ORIGINAL ARTICLE

Incline plyometrics-induced improvement of jumping performance

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Abstract The aim of this study was to examine the effects of incline plyometrics training on muscle activation and architecture during vertical jumping and maximum strength. Twenty male participants were divided in two training groups which followed after a 4 week training program. The incline plyometrics group ($n = 10$) trained by performing consecutive jumps on an inclined surface (15°) while the plane plyometrics (PP) group ($n = 10$) performed the same jumps on a plane surface. Both groups trained four times per week and performed 8 sets of 10 jumps in each session. Subjects performed squat jumps, counter movement jumps and drop jumps (DJ) prior to and immediately after the training period, while the electromyographic activity of the medial gastrocnemius (MGAS) and tibialis anterior muscles and the architecture of MGAS were recorded. Maximal isokinetic and isometric strength of the plantar flexors were performed. Analysis of variance showed that only the IP group improved fast DJ height performance by 17.4 and 14.4% (20 and 40 cm, $p < 0.05$). This was accompanied by a significantly higher MGAS activity during the propulsion phase (24% from 20 cm and 50% from 40 cm, $p < 0.05$) of the DJ and a longer working fascicle length (5.08%, $p < 0.05$) compared with the PP group. There were no significant changes in isokinetic and isometric strength of the plantar flexors after training for both groups. The increase of jumping performance, after

incline plyometrics should be taken into consideration by coaches, when they apply hopping exercise to improve explosiveness of the plantar flexors.

Introduction

A variety of training programs and exercises have been used to improve performance through an effective use of the stretch shortening cycle (SSC) (Markovic 2007). The most popular and commonly used type of training is plyometrics, which include vertical jumps usually performed from a double leg take-off position, after dropping from a pre-determined height (Bobbert 1990). Even though the majority of studies have shown a positive effect on vertical jumping performance, research on the effectiveness of plyometric training is sometimes inconclusive (Markovic 2007). Some studies have shown that training (Thomas et al. 2009; Luebbers et al. 2003) consisting of counter movement jumps (CMJ) or drop jumps (DJ) increases jumping height (Gehri et al. 1998), while others have failed to find significant adaptations (Chimera et al. 2004; Young et al. 1999), despite of alterations in lower limbs muscle activity (Chimera et al. 2004). These inconclusive results may be attributed to several factors such as differences in training program characteristics and type of jumping exercises (Markovic 2007).

Another factor which has not received adequate consideration for improving plyometrics effectiveness is to modify training exercises such that they take advantage of the force generating properties of muscles whose performance is critical for the final output. Holcomb et al.

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(1996a) applied a training program consisting of modified drop jumps to increase loading through a greater range of motion of the lower limb joints. Although this training program increased joint moments during vertical jumping, there were no significant increases in jumping height. Further, some studies attempted to train the plantar flexors and cause Achilles tendon overload by using meridian strength shoes in training (Kraemer et al. 2000; Ratamess et al. 2007). The results showed that complex training with meridian shoes caused similar increases in jumping performance with normal shoes. It seems that the meridian shoes caused greater improvements in long sprinting performance rather than the jumping ability compared to complex training with normal shoes (Ratamess et al. 2007). Therefore, the role of training exercises which are modified to take into account the mechanical properties of the plantar flexors is still not clear.

Modifications in the joint range of motion when performing a vertical jump could alter the range of muscle or tendon length during the movement. The behavior of the medial gastrocnemius (MGAS) fascicles has been described as a "catapult action" (Hof et al. 2002). Particularly, MGAS fascicle length (FL) decreases at the instant of initial contact (Ishikawa and Komi 2004), it remains relatively constant during the braking phase followed by a decline during propulsion (Hof et al. 2002). Simultaneously, the ankle is initially in semi neutral position and then it is plantar flexed. However, it is known that isometric MGAS force production is affected by muscle length (Kawakami et al. 1998) and, in turn, by the angle of the ankle joint. Thus, the position of the ankle joint is of great importance for force production (Narici et al. 1996; Maganaris 2003) even to dynamic conditions such as the propulsion phase of DJ.

During jumping, MGAS produces a large amount of force at a slow velocity (Bobbert et al. 1986a), because its length remains close to optimum (Bobbert and van Ingen Schenau 1988). However, the amount of force produced by the MGAS could be much greater if jumping technique can be modified such that the muscle works at a length range near to its maximal force potential. Kawakami et al. (1998) found that the MGAS muscle produces more force at more dorsiflexed ankle joint position. If this is the case, then changing the ankle range of motion when participants perform jumps toward more greater lengths may improve MGAS force and, in turn, jumping performance. Thus, the idea for modifying jumping technique to achieve optimal loads of muscles seems promising. To achieve this, someone could perform jumps on an incline surface. In our recent study, it was suggested that incline hopping might be more beneficial to improve jumping performance compared to the classical plane hopping as it takes greater advantage of the force–length properties of the

gastrocnemius muscle (Kannas et al. 2011). No previous experiment has been conducted to investigate the effectiveness of muscle-specific plyometric training on an inclined surface. The aim of the study was to investigate the effects of incline plyometric training on jumping performance, MGAS architecture and EMG activity of plantar and dorsiflexors.

Materials and methods

Participants

Twenty male students (age: 21.3 ± 1.4 years, height: $173.69. \pm 6.4$ cm, weight: 74.9 ± 7.8 kg), all volunteers of the Department of Physical Education and Sports Sciences, signed an informed consent form prior to their inclusion in the study. Approval for the experiment was obtained from Aristotle University Ethics Committee on Human Research. No participation to a particular strength and/or plyometric training program over the last 8 months was mentioned.

Training

Participants were randomly assigned to one of two training groups: the incline plyometric (IP) group ($n = 10$) and the plane plyometric (PP) group ($n = 10$). A total of 16 sessions (four sessions/week, 4 weeks) were performed by both experimental groups. Each training session was divided into three phases: warm-up (10 min jogging, stretching exercises mainly for the triceps surae and hamstrings, submaximal contractions of the plantar flexors), main phase (8–10 sets of 10 maximum jumps, rest between the sets 2 min) and the recovery (5 min stretching). Participants of the experimental groups performed two training sessions, 1 week before the beginning of training, in order to familiarize with the technique of the jumps.

For the main phase, the IP group performed plyometric jumps with their knees fully extended on an inclined (15°) ramp (Fig. 1). To minimize the fear imposed by the unfamiliarity of jumping on inclined surface, vertical rods (1.5 m) were placed along the training ground creating squares to visually guide the participant. The PP group performed classical plyometric jumps on a plane ramp. Special attention was given to keep the knees straight and execute the jumps "as fast and high as possible". To assure similar performance between the two groups, we measured the contact times of the jumps performed by either group using an ERGOJUMP (Globus, Italy). The mean contact time was 207 ± 42 ms for the IP group and 203 ± 48 ms, for the PP group.
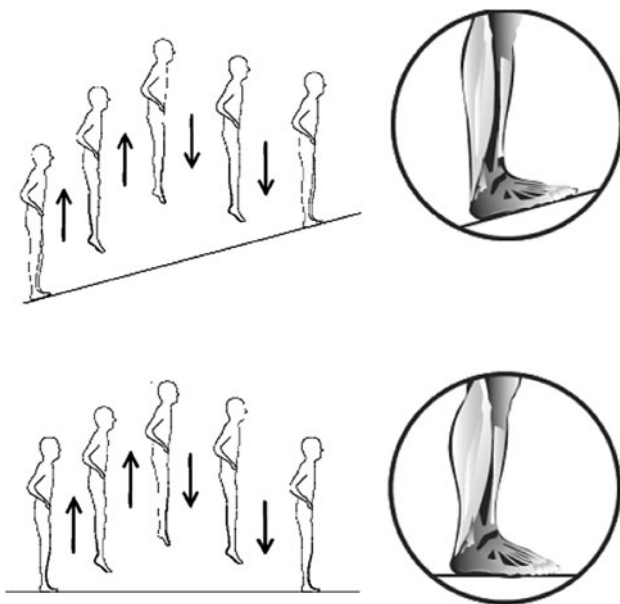
Fig. 1 Incline plyometric jumps performed with knees fully extended along on inclined (15°) ramp. Plane (classic) plyometric jumps performed with knees fully extended

Jumping ability

All jumps were performed on a customized uni-axial force plate (60 × 40 cm). The platform uses a strain gauge (Model LC4204—K600, A&D Co. Ltd., Japan) capable to measure vertical ground reaction force (linearity <0.6% of full scale deflection; hysteresis <1% of full scale deflection; range 0–7 KN; overload = 14 KN; natural frequency >650 Hz). The analog signal from the force transducer was amplified by a customized charge amplifier (sampling rate: 1,000 Hz, output voltage: ± 10 V; adjustable gain: 1–100) interfaced to a Biopac MP100 Data Acquisition unit (Biopac Systems, Inc., Goleta, CA).

After warm-up (10 min jogging, static stretching and various submaximal vertical jumps and jumping drills), participants were asked to perform three maximum squat jumps (SJ, the knee flexion angle was 90°), CMJs and DJs from 20 and 40 cm in a randomized order. Since the degree of knee flexion during landing determines to a major extent the contribution of the different muscle groups (knee extensors vs. plantar flexors) (Bobbert et al. 1986a), all DJs were accomplished under two different task conditions defined by the following instructions: i. for the slow Drop Jumps (DJ), "jump as high as possible after landing" ii. for the fast Drop Jumps (DJ$_f$) "jump as fast as possible after landing". A twin axis electronic goniometer (Biopac Systems Inc, Goleta, CA) was used to record knee joint angle during all jumping tests. During the test, participants were instructed to minimize upper body movement. DJs were considered as being "slow" or "fast" when the maximum

knee joint angle was greater than 60° or less than 50°, respectively. The best jump based on maximum height output, was used for further analysis. All tests were supervised by the same investigator and standardized encouragement was provided to all participants.

Vertical ground reaction force (F_z) and contact time (CT) were taken as measures of jumping performance. Take-off velocity (V_{to}) was calculated by the integration of F_z over the propulsive phase:

$$\int_{t_1}^{t_2} (F_z(t) - m \times g)\mathrm{d}t/m \tag{1}$$

where m is the mass and g is the acceleration of gravity

The height of the jump was calculated through V_{to} using the following equation:

$$H = V_{to}^2/2g \tag{2}$$

where V_{to} is the take-off velocity

Isokinetic strength testing

All tests were performed on a Kin-Com (Kin-Com, Chatanooga Group Inc, USA) dynamometer. The analog signals (moment, angular position and angular velocity) from the dynamometer were amplified using a DA 100 B amplifier (Biopac, Common mode rejection ratio >90 IB, bandwidth = 0.05–500 Hz). The participants lied supine while the axis of their right ankle was aligned with the axis of rotation of the dynamometer. The participants were stabilized with straps on the isokinetic dynamometer with the knee fully extended while joint angle was monitored using the aforementioned electronic goniometer.

The participants were familiarized with the apparatus and testing procedure over a period of 1 week (three sessions of 40 min). In the main testing session, participants performed three maximal plantar flexion efforts with their dominant limb, at three concentric (30°, 60° and 120° s^{-1}) and three eccentric (30°, 60° and 120° s^{-1}) angular velocities randomly presented. Consistent and identical verbal encouragement was provided during the test. A 2 min rest was allowed between trials to eliminate the effects of fatigue. The trial displaying the maximum torque was selected for further analysis. Maximal isometric plantar flexion (three repetitions) was evaluated at −15° (dorsi flexion), 0° (neutral position) and 15° (plantar flexion). Contraction time was 5 s and inter-trial rest was 5 s. To quantify aponeurosis elongation, each subject then performed two ramp isometric contractions of 10 s by increasing gradually their effort until maximal force is achieved. During submaximal levels of contraction, visual feedback of the target and the produced force were displayed on a computer monitor at eye level. The trial with the greater produced force was used for further

analysis. The whole length (L_0), from the heel up to the distal point of the aponeurosis on the ultrasound image at rest (Muramatsu et al. 2001) was also measured. Thus, aponeurosis strain was calculated as the ratio of elongation to resting length (Magnusson et al. 2001). All tests were performed at the same time of the day to avoid any chronobiological effect.

Electromyography (EMG)

Two bipolar silver chloride surface electrodes (Motion control, IOMED, Inc., voltage range: +4 to +12 V) with 2 cm (center-to-center) interface distance were placed on the muscle bellies of MGAS and tibialis anterior (TA) during both jumping and force tests. Low impedance at the skin–electrode interface was obtained ($Z < 1,000\ \Omega$) by abrasion of the skin and preparation by shaving and cleaning it with alcohol. Placement of the electrodes at the exact same skin position before and after training was assured by marking the periphery of skin electrode area with permanent and indelible ink. The EMG signals were amplified with a bandwidth frequency ranging from 1.5 to 2 kHz (common-mode rejection ratio = 90 IB; Z input = 1 $M\Omega$; Gain = 1,000), filtered (cut off 10–500 Hz) and digitally sampled at a frequency of 1,000 Hz (full-wave rectification, 4th-order, zero-lag Butterworth filter).

Architectural parameters

In vivo MGAS architecture was measured using B-mode ultrasonography (SSD-3500,
7.5 MHz, Aloka, Japan) at 30 Hz and stored digitally. The exact position was 30% of the distance between the popliteal crease and the center of the lateral malleolus (Fukunaga et al. 1992). This location was chosen as the cross sectional area of muscle group is maximal (Fukunaga et al. 1992). To avoid any probe displacement (Klimstra et al. 2007) during testing, the probe was secured with special straps while a skin marker was placed on the skin and it was continuously visible on the US video footages. For analysis, a continuously visual able point (P) where a particular fascicle was attached at the deep aponeurosis was chosen. This cross point (P) was selected after careful inspection of the US scans.

Synchronization

The Fz data, EMG signals and ultrasound videos were interfaced to a Biopac MP100 data acquisition unit (Biopac Systems, Inc., Goleta, CA). The dynamometer and ultrasound signals were fed through BNC connectors (Models CLB 102 and CLB, Biopac Systems, Inc., Goleta, CA) to a 12-bit analog-to-digital converter. This allowed simultaneous recording of force, EMG and US video data.

Data analysis

Each jump was divided into three phases: the pre-activation phase, defined as the period of 100 ms prior to contact with the ground, the braking (BRA) and propulsion (PRO) phases which were determined by the contact time and the minimum knee joint angle position (Kellis et al. 2003; Viitasalo et al. 1998).

The maximum value of MGAS EMG over the three phases of the jumps was normalized with the EMGmax during propulsion phase of SJ of MGAS. Antagonist co-activation was expressed as the ratio of maximum EMG activity of TA to the maximum EMG value of MGAS during the same phase of the jump (Kubo et al. 2007). The MGAS EMG 100 ms before the contraction (pre-activation) and the maximum value of MGAS EMG during isokinetic tests were normalized with the EMGmax during isometric contraction at 0°. The TA: MGAS co-activation ratio was also calculated.

The angle of that line and the aponeurosis was defined as fascicle angle (Kawakami et al. 1998). A straight line between the deep and superficial aponeurosis was considered as FL. A fascicle was chosen such that it is traceable throughout the contraction. All architectural data during jumping tests were measured at three different time points: at initial contact with the ground, at the end of the braking phase and finally at the take-off. Moreover, the values of FL during the three time points were normalized with the standing values of each subject before jumping (Kurokawa et al. 2001). All architectural data during isokinetic and isometric tests were measured at the time of maximum torque.

Statistical analysis

The effect of the two types of plyometric training on primary variables was analyzed by employing a 2 (Time) × 2 (Group) analysis of variance (ANOVA) model with repeated measures on time (pre, post). The between subjects factor was the group (IP and PP). Significant time × group interactions were further analyzed using pre–post training differences (Tukey test) separately for each training group. The level of significance was set at $p < 0.05$ for all tests.

Results

Jumping height

The initial absolute values and the relative changes in jumping height after training are shown in Table 1 and Fig. 2, respectively. A significant ($p < 0.05$) interaction between group and time factors was found for DJ_{f20} ($F_{(1,18)} = 12.73$,

Table 1 Initial absolute values (pre-training) of jumping height, isokinetic torque and isometric force for incline plyometrics and plane plyometrics training groups

|	Jumping performance (cm)					
	SJ	CMJ	DJ_{20}	DJ_{f20}	DJ_{40}	DJ_{f40}
Incline plyometrics	30.83 ± 5.41	36.22 ± 4.50	30.40 ± 5.70	27.69 ± 3.16	31.36 ± 5.21	28.30 ± 2.03
Plane plyometrics	31.75 ± 2.53	35.78 ± 3.11	30.37 ± 2.74	28.22 ± 2.33	31.08 ± 3.02	28.75 ± 1.97
	Isokinetic torque (Nm)					
	Concentric			Eccentric		
Angular velocities (° sec^{-1})	30	60	120	30	60	120
Incline plyometrics	141 ± 26	103 ± 27	101 ± 25	176 ± 79	164 ± 45	149 ± 28
Plane plyometrics	144 ± 32	99 ± 22	89 ± 21	184 ± 70	174 ± 34	152 ± 29
	Isometric force (N)					
Ankle joint (°)	15 (Plantar flexion)		0		15 (Dorsi flexion)	
Incline plyometrics	89 ± 22		152 ± 28		175 ± 54	
Plane plyometrics	100 ± 30		127 ± 28		168 ± 28	
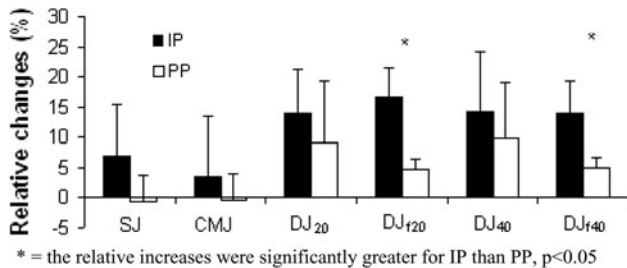
Fig. 2 The relative changes in height during jumping tests for incline plyometrics group (IP, closed) and plane plyometrics group (PP, open)

$p = 0.002$) and DJ_{f40} ($F_{(1,18)} = 7.79$, $p = 0.012$). Post-hoc Tukey tests showed that DJ height increased after IP training ($p < 0.05$) but not after PP training.

EMG during jumping

The relative changes in EMG activity are shown in Fig. 3 and Table 2. A significant interaction was found between group and time factors on EMG of MGAS during the propulsion phase of DJ_{f20} ($F_{(1,18)} = 7.56$, $p = 0.013$) and DJ_{f40} ($F_{(1,18)} = 10.83$, $p = 0.004$). Post-hoc Tukey tests showed that EMG MGAS changed significantly for the IP group ($p < 0.05$) but not for the PP group. No other significant changes were observed in EMG parameters during jump tests for both training groups ($p > 0.05$).

Architecture during jumping

The relative training changes in FL and pennation angle (PA) and during all jumping tests are shown in Table 3.
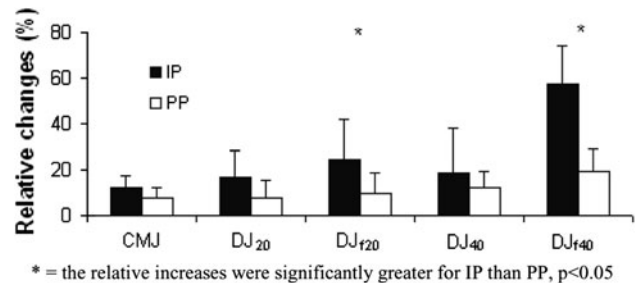

Fig. 3 The relative changes in activity of medial gastrocnemius (MGAS) in propulsion phase during jumping tests for incline plyometrics group (IP, closed) and plane plyometrics group (PP, open)

Non-statistically significant training effects on FL and PA were found ($p > 0.05$) for both training groups. In contrast, a significant interaction was found between group and time factors on FL/FLstanding ratio during take-off of DJ_{f20} ($F_{(1,18)} = 5.64$, $p = 0.029$) and DJ_{f40} ($F_{(1,18)} = 4.88$, $p = 0.04$). Post-hoc Tukey tests showed that FL/FLstanding ratio significantly decreased ($p < 0.05$) only after IP training while no significant changes were observed after PP training ($p > 0.05$).

Isokinetic and isometric tests

The initial values of isokinetic torque and isometric force for both training groups are presented in Table 1. Non-statistically significant training effects on isokinetic torque and isometric force were found ($p > 0.05$) for both IP and PP groups. No significant interactions were found in activity of MGAS, TA/MGAS co-activation, FL and PA during isokinetic and isometric tests for both training groups ($p > 0.05$).

Table 2 Relative (pre-post training percentage) changes in medial gastrocnemius electromyographic activity and coactivation (tibialis anterior/medial gastrocnemius EMG ratio) ratio during preactivation and braking phases after each training protocols

	Gastrocnemius EMG		Tibialis anterior/medial gastrocnemious EMG ratio	
	Incline plyometrics	Plane plyometrics	Incline plyometrics	Plane plyometrics
CMJ				
Pre-activation	7.56% ± 9.52	6.74% ± 9.03	7.56% ± 13.45	8.42% ± 12.43
Braking	8.51% ± 10.99	7.72% ± 11.35	12.11% ± 9.72	9.43% ± 10.45
DJ 20 cm				
Pre-activation	16.52% ± 2.38	31.15% ± 13.22	8.96% ± 22.46	−13.44% ± 32.71
Braking	11.82% ± 2.94	10.60% ± 15.40	22.17% ± 16.96	21.44% ± 32.46
DJ 40 cm				
Pre-activation	35.43% ± 14.31	14.42% ± 12.80	8.98% ± 21.56	−3.39% ± 8.28
Braking	12.63% ± 17.04	8.67% ± 10.40	8.96% ± 24.74	−1.43% ± 7.81
DJf 20 cm				
Pre-activation	0.44% ± 8.38	33.73% ± 9.24	8.99% ± 21.43	13.50% ± 24.48
Braking	−7.69% ± 7.38	7.62% ± 9.78	8.96% ± 24.74	−1.99% ± 7.69
DJf 40 cm				
Pre-activation	−3.70% ± 7.76	13.31% ± 6.62	15.39% ± 23.11	0.25% ± 9.13
Braking	−19.92% ± 5.64	8.69% ± 2.27	8.96% ± 24.74	−1.92% ± 7.71

Aponeurosis strain

A significant interaction was found between group and time factors in aponeurosis strain ($F_{(1,18)} = 9.11$, $p = 0.007$). Post-hoc Tukey tests showed that aponeurosis strain changed only for the IP group ($p < 0.05$) but for the PP group (Fig. 4).

Discussion

The major findings of this study were that: (a) plyometric training performed on an inclined surface improved jumping ability more than plyometric training performed on a plane surface, (b) MGAS activity during the propulsion phase of the fast drop jumps increased only after incline training, (c) the working range of MGAS FL shifted to an optimal one after incline while no differences were found after plane training.

In the present study, no significant adaptations in jumping height were found after PP training (Fig. 2). This is in agreement with Young et al. (1999) who showed that a 6 week plyometric program failed to improve jumping height. It could also be hypothesized that plane hopping could not load the muscles sufficiently enough to increase their strength capacity in such short training period. In contrast, in the present study we used incline hopping to load the plantar flexors more than classical jumping exercises by taking advantage of the force–length relationship of the MGAS. It seems that our hypothesis was confirmed since incline exercise improved jumping height (Fig. 2) in DJ_{f20} and DJ_{f40}. Kubo et al. (2007) also reported that

jumping ability improved after plantar flexors plyometric training performed unilaterally during 12 weeks on a sledge apparatus. These results are in line with previous studies showing that the overload of the plantar flexor muscle-tendon complex caused by the use of meridian strength shoes during complex training, would increase jumping and sprinting ability (Kraemer et al. 2000; Ratamess et al. 2007). However, these studies used combined strength, sprint and plyometric exercises and therefore direct comparison with the present findings is difficult. This is in contrast to Holcomb et al. (1996b) who used modified plyometrics and showed non-significant jumping height improvements, despite the increase in joint power after training. The lack of positive effects on jumping performance could probably be due to alteration in coordination after this specific type of training. This seems to be partially supported by our results as we observed changes only in fast DJs, which are closer to the training stimuli, while they are affected more by plantar flexor activation than slower DJs (Bobbert et al. 1986b). Moreover, it could be postulated that the greater aponeurosis strain might have caused an alteration of relative working FL and an increased EMG activity during the propulsion phase. These effects are clearer during the bounce DJ since final performance in this type of jump depends largely on the muscle–tendon properties of plantar flexors. However, it should be mentioned that indicates that there was a (non-significant) increase in jumping height at all jumping tests (Fig. 2). These observations support the idea that the overall jumping performance is positively affected by plantar flexor muscle and Achilles tendon properties.

Table 3 Relative changes of fascicle length and pennation angle of MGAS at the three phases of jumping tests

Training Group

	Incline Fascicle length	Plane Fascicle length	Incline Pennation angle	Plane Pennation angle
SJ				
Pre-activation	−9.87% ± 11.24	−8.84% ± 12.86	11.43% ± 21.71	12.90% ± 23.31
Propulsion	−10.99% ± 19.02	−8.78% ± 20.07	17.97% ± 38.46	9.35% ± 20.78
CMJ				
Pre-activation	12.12% ± 23.4	11.56% ± 25.76	1.63% ± 15.92	−2.05% ± 20.89
Braking	15.15% ± 43.7	20.24% ± 6.62	2.54% ± 12.63	2.75% ± 14.74
Propulsion	8.64% ± 11.57	−10.52% ± 10.55	−9.02% ± 13.94	14.13% ± 19.62
DJ 20 cm				
Pre-activation	−1.39% ± 9.73	−20.87% ± 10.55	−2.24% ± 7.26	12.30% ± 21.28
Braking	−3.22% ± 10.05	−1.17% ± 3.25	−5.62% ± 10.19	−8.73% ± 8.77
Propulsion	−3.90% ± 15.97	−13.48% ± 12.13	16.78% ± 16.77	12.83% ± 14.68
DJ 40 cm				
Pre-activation	−1.05% ± 14.01	−10.83% ± 6.76	4.56% ± 25.48	3.31% ± 12.48
Braking	−0.05% ± 18.16	−13.84% ± 16.40	4.05% ± 26.48	19.02% ± 24.91
Propulsion	−6.82% ± 16.21	2.29% ± 19.69	−4.09% ± 18.62	8.93% ± 16.64
DJf 20 cm				
Pre-activation	6.71% ± 14.27	0.80% ± 15.18	6.62% ± 23.24	13.5% ± 14.31
Braking	−4.12% ± 9.01	−0.96% ± 15.17	−6.27% ± 9.18	−5.59% ± 9.90
Propulsion	8.52% ± 10.99	−1.72% ± 9.09	2.52% ± 8.85	−2.56% ± 7.25
DJf 40 cm				
Preactivation	−8.66% ± 4.90	−3.62% ± 6.72	6.60% ± 13.18	2.58% ± 8.90
Braking	−7.62% ± 16.96	−15.16% ± 11.21	13.04% ± 18.92	10.23% ± 16.45
Propulsion	0.36% ± 13.98	−4.91% ± 13.98	5.25% ± 15.11	0.90% ± 28.73

In the present study, no significant effects on muscle architecture parameters were observed for both groups (Table 3). However, when the FL was divided by the value obtained during single stance (Kurokawa et al. 2001), the decrease of the FL during take-off phase of the DJ was significantly smaller after IP training than PP training. This suggests that MGAS fascicles were in greater (relative) length during take-off after IP training. Based on the force–length relationship, the greater FL enables MGAS to produce higher level of force (Kawakami et al. 1998). This is in line with previous studies showing that sprint and jumping training or resistance training with low loads and high velocity alters muscle architecture (Alegre et al. 2006; Blazevich et al. 2003). If the FL increased after IP training, then one might expect an alteration in tendon/aponeurosis displacement and strain, due to the fascicles–aponeurosis interaction. This appears to be supported by the higher aponeurosis elongation and strain displayed by the IP group as opposed to the PP group (Fig. 4). For the same muscle force generating potential, a more compliant tendon and aponeurosis would shift the force–length relationship to the right (Lemos et al. 2008; Lieber et al. 1992). This is a possible explanation for the different FL of the MGAS during take-off of the fast DJs (Table 3). In addition,
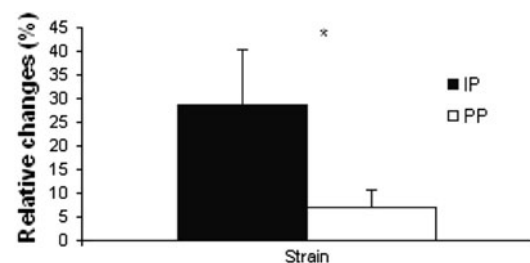
* = the relative increases were significantly greater for IP than PP, p<0.05

Fig. 4 The relative changes in aponeurosis strain (MGAS) for incline plyometrics group (IP, closed) and plane plyometrics group (PP, open)

increases in tendon elongation after training may lead to a higher amount of elastic energy stored during the braking phase which is released during the subsequent propulsive phase (Kubo et al. 2007).

The different adaptations in jump height between the two experimental groups may also be due to neural adaptations (Viitasalo et al. 1998), such as changes in motor unit recruitment (Van Cutsem et al. 1998) or muscle co-activation (Chimera et al. 2004). The increased MGAS activation (Fig. 3) for the IP group is indicative of a greater force

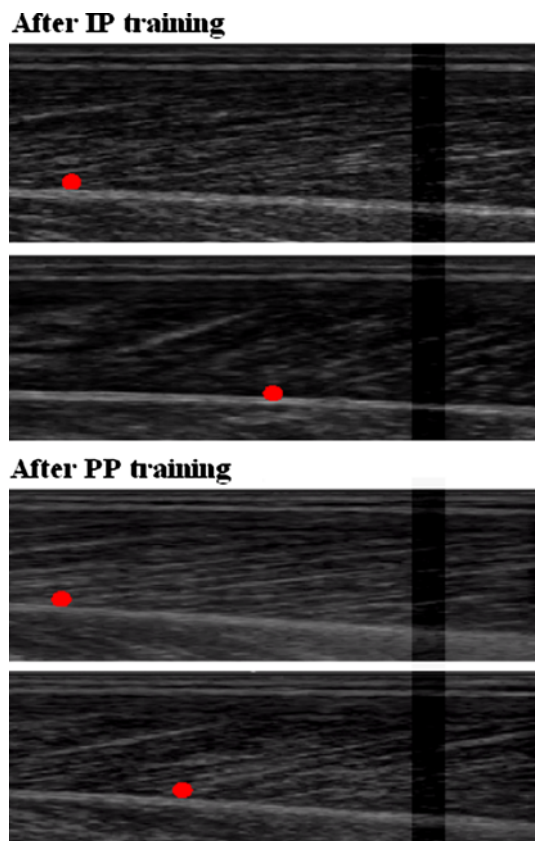**After IP training**

After PP training

Fig. 5 A typical example of deep aponeurosis elongation for incline plyometrics group (IP) and plane plyometrics group (PP)

production during propulsion, which is a very important phase for final jumping performance. This is in agreement with Kubo et al. (2007) who found that after 12 weeks of plyometrics training, plantar flexor EMG increased during the propulsion phase of jumping. It seems reasonable that IP training affected MGAS EMG activity during fast DJs, supporting the idea of task specific adaptations.

Training results may also be affected by changes in co-activation of antagonistic muscle groups around a joint. Our results showed no adaptations in muscle co-activation around the ankle during jumping (Table 2) for both training groups. These results are similar to some reports which suggest that plyometric or power training does not change the activity pattern of antagonist muscles during jumping (Kyrolainen and Komi 1995; Kubo et al. 2007). In contrast, there are studies which support that plyometrics training affects muscle co-activation, without any significant effect on final performance (Chimera et al. 2004; Kubo et al. 2007). However, most of these studies refer to knee muscle co-activation. Despite this, it could be suggested that the differences observed between the two groups are not due to co-activation adaptations.

In line with previous results (Duchateau and Hainaut 1984; Blazevich and Jenkins 1998) and the so-called specificity principle (the human muscle adapts specifically its

contractile properties to the type of contraction performed during training), both our training groups showed no significant improvements in muscle strength. Similarly, there were no changes in EMG activity as well as in FL and PA pre- and post- intervention, during strength measurements. The only significant effect was the increase of compliance of MGAS aponeurosis (Fig. 5). A change in aponeurosis properties may also affect the force–length relationship of the muscle–tendon unit (Kawakami and Lieber 2000). However, Lemos et al. (2008) showed that FL and PA were identical after increasing aponeurosis compliance, during maximal force production. Simulation data (Kawakami et al. 1998) showed that increases in compliance would lead to diminished level of force production even if muscle force capability was increased. Consequently, it could be suggested that the increased compliance of the aponeurosis during maximum strength tests might be responsible for the lack of strength differences after training.

In conclusion, fast DJs' height increased after 4 weeks of incline hopping exercises, while no effect was found after training on a plane surface. Training at inclined surface increased aponeurosis strain, normalized FL of the MGAS during take-off and EMG of MGAS during propulsion of fast DJs. These factors possibly enabled MGAS muscle to produce more force and contribute to an increased performance after incline hopping training.

Perspectives and limits

The benefits of plyometric training on jumping ability have been previously established. However, training effects are largely affected by various factors, the most important being the type of exercises chosen. Plyometrics often consists of general jumping exercises, most of which fail to focus on a particular joint (Foure et al. 2009; Spurrs et al. 2003). Our study shows that incline hopping exercises are particularly effective in increasing fast drop jumping performance.

The acute effects of the incline training seem to be promising. However, special caution has to be given on the possible tendon adaptations due to the extreme stretching which is offered during incline plyometrics. To our knowledge no data exists on long-term effect of such training. Further research is required to study in detail such training exercise programs and their possible adaptations on jumping performance.

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