drop heights between the 2 training groups suggests that other adaptations than Achilles tendon stiffness have

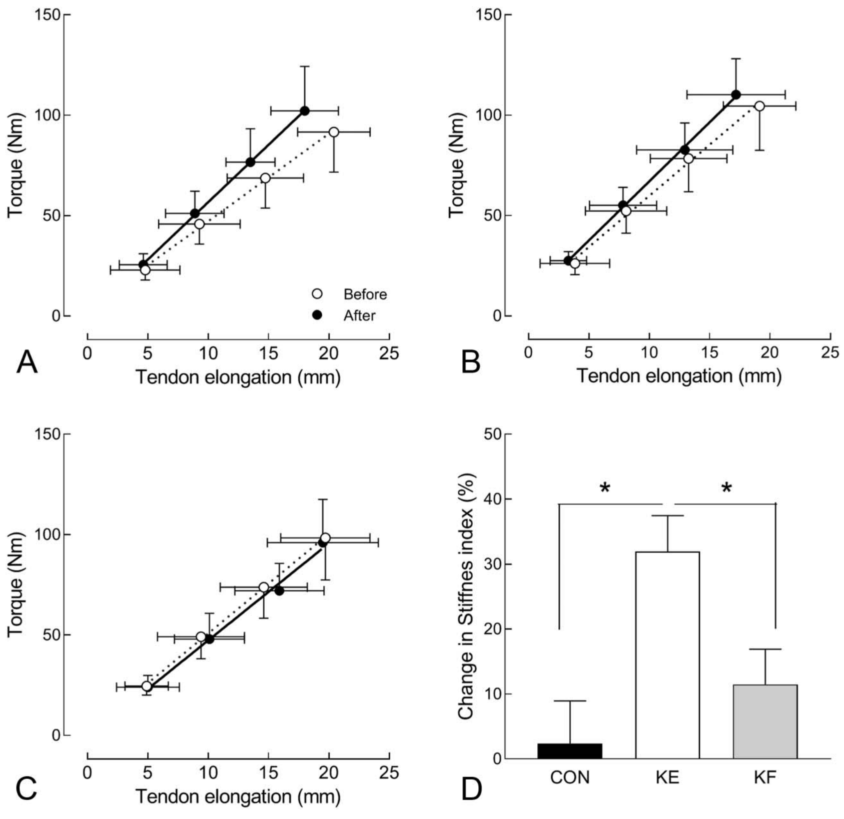

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Figure 1. Association between torque and tendon elongation (stiffness index) before (open circles) and after (filled circles) training with the knees extended (KE) group (A, $n = 11$) or knees flexed (KF) group (B, $n = 11$) and for the control group (CON, $n = 10$). The dashed (before) and continuous lines (after) represent the linear regression from data collapsed within each group. D, Changes in stiffness index (%) for CON, KE, and KF groups. The increase in stiffness index was significantly greater for the KE group than for the CON ($p < 0.01$) and KF ($p < 0.05$) groups. Data are expressed as mean ± *SD*.

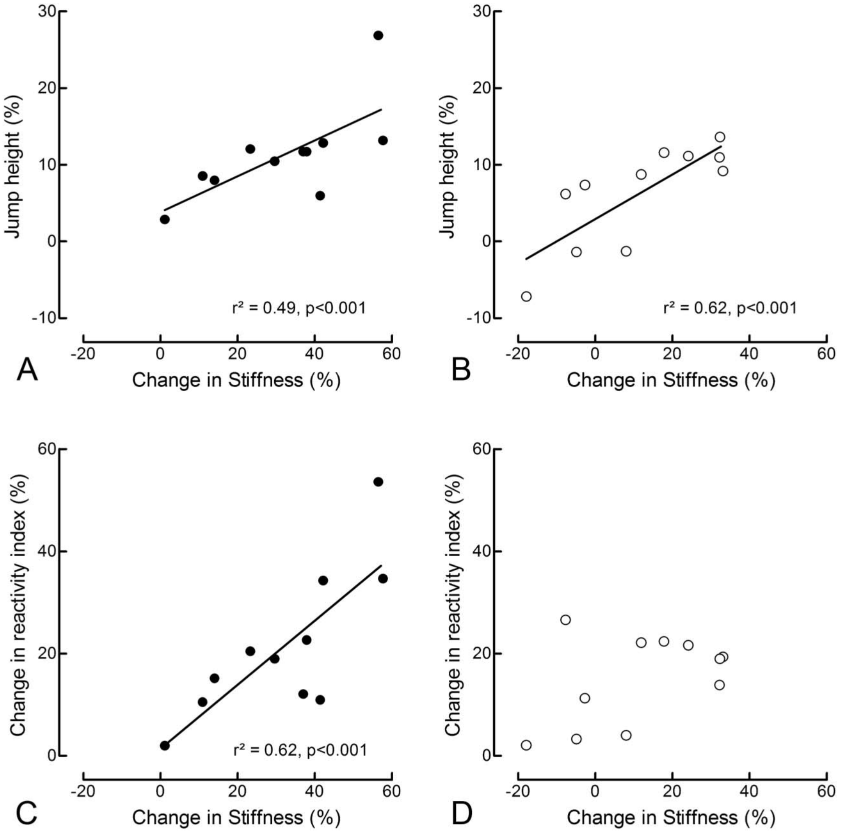

Figure 2. Changes (expressed in %) in jump height (A and B) and reactivity index (C and D) plotted against changes in stiffness index for each subject for the knees extended (KE) group and the knees flexed (KF) group when measured during drop jump from 20-cm height. Linear regression analysis indicated a significant relation ($p < 0.001$) and coefficient of determination (r^2) between pairs of variables, except between changes in reactivity index and stiffness index for the KF group ($p > 0.05$).

contributed to the improvement in drop jump performances for these drop heights.

As reported previously (for a review, see Ref. 31), our study indicates that a training program of plyometric exercises for 10 weeks improves the maximal torque of the plantar flexor muscles tested during an isometric MVC. Although plyometric training is not the most effective method to increase the maximal muscle force in trained athletes, some studies have shown that it can be a sufficient stimulus to increase muscle force in moderately trained individuals (2,11,24,25,30).

Regardless of drop height, plyometric training increased jump height (range, 6.3–13.6%) in the 2 training groups, in agreement with previous studies (6,9,13,15,24,25,32,39). This increase in jump height was accompanied by a reduction in contact time for drop jumps performed from the 20-cm height, a change that has been sometimes reported (9,15,25,32) but not always (31,38). The contrasting observation that training with low drop heights, as used in the current study, reduces ground contact time but not training with high drop height led Taube et al. (39) to suggest that the adaptation stimulus is more related to the constraint of the task (i.e., loading condition) than the instruction given to the subject at ground contact (i.e., rebound as fast as possible). However, the reduction in contact time at the 20-cm drop height in our 2 training groups, despite different loading conditions of the Achilles tendon, seems to be the consequence of our instruction. Indeed, subjects in both of our groups, had to react as quickly as possible at ground contact to minimize contact time and then to jump as high as possible. More importantly, the 2 jumping techniques substantially increased (13.5–22.5%) the reactivity index for all drop heights, except for drop jumps performed from 40-cm height by the KE group.

Moderate differences in drop jump performance were observed between the 2 training groups. The only significant difference was a greater gain in jump height at the 20-cm drop height for the KE group than for the KF group with no difference between groups at the 40- and 60-cm drop height. Although no clear explanation for these divergent results can be provided, our data indicate that the increase in jump height in the KE group has been optimized at low but not high impact force. In contrast, the increase in jump height during the CMJ was much greater for the KF group than for the KE group. This observation is consistent with the training principle of specificity (31,32), as this group trained with drop jumps that involved greater knee flexion. This group difference may be attributable to neural adaptations (i.e., intensity and pattern of muscle activation) (2,14,16,39) or changes in muscle-tendon properties of the different leg extensor muscles. Initially, our intention was to investigate the adaptation of both Achilles and patellar tendons in the 2 jumping techniques but our inability, in a pilot study, to track patellar tendon elongation consistently during contractions at different intensities in all subjects prevented this possibility. Further research is needed to examine the adaptation of patellar tendon stiffness with plyometric training.

A major finding in our study was the substantial increase (+32%) in stiffness index of the Achilles tendon after the 10-week plyometric training for the KE group with no statistical increase (+11%; $p = 0.28$) for the KF group. Although some studies have reported an increase in Achilles tendon stiffness after plyometric training (5,11,41), other have not observed such an adaptation (13,24). These contrasting results are often explained by several variables, including the loading intensity (drop height), the volume of jumps performed in each session, or the total duration of the training program. Because of a similar intensity (dropping heights) and training volume for the 2 groups, our study indicates that the technique used during ground contact is a key factor in the adaptation of Achilles tendon stiffness. The greater increase in the stiffness index for the KE group is consistent with the expectation that the stress generated in the biarticular gastrocnemius at ground contact would be greater with less knee flexion. In the KF condition, the gastrocnemii are stretched to a shorter length, thereby reducing the load on the Achilles tendon (3). Similar to previous studies (13,24), training did not change Achilles tendon CSA. Although ultrasound imaging technique cannot detect small variations in CSA (36), our finding nevertheless suggests that the increase in tendon stiffness mainly arise from intrinsic structural changes in the tendon (41). Regardless of the exact mechanism responsible for the increase in stiffness, our results indicate some specificity in the adaptation of Achilles tendon as a function of the jumping technique adopted during training with drop jumps.

The significant positive associations between the increases in Achilles tendon stiffness and jump height for the 2 training groups or between the increase in Achilles tendon stiffness and the reactivity index for the KE group when drop jumps were performed from the 20-cm height indicate that part of the adaptations in performance were the result of changes in the mechanical properties of the Achilles tendon. As a stiffer tendon transmits force more quickly to the skeleton (4,5,16), this parameter together with changes in neuromuscular activity and optimization of muscle-tendon interaction (2,14,16,39) seems to be an important factor for improving jump performance at low impact force. Nevertheless, the lack of significant association between the gains in Achilles tendon stiffness and jumps performance at 40- and 60-cm drop heights for both training groups may be explained by differences in the relative adaptations in neural (26) and mechanical (17) mechanisms or between muscle and tendon stiffness as a function of the drop height. It has been indeed suggested that the adaptations elicited by plyometric training may involve both tendinous (6,11) and muscular (13,24) structures.

A few points may have influenced our results and deserve consideration. First, tendon elongation at different forces was measured in separate trials and not during a single ramp contraction, as done in many studies (35). Because of its viscous properties and associated stress-relaxation characteristics (40), tendon elongation may be slightly overestimated when a constant force is maintained for a certain period. This effect, however, is limited as we used brief contraction (3–4 seconds) that were performed in a counterbalanced order across subjects. Second, the stiffness index was determined from the slope of the association between torque and tendon elongation between 20 and 80% of MVC force and not up to the maximal force. However, we have observed a linear relation between the force produced by the plantar flexors and elongation of the free component of the Achilles tendon between 20 and 100% MVC in a previous study (see Methods) and is usually reported between 40 and 100% MVC (24,29,37). We opted for the lower force because it greatly limits the influence of ankle joint rotation during maximal plantar flexion (19), thereby reducing the potential overestimation of tendon elongation. Even if our measurement procedures may have slightly influenced the exact value of the Achilles tendon stiffness, we are confident that the current data represent real training-related changes as subjects of both training groups were tested in the same conditions before and after training. Third, although our study shows clear differences for the main parameters (Achilles tendon stiffness; jump height from the 20-cm drop height; CMJ performance) between the 2 training groups, there was no significant difference for other variables (e.g., MVC force; reactivity index for the 20-cm drop height; jump height for the 60-cm drop height). In addition to a possible lack of statistical power because of a small sample size, variations in the extent of adaptations among subjects may have also contributed to the absence of difference. These variations may be due in part to the fact that drop jumps exercises during training were not optimized according to the individual capacities but performed from the same height for all subjects, which could have resulted in suboptimal loading for some subjects (6).

In summary, our study indicates that the index of Achilles tendon stiffness increased more after plyometric training when subjects performed jump exercises with lesser amount of knee flexion. Although the increase in jump height was greater for the KE group than for the KF group, the change in Achilles tendon index was positively associated with the change in jump height in the 2 training groups but only when performed from the 20-cm drop height.

Practical Applications

Although the specificity of neuromuscular adaptations elicited by strength training are usually well accepted in the field, specific adaptations in jump performance when different techniques are used during plyometric training is not well known and typically not often considered by coaches. Our results indicate that regardless of the amount of knee flexion adopted at ground contact during drop jump exercises, 10 weeks of plyometric training substantially improves jump height in moderately trained individuals. However, bounce-type drop jump (KE group) induced greater improvements in jump height for low (20-cm) drop jumps, whereas CMJ-like drop jumps (KE group) induced greater gains in CMJ performance.

As contact time was only reduced for the 20-cm drop jump for both groups, it is recommended that athletes be encouraged to produce greater forces in a minimal of time (e.g., sprinter; see Ref. 33) and to favor the use of drop jumps from low to moderate drop heights. Critically, these jumps must be performed with the intent to rebound as fast as possible in the specific and precompetitive phases of their training program. The greater training-related gain in Achilles tendon stiffness when drop jumps are performed with less knee flexion is an additional advantage in sports requiring high rates of force development and repeated dynamic actions of the plantar flexor muscles. These results have important implications in the optimization of training protocols of athletes involved in explosive sporting activities.

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