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Effects of plyometric training on passive stiffness of *gastrocnemii* and the musculo-articular complex of the ankle joint

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This study aimed to determine simultaneously the effects of plyometric training on the passive stiffness of the ankle joint musculo-articular complex, the *gastrocnemii* muscle–tendon complex (MTC) and the Achilles tendon in order to assess possible local adaptations of elastic properties. Seventeen subjects were divided into a trained (TG) group and a control (CG) group. They were tested before and after 8 weeks of a plyometric training period. The ankle joint range of motion (RoM), the global musculo-articular passive stiffness of the ankle joint, the maximal passive stiffness of *gastrocnemii* and the stiffness of the Achilles tendon during isometric plantar flexion were determined. A significant increase in the jump performances of TG relative to CG was found (squat jumps: +17.6%, $P = 0.008$; reactive jumps: +19.8%, $P = 0.001$). No significant effect of plyometric training was observed in the ankle joint RoM, musculo-articular passive stiffness of the ankle joint or Achilles tendon stiffness ($P > 0.05$). In contrast, the maximal passive stiffness of *gastrocnemii* of TG increased after plyometric training relative to CG (+33.3%, $P = 0.001$). Thus, a specific adaptation of the *gastrocnemii* MTC occurred after plyometric training, without affecting the global passive musculo-articular stiffness of the ankle joint.

In natural locomotion, the stretch-shortening cycle is a typical solicitation of the human muscle–tendon complex (MTC). The MTC stores potential elastic energy during the eccentric phase and restores a part of this energy during the concentric phase (Komi, 1992). Plyometric training has already been shown to increase vertical jump performances (e.g. Spurrs et al., 2003; Kyrolainen et al., 2005). Functional performances are also partially influenced by the elastic properties of the musculo-articular complex (MAC) passive structures (Siegler et al., 1984) such as muscles, tendons, skin, subcutaneous tissue, fascia, ligaments, joint capsule and cartilage (Wright, 1973).

In the active condition (i.e. during a muscle contraction), changes in the mechanical properties have been quantified after plyometric training *in vivo* (e.g. Cornu et al., 1997; Kubo et al., 2007). In humans, a mean increase of 59% in MAC stiffness and 23% in MTC stiffness were determined using sinusoidal perturbations (Cornu et al., 1997) and the quick release technique (Pousson et al., 1995) after 7 and 5 weeks of plyometric training, respectively. Kubo et al. (2007) found an increase of 63.4% in joint stiffness assessed during drop jumps (DJ) after 12 weeks of plyometric training. It has been shown that jump performance gains after plyometric training are a consequence of changes in the mechanical properties of MTC rather than muscle activation strategies (Kubo et al., 2007). Specific adaptations could have occurred between tendon and muscle structures as hypothesized by Pousson et al. (1990), but may also be between mono- and bi-articular structures as it was established after acute solicitation (Hoang et al., 2007). To the best of our knowledge, no study has been performed to specifically determine changes in *gastrocnemii* passive force–length relationship and ankle MAC passive stiffness in humans after plyometric training.

Passive cyclic stretches are classically performed in order to obtain passive torque–angle relationships, from which mechanical properties of the MAC could be extracted (Magnusson, 1998; Nordez et al., 2006; Mahieu et al., 2008). Recently, a mathematical model developed by Hoang et al. (2005) has been applied to data using torque–angle relationships obtained during cyclic passive stretches of the ankle joint performed at various knee flexion angles. Considering that the *gastrocnemii* are the only structures crossing both ankle and knee joints and significantly contribute to the passive torque produced by the ankle, it is then possible to assess the passive tension–length relationship of the *gastrocnemii*. In addition, mono-articular (mainly the *soleus*, ankle plantar flexor) and bi-articular (*gastrocnemii*, ankle plantar flexors and knee flexors) structures may be solicited in different ways because they do not have the same functional role, given their anatomical insertions (i.e. *soleus* principally involved in postural functions and *gastrocnemii* mainly implicated in explosive actions).

The aims of this study were to determine simultaneously the effects of plyometric training on the passive stiffness of the ankle MAC, the *gastrocnemii* MTC and stiffness of the Achilles tendon in order to clarify possible local adaptations (i) between muscles within the *triceps surae* muscle group and (ii) between muscle and tendon within the *triceps surae* MTC.

Material and methods

Subjects

Seventeen males volunteered to participate in this study and were randomly assigned to trained (TG) ($n = 9$, 18.8 ± 0.9 years) and control (CG) groups ($n = 8$, 18.9 ± 1.0 years). Anthropometric data of the subjects are given in Table 1. All subjects were involved in explosive sport practices (basketball, volleyball and handball) and did not change their usual activity (about one training and one match per week) during the period of the study. Subjects were fully informed about the nature and the aim of the study before they signed an informed consent form. This study was conducted according to the Helsinki Statement (1964).

Experimental design

Pre-tests and post-tests were set up to assess the effects of an 8-week plyometric training program. Subjects were tested in three independent tests performed on different days in a randomized order: (i) a jump test determining performances in squat jump (SJ) and reactive jump (RJ); (ii) a passive test determining the ankle joint range of motion (RoM), and the passive torque during passive cyclic stretches was performed for different knee flexion angles; and (iii) an Achilles tendon stiffness test determined during isometric plantar flexion (PF). All of the trained subjects performed the three test sessions before (pre-tests) and 1 week after (post-tests) the end of the training period. Untrained subjects were retested 9 weeks after the pre-tests.

Table 1. Mean height, weight and external anatomical measurements performed on each subject and used to determine moment arm of gastrocnemii using published anthropometric data from study on cadaveric legs (Grieve et al., 1978) as: the length of the shank (Ls), the reference length of gastrocnemii (L_{ref}) and the foot length (L_f) as described in Hoang et al. (2005)

	Control group	Trained group (NS)
Height (cm)	181.3 ± 7.5	179.2 ± 6.1
Weight (kg)	72.4 ± 9.1	68.5 ± 7.1
L_s (cm)	43.1 ± 2.5	42.6 ± 2.6
L_{ref} (cm)	45.0 ± 2.4	44.1 ± 2.7
L_f (cm)	17.8 ± 1.0	17.3 ± 2.7

NS, non-significant difference between control and trained groups. Results are presented in terms of mean ± standard deviation.

Training program

The plyometric training program was based on different kinds of jumps, as defined in the literature (e.g. Pousson et al., 1990; Cornu et al., 1997; Spurrs et al., 2003). More precisely, the subjects performed: (i) SJ, defined as vertical jumps without prior counter-movement; (ii) vertical counter-movement jumps (CMJ); (iii) DJ (i.e. hopping, jumps from either low (40 cm), medium (60 cm) or high (80 cm) platforms); and (iv) a series of jumps over hedges using alternatively one foot or both feet. During the first 5 weeks, a constant increase in the number of exercises, the number of jumps per exercise and the progressive introduction of stronger exercises (series of jumps from platforms where the height was increased) was followed. The training period lasted 8 weeks and included two sessions of 1 h per week for a total of about 3200 jumps (from 150 to 280 jumps per session).

Jumps performances

Performances in SJ and RJ were determined for all subjects, using Bosco's jumping mat (Ergojump, Globus Italia, Codogne, Italy) 1 week before the training period and 1 week after the end of the training program (Cutlip et al., 2005). The SJ was performed with a start angle fixed at 90° of knee flexion (using a rope to set the initial position). The maximal height in SJ was measured from three trials with a 2-min rest in between. The average height in the eight RJ performed without knee flexion was also assessed. During jumps, subjects were instructed to place their hands on their hips to minimize the contribution of free segments (i.e. arm movements during jumps). The test was repeated if the subject did not follow the instructions of jump procedures (i.e. hands positions, knee flexion during RJ).

RoM and musculo-articular passive torque and stiffness

The passive torque measurement method was similar to that used by other investigators (e.g. Riemann et al., 2001). A Biodex system 3 research® (Biodex medical, Shirley, New York, New York, USA) isokinetic dynamometer was used to measure the torque produced in resistance to passive stretch (T), ankle joint angle (θ_a) and ankle joint angular velocity (ω). Subjects were lying prone, legs fully extended, with the thighs, the hip and the shoulders secured by adjustable lap belts and held in position (Fig. 1). The right ankle joint was securely strapped to a footplate connected to the level arm of the dynamometer. The input axis of the dynamometer was carefully adjusted to the axis of rotation of the right ankle joint. The device enabled us to change the knee angle (θ_k). The reference angle of the knee joint ($\theta_k = 0°$) corresponded to the knee fully extended. The reference angle of the ankle joint ($\theta_a = 0°$) was defined as the foot perpendicular to the tibia.

Surface electromyographic (sEMG) signals of the medial *gastrocnemius*, lateral *gastrocnemius* and *soleus* muscles were recorded to ensure that no muscle activity occurred during the passive stretching procedures. sEMG signals were also visualized in real time by the subject and the principal investigator during tests. Active surface electrodes with an inter-electrode distance of 10 mm (DE-2.1, Delsys® Inc, Boston, Massachusetts, USA) were placed on muscles according to SENIAM recommendations (Hermens et al., 2000). One reference electrode was placed on the medial femoral epicondyle. sEMG and mechanical (T, θ_a and ω) signals were sampled at 1000 Hz

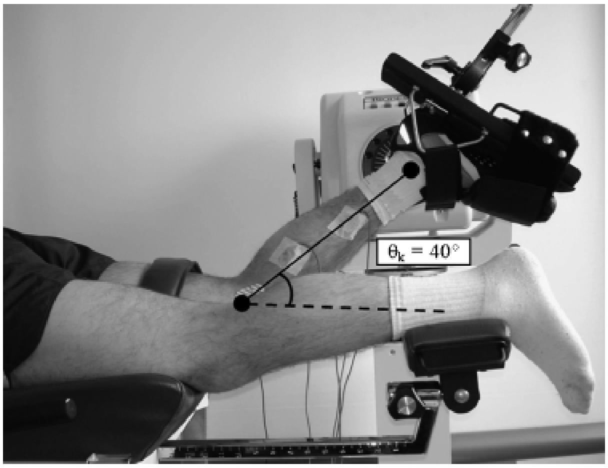

Fig. 1. Subject position during passive cyclic stretching tests. Between each trial, the knee flexion angle was randomly changed by a displacement of the bench from the right to the left position, and the dynamometer motor from the bottom to the top position and inversely (where $\theta_k = 0^\circ$ corresponding to the leg fully extended).

using an A/D converter (National Instrument, Delsys® Inc.) and stored on a hard drive using EMGWorks 3.1 software (Delsys® Inc.) for further analysis.

Before both pre- and post-tests, a familiarization session was first performed to evaluate the RoM and passive stretches of the *triceps surae* muscle group. The pre- and post-test sessions were similar and included four different tests: (i) one maximal ankle joint range of motion (RoM) measurement in dorsi flexion (DF). During this test, the foot was passively dorsi flexed ($\omega = 5^\circ$/s), starting from 30° in PF with the knee fully extended. The subjects used a stop switch when they perceived that the muscles had reached the maximum tolerable stretch. This point was operationally defined as the maximal ankle RoM in DF. The foot was then immediately returned to the starting position. (ii) Five cyclic ($\omega = 5/^\circ$s) passive motions from 30° in PF to 30° in DF with the knee fully extended. (iii) Five cyclic passive repetitions ($\omega = 5^\circ$/s) for five randomly tested knee flexion angles ($\theta_k = 20^\circ$, 40°, 60°, 80° and 100°). The range of stretch was increased by 2° in DF for each increase of 20° of knee flexion angle in order to apply Hoang's model (Hoang et al., 2005). Five minutes of rest between each stretching series of tests were allowed. (iv) Two maximal voluntary contractions under isometric conditions with the knee fully extended ($\theta_k = 0^\circ$) and at an ankle angle of 15° in PF for sEMG normalization purposes.

All of the data were processed using standardized programs computed with Matlab® (The Mathworks, Natick, MA, USA). External passive torque and angle position data were filtered using a Butterworth second-order low-pass filter (10 Hz). Recorded torque was corrected from gravity and isokinetic tool weight. The maximal RoM value was first determined. If, during the passive measurements, sEMG values were found to be $>1\%$ of the maximal voluntary contraction for a given subject, its data were disregarded for analysis (e.g. Reid & McNair, 2004; Gajdosik et al., 2005).

From the passive torque–angle relationship obtained at knee fully extended, the maximal passive torque and the musculo-articular stiffness, calculated as the slope of a fourth-order polynomial model (Magnusson et al., 2000; Nordez et al., 2006), were determined at 29° of DF (i.e. the common angle for all subjects where plantar flexors structures are the most stretched). Passive torque–angle relationships were also determined for each cyclic repetition for each passive test (Fig. 2(a)).

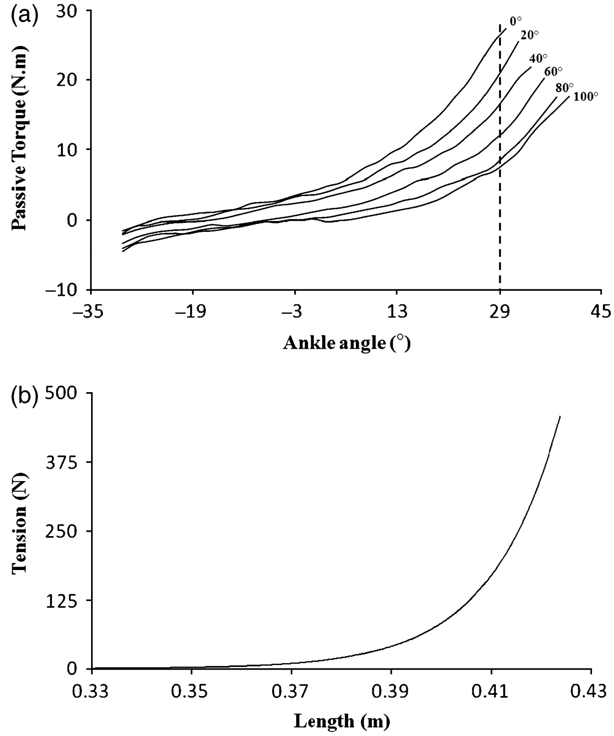

Fig. 2. (a). A typical raw passive torque–angle relationship during plantar flexion efforts obtained for one subject during passive stretching for different knee flexion angles (θ_k): 0° (corresponding to the leg fully extended), 20°, 40°, 60°, 80° and 100°. The dotted line represents the ankle angle where ankle MAC maximal passive torque and stiffness were determined. (b). The tension–length relationship of *gastrocnemii* determined according to Hoang's model (Hoang et al., 2007) using the dorsi flexion part of the passive torque–angle relationships (ankle angle corresponds from 0° to 30° in dorsi flexion).

Gastrocnemii's musculo-tendinous tension and stiffness

The model of Hoang et al. (2005) assumes that the passive torque measured at the ankle joint is the sum of the passive torque produced by (i) mono-articular structures such as single-joint muscles (mainly the *soleus*) and ligaments that cross the ankle joint generating a passive torque in PF (T_P); (ii) mono-articular structures of the ankle joint producing a passive torque in DF (T_D); and (iii) bi-articular muscles (i.e. the *gastrocnemii*) crossing the ankle and the knee joints also generating a passive torque (T_G). The contributions to the passive ankle torque from other structures such as the *plantaris* muscle, nerves, blood vessels and skin are expected to be negligible (Hoang et al., 2005). The torque–angle relationships of the single joint structures and length–tension relationships of the *gastrocnemii* were treated as exponential functions above slack length (Sten-Knudsen, 1953; Nordez et al., 2006). Under these assumptions, the total passive torque measured at the ankle joint was defined as follows (eq. [1]):

$$T(\theta_a, \theta_k) = T_P - T_D + T_G \tag{1}$$

with:

$$T_P = \frac{E_P}{\alpha_P}[e^{\alpha_P(\theta_a-\theta_P)} - 1] \quad \text{if } \theta_a > \theta_P \tag{2}$$

$$T_D = \frac{E_D}{\alpha_D}[e^{\alpha_D(\theta_D-\theta_a)} - 1] \quad \text{if } \theta_a < \theta_D \tag{3}$$

$$T_G = m_g\left(\frac{E_G}{\alpha_G}[e^{\alpha_G(l_g-l_G)} - 1]\right) \quad \text{if } l_g > l_G \tag{4}$$

where (E_P, α_P), (E_D, α_D) and (E_G, α_G) are parameters relating to the stiffness of the mono-articular structures of the ankle in PF, DF and to the stiffness of the *gastrocnemii,* respectively. θ_P and θ_D are ankle angles where ankle plantar flexors and dorsi flexors are slack, respectively. m_g is the moment arm of the *gastrocnemii* at the ankle. l_g is the length of the *gastrocnemii* and l_G is the slack length of the *gastrocnemii.*

With respect to the parameters of eq. (1), T and θ_a were determined from direct measurements. l_g and m_g were estimated using knee and ankle angle measurements according to published anthropometric data classically used in the literature (Grieve et al., 1978; Hoang et al., 2005). The mean anthropometric data of both groups of subjects are reported in Table 1. B stretching cycles were performed from 30° in DF to 30° in PF, data from the PF half (i.e. the data from 30° in PF to 0°) of each cycle were discarded. The remaining parameters (E_P, α_P, E_D, α_D, E_G and α_G) were unknown and were estimated with non-linear minimization of the least squared difference between modelled [i.e. eq. (1)] and experimental curves (Marquard, 1966).

In the present study, the three main parameters of interest were E_G, α_G and l_G [eq. (4)], which were used to construct passive length (l_g)–tension (F) curves of the *gastrocnemii* [Fig. 2(b)] using eqs. (5) and (6):

$$F(l_g) = \frac{E_G}{\alpha_G}\left[e^{\alpha_G(l_g-l_G)} - 1\right] \quad \text{if } l_g > l_G \tag{5}$$

$$F(l_g) = 0 \quad \text{if } l_g \le l_G \tag{6}$$

The maximal tension and stiffness (i.e. calculated as the slope of the relationship) for the maximal common range of *gastrocnemii* length (i.e. between pre- and post-tests) were then extracted from this relationship.

Achilles tendon stiffness

For this test, subjects lay prone with the hip and shoulders secured by adjustable lap belts and held in position. The right ankle joint was securely strapped to the Biodex® dynamometer as described above, with the leg fully extended, and with the foot perpendicular to the tibia ($\theta_a = 0°$). After a warm-up, subjects practiced familiarization trials to perform a constant isometric increasing torque development in PF, from a relaxed state to 100 Nm within 10 s. Subjects were instructed to perform isometric PF at a constant velocity to 100 Nm as described by a feedback model on a white board where the curve of torque produced during isometric PF was visualized in real time by the subjects and the investigators. Three trials were performed by each subject with a 2-min rest between trials. Displacement of the distal myotendinous junction (MTJ) of *gastrocnemii* was measured using ultrasonography. The MTJ of *gastrocnemii* was defined at the most distal identifiable portion of the *gastrocnemii* muscle using ultrasonography (Rosager et al., 2002). An ultrasonic apparatus (Philips HD3, Philips Medical systems, Andover, Massachusetts, USA) with an electronic linear array probe (7.5-MHz wave frequency; L9-5, Philips medical systems) mounted on an externally fixed bracket was strapped onto the skin of subjects to obtain longitudinal ultrasonic images of the distal MTJ of *gastrocnemii.* The width of the transducer array was 45 mm.

Ultrasonographic videos were recorded on a hard disk at 25 Hz. In order to synchronize torque and ultrasonographic videos, the signal of the switch used to start the video was also recorded using the Delsys® system. Images were selected (Adobe Premiere element, Adobe Systems Inc., San Jose, California, USA) from a relaxed state to 100 Nm every 10%. Ultrasound images of the MTJ were quantified using open-source digital measurement software (Image J, NIH, Bethesda, MD, USA). The ratio of the calculated muscle force (F_m) and the elongation of the Achilles tendon allows for calculation of the stiffness of the Achilles tendon. Tendon displacement is classically attributed to both angular rotation and contractile tension, because any angular joint rotation occurs in the direction of ankle PF during an "isometric" contraction (Magnusson et al., 2001). This MTJ displacement determined during isometric contraction is corrected by displacement of the MTJ attributed to joint rotation alone (i.e. during passive stretching on range of motion, between 0° and 20° in PF) (Magnusson et al., 2001). In the present study, no correction was applied considering that the ankle joint rotation effect is assumed to be similar for each subject between pre- and post-tests. Changes in elongation of the Achilles tendon between pre- and post-tests were then interpreted as an effect of the plyometric training protocol.

The ankle joint torque measured by the dynamometer was converted to muscle force (F_m) by eq. (7) (Kubo et al., 2008):

$$F_m = k \times T \times m_g^{-1} \tag{7}$$

where k is the relative contribution of the physiological cross sectional area of the GM within the plantar flexors (18%) and m_g is the moment arm length of *gastrocnemii* at 0°, which was estimated from the limb length of each subject (Grieve et al., 1978). In the present study, the F_m and elongation values were fitted to a Sten-Knudsen model (Sten-Knudsen, 1953; Nordez et al., 2006), whose slope was adopted as stiffness for muscular forces of 80, 160, 240 and 320 N (Fig. 3).

Reliability

A pilot study was conducted in conjunction with the current study to estimate the reliability for the methods described above for determination of range of motion, ankle MAC passive stiffness and *gastrocnemii* MTC passive tension and stiffness. Five subjects (22.2 ± 0.2 years, 181.7 ± 6.1 cm, 74.1 ± 6.1 kg) participated in two repeated testing sessions, with the same protocol, completed at the same time of the day with 2 days of rest in between. Day-to-day reliability was

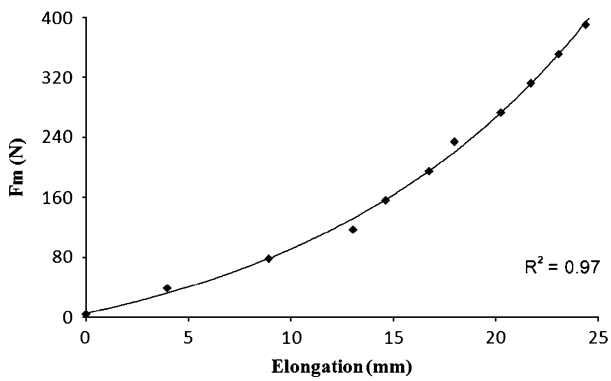

Fig. 3. A typical example of the muscle force (F_m)–elongation relationship obtained for one subject. The slope of the F_m–elongation relation for F_m of 80, 160, 240 and 320 N was calculated as the stiffness of the Achilles tendon.

Table 2. Intra-class correlation (ICC), standard error of measurement (SEM) and coefficient of variation (CV) calculated to establish day to day reliability for range of motion (RoM), maximal torque in plantar flexion (T_{max}), maximal stiffness (S_{max}), the three parameters (α_G, E_G, l_G) obtained using the model of Hoang et al. (2007), the maximal tension (T_{Gmax}) and the maximal stiffness (S_{Gmax}) of gastrocnemii

Day-to-day reliability (2, *k*)	ICC	SEM	CV (%)
RoM (°)	0.83	2.9	6.9
T_{max} (Nm)	0.99	0.8	1.6
S_{max} (Nm/°)	0.80	0.10	11.6
E_G	0.94	0.001	9.4
α_G	0.97	4.6	5.4
l_G (m)	0.81	0.008	2.5
T_{Gmax} (N)	0.98	30.8	5.6
S_{Gmax} (N/mm)	0.98	4670.2	10.8

determined for the RoM, the maximal musculo-articular stiffness, the three parameters extracted from Hoang's model (E_G, a_G, l_G), the maximal tension and the maximal stiffness of *gastrocnemii*. Intraclass correlation coefficients (ICC) (2, *k*) (Fleiss, 1986) were calculated and are presented in Table 2 (ICC ranged from 0.80 to 0.99). In addition, the standard error of measurement and coefficient of variation associated with each ICC were calculated. Coefficients of variation ranged from 1.6% to 11.6% (Table 2). These results support the reliability of the methods proposed in the present study.

Statistics

After checking the distribution of data using a Shapiro–Wilk test, parametric statistical tests were performed using Statistica® software (Statsoft Inc., Tulsa, Oklahoma, USA). The Grubbs test was also applied to detect outliers in each group (Grubbs, 1969). Two-way multivariate analyses of variance (ANOVA) (group × test) were performed to assess the statistical significance of changes in RoM, jumps tests, global passive torque (T_{max}) and stiffness (S_{max}) at 29° in DF, maximal passive tension (T_{Gmax}), maximal passive stiffness (S_{Gmax}) of the *gastrocnemii* and of the Achilles tendon. A Newman–Keuls *post hoc* analysis was conducted where appropriate. The critical level of significance in the present study was set at $P<0.05$.

Results

Using the Grubbs test (e.g. Lambertz et al., 2003), one subject of the CG was excluded from the study because the S_{max} value difference between the pre- and the post-test represented a significant outlier ($P<0.05$) compared with all subjects of the CG.

Jumps performances

An interaction between "group" and "test" factors was found on SJ ($P=0.003$) and RJ ($P=0.01$) performances. For the TG, a significant increase in height was shown in SJ (mean: +17.6%, $P=0.008$) and in average performance on eight RJ (mean: +19.8%, $P=0.001$) in comparison with CG (Table 3).

Range of motion, musculo-articular passive torque and stiffness

No significant change in DF RoM was found ($P=0.35$) between pre- and post-tests regardless of the considered group (Table 3). Experimental data and a fourth-order polynomial model showed an excellent correlation with a mean $R^2=0.99$. For both groups, there were no differences between pre- and post-test torque–angle relationships (Fig. 4). No interaction between "group" and "test" factors was shown for T_{max} ($P=0.66$) and S_{max} ($P=0.42$) of ankle joint MAC (Table 3).

Gastrocnemii's musculo-tendinous tension and stiffness

With respect to T_{Gmax}, no significant interaction was found between "group" and "test" factors ($P=0.28$). Nevertheless, a significant interaction was found between "group" and "test" factors for T_{Gmax} ($P=0.03$). For the TG, there was a significant increase in T_{Gmax} (mean: +33.3%, $P=0.001$) relative to CG (Table 3).

Table 3. Jump performances (SJ, squat jump and RJ, reactive jump), range of motion (RoM), maximal torque (T_{max}), maximal musculo-articular stiffness (S_{max}), maximal tension (T_{Gmax}), maximal stiffness (S_{Gmax}) of gastrocnemii and difference in gain between both control and trained groups

	Trained group		Control group		Gain (%)
	Pre test	Post test	Pre test	Post test	
SJ maximal height (cm)	42.8 ± 7.1	47.4 ± 5.7	42.1 ± 6.3	39.2 ± 2.8	+18†
Average height on eight RJ (cm)	32.8 ± 6.2	39.8 ± 5.0	32.2 ± 6.0	33.1 ± 5.6	+20‡
RoM (°)	44.7 ± 11.0	47.7 ± 5.1	48.4 ± 7.4	45.8 ± 8.1	+15 NS
T_{max} (Nm)	28.1 ± 4.9	30.8 ± 7.5	25.7 ± 7.0	27.3 ± 6.3	+2 NS
S_{max} (Nm/°)	0.67 ± 0.19	0.81 ± 0.16	0.73 ± 0.29	0.76 ± 0.23	+16 NS
T_{Gmax} (N)	502.3 ± 110.9	603.3 ± 137.9	429.9 ± 99.5	478.4 ± 112.4	+10 NS
S_{Gmax} (N/mm)	42 458 ± 11 495	57 780 ± 17 923	31 613 ± 10 385	33 696 ± 12 392	+33‡

Results are presented as mean ± SD.

†$P<0.01$, ‡$P=0.001$ (Newman–Keuls *post hoc* test).

NS, non-significant (no interaction between group and test factors).

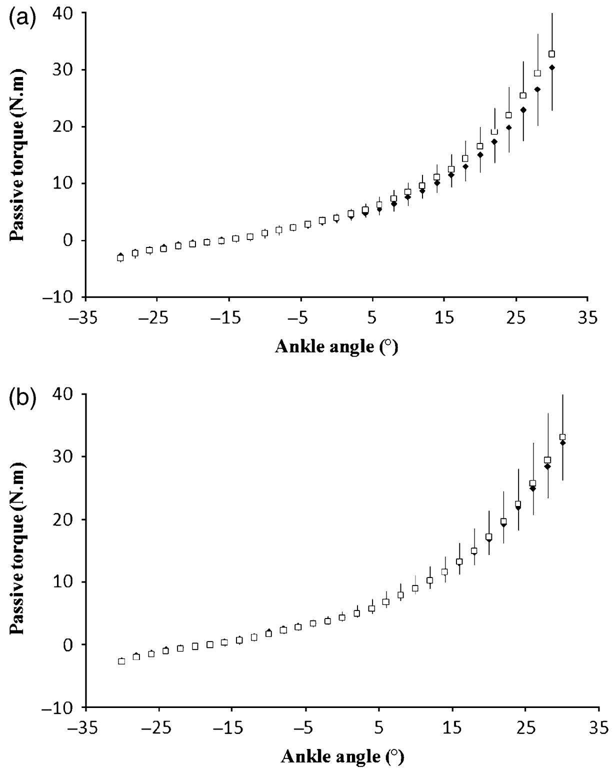

Fig. 4. Relationship between passive torque and ankle angle before (◆) and after (□) 8 weeks of plyometric training [(a) control group, (b) trained group]. Values are the mean ± SD.

Achilles tendon stiffness

For technical reasons, some videos were unusable. The effects of plyometric training on Achilles tendon stiffness were analyzed in six subjects of the TG group and in seven subjects of the CG group. The Sten-Knudsen model applied on force–elongation curves showed an excellent correlation ($R^2 = 0.98 \pm 0.02$). No significant change in Achilles tendon stiffness was found for 80 N (TG: 15.0 ± 2.6 to 17.3 ± 8.5 N/mm and CG: 15.1 ± 5.3 to 15.8 ± 5.0 N/mm), 160 N (TG: 23.7 ± 1.9 to 25.9 ± 10.2 N/mm and CG: 24.7 ± 12.4 to 23.4 ± 11.7 N/mm), 240 N (TG: 32.5 ± 2.2 to 34.4 ± 13.6 N/mm and CG: 34.3 ± 19.7 to 31.0 ± 18.8 N/mm) and 320 N (TG: 41.3 ± 3.3 to 43.0 ± 17.8 N/mm and CG: 43.9 ± 27.0 to 38.6 ± 26.0 N/mm) between pre- and post-tests for either the TG or the CG ($P > 0.05$).

Discussion

The aim of this study was to determine the effects of plyometric training on the mechanical properties of the passive structures of the ankle joint MAC and specifically on the *gastrocnemii* and the Achilles tendon.

The results obtained with respect to the increases in SJ and RJ performances (respectively, +17.6% and +19.8%) after the plyometric training for the TG are in accordance with the results published by other research groups. For instance, an increase of 9.1% was found in SJ after 8 weeks of plyometric training in handball players (Toumi et al., 2004). In addition, a meta-analytic review reported an increase of 4.7% in SJ performances after a plyometric training regime (Markovic, 2007). Therefore, our jumps results demonstrated the functional efficiency of our plyometric training program.

With respect to the ankle joint range of motion in DF, no significant change was found after our plyometric training program. To our knowledge, no previous study has determined the effect of plyometric training on ankle range of motion in DF. Mahieu et al. (2008) have shown that 6 weeks of eccentric training increased ankle joint range of motion in DF by approximately 6° for the TG, but no interaction was found between the group and the test factor. Nevertheless, these results are somewhat difficult to compare with the data reported herein, because the training intensity differed between these two training protocols. Indeed, eccentric training was performed every day over 6 weeks and our plyometric training was performed twice a week over 8 weeks. In addition, the experimental subjects' characteristics were also different from those in this study.

Interestingly, the major result of our study concerns the significant increase in MTC passive stiffness of *gastrocnemii* MTC during PF assessed non-invasively in humans after plyometric training. No significant change was found for either maximal passive torque or stiffness of ankle MAC. Mahieu et al. (2008) found that the passive resistive torque determined after 6 weeks of eccentric training using passive cyclic stretching on the plantar flexors decreased without any change in ankle MAC stiffness. These results emphasize the fact that the plyometric training may have a different effect on the passive properties of tissues crossing the ankle MAC.

The lack of change in ankle MAC stiffness and the increase in *gastrocnemii* MTC stiffness obtained in the present study could be explained through specific adaptations of mono-articular and bi-articular structures crossing the ankle joint. Indeed, bi-articular structures involved in PF (mainly *gastrocnemii* muscles) are largely composed of fast muscle fibers whereas mono-articular structures (mainly *soleus* muscle) are composed predominantly of slow muscle fibers (Nardone et al., 1990). It can then be hypothesized that MTC of *gastrocnemii* and *soleus* may have a different response to plyometric training. In addition, a significant increase in passive stiffness of *gastrocnemii* MTC had already been established 1 day after eccentric exercises (Hoang et al., 2007). Then, it appears that a specific adaptation of muscles involved in explosive actions (*gastrocnemii)* seems to occur after plyometric training. Nevertheless, adaptation of *gastrocnemii* MTC stiffness after plyometric training did not lead to an increase in global ankle MAC stiffness.

Alternatively, the mechanical changes in *gastrocnemii* MTC stiffness observed could have arisen from different stiffness-specific adaptations of muscle and tendon as hypothesized in other studies (e.g. Pousson et al., 1990). Considering the effects of plyometric training on Achilles tendon stiffness as described in the literature, the results appear to be contradictory. For instance, it has been shown that Achilles tendon stiffness was unchanged after 12 weeks of plyometric training (Kubo et al., 2007). In contrast, Burgess et al. (2007) observed a 29.4% increase of Achilles tendon stiffness after 6 weeks of plyometric training (Burgess et al., 2007). It has been shown that an increase of tendon stiffness after isometric or strength training was identified as a better muscle strength transmission to the skeleton (e.g. Kubo et al., 2006). Before interpreting the present results on tendon stiffness, the calculation of the muscular force produced by the medial *gastrocnemius* during PF should be mentioned. The of GM to the muscular force production was defined as the percentage of the physiological cross-sectional area of this muscle to that of *triceps surae* muscles as has been described in previous studies e.g. Mahieu et al. (2008), and used 18% as the corresponding value in the light of the findings of Fukunaga et al. (1996). This approach assumes that the relative contribution of the plantar flexors remains constant. Our results are in accordance with those of Kubo et al. (2008) and showed that plyometric training had no effect on Achilles tendon stiffness. The strain magnitude (Arampatzis et al., 2007; Kongsgaard et al., 2007) and the duration of the applied mechanical load (Kubo et al., 2001) affect the adaptation responses of the human tendons. Further, it is questionable whether plyometric exercise in sportsmen (i.e. volleyball, handball and basketball players) twice a week over a period of 8 weeks is a sufficient stimulus to induce further adaptation effects on the Achilles tendon than the stimulus provided by the mechanical load applied during their normal physical exercise. In this study, no change in Achilles tendon stiffness and an increase of *gastrocnemii* MTC passive stiffness were found after plyometric training. It can be hypothesized that the increase in MTC passive stiffness of *gastrocnemii* occurs mainly within muscular structures by an increase in the collagen concentration as described in isolated muscle after jump training (Ducomps et al., 2003).

Finally, this study has allowed for the determination of the effects of 8 weeks of plyometric training considering dissociated potential change in passive stiffness of the *gastrocnemii* MTC and Achilles tendon stiffness from global passive properties of ankle MAC measurements. This dissociation allows for assessment of non-invasively specific adaptations of mono and bi-articular structures and/or muscular and tendinous tissues that belong to the plantar flexors after plyometric training. The main conclusions are that plyometric training induces an increase in functional performance associated with an increase in *gastrocnemii* MTC passive stiffness, without any significant change in Achilles tendon stiffness.

Perspectives

The actual implications *in vivo* of the passive properties of ankle MAC structures on functional performance are always unclear. Further research is required to identify the exact consequences of MAC passive properties on the active muscle contraction efficiency, which will allow us to model the behavior of the MAC passive elastic stiffness and to develop new rehabilitation programs taking into account this passive behavior implication for the force production and the locomotion efficiency. Alternatively, the implication of changes in passive elastic properties will affect the energy storage–recoil processes especially involved in plyometric and eccentric training. The comparison of the specific effects induced by these chronic solicitations on the passive elastic properties would be of interest to the field.

Key words: range of motion, jump, tendon, muscle, stiffness, torque, human.

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